A Compact Retarding Potential Plasma Analyzer

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Abstract

Since the beginning of in-situ plasma measurements there has been extensive use of instruments utilising a retarding potential for the determination of the energy of the detected particles. Most of these instruments, however, were detecting the total current generated from the incidence of the charged particles onto a collector. The limitations of the current measuring equipment's sensitivity and the expected plasma density dictate the size of the collector area. In the current trend for cheaper, faster, smaller missions this could be a significant limitation. Presented here, is a retarding potential analyser (RPA) utilising a microchannel plate detector and, thus, offering great scope for miniaturisation. The sensor incorporates a dual RPA structure to prevent UV generated events. The above structure gives a differential energy response with a FWHM that depends on the percentile voltage difference of the two RPAs. Due to the fact that there is no direct path from the entrance of the instrument to the detector, the energy response is highly dependent on the shape of the grid that supports the second RPA. The CID was flown upon the STRV 1A spacecraft, where its primary role was to provide information on the effectiveness of the Active Neutralizer Experiment in reducing the spacecraft potential. A preliminary analysis and validation of the collected data is presented here.
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CHAPTER 1

Review of retarding potential analyzers

(Principles of operation and design characteristics)

One of the constantly recurring problems in particle physics is the measurement of the total kinetic energy of a stream of charged particles. A commonly adopted solution to this problem, both in laboratory tests and in in-situ space plasma measurements, is the use of a retarding electrostatic field where the kinetic energy of the particles is deduced from the height of a potential barrier that they can just surmount.

Two types of instrument operating on the above technique have been extensively used for space missions. The Langmuir probe (LP) and the Retarding Potential Analyzer (RPA). Both types give measurements of a current (I) flowing when a variable voltage (V) is applied either on the probe surface (LP) or on a grid (RPA). Density, temperature and spacecraft potential can be determined from the obtained I(V) curve.

As both of the above types of instrument have been used for in-situ plasma measurements for about 40 years, the literature available for them is very extensive. Based on this information, the operation characteristics of those two types of instrumentation will be presented in this chapter, along with the most important developments they have undergone over the years.
1.1 Langmuir Probes

Langmuir probes have been used for many years on rockets and satellites to perform in-situ measurements of the electron temperature, $T_e$, electron and ion density, $N_e$ and $N_i$, and the spacecraft potential, $V_s$, relative to the plasma. Most of the following discussion is limited to cylindrical probes, which is the most frequently used probe geometry. Much of it, however, applies to LP’s of any geometry (i.e. spherical, planar). The first cylindrical probes to be used in space were 23cm long, thin (0.056cm) stainless steel wires (Brace, 1998). On later missions (i.e. Dynamics Explorer; Krehbiel et al., 1981) the LP’s were shorter and had larger diameters (5 x 0.4cm).

1.1.1 Overview of the measurement method

The typical volt-ampere curve (fig. 1.1) illustrates how the measurements are deduced from the curves. The curve represents the sum of the ion and electron currents, $I_i$ and $I_e$, collected from the plasma surrounding the sensor by repeatedly sweeping the collector voltage $V_a$ with respect to the spacecraft potential $V_s$. The curve originates in the ion saturation region where the probe potential is sufficiently negative to prohibit plasma electrons from reaching it. Thus, at this point, the collected current is primarily due to ions. In the electron retardation region, where the LP potential is less negative, some of the electrons overcome the potential barrier and produce an exponentially increasing current. The temperature, $T_e$, determines the power of the exponential, with lower $T_e$ yielding a narrower retarding region. In the electron saturation region, the probe is positive with respect to the plasma potential, $V_p$, and, thus, attracts electrons.

The first step in the analysis of the volt-ampere curve is to employ the LP current equations to fit the ion saturation and electron retardation regions in order to obtain $N_i$. 

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Figure 1.1. A typical Volt-Ampere curve. The sweep voltage $V_a$ is applied with respect to the spacecraft floating potential $V_s$. $N_i$, $N_e$ and $T_e$ are derived from different parts of the curve as discussed in the text (Brace, 1998).

$T_e$ and $V_p$. The plasma potential is taken as either the last point in the retardation region that provides a good fit to the exponential, or the inflection point between the electron retardation and saturation regions. All potentials referred to in the following Langmuir probe equations are measured with respect to this point. Once $V_p$ has been determined, the electron saturation region is fitted to obtain $N_e$. The following equations were derived and published by I. Langmuir and J. M. Mott-Smith in 1926 (Brace, 1998) and apply to orbital-motion-limited collection. To remain orbital-motion limited, the collector radius must be small compared to the Debye length applicable in the plasma region where the measurement is taken. The electron saturation current is given by
\[ I_e = N_e A e 2\pi^{1/2} \left( \frac{kT_e}{2\pi m_e} \right)^{1/2} (1 + eV/kT_e)^{1/2} \]

where:

- \( A \) = probe surface area
- \( e \) = electron charge
- \( k \) = Boltzmann constant
- \( m_e \) = electron mass
- \( V \) = probe potential relative to \( V_p \)

In equation 1.1, 1 represents the random electron flux that strikes an uncharged cylindrical probe and \( eV/kT_e \) represents the additional current that is collected when the probe is positive with respect to \( V_p \). For LP bias voltages where \( eV/kT_e \gg 1 \) the electron saturation current becomes essentially independent of \( T_e \), thus, allowing measurement of \( N_e \) without knowledge of \( T_e \).

The \( N_i \) is derived from the ion saturation current which is described in equation 1.2 for the case where the ion velocity vector is perpendicular to the probe axis.

\[ I_i = A N_i q_i v_i \pi^{1/2} \left( 1 + \frac{kT_i}{m_i v_i^2} + \frac{2eV}{m_i v_i^2} \right)^{1/2} \]

where:

- \( q_i \) = ion charge
- \( v_i \) = ion drift velocity in the spacecraft rest frame
- \( T_i \) = ion temperature
- \( m_i \) = mean ion mass
The three terms in equation 1.2 represent, in order of appearance, the current produced by ions swept out by the side of the collector moving at spacecraft velocity, additional ions that reach the probe through their own thermal motion and finally, ions that are attracted to the probe by its accelerating potential.

The \( T_c \) is derived from the equation for the retarding region, which applies to LP's of any geometry,

\[
I_c = A N_e e^{(kT_e / 2\pi m_e)^{1/2}} \exp(eV/kT_e)
\]  

(1.3)

The effect of increasing \( T_e \) is to increase the retarding potential required to cut-off thermal electrons and achieve ion saturation. The width of the retarding region is proportional to \( T_e \).

1.1.2 Measurement accuracy

The expected accuracy is given as better than 10% in general, about 5% for \( T_e \). Depending on the electrometer noise level and the interference from other spacecraft systems, the density can be measured with even higher precision (Brace, 1998).

There are two types of factors that can affect the LP measurement accuracy:

1. Limitations inherent in the technique

Photo-emission can introduce errors in the measurement of \( N_e \) at densities less than \( 10^2 \text{cm}^{-3} \) where the background currents become comparable to the plasma electron generated ones. The same limitation applies for the measurement of \( N_i \) but the density limit is even higher \( (<<10^4 \text{cm}^{-3}) \). In the absence of sunlight, the density limits are reduced to 1-10cm\(^{-3}\) for electrons and \( 10^2 \text{cm}^{-3} \) for ions. Since plasma neutrality requires \( N_e \) to equal \( N_i \), researchers use either of the two measured densities depending on the
level of confidence they offer. In particular, the measurements in regions with higher density (\(\sim 10^5 \div 10^6 \text{cm}^{-3}\)) are used for the determination of a normalisation factor which in turn is used for the calculation of low densities. Generally, the ion density measurements are more accurate for densities down to \(2 \times 10^4 \text{cm}^{-3}\) which is, typically, the point of switch-over from \(N_i\) to \(N_e\).

2. Implementation issues

For successful LP measurements, the following conditions are critical:

a) **Proper sensor placement.** In order to make sure that the probe is placed in the undisturbed plasma, a boom is required (30 to 100 cm-long in the ionosphere). Two independent probes (orthogonal to each other) are required in spinning satellites to assure that at least one is in the undisturbed plasma at all times.

b) **Collector surfaces.** The accuracy of the temperature measurements is affected by the characteristics of the sensor surface (Krehbiel et al., 1981). The work function of different crystal surfaces can vary by as much as several tenths of a volt and thereby introduce an uncertainty in the value of \(V\) in equations 1.1 to 1.3. Chemical vapour deposition of oriented metal crystal (rhenium pentachloride in Dynamics Explorer-2; Krehbiel, 1981) produces surfaces with potentials uniform to within 5 mV.

c) **Probe contamination.** Sensor contamination by spacecraft outgassing or other sources can have an effect similar to the above. This can be prevented by either bake-out of the sensor surface at high temperatures (>300°C), which poses relatively high demands on the power supply of the vehicle, or by high energy ion and electron bombardment. In DE-2 the latter method was successfully implemented by application of a 150 V bias on the probe surface.

d) **Magnetically induced potentials.** When a spacecraft moves through the geomagnetic field, \(B\), at a high velocity, \(v\), a potential gradient is induced in the
collector. The induced potential \( V = B \times v \cdot \ell \), for a collector of length \( \ell \) can produce the same kind of error as probe contamination or surface work function patchiness. This error can be reduced by using short probes (small \( \ell \)) or, if feasible, by aligning the probe with either \( B \) or \( v \). The maximum voltage induced on the short probes flown on DE (5cm) was 15mV (Brace, 1998).

e) Electronics. The task of the electronics is to apply the required range of \( V_a \) to the LP and to measure the resulting currents. In the ionosphere the density varies over 5 to 6 orders of magnitude thus, the electrometer must have a wide dynamic range. In early flights (prior to 1970) this was achieved by sequencing through two voltage sweep amplitudes and four electrometer ranges. In more recent missions (i.e. DE, Krehbiel, 1981) use of adaptive electronics was employed. For the LP’s on DE, the electrometer gain was set using the ion current at the beginning of each cycle (full scale was defined at -3.3V). Then the \( V_a \) is swept at the rate that was determined by the plasma conditions during the previous sweep. If the predicted conditions (the framing) are correct, the electrometer output will rise at 1.41V and then to 9.5V (the defined electron saturation current level). At this point the electrometer gain was dropped by a decade and the electron saturation current was measured again at the final \( V_a + 2V \). Successful framing meant that only the values of gain settings, sweep amplitudes and sweep biases needed be stored allowing a full sweep to be performed every half second. However, a small number of raw volt-ampere curves were stored for verification or calibration of the in-flight measurements.

f) Spacecraft design. Since LP measurements are always made with respect to \( V_s \), the spacecraft potential, the \( V \) in equations 1.1 to 1.3 is modulated by \( V_s \). It is, therefore, necessary that the spacecraft design has incorporated steps to assure a stable value of \( V_s \) near 0V. The steps that are typically taken are: (1) Sufficient external conducting
area to return the LP collected current back to the ionosphere; and (2) negative solar
arrays (positive ground), to avoid drawing an electron current greater than the rest of
the spacecraft is able to return to the ionosphere. The LP on DE-2 was designed to
operate fully over a range of \(-5V \leq V_s \leq 5V\) and, with reduced effectiveness, at up to
two additional volts of \(V_s\).

1.2 Retarding Potential Analyzers

This section will be concerned only with planar RPAs (i.e. spherical RPAs or
SRPAs are excluded) since they have been the most commonly used in space flight and
the principles of operation are applicable to every type.

The RPA technique can be extended well beyond the energy range of the LP (to
several keV) making it useful for studies of solar wind and lower energy
magnetospheric plasmas.

1.2.1 Operation characteristics of a basic RPA

Figure 1.2a illustrates a RPA in its simplest form. The particles, of charge \(e\), are
assumed to enter from the left in a beam of infinitesimal extend and perfect collimation
with kinetic energy \(E = e V_o\). They are retarded by the axially directed electrostatic
field between the electrodes and are collected at plate C. If \(V_o > V_1\), they will reach the
plate, be collected and appear as a current \(i_i\); if \(V_o < V_1\), they will be repelled. Hence,
if the beam is monoenergetic, the I-V characteristic (the current \(i_i\) as a function of the
retarding potential \(V_1\)) will be as shown in Figure 1.2b. This infinitely sharp drop of the
Figure 1.2. (a) A basic RPA. (b) Ideal retarding potential cut-off curve. (c) Usual cut-off curve. The slope at the rise is due to trajectory effects. The effect of reflection is shown in the dotted curve (Simpson, 1961).
current is characteristic of an ideal curve. If contact potentials are not present (i.e. neglecting the work function of the collector), the total kinetic energy of the particles is $eV_2 = eV_o$. The usual design problem in RPAs is to achieve to some desired approximation the ideal curve.

The infinitesimal collimated beam is an idealisation. Real streams of particles have a finite diameter, $r_o$, and a finite angular aperture, $\theta$. In parallel plate geometry, the finite diameter causes no difficulty, but the angular dispersion means that the kinetic energy of the particles is divided into parts associated with the axial and transverse components of their momentum according to the relation:

$$\frac{\text{transverse energy}}{\text{axial energy}} = (\tan \theta)^2. \quad (1.4)$$

Since only the axial momentum will be effective in overcoming the retarding potential, the curve cut-off for a finite angular aperture will have a base width (Fig. 1.2c) of

$$\Delta V/V_0 = \Delta E/E = 1 - \cos^2 \theta = \sin^2 \theta. \quad (1.5)$$

$\Delta E$ then represents the limiting resolution of this retarding geometry and in principle can be reduced to any desired level by aperturing the beam in angle.

In practice, however, this resolution is not available, since it is necessary to provide a hole in one plate for the beam to enter. When this is done, $\Delta E$ has a fixed lower limit due to the lens effect at the hole. Near the axis, in the plane of a circular aperture between two fields of strength $E_1$ and $E_2$, there exists a lens whose focal power for particles with energy $eV_o$ is (Simpson, 1961)
\[ \frac{1}{f} = \frac{(E_2 - E_1)}{4V_o}. \quad (1.6) \]

In the case of a planar RPA with an interplate distance \(d\) and the collector at potential \(V_o\) we get

\[ \frac{1}{f} = -\frac{1}{4d} \quad (1.7) \]

where the negative sign signifies divergent action. Hence, a parallel beam after passing through an entrance aperture of radius \(r_o\), will have a divergence of

\[ \sin \theta = \frac{r_o}{f} = \frac{r_o}{4d} \quad (1.8) \]

and the limiting resolution will be

\[ \frac{\Delta E}{E} = \sin^2\left(\frac{r_o}{4d}\right) \quad (1.9) \]

or for small angles

\[ \frac{\Delta E}{E} = \frac{r_o^2}{16d^2}. \quad (1.10) \]

Another problem is that the particles, arriving at the collector, may not all be collected. Charged particles hitting a surface give rise to secondary electrons, the number of which is a function of incident energy. We can thus, define a reflection coefficient, \(R\), as the ratio of the number of electrons leaving the surface to the number
of incident particles. The effect of reflection on the characteristic curve is shown in Figure 1.2c (dotted line) where R increases with the energy of the incident particles.

1.2.2 Review of RPA designs for space flight

The instruments used for in-situ plasma measurements have been more sophisticated than the one described in the previous section. The following review presents instruments with historical significance as well as the main design developments they have undergone over the past 40 years.

1. The charged particle traps on LUNA 1, 2 and 3. One of the simplest designs flown is illustrated in Figure 1.3. It was the first RPA to measure extraterrestrial plasmas. Four of these instruments were used to study the interplanetary ionised gas from a Soviet cosmic rocket sent to the moon on September 12 1959 (Gringauz et al., 1960). Three rockets were sent to the moon but the data presented were mainly obtained during the flight of the second rocket. The four ‘charged particle traps’, used on the second rocket, comprised three electrodes: An external hemispherical grid (the shape of this grid makes this sensor an SRPA) with a 30mm radius; a plane grid; and a plane collector. The potentials of the electrodes relative to the body of the container were: collectors, \( \phi_k = -60 \) to \(-90V\); internal grids, \( \phi_{e1} = -200V\); and external grids, \( \phi_{e2} = -10, -5, 0 \) and 15V respectively. The main purpose of the internal grids was the suppression of photoelectrons produced by the incidence of the sun’s UV radiation upon the collector and by the secondary electrons produced on the collector when bombarded by electrons and protons. The four instruments were sensitive to electrons with energies greater than 200eV and to all ions, with the exception of the fourth trap.
Figure 1.3. Schematic of the three electrode charged particle trap. 1) Body of the container; 2) external grid; 3) internal grid; 4) collector (Gringauz et al., 1960).

Figure 1.4. Schematic of the modulated faraday cup (Bridge et al., 1960).
which accepted only ions with energy greater than 15eV. No voltage sweeping was used.

2. **The Modulated Faraday Cup (MFC).** This instrument was first presented by Bridge (Bridge et al., 1960) and it was flown initially on Explorer 10 in 1961 (Bonetti et al., 1963). Instruments based on the same technique, however, are still used for space flight. Figure 1.4 is a schematic of the instrument originally presented by Bridge. It is basically a Faraday cup with four grids placed in front of the collector. The main reason for the development of this instrument was the suppression of photoelectric currents generated when the cup faced the sun. The photoelectric current is of the order of $10^{-8}$ A cm$^{-2}$. Although this current can be easily suppressed by placing another grid in front of the collector and maintaining it at a few tens of Volts negative with respect to the collector (as in the ion traps above), there remains a reverse photocurrent produced by light reflected from the collector onto this suppressor grid. Photoelectrons emitted from the suppressor grid produce a current that reduces the measured proton current. This reverse current could be as much as 10% of the direct current and, thus, it would cause large difficulty in the measurement of proton current densities.

This difficulty is overcome by modulating the collected current using an alternating electric field. The modus operandi of the MFC can be seen in Figure 1.4. Grid 1 is kept at the potential of the vehicle skin (to prevent interaction between the ambient plasma and the retarding potential); Grid 2 modulates the incoming ions by means of a square wave voltage which is periodically positive with respect to the vehicle (in this application the RP values were: 10, 30, 100, 300, 1000, 3000V). Grid 3, also at vehicle potential, serves as an electrostatic shield between the modulating grid and the
collector (preventing capacitive coupling between Grid 2 and Collector). Grid 4 (the secondary electron and photoelectron suppressor) is maintained at about 100V negative with respect to the collector which is close to the vehicle potential. During the part of the modulating cycle when the voltage on Grid 3 is zero (the spacecraft potential), ions and electrons flow into the MFC. The electrons are repelled by the negative potential on Grid 1 but the ions reach the collector. When the modulation voltage is positive and equal to or greater than the energy of the incoming ions, the ions cannot pass Grid 3. The electrons are first accelerated and then decelerated by Grid 3 and arriving on Grid 1 are repelled as before. There is, thus, an alternating current signal at the collector caused by the arrival and non-arrival of ions. The photoelectrons from the Collector and from Grid 1, are not influenced by the modulating voltage because they are shielded from it by Grid 2. Therefore, the photocurrent gives a DC but no AC signal. The AC signal is amplified and demodulated to provide a DC output voltage. A narrow band filter centred on the modulation frequency (1.5kHz in the original instrument) is used to improve the signal to noise ratio. The MFC presented by Bridge et al. (1960) had an effective collector area of 25cm² which, combined with the fact that the narrow band noise corresponded to an input current of $2 \times 10^{-11}$A, allowed for a minimum detectable current density of about $10^{-12}$Acm². For the sake of absolute correctness, it should be noted that the MFC flown aboard Explorer 10 used two separate modulator grids connected to two separate power supplies. One supply provided the low voltage levels of 5, 20, 80V and the other the levels of 250, 800, 2300V both at a square wave frequency of 1.4kHz. Grid 4 was biased at -130V. The combined transparency of all the grids was 23% which gave an effective collector area of 28cm² (actual collector surface 121cm²).
A distinction can be made now (based on the collector produced signal) between DC and AC RPAs. The AC RPAs offer better photocurrent rejection and thus, are suitable for missions where measurements in the sun direction are required (i.e. solar wind measurements). Even the DC RPAs, however, can yield accurate data provided that they operate at relatively high plasma densities and the photocurrents generated are slowly varying with time. In the years that followed the first missions, RPAs have improved in two ways: a) the number of grids utilised has increased in order to achieve uniform electric fields as will be discussed in more detail in the following section; and b) the available electronics systems for measurement and control have allowed onboard operations to be performed on the acquired data, thereby, reducing the required capacity for data storage. The details of two instruments (one DC and one AC RPA) built in the late 1970s are indicative of the design features of the modern RPAs.

3. The DC RPA on the Pioneer - Venus Orbiter (PVO) (Knudsen et al., 1979). The PVO RPA (ORPA) was designed to measure most of the plasma parameters within and near the Venusian ionosphere. Instrument design. The sensor had seven grids (Fig. 1.5) 6cm in diameter covering nearly the whole sensor front (8cm diameter). The large entrance grid, Go, and the small (1.9cm diameter) collector, C, surrounded by a guard ring, GR, provided for a radially uniform particle flux around the sensor axis. The collector sampled either electrons or ions from the uniform central region. Thus, disturbing field effects at the grid edges were avoided. The first two grids were connected together to reduce the electric field produced outside the sensor by the stepping retarding potential. The retarding grid G2 was also a double grid which provided a reasonably uniform retarding field in the photoelectron mode (the instrument was operated in three
different modes which will be discussed shortly). The grids G₀, G₁ (the ion suppressor grid) and G₂ were coated with Aquadag, a graphite emulsion, to achieve a uniform surface potential. All other conducting sensor parts were gold plated. Grid G₃ was the displacement current shield and grid G₄ was the electron suppressor. All grids had an optical transparency of 0.82 except G₄ with transparency of 0.9. An Aquadag coated aluminium ground plane of 30cm diameter (placed around the sensor entrance) was used to provide a plane plasma sheath.

**Modes of operation.** The sensor used three different voltage programs to measure electrons, ions and photoelectrons.

a) Electron mode

C and GR were both set at 47V making the collected ion current negligible. A potential difference of 20V was applied between grid G₄ (at 27V) and C to suppress most of the secondary electrons. G₀, G₁ and G₂ acted as the RPA grids and they were stepped together from 6.8 to -4.2V (with respect to satellite ground) in 64 -0.176V steps. For higher accuracy, 20 finer steps of -0.044V (covering five coarse steps) could be used.

b) Ion mode

Here G₀ was set at either 0V or -4.6V with respect to the spacecraft. G₁ and G₂, acted as the RPA grids and were stepped together in the range of -0.1 to 36V (referenced to the plasma potential) at 80 steps of \( J \times 0.011V \), where \( J = 1, 79 \). G₃, C and GR were all set at -4.6V and G₄ at -24.6V.

c) Photoelectron mode

The ambient photoelectron integral flux was measured with G₀ set at 0V, G₁, G₃, C and GR set at 47V and G₄ at 27V. G₂ was stepped through the range of 0 to -50V in 48 steps of \( J \times 0.044V \).
Figure 1.5. Schematic of the ORPA grid arrangement. (Knudsen et al., 1979).

GRID DESIGNATORS
G1 - INPUT (DUAL 50/100)
G2 - RETARDING (DUAL 100/50)
G3 - SUPPRESSOR (100)
G4 - SHIELD (50)
APERTURE = 12.57 cm²
OPTICAL TRANSMISSION = 0.391
Aeff = 4.91 cm²

Figure 1.6. Schematic cross section of the RPA for DE-2. The numbers in parentheses describing the grids, give the number of 1mil wires per inch. The nominal grid element separation is 2.5mm (Hanson et al., 1981).
The ORPA remained in the same mode for complete spacecraft spin.

The collector current was amplified by a linear electrometer with sensitivity of approximately $6 \times 10^{-13}$ to $1.3 \times 10^{-4}$A in eight overlapping ranges. The electrometer went into a zero adjust sequence after every scan. A background compensation circuit was incorporated in the electronics. Before every retarding scan, with the retarding potential at its maximum value, the background current produced was compensated until the electrometer voltage output (in the range of $0 - 10$V) was below $0.5$V. Currents in the range of $10^{-8}$ to $3 \times 10^{-12}$A could be compensated. The compensation current was held fixed for the duration of the next scan. The scan together with zero and background current adjustments typically required $0.3$s. Thus, approximately 40 scans could be completed during one spacecraft spin cycle.

4. **The RPA on Dynamics Explorer - 2 (DE-2)** (Hanson et al., 1981). This instrument could in fact operate as both a DC and an AC RPA to measure the energy spectrum of thermal ions. Figure 1.6 shows a schematic of the sensor. The two entrance grids, $G_1$, were kept at spacecraft potential, while the next two grids, $G_2$, were the retarding ones with the voltage applied to them being in the range $0$ to $32$V. Grid $G_3$ was the suppressor (kept at $-15$V) and $G_4$ was the collector shield kept at vehicle potential. The collector was also at virtual ground. The modulation of the ion current was achieved by superposition of a $3.4$kHz voltage with peak to peak amplitudes of $0, 25, 50, 100, 200, 300, 450$ and $600$mV. The dwell time at each RPA voltage step was either $16$ms or $32$ms.

From the above two sensor examples, it is obvious that DC and AC RPAs differ only in the produced signal with their design been dictated principally by the measurement objectives of the mission. It should be noted, however, that MFCs offer better noise rejection and the advantage of a selectable $\Delta E/E$ response.
5. **Other RPA designs and applications.** Most RPAs have had acceptance angles of 45° to 60° (as dictated by the dimensions of the instrument and the grid transmission reduction with angle of incidence) although, in principal, smaller acceptance angles are possible. Since the usual Faraday cups are cylindrically symmetric, their transmission function depends only on energy and the polar angle with respect to the direction along the axis of the cup. Consequently, the measurements provide no information on the azimuthal angle of incidence of the plasma. This limitation can be overcome, to some extend, by splitting the collector into several segments (usually two to four). The MFC used in the M.I.T. plasma experiment on Pioneer 6 (Lazarus et al., 1966) had its collector split into two segments and a collimator that limited the angular acceptance range to ± 20° in the azimuthal direction while allowing the usual range of ± 60° in the 'vertical' direction (Fig. 1.7).

![Figure 1.7. Schematic of the M.I.T. RPA on Pioneer 6. The modulator grid voltage varied between V₁ and V₂ at 1800cps (Lazarus et al., 1966).](image-url)
The ion drift meter (IDM) on DE-2 (a slightly simpler Faraday cup based design than the one discussed above from the same spacecraft) had its collector split in four segments and a square entrance aperture serving as a collimator (Heelis et al., 1981).

Retarding potential grids have been used to provide ion energy measurements in ion mass spectrometers utilising magnetic field and individual particle detectors (as opposed to current collectors) i.e. the Energetic Ion Composition Spectrometer (EICS) on DE-1 (Shelley et al., 1981) and the Retarding Ion Mass Spectrometer (RIMS) on DE-1 (Chappell et al. 1981) which, in addition to a particle detector, used a current collector for the lower part of the orbit where the particle detector was turned off in order to be protected from very high count rates.

Another very interesting design is the Differential Ion Flux probe (DIF probe) flown on Spacelab 2 (Stone et al., 1985). It consisted of an electrostatic deflection and collimation system (EDCS) mounted in front of an RPA. Figure 1.8 is a schematic of the flight model DIF probe sensor head. A stream of ions arriving at the entrance slit with an angle of attack \( \theta \), which lies in a plane perpendicular to the collimation slits (the analysis plane), and with some energy \( E \), will be deflected through the exit slit by application of a specific voltage \( \phi_d \), of opposite polarity to the deflection plates. At any given deflection potential, the field of view in the analysis plane is limited by the EDCS to \( \Delta \theta \). Therefore, by sweeping \( \phi_d \), the probe can differentially scan over the range of \( \pm \Omega \). For a different ion energy a different \( \phi_d \) is required to deflect the ions the same amount for any given value of \( \theta \). Thus, the EDCS can be viewed as a filter which at any given \( \phi_d \) it admits only ions satisfying a relation \( f(\theta,E) = \phi_d \), where \( f \) is a characteristic of EDCS. After passing through EDCS the ions enter the RPA section at an angle \( \alpha \), which is much smaller than \( \theta \), and their energy \( \phi_r \) is measured. Knowledge
Figure 1.8. Functional schematic of the DIF probe showing a cross section perpendicular to the deflection plates and collimation slits (Stone et al., 1985).
of $\phi_d$ and $\phi_r$ can be used to determine the $\theta$ and $E$ of the ions. Simulations and calibration measurements yielded the following values: $\Delta\theta = 5^o$, $a \leq 5^o$ and $\Omega = 60^o$.

1.2.3 Measurement of ionospheric quantities from RPA data

As it has already been discussed, the RPA measures the current collected with respect to the retarding voltage applied. The ion current is given by (Knudsen, 1966):

$$I = A \cdot Tr \cdot e \cdot u \cdot \cos\alpha \cdot \sum_j N_j \left[ \frac{1}{2} + \frac{1}{2} \cdot \text{erf}(\kappa_j) + \frac{\exp(-\kappa_j^2)}{2\sqrt{\pi} \cdot \alpha_j} \right]$$

(1.11)

with

$$\kappa_j = \alpha_j - b$$

$$\alpha_j = \frac{u \cdot \cos\alpha}{c_j}$$

$$c_j = \sqrt{2 \cdot k \cdot T^+ / M_j}$$

$$b = \sqrt{e \cdot (V + \phi) / k \cdot T^+}$$

where $e$ is the electron charge, $u$ is the ion velocity relative to the satellite, $a$ is the angle of attack, $Tr$ is the grid transparency, $A$ is the grid area, $V$ is the retarding voltage and $\phi$ is the potential of the instrument surface relative to the plasma. $N$ and $M$ are the concentration and the mass of the ionic constituent (denoted by $j$) respectively.

The shape of the characteristic curve depends on ion temperature, the ionic masses, the velocity of the RPA and the ratios of ion concentrations. The ionic concentrations, in addition to the other plasma quantities (temperature, instrument potential), can be derived by a least squares curve-fitting technique (Patterson, 1969) provided that the
constituent ion masses are specified. Alternatively, of the current with respect to the retarding voltage may be used. This can be written in the form (Knudsen, 1966):

\[ \psi = \sum_j \psi_j \]  

(1.12)

where

\[ \psi = -\frac{\sqrt{\pi} M_1 c_1}{\text{Tr} A e^2 N_1} \frac{dI}{dV} \]  

(1.13)

and

\[ \psi_j = \frac{N_j}{N_1} \left(\frac{M_1}{M_j}\right)^{1/2} \exp[-(\alpha_j - b)^2] \]  

(1.14)

where the subscript 1 is used to represent the dominant ionic species. As we have seen in the previous section, the derivative can be obtained electronically which is potentially advantageous as it offers mass differentiation and better noise reduction, thus, yielding higher accuracy values for total density; \( N = \frac{I}{A \text{ Tr e u cosa} \right), where I is the measured current at zero or very low RPA voltage (Knudsen et al, 1979). According to Heelis and Hanson (1998), however, the use of modern analogue to digital converters and fast computers can equalise most of these advantages over using the original I-V characteristic.
Figure 1.9. The different I-V characteristics observed in the ionospheric environment of Atmospheric Explorer serve to illustrate the advantages and difficulties in retrieving ionospheric parameters from a RPA with a solid conductor collector (Heelis and Hanson, 1998).

Figure 1.9 illustrates the mass discrimination ability of a planar RPA with a solid conductor collector. The RPA mass discrimination ability is relied upon the spacecraft velocity being large relative to the ions' drift velocity. When the dominant ions are well separated in mass they can be easily resolved in the I-V curve. At Panel 1 (Fig. 1.9), the \( H^+ \) or \( He^+ \) peak is distinguished from the \( O^+ \) and \( N^+ \) peak which is, in turn,
distinguishable from that of their molecular counterparts (Panels 2 to 5). The resolution limitations are clearly shown in Panel 6, where the NO\(^+\) and O\(_2\)\(^+\) ions (with atomic mass units of 30 and 32 respectively) produce a single peak. The Fe\(^+\) peak in Panel 3 was produced by meteoric ions.

1.2.4 Sources of error

The theoretical expression given in equation 1.11, is based on the assumptions that: a) the plasma sheath boundary is plane and parallel to the RPA face; b) the planes of the grids are equipotential surfaces; c) the grids and the collector are infinite in extent; and d) the transparency of the grids is neither a function of retarding potential nor of incidence angle.

Knudsen, 1966, using values representative of typical RPAs in low earth orbits and representative total ion densities (2 \(10^5\) cm\(^-3\)) consisting of O\(^+\) and molecular ions (NO\(^+\) and O\(_2\)\(^+\)) calculated that the effect of sheath curvature yields a maximum error of 9\% in the derived ion temperature (typically less than 2\%), negligible error in derived vehicle potential but a maximum error of 60\% in the derived ion density. Comfort et al., 1982, give the correction required for a curved sheath (arising from the dependence of the measured flux on the angle of incidence acceptance of a limited aperture RPA) within the thin sheath approximation. The thin sheath approximation can be used, irrespective of the Debye length, when \(|Z e \phi_{sc} / k T_i| \tan^2 \theta_p \ll 1\), where \(\phi_{sc}\) is the spacecraft potential relative to space and \(\theta_p\) is the instrument acceptance angle.

As we have seen before, the determination of the incoming particles' energy (normal to the RPA surface) is based on the condition that particles are detected only if \(mu^2/2 > qV_r\), where \(u\) is the particle velocity component normal to the sensor surface and \(V_r\) is the retarding potential. However, it is impossible to produce a true
equipotential plane with a conducting grid. The potential tends to 'sag' between the grid wires (Donoso and Martin, 1986; Donoso et al., 1986; Goldan et al., 1973), producing a non-uniform retarding potential. For the usual RPA configuration where the retarding grid is surrounded by two grounded grids in order to maintain the uniformity of the electric field, the largest deviation of the retarding potential occurs midway between the grid wires and is given by (Enloe and Shell, 1992):

\[
\frac{\Delta V_r}{V_r} = 1 - \left[ \frac{2 \pi (d / a) - \ln 4}{2 \pi (d / a) - 2 \ln(2 \sin(\pi r / a))} \right] \quad (1.15)
\]

where \( r \) is the radius of the grid wires, \( a \) is the distance between the centres of the wires and \( d \) is the distance between the grounded and biased planes. The consequence of a non-uniform retarding potential is a softer sensor response and an increased value for the derived particle temperature. For practical analyzer dimensions the error lies typically in the range of 5% - 10% (Goldan et al., 1973 calculated an effective retarding potential instead of the actual used to interpret the data from the RPA on OGO 4 and found that the originally calculated temperature was too high by at least 32%). From equation 1.15, the most obvious solution is to increase \( d / a \). Since there are limitations to the increase of \( d \) (Donoso et al., 1986) reduction of \( a \) is required, which means the use of fine meshes. These meshes, however, have reduced optical transmission (\( Tr = 0.5 \) for a 1000lpi mesh) and the gain in energy resolution is very small for \( d / a > 10 \). A solution that has been used extensively is the use of multiple grids biased at the retarding potential. Since multiple grids form a more uniform potential in the centre of the retarding region, coarser, more transparent, meshes can be used. Computer simulations of the retarding potential distributions in multiple grids, have
shown that the maximum fractional deviation of the retarding potential is reduced by more than a factor of 2 for each additional retarding grid (Enloe and Shell, 1992). For $d/a = 4.0$ and $r/a = 0.02$ the fractional deviation reduced from 18% for one grid to 0.7% for 5 grids.

Since the transparency of the grids depends on the angle of incidence of the incoming particles, a correction is required for $Tr$ in equation 1.11. Troy and Mayer, 1975, found that the error in temperature is negligible but the error in density increased linearly with the grid parameter (from 8.3% to 16.6% for grid parameter values of 0.1 to 0.2).

The assumption for infinite grid and collector surfaces (so that the existence of fringe fields near the walls of the sensor can be ignored) is valid provided that either the entrance aperture is limited, or the collector diameter is smaller than the sensor entrance, subject to an adjustment for the effective collection Area ($A$ in eq. 1.11). An error, related to the finite collector area, could arise from the use of a modulated retarding potential. If some of the incoming particles, having been deflected by the retarding potential in the plane perpendicular to the sensor axis, miss the collector only at the peak of the modulating potential, the alternating collector current they produce will be in phase with that of the rest of the particles ($180^\circ$ out of phase with the modulator). Usually the error imparted in the measured density from the above effect is only of the order of a few percent (Vasyliunas, 1971).

1.3 Case for a new RPA based design

As we have seen, most of the RPA designs flown to date, have used solid conducting collectors. Consequently, the sensitivity of the electrometer measuring the collected current, together with the plasma density in the region of interest and the
requirement for the measurement to be completed in the smallest possible time interval, dictate the size of the collector. For a 5cm$^2$ collector aboard a spacecraft orbiting the earth within the plasmasphere, the lowest measurable plasma density is 100cm$^{-3}$ (Heelis and Hanson, 1998). Typically Faraday cup RPAs (including electronics) have a mass of more than 2kg and a power consumption of a few Watts.

Since the current trend is the miniaturisation of the cost of unmanned space missions, which leads to smaller spacecraft with smaller payloads, it would be worth investigating the possibilities of miniaturising a RPA based instrument. The requirements imposed on the new instrument were a) to be sufficiently small and lightweight, so that it could be easily accommodated even on a microsatellite, b) to have a flexible ion optical layout so that it could be easily adapted for different applications, c) to cause minimal disturbance to the plasma flow when used in plasma chamber studies and d) to be electrically screened.

The design was chosen to be cylindrically symmetric in common to most planar RPAs. The use of a detector with sensitivity independent of its active area would greatly reduce the diameter of the new instrument. Particle detectors based on electron multiplication have been used in imaging instruments and spectrometers, including spectrometers with incorporated RPAs, for well over 30 years. However, the requirement for a high voltage power supply together with the sensitivity of those detectors to UV light seem to be the main deterrents for their usage in simpler RPA instruments. The detector chosen was a pair of microchannel plates (mcps) in chevron configuration (see Chapter 2) as it is much smaller than the other candidate, the channel electron multiplier (cem). It should be noted that the Rice University suprathermal ion detector aboard the ATS 1 was a modulated RPA using a cem particle detector (Freeman, 1968).
To fulfil the second requirement, a tubular stack assembly was adopted where most of the sensor components were simply either conducting or insulating ring shaped spacers (Fig. 1.10). Hence the ion beam collimator properties can be varied simply by using spacers of different thickness and apertures of different diameter. The inner diameter of the insulating spacers had to be larger than that of the conducting ones, so they would be ‘hidden’ from the charged particles, to prevent insulator surface charging.

Containing the whole sensor in an aluminium tube would provide the required electrical screening, as well as ease of mounting. Also, feeding the cables through the rear end of the cylinder would minimise plasma disturbance in chamber studies.
Figure 1.10. Photo of most of the components of a sensor with a tubular stack assembly. The ring spacers (conducting and insulating) are clearly shown as are the cylindrical sensor housing and the insulating sleeve where the sensor was contained.
CHAPTER 2

Equipment - Facilities utilised and Characteristics
of Microchannel Plate Detectors

2.1 Laboratory test equipment

The main components of the test equipment and the way they were set-up are illustrated, schematically, in Figure 2.1 and are described below in some detail:

a) Edwards vacuum system. This is the vacuum chamber where all the calibration tests took place. It was fitted with all the necessary feed-through connectors and, with the operation of a He cryopump, it could achieve pressures down to $3 \times 10^{-7}$mbar ($2.2 \times 10^{-7}$Torr), although, during the tests, the achieved vacuum was never better than about $2 \times 10^{-6}$mbar ($1.5 \times 10^{-6}$Torr). The chamber was vented with nitrogen which was found to be the main constituent in residual gas measurements with a quadrupole residual gas analyser (James 1998).

b) X-Y table. It provided movement of the ion gun along the vertical (Y) and the horizontal (X) axes. The X-axis was perpendicular to the axis of the ion gun (Z-axis). The X-Y table movements were controlled by a Personal Computer and had a minimum step of 1µm. There were no table movement diagnostics; i.e. there was no information of erroneous table operation. The position reading was done by the software, based on the user inputs.

c) Rotary table. It was the mount for the instruments to be tested. The selected speed
Figure 2.1. Schematic of the laboratory test set-up. The SDIB and termination boards were used with the CCL card (the sensor flight electronics unit). When the sensor (CID) was tested independently, the LeCroy supplied the HV.

was 200 steps/s with 1° of rotation corresponding to 36 steps. As in the case of the X-Y table, the position reading was software implemented.

d) Ion gun. The ion gun was the main particle source used during all the instrument calibration tests. Figure 2.2 illustrates the main ion gun components. Electrons emitted by the filament, biased at 100V below the selected ion energy, are accelerated towards the aperture of the chamber, which is biased at the selected ion energy.
Figure 2.2. Schematic of the ion gun. The gun was the main plasma source during the sensor calibration.

When they reach the aperture, they have enough energy to ionise the residual particles. The ions produced are accelerated outwards by the voltage difference existing between the chamber and the extractor. The voltage difference was set-up by a fixed voltage divider where $V_{\text{extractor}} = 91.2\% V_{\text{chamber}}$. The extractor aperture was 0.25mm in diameter. The ions exiting the extractor aperture acquire their final energy between the extractor and the grounded cylindrical electrode which is part of the Einsel lens used to focus the ion beam.
The Einsel lens comprised three cylinders with the middle one overlapping the other two. The middle cylinder was biassed at the focus voltage while the other two were kept at ground. The field distribution and the focussing characteristics of the above design can be determined only by numerical methods (Szilagyi, 1988). Since an ion gun performance simulation was never performed, the exact relationship between the ion beam details (diameter, angular distribution) and the focus voltage used is not known.

e) Custom made ion source. It was used to test the energy response of the instruments at low energies (<40eV). A current of ~0.7A was passed through a short piece of Tungsten wire biassed at -60V and the emitted electrons were accelerated towards a metal plate, which had a 1mm diameter aperture. The metal plate was biassed at the voltage corresponding to the required ion energy. The source was designed to be mounted only on the front end of the tested instrument. Hence it was not suitable for angular response tests. As the sensor body was always at 'ground', all ions, produced in the area between the metal plate and the sensor, were accelerated towards the sensor.

f) LeCroy HV power supply. The LeCroy system consisted of a mainframe and up to eight plug-in HV pods. Four types of pod were available: 3.3kV +ve, 3.3kV -ve, 7.0kV +ve and 7.0kV -ve. A positive 3.3kV pod with four outputs was used to supply the filament bias, the chamber voltage and the focus voltage into the ion gun. A negative 7.0kV pod provided the instrument's mcp detector voltage. A selectable current limit in the range of 5-511μA, as well as a fast current trip whenever a current surge of ~50μA occurred for ~50μsec, provided protection against detector damage due to HV breakdown.
g) **Brandenburg N10 power supply.** This provided 0 to 3000V and could be controlled either via a front panel thumbwheel switch (1V steps) or via an analogue voltage input. The latter option was preferred as it could be PC controlled by a parallel digital output driven into an external 8-bit DAC. The Brandenburg was used to supply the instruments’ RPA voltage.

h) **Faraday cup.** It had an entrance aperture of 3.4mm in diameter and it was surrounded by a ‘grounded’ shield with a coaxial aperture of a 2.8mm diameter.

i) **PC equipment.** A 386 PC running at 25MHz was used both to control the experiments and to store the acquired data. A GPIB board was installed in order to control the movement of the X-Y and the rotary tables as well as the output of some low voltage (0-30V) power supplies and the outputs of several digital multimeters measuring the actual voltages applied by the power supplies. Another board, incorporating both digital and analogue inputs and outputs, was used to output voltages (0-12.5V) and commands as well as to collect the instrument generated data.

j) **Signal processing circuit.** It comprised an Ortec 142B charge sensitive preamplifier, which drove the sensor anode signal to a 572 Spectroscopy Amplifier. The main amplifier had fine and coarse gain controls which were permanently set at 0.5 (coarse) and 20 (fine) giving a nominal 10X gain. The amplified and shaped pulse (0.5μs shaping time) was then fed to either a Canberra 8075 ADC (for pulse height analysis) or to a SCA (for plain data acquisition) and a counter. The ADC or SCA output was fed to the PC. The Canberra 8075 is a 14 bit Wilkinson (peak detector) ADC with a selectable resolution of 256 to 8k (the number of parts into which the full scale inputs can be divided). Both the ADC and the SCA had their ULDs set at maximum (~10V) and their LLDs set at either the corresponding flight electronics.
amplifier threshold or at a level that reduced the detector background events to a rate of <10 pulses/s.

2.2 Simulation software

This was developed by Dr. R.D. Woodliffe at Mullard Space Science Laboratory (MSSL). The simulation is basically in three parts. The first part involves the accurate determination of the electric potential inside the simulated instrument, taking into account and representing as accurately as possible its geometry and its specific design characteristics. This is accomplished by dividing the interior into a grid and determining the potential at each grid point. The potential at each point is related to the potential at its neighbouring grid points by the Laplace equation. If the grid is made sufficiently fine, then the Laplace equation can be expressed in terms of a Finite Difference equation relating each grid point potential to its closest neighbours. This equation will be different at each grid point, but if these equations are applied at successive points and this operation is repeated for many iterations, the potential at each grid point will converge to a good approximation of the true electric potential at that point. Having obtained an electric potential solution, it is then necessary to fit a cubic spline to the grid so that we may interpolate between the grid points and obtain the electric field anywhere inside the analyser. The final stage of the simulation involves trajectory tracing of a large number of ions through this electric field to obtain the analyser response. The full range of possible input parameters are used, i.e. a typical ion will begin its journey at a random starting position at the first collimator hole with a random energy and random direction (within the optical field of view of the sensor). The program performed 2D simulations on the assumption that the
instrument was cylindrically symmetric but, subsequently, it was re-written using cylindrical co-ordinates, to acquire 3D simulation capability.

2.3 Microchannel plates

As we have already seen in Chapter 1, a detector using mcps was preferred over a cem detector purely on size considerations. In the following sections, the basic mcp characteristics will be described and, where relevant, the cem properties will be cited. Most of the contents of the following subsections have been based on the works of Fraser (1989), Mullard Limited (1976) and Edgar (1993).

2.3.1 General description

A mcp (Fig. 2.3) is an electron multiplier consisting of an array (typically $10^4$-$10^7$) of tubes, called pores or channels, fused together in the form of a thin disc (typically ~1-2mm thick). Typical channel diameters are in the range 10-100μm and have length to diameter ratios (a) between 40 and 100. Microchannel plates (as well as cems) are manufactured (Fig. 2.4) from lead glasses with up to 48% lead by weight. The glass of the polished blank (penultimate step in Fig. 2.4) is then baked at a reducing hydrogen atmosphere, thus most of the lead is removed. This reduction process produces a highly resistive 0.1 to 1μm thick (Feller, 1991) semiconducting layer on the surface of the pore walls, which acts both as a continuous dynode and as its own dynode resistor chain. In particular, the secondary electron yield of the silica-like surface layer of the pores (5-10nm thick; Feller, 1991), which is depleted of lead and enriched with potassium.
Figure 2.3. Cutaway view of a mcp (Wiza, 1979).

and carbon, determines the mcp gain. At the final stage of the production process, metallic layers, usually nichrome or inconel, are vacuum deposited on to the polished surfaces of each mcp with, typically, a one channel-diameter penetration (or end spoiling). These layers act as electrodes which connect all the channels in parallel. Therefore, the total resistance between the two electrodes (mcp resistance) is the parallel combination of the resistance for each channel, which is typically in the range $10^8$-$10^9 \Omega$. 
Figure 2.4. Steps in the manufacture of mcps. A hollow billet of lead oxide cladding glass is mechanically supported by the insertion of a rod of etchable core glass and then pulled through a vertical oven producing a ‘first draw’ fibre of ~1mm diameter. Lengths of first draw fibre are then stacked together in a regular hexagonal array which is itself drawn to produce a hexagonal ‘multifibre’. Lengths of multifibre are stacked in a boule and fused under vacuum. The boule is sliced and the slices are polished to the required mcp thickness and shape. The solid core glass is then etched away, leaving the channel matrix to be fired in a hydrogen oven to produce a semiconducting surface layer with the desired resistance and secondary electron yield (Fraser, 1989).
2.3.2 Electron Gain

When a voltage $V$, of the order of 1kV, is applied to the end electrodes, an electric field $E$ is established which is parallel to the channel axis. The current per channel, $i_s$, given by:

\[ i_s = \frac{V}{R_{ch}} \]  

(2.1)

where $R_{ch}$ is the resistance of a single channel, flows through the semiconducting layer in each channel. If we take each MCP channel in isolation, it behaves as a cem; in fact the first MCP models were actually assembled from thousands of single channel electron multipliers ($\sim 150\mu m$ channel spacing) by bonding them together with a low melting point solder or frit glass (Wiza, 1979 and references therein).

2.3.2.1 The Straight Channel Electron Multiplier

When an electron collides with the channel wall, 6 secondary electrons may be produced. These electrons follow a parabolic trajectory (Fig. 2.5) and then collide with the opposite wall. The kinematics are such that $\delta^2$ secondary electrons are produced in the second stage, $\delta^3$ in the third, etc., so that the overall gain $G$ is given by:

\[ G = \delta^n \]  

(2.2)

where $n$ is the number of collisions along the length of the channel.

The time $\tau$ and distance $S$ between collisions for a straight channel with diameter $d$, is given by:
\[ \tau = d \sqrt{\frac{m}{2eV_0}} , \quad (2.3) \]

\[ S = \frac{1}{2} \frac{e}{m} \tau^2 , \quad (2.4) \]

where it is assumed that a) the electrons have been emitted normally from the wall with energy \( V_0 \) (~1eV) and b) that the electric field is uniform and parallel to the channel axis.

Figure 2.5. Electron multiplication in a straight channel multiplier (Wiza, 1979).

The electrons will collide with the wall with an energy

\[ V_c = E S , \quad (2.5) \]

\[ = \frac{V^2}{4V_0 a^2} , \quad (2.6) \]
where \(a\) is the length to diameter ratio of the channel. Microchannel plates with \(a = 40\) are often referred to as 'single thickness plates' while, if \(a = 80\), they are called 'double thickness plates'.

There will be \(n\) collisions along the length of the pore where

\[
n = \frac{ad}{S},
\]

(2.7)

\[
= \frac{4V_o a^2}{V},
\]

(2.8)

This model, used among others by Adams & Manley (1966) and Eberhardt (1981), predicts a finite number of collisions with approximately constant separation and, thus, it allows the continuous electron multipliers to be described as a conventional discrete dynode secondary electron multiplier ('dynodised' model). This discrete separation, however, is not seen in practice due to the statistical nature of the multiplication process and the variable penetration depths of the incident particles.

The number of secondary electrons (\(\delta\)) produced per collision is given by:

\[
\delta = A V_e^\delta, \tag{2.9}
\]

where \(A (~0.2, \text{Wisa, 1979})\) is a proportionality constant. Using equations 2.6, 2.7 and 2.9, equation 2.2 becomes:

\[
G = \left(\frac{AV}{2aV_o^\delta}\right)^{4V_o a^2/V}, \tag{2.10}
\]
which makes apparent that the gain depends only on the length to diameter ratio and not to the individual dimensions of the pore. This is the property that permits the miniaturisation of the mcp pores. An increase in \( V \) (corresponding to an increase in \( E \)) causes an increase in \( \delta \), the secondary electron yield, since each collision occurs at a higher energy \( V_c \) (equation 2.9). At the same time, however, the number of collisions must decrease (equation 2.8), resulting in an extremum in the \( G \) versus \( V \) characteristic. Equation 2.10 also exhibits an extremum in \( a \), suggesting that there is a gain for which the inevitable variations in \( a \) from channel to channel have minimal effect. From equation 2.9 and the condition \( d(\ln G)/da = 0 \) we find that:

\[
a_M = \frac{AV}{3.3V_o^{1/2}} = \frac{V}{16.5} \quad (2.11)
\]

or, using the normalised voltage \( W \), the potential difference between two points separated by an axial distance \( d \) (the pore diameter)

\[
W = \frac{V}{a_M} = 16.5 \quad (2.12)
\]

and

\[
G_M = \exp(0.184A^2V) = \exp(0.0074V) \quad (2.13)
\]

where \( a_M \) and \( G_M \) are the \( a \) and \( G \) values at the extremum. The results indicate that the gain is maximum for \( \delta = 1.65 \), while for \( V = 1000V \) \( a_M = 60 \) and \( G_M = 1635 \).

Guest (1971, 1988), used statistical computer models, combined with an analytical description similar to the above, to study the mcp behaviour. He found that gain is a
maximum for $W \sim 22$ ($\delta = 2$, for $V = 1000\, \text{V}$ and $M = 45$) with unity gain ($\delta = 1$) occurring for $W \sim 11$. Figure 2.6 shows the universal gain curve for a series of channels of varying $a$, $W$ and $V$ derived from a simulation. The input parameters have

![Electron gain curve](image)

Figure 2.6. Universal gain curve for a mcp. The primary electron energy is $2\, \text{keV}$ (Guest, 1971).
been kept constant; a 2keV electron with an angle of incidence of 13° relative to the mcp channel axis.

2.3.3 Ion Feedback

As the gain increases so does the probability that electron collisions with gas molecules will produce positive ions. These molecules may either be from residual gas or from gas desorbed from the channel wall during electron bombardment. Adams & Manley (1966) have estimated that the number of ions produced, N, is

\[ N = 6n_e p W, \]

where \( n_e \) is the number of electrons in a region of width W at a pressure p in Torr.

These ions are accelerated towards the entrance of the channel and, on collision with the channel wall, initiate after-pulses. The amplitude of these pulses depends on how far up the channel, the ions had travelled before hitting the wall. If the gain and the ambient pressure are high enough, these extra events could result in a regenerative feedback situation, which in extreme cases could lead to the distraction of a channel. The need to avoid ion feedback limits the maximum electron gain, that a single straight channel can supply, to \( \sim 10^5 \) (Wiza, 1979). Electron multiplier manufacturers Mullard Limited (1976) suggest that for pressures less than \( 10^{-5} \) Torr, gains in excess of \( 10^5 \) are obtainable without problems while at \( 10^{-3} \) Torr plates have been operated successfully with gains of several thousand.

Ion feedback in cems can be overcome by bending, curving or spiralling the tubes. Any ions produced can move only a short way down the multiplier before striking the wall. The energy on impact is scarcely sufficient to produce secondary electrons and
those that are generated can hardly multiply in the available channel length. In these single channel multipliers, gains higher than $10^8$ can be achieved. To obtain comparable gains with mcps, two options are available: either to use a single plate with curved channels, or to use a stack of usually two or three straight channel mcps.

2.3.3.1 Curved Plates

Curved channel plates or ‘C-plates’ are mcps manufactured with curved channels. The gain expression is different to that for a straight channel. Adams & Manley (1966) have shown that in most curved channel geometries the electrons do not traverse the diameter of the channel, but simply make repeated collisions with the outer wall. This means that the diameter and hence the length to diameter ratio is not important in a curved channel. The important parameter is the included angle of the curve. Curved channel plates can supply ion feedback-free gains of the order of $10^6$. A variant of the ‘C’ is the ‘J’ plate where only the end of the channel is curved.

2.3.3.2 Plates in Cascade

Standard mcps have channels set at a bias angle, usually up to $15^\circ$, to the axis of the plate. If two or more plates are mounted in cascade with their axial directions opposed (Fig. 2.7), the directional change they provide, is sufficiently large so as to inhibit positive ions produced at the output of the rear plate -the most likely region for ion production- from reaching the input of the front plate. This configuration is sometimes called a two stage detector, ‘V-plate’ or most commonly the ‘chevron pair’. Often the process is extended to three mcps (the three stage detector or the ‘Z stack’), or five mcps (the five stage multiplier or ‘V-Z stack’). Using these configurations, gains of $10^7 - 10^8$ are obtainable with straight channel mcps.
Figure 2.7. Operation of a chevron pair (Wiza, 1979).

Figure 2.8. PHD of a MCP operating in the low gain regime (Guest, 1971).
2.3.4 Saturation

In the low gain regime (G<10^4), the output pulse height distribution (PHD) of a single mcp has a nearly negative exponential shape (Fig. 2.8). A cascade electron may follow a great variety of trajectories between collisions with the channel wall. The spread in the electron collision energies leads to an ill-defined secondary electron yield at each collision and consequently, to a large spread in gains. Guest (1971) computed a collision energy range of 0-500eV with 25% of electrons having energy less than 54eV, 50% less than 110eV and 75% less than 245eV.

As the gain increases, the PHD (Fig. 2.9) becomes peaked (pseudo-Gaussian) or 'saturated'. Gain or pulse saturation is the effect by which the magnitude of the output

![Figure 2.9. Saturated PHD from a chevron pair operating at 1kV/plate (Wiza, 1979).](image)
charge cloud stabilises or 'saturates'. According to the Guest (1988) gain model, at low gains, i.e. before saturation occurs, the electric field is uniform along the channel (Fig. 2.10). As saturation begins, the potential distribution along the channel gradually changes. The field near the channel output decreases while the field near the input rises. At some point, the field at the output reaches a value that corresponds to unity incremental gain (by equation 2.5 low E means low $V_c$ yielding low $\delta$ in equation 2.9). As the plate goes further into saturation, the 'unity gain region' stretches back along the channel while the field at the input rises. Eventually only the region near the channel input contributes to the effective gain, but the local field is now much stronger than it was in non-saturated operation.
There are two mechanisms that are generally believed to cause gain saturation:

1. **Space charge.** As the cloud of secondary electrons travels along the channel growing steadily, a space charge potential is created within it which reduces the time of flight and the gain in energy of the secondary electrons. The space charge density has its maximum value when one secondary electron is emitted from the wall at each impact of an electron from the cloud (Baumgatner & Gilliard, 1976).

2. **Positive wall charging.** The passage of an avalanche progressively depletes the semiconducting channel wall of charge, which cannot be replenished by the strip current on the timescale of the pulse transit time (using equations 2.3 and 2.8 and assuming $V = 1000V$, $a = 40$ and $d = 12.5$, we find: $\tau_{mcp} = n\tau = 135ps$). Hence, a retarding ‘wall charge’ electric field becomes established and electron collision energies gradually decrease until, near the exit, they are sufficient to eject only one secondary per electron impact.

Space charge is the most likely process for curved channels (Adams & Manley, 1966) and wall charging for straight channels (Adams & Manley, 1966; Loty, 1971; Guest, 1988).

Saturated PHDs are described by the modal gain (the peak gain) and the gain resolution (the ratio of the PHD FWHM to the modal gain). In applications where it is important for the output current to remain proportional to the input current, i.e. image intensifiers in the proportional mode, the mcps are operated in the low gain regime with a negative exponential PHD. In mcp applications where the only requirement is to obtain one pulse per input event, such as particle and photon counting detectors, the pulse amplitude is not important as long as it remains above a LLD threshold determined by the noise rejection required. In these applications a saturated PHD with
a narrow FWHM, to keep most pulses above the LLD threshold, is necessary to optimise the counting linearity of the detector.

The gain in the saturation regime is a function of both $a$ (the length to diameter ratio) and $d$ (the pore diameter). Loty (1971) made calculations, based on the wall charge model, which predict a saturated gain dependence of a straight channel mcp on $V d a^{-1}$. This was confirmed by a numerical model by Fraser et al. (1983), who also indicated that the FWHM of the PHD should decrease with pore diameter. They also suggested that the minimal FWHM is always obtained when the individual stages of the multiplier are independently operated in 'hard' saturation. The criterion for 'hard' saturation is a bias voltage, for each plate, exceeding a level $V_s$ where

$$V_s = (8.94 a + 450)V.$$  \hspace{1cm} (2.15)

2.3.5 Gain Depression with Count Rate

As described above, charge depleted from the channel wall during the passage of a pulse must be replenished by the conduction current flowing between the mcp faces. Treating the mcp channels as RC circuits, where $R$ is the channel resistance and $C$ the effective channel capacitance, it has been estimated (Wiza, 1979; Eberhardt, 1981) that charge replenishment should occur with a time constant $\tau = 10\text{ms}$. Treatment of the mcp as a distributed impedance (Gatti et al., 1983), on the other hand, indicated a complete recharge time of more than $5\tau$. Therefore, assuming a $5\tau$ recharge time, at excitation frequencies greater than 20Hz, the charge depleted from the channel wall would never be replenished and its gain should fall, since the steady state electric field would never be re-established. At high enough count rates, the gain can be so reduced that a significant part of the PHD lies below the corresponding setting of the LLD of
Figure 2.11. Modal gain variation with count rate for a chevron pair. One count/s is equivalent here to 0.05 counts/mm² s or 10⁵ counts/channel s. The CsI insulating layer at the input surface of the front MCP has no effect on the count rate characteristic (Fraser, 1989).

the measurement system, distorting the counting linearity of the detector. Timothy (1981) found that a rate of 12.5 counts/s per channel produces a 25% gain reduction in a single curved MCP. Chevron pairs of MCPs, however, operating at higher gains (more than 10⁷, compared with 1.2 10⁶) can exhibit an equivalent gain reduction at count rates of only 0.01 counts/s per channel (Fig. 2.11). In order to extend the RC model to multistage detectors, Eberhardt (1981) assumed that the lateral capacitance existing between the emitting channels and the surrounding quiescent channels was high enough (50 times the axial capacitance for a Z-plate) to supply the required
charge. Pearson et al. (1988) have shown that mcp count rate characteristics depend on the fraction of the plate area that is illuminated. At low count rates there are still many quiescent channels within each excited area, hence all beam sizes give the same gain. At high count rates, however, the number of quiescent pores decreases as the illuminated area increases. Thus, the amount of available charge is reduced and the count rate performance worsens with active area.

Alternatively, the gain depression can be analysed by relating the amount of pulse current delivered by the mcp to the magnitude of the conduction current available to replace the abstracted charge. The conduction current is usually of order $10^{11}$ to $10^{12}$ A per channel. It has been found empirically that the maximum pulse current which can be abstracted is between 10% and 30% of the available conduction current for single curved mcps, chevrons and Z-plates (Fraser, 1989 and references therein). Thus, reduction of the charge per pulse and/or of the mcp resistance (higher conduction current for the same mcp voltage bias), result in higher achievable count rates. It should be noted, however, that the strip current can vary with the input current. Fraser et al., 1991, found that, in multistage detectors, the ratio of pulse current per channel to strip current can exceed unity. As this effect is independent of the position of the illuminated area, relative to the centre of the mcp, it seems that the lateral capacitance employed by Eberhardt (1981) is not the most probable explanation.

The increase in count rate performance by plate resistance reduction is limited due to the negative temperature coefficient of the mcp resistance (-1.5%/K). In mcp mountings, conduction current induced thermal energy has to be removed radiatively due to the poor lateral conduction through the plate edges. The lowering of the channel resistance is constrained by the onset of thermal runaway which typically
occurs at power densities exceeding 0.1W/cm² over the mcp surface i.e. mcps with a 25mm active area are thermally unstable below R = 5MΩ giving a count rate limit of 10⁸ cm⁻² s⁻¹ (Feller, 1991). Conductively cooled 500kΩ mcps, however, have been successfully operated at ohmic heating densities of 0.78W/cm² suggesting count rate capabilities of order 3×10¹⁰ cm⁻² s⁻¹ (Tremsin et al., 1996). It was also found that gold-coated plates exhibited much better count rate characteristics in comparison with conventional nichrome-coated mcps. This was due to the lower resistivity of gold and possibly, to the precise details in the electrode metal-mcp glass interface. It was shown, in particular, that the input surface coating is the most critical for the count rate characteristics, as well as for the output gain.

2.3.6 Quantum Efficiency and Energy Dependent Gain

As well as ions, mcps and cems are sensitive to electrons, UV radiation and X-rays. Thick mcps, ~5mm, have good quantum efficiencies (QE) for γ-rays. This section, will be concerned with the QE of mcps for ions, since these are the particles of interest for the present work.

2.3.6.1 Absolute Detection Efficiency of mcps for ions

When using a mcp for ion detection, the detection efficiency is of primary importance in determining absolute intensities. The absolute detection efficiency is determined as the probability for the detection of an electric pulse per incoming particle. Absolute detection efficiencies have been investigated as a function of the incident beam energy and angle. The results reported scatter widely (35-85%). As the walls of the individual channels which make up the mcps are of finite thickness, thus forming an interchannel web, one would expect that the open
area ratio (OAR) of a MCP (typically ~60%) would form the upper limit to the areal efficiency for incident particles. Panitz and Foesch (1976), however, suggested that a small positive bias (~22V) of the MCP front face and a channel bias of ~15° would be enough to direct the secondary electrons, produced by the impact of incoming particles on the interchannel area, into neighbouring channels and predicted that under optimum conditions an areal detection efficiency of ~100% was possible. Gao et al. (1984) found that a small positive bias (up to 20V) on the front MCP face did increase the detection efficiency by about 20%. Sakurai and Hashizume (1986) on the other hand, having varied the front face voltage between -1.6 to 1.3kV, found only a 4% increase for a front face bias of ~98V. They argued that, although it is possible to collect about 60% of the secondary electrons emitted outwards from the front MCP surface by applying a positive potential, the energy of those electrons (of the order of a few eV) lies in a range where the MCP detection efficiency is extremely small. Müller et al. (1986) used a grid biased at -100V relative to the MCP front face to repel secondary electrons emitted outwards from the MCP surface. They found that, for an ion incidence angle of 47° relative to the MCP surface normal, the detection efficiency of the MCPs, for Mg⁺ ions, increased with ion energy from 49% at 2.1keV to 81% at 4.4keV. Also, they projected that with an ideal mesh (100% transmission) the detection efficiency, for the same ion energies, would be in the range of 52% to 97%. However, more pertinent to the detector arrangement used in the instruments presented in this work, is the MCP detection efficiency when there is no secondary electron collection from the interchannel web, i.e. the MCP front surface is either at zero or at negative bias.

Figure 2.12 is taken from a study by Gao et al. (1984) and shows the absolute efficiencies for H⁺, He⁺, O⁺ ions at normal incidence. Within experimental
Figure 2.12. Absolute detection efficiencies for H\(^{+}\) (circle), He\(^{+}\) (triangle) and O\(^{+}\) (square) particles at normal incidence to the detector surface (Gao et al., 1984).

Figure 2.13. Absolute detection efficiencies of a mcp as a function of impact energy.

The broken line shows the saturation of absolute detection efficiencies at 63.5% (Oberheide et al., 1997).
uncertainties, they concluded that the efficiencies are identical for all ion species tested and show an increase with particle energy at first, followed by a plateau near and above 3000eV at about 60% efficiency. Oberheide et al. (1997) obtained similar results of efficiency dependence on particle energy (Fig. 2.13), but a slightly lower efficiency saturation impact energy (2.5keV). They also found a dependence of the absolute efficiency on mass with the lower mass ions (for the same impact energy) having higher efficiency. Brehm et al. (1995) also found that the detection efficiency increases with energy from a threshold at ~0.5keV to a more or less constant efficiency above 3keV and up to the maximum applied impact energy of 5keV. The efficiency saturation level, however, was much lower at ~41%. In contrast Schecker et al. (1992) found that the QE for hydrogen ions levels out at 60% for energies above 1keV and Tobita et al. (1987) reported constant detection efficiency for He⁺ ions, of about 50±10% in the impact energy range 1-10keV.

The QE of mcps also depends on the angle of incidence of the radiation or particle, although very little data has been published on the QE variation with angle for ions. Gao et al. (1984) have found that this is independent of particle species and energy. Figure 2.14 shows the relative efficiencies they measured, with respect to the angle between the mcp channel axis and the incoming particle trajectories. The relative angular efficiency is essentially constant (close to 100%) between 6° and 16° with respect to the direction of the channel axis.

The absolute detection efficiency of cems is given as greater than 80% for ion energies in the range 2 - 40keV (Lecomte and Perez-Mendez, 1978). Therefore, it seems that in terms of absolute detection efficiency cems are preferable to mcps.
Figure 2.14. Relative detection efficiency as a function of the angle between the particle trajectory and the channel axis (Gao et al., 1984).

2.3.6.2 Impact Energy Dependent Gain

Hellsing et al. (1985), using He⁺, Ne⁺ and Ar⁺ ions, found that the average mcp gain increased with particle energy (Fig. 2.15). In particular, they found that the gain is independent of ion mass below 4keV and above 20keV, but in the intermediate energy region the average gain was generally higher for He⁺. They concluded that the average gain is closely correlated with the ion-induced secondary electron emission (IEE). That is due to the mode of operation of the chevron detector. The peaked PHD produced is due to saturation occurring on the rear mcp while the front mcp is still operating in the linear regime. Thus, the number of electrons leaving an excited
channel on the front plate, is directly proportional to the number of secondary electrons ejected in the ion-channel wall collision. Depending on the interplate bias and distance, an increase in the IEE yield would cause additional channels in the rear mcp to saturate.

Oberheide et al. (1997) obtained similar results of the dependence of mcp gain to impact energy. They also found that, due to the lower IEE yield of the mcp electrode material (for 3keV Ar$^+$ ions, nichrome IEE ~ 2.3 mcp material IEE ~5), the absolute
efficiency of the mcp depends on the depth of penetration of the electrode material down the mcp pores. The chevron pair, they used, had a front surface electrode penetration of half a pore diameter and a back surface penetration of two pore diameters producing an absolute efficiency of 63.5%. The efficiency of the same detector with the plates turned over, was reduced to 45%.

2.3.7 Dark Noise

The background count rate of mcps is usually uniformly distributed over the mcp area at a density of less than 1 count cm\(^{-2}\) s\(^{-1}\) with the mcp noise PHDs having exponential form. The principal noise source (>90%) in well outgassed, blemish free mcps operated at pressures below 10\(^{-6}\)mbar is internal radioactivity. Most channel plate glasses contain potassium (~5% by weight) in order to provide ease of drawing of fibre (Fig. 2.4) and to enhance the secondary electron yield of the finished multiplier. The beta emitter \(^{40}\)K (half-life 1.28 \(10^9\) years), which is present as 0.0118% of naturally occurring potassium, is the main noise source for Philips mcps. US manufactured mcps, as well as potassium, contain rubidium of which 28% of all its atoms is \(^{87}\)Rb, another long lived beta emitter.

Additionally, noise ‘hotspots’ (localised noise sources) can exist as a result of field emission from dust particles on the mcp surfaces or from mcp imperfections, with poor high voltage contacts and with local trapping of gases evolved from the channel surfaces.
CHAPTER 3

The Cold Ion Detector

The Cold Ion Detector (CID) was made under contract with the Defence Evaluation Research Agency (DERA). The objective of the instrument was to measure the energy distribution and the density of cold ions in the Magnetosphere from the Space Technology Research Vehicle (STRV 1A) as well as the spacecraft potential. STRV 1A was a 55kg spacecraft built by DERA. The CID would be used in two ways: 1) to measure the environment of the spacecraft and monitor the spacecraft potential under ambient conditions; and 2) to observe the effect of the Active Neutraliser Experiment on the spacecraft potential. The STRV 1A and its instrumentation complement are discussed more extensively in Chapter 4.

3.1 Instrument Design.

The CID experiment design had to fulfil the following requirements:

a) To be free from contamination by light.

b) To be free from contamination by energetic electrons.

c) To be light-weight, mass less than 0.6kg, and to occupy a small volume both inside and out of the spacecraft.

The first requirement rendered it necessary to overcome one of the biggest disadvantages of a sensor with an in-line configuration using a mcp detector. Detectors using mcps, are sensitive to UV light. Even though the mcp detection
efficiency for UV is less than that for particles, the resulting signal is indistinguishable from that of particles. An in-line sensor configuration provides, by definition, a straight free path for particles entering the entrance aperture to the detector. There was but one option, to insert a light-trap in the line of sight of the sensor. The trap had to be positioned after the collimator, otherwise the design would get very complicated and the effectiveness of the sensor doubtful. Also it had to be as close as possible to the rear aperture of the collimator, so that the required trap size would be minimised. The first design tried, was a metal disk which acted as a light trap and was mounted on the centre of the RPA grid. It was expected that the RPA field would sufficiently deflect the particles with energy higher than the retarding potential so as to get around the light-trap. The simulations showed that this design would not work, even if only the light-trap was made to be the RPA and it was suspended through an insulator from a grid at zero potential. The latter design was tried next, but with the light-trap being cone-shaped to actively deflect the particles around it. This effort was partly successful and it exhibited differential energy response, although, most of the particles were still lost going back to the rear aperture. The final design, reached at after quite a few more attempts, uses a combination of two RPAs. The rear aperture of the collimator would serve as the 1st RPA electrode, passing only particles with energy higher than its bias. The cone, biased at a potential higher than that of the 1st RPA, would act as a Deflector directing particles with energies, below its bias around it, while blocking particles with higher energies. The grid, where the deflector was to be mounted upon, would be at ‘ground’ relative to the cone, and would act as an Accelerator directing the deflected particles towards the detector. Since the range of accepted energies was dependent upon the voltage difference between the two RPAs, we had an instrument
that its energy response could be altered even in-flight to accommodate different experiment requirements.

The second requirement would be fulfilled: a) by the existence of the light-trap, preventing a direct path to the detector for axial electrons, b) by the high negative bias of the front face of the detector; and c) by containing the analyzer in a 2mm thick aluminium tube which would also provide electrical screening for the sensor.

The space limitations imposed by the third requirement meant that in the predetermined dimensions of the CID electronics (CIDEL) box there was not enough space to accommodate the extra power supply required in order to have an instrument with variable resolution. Instead, a voltage divider would be used to supply a fixed percentage voltage difference to the two RPAs. In addition, the voltage divider itself, as well as a resistor connecting the rear face of the detector to ‘ground’, had to be housed inside the sensor body which, consequently, had to be elongated to accommodate them.

3.2 Sensor Description

Having decided on the main aspects of the instrument design, the engineering model (CID EM) was built. A schematic of the cross sectional view of the sensor is shown in Figure 3.1.

The analyzer consists of four main sections:

a) The Collimator comprises two plates, 10mm apart, both with axial holes 1mm in diameter. The beam accepted, has a conical shape with a half angle given by $\tan \theta = \frac{d}{l}$ where $d$ is the aperture diameter and $l$ the distance between the plates. For the
Figure 3.1a & b. Cross sectional view of the CID. The sensor is shown here in its flight model configuration where the Accelerator incorporated an additional steel mesh ~2mm behind the Accelerator grid.
values given above and taking into account the finite thickness of the plates (0.3mm), $\theta$ is $5.54^\circ$.

b) The Electrostatic Energy Analyzer which comprises the 1st RPA and the Deflector. The two electrodes are operated through the fixed potential divider, shown in Figure 3.1 in the flight model (CID FM) configuration, where it had been set up to supply the 1st RPA with $\sim 91\%$, exactly $100/110$, of the Deflector voltage. Due to manufacturing difficulties, the Deflector was shaped as a cone of smaller base diameter attached to a metal disk with the originally planned diameter.

c) The Accelerator was laser-machined from 0.127mm thick copper sheet, in the shape of a three-spoke cartwheel (Fig 3.2), with one of the spokes having double the width of the other two ($1.5\text{mm against } 0.75\text{mm giving it an open area ratio of } 89\%$). This was done in order to provide shielding for the cable connecting the Deflector to the power supply. The Deflector was supported by the Accelerator via a 1mm long insulator, allowing Deflector-Accelerator voltage differences up to 1300V, with its diameter being smaller than the base of the Deflector cone.

d) The MCP uses a pair of mcps in chevron configuration in front of a metal plate anode to detect the particles. The front face of the mcp pair is kept at a high negative bias (in the range of -2400V to -3300V) thus, attracting ions while repelling any secondary electrons and photoelectrons produced inside the analyzer. The rear mcp face is connected to ‘ground’ through a 50M$\Omega$ resistor, creating a voltage difference between itself and the anode (at virtual ‘ground’) in order for the anode to attract the mcp produced electron cloud and minimise charge losses.
Figure 3.2. The Accelerator grid.

All the analyzer components are stacked inside an insulating sleeve, into which channels have been cut to carry the wires which make connection to the analyzer electrodes. Behind the sleeve is the resistor assembly for the voltage divider and the resistor used for the rear mcp face bias. The sensor is contained within a 2mm thick aluminium body which is kept at the same potential with the front aperture and the accelerator. The whole structure is held in place by two screwed caps mounted at either end of the sensor body.
Originally, the sensor was to be clamped on the centre wall of the spacecraft with its axis coinciding with the spacecraft’s spin axis. Later on, however, that space was given to the main antenna of the spacecraft thus, making it necessary for a collar to be fitted on the sensor body, 75mm aft the front end.

3.3 Sensor Simulation Results

The simulations were based on the three stage technique described in Chapter 2. Realistic gaps were allowed for insulators across which the potential was assumed to vary linearly. The sensor was assumed to have cylindrical symmetry. During the last stage (trajectory tracing) the ions would start their journey at a random position at the front aperture with a random energy and a random direction. Restricted by the computer time available, the maximum number of particles to be traced through the sensor was set at 10,000. This amount was considered large enough to provide an accurate assessment of both the angular and energy response of the instrument. The simulations were performed for a sensor with a 10° field of view. Figure 3.3 shows a bunch of particles traced within the sensor at an energy sufficient to overcome the potential barrier of the 1st RPA. Some trajectories strike the rear aperture of the collimator but the rest pass through and, after getting deflected by the Deflector, they ultimately reach the detector. Each cross in Figure 3.4, represents the initial energy and direction of a successful particle trajectory in the above simulation. The angular response is cylindrically symmetric about the axis of the sensor and has a half angle of acceptance of ~4°, which is ~20% less than the one calculated from the collimator’s geometry. The difference is mainly due to the diverging effect of the potential applied to the 1st RPA. In general the simulation results showed a sensor with reasonably uniform response within the field of view and energy passband. The
Figure 3.3. Ion trajectories traced through the CID during simulation.

Energy response of the sensor, integrated over all input angles, is illustrated in Figure 3.5. In this simulation, the instrument was assumed to have a 10% voltage difference between the deflector and 1st RPA electrodes, which results in an energy passband with $\Delta E/E \approx 15\%$ FWHM.
Figure 3.4. Scatter plot of successful ion trajectories relative to angle of incidence and energy.

Figure 3.5. Simulated energy response of the CID integrated over angle.
3.4 CID Laboratory Test Set-Up

The CID was mounted on the rotary table with the axis of rotation passing through the middle of the collimator. The ion gun was mounted on the X-Y table. The Le Croy provided the mcp voltage and the Brandenburgh supplied the deflector voltage. The anode signal was pre-amplified by a Canberra 142B pre-amplifier while the main amplification and signal shaping was provided by the Canberra 572 Spectroscopy Amplifier. The amplifier settings were: shaping time 0.5μs, coarse gain 0.5 and fine gain 20. The signal was then fed to: a) a counter through an SCA, for a quick look at the count rates; and b) to a Canberra ADC, for the pulse height analysis tests. The count rate data was read in the PC through an Analog Instruments MIO 25 card connected either to the ADC or the SCA output. The CID body was connected to the vacuum chamber wall which was the common earthing point for all the equipment. In order to reduce the noise pick-up from the mains and other sources, a low-pass filter was fitted on the output of the mcp voltage supply (the Le Croy). The resistive element of the filter was 10MΩ and its capacitive element was 3.2nF, yielding an RC time of 32ms. Prior to operation, the CID was allowed at least 48 hours for out-gassing every time it had remained at atmospheric pressure for more than 4 hours.

3.5 MCP Performance Tests

The MCP comprised a chevron pair of 2mm-thick Philips mcps 14mm in diameter. The channel diameter was 25μm, giving a length to diameter ratio of 80:1, with a centre to centre pitch of 31μm (open area ratio of ~0.63). The bias angle of the channels was 13° relative to the mcp face normal. The plates were matched with a nominal resistance of 340MΩ per plate. In order to prevent unwanted events
generated by the interaction between the front mcp face contact and the mcp itself, the rear face contact was 1mm smaller in diameter thus, reducing the mcp active area diameter to 11mm (the sensor inner diameter was 12mm). The mcps were neither baked nor scrubbed. All tests were performed with the plates integrated on the CID. The mcp gain was determined using an ‘end to end’ calibration technique whereby, test pulses of accurately known amplitude were fed to the preamplifier input via a 2.39pF capacitor. Knowledge of the pulse amplitude V (in volts) and the capacitance C (in Farads) yields the charge per pulse Q (Q = C V / 1.602 \times 10^{-19} \text{ electrons}). Recording the channel number the test pulses are registered after amplification, a direct measure, of the MCP generated ones, can be obtained without having to rely on the accuracy of the calibration of each component in the amplification circuit.

3.5.1 Performance of the Engineering Model mcps

The engineering model (EM) mcps were integrated in the EM CID seven months after they were delivered. During that period, they were stored on a desiccator using silica gel as the dry desiccant. The mcp stack resistance, measured under vacuum, was ~1.05G\Omega, or 500M\Omega per plate, which is 47% higher than the manufacturer supplied value of 340M\Omega. According to Philips officials, the mcp resistance increases with storage time. The increase is steeper in the first few months and gradually less rapid thereafter. This change of the resistance value does not affect the mcp gain characteristics, but it could possibly affect the amount of charge collected by the anode. As the current drawn by the MCP would be reduced for the same MCP bias, the voltage difference set up by a 50M\Omega resistor between the anode and the rear face of the mcp stack would also be reduced. This, in turn, could lead to a weaker signal due to an increased amount of electrons hitting the sensor wall before
reaching the anode. For the nominal mcp resistance and the specified MCP bias voltage range of -2400 to -3300V, the mcp stack resistance would be 730MΩ and the current drawn in the range of 3.29 to 4.5μA. This results in a voltage difference between anode and mcp rear face of 164.5 to 225V. For the actual mcp stack resistance value (1.05GΩ) the current drawn is in the range of 2.29 to 3.14μA and the corresponding voltage difference is 114.5 to 157V. Assuming that the field between the rear mcp face and the anode is uniform and that the electrons are exiting from the mcp at 90° to the sensor axis, then the equation of motion 

\[ y = \frac{1}{4} E \frac{e}{W} x^2 \]

of a charged particle in a uniform electric field can be solved. For \( y=0.4\text{mm} \) (the anode - mcp distance), \( x=1.5\text{mm} \) (the minimum radial distance between the outer active mcp pores and the sensor inner wall) and \( E=114.5/0.4=286.25\text{V/mm} \), we find that the minimum energy (W) required for the output electrons to hit the sensor wall is ~403eV. The energy spread of the output electrons has been measured to be in the range of 0-500eV, but with the distribution continuously decreasing with energy. Computer models have shown that 75% of the electrons have exit energies less than 77eV (Guest, 1971). Experiments (Koshida and Hosobuchi, 1985) have yielded distributions where, in the saturated mode, the number of electrons with energies higher than 50eV ranges from 35 to less than 18% of the total. Using the above mentioned distributions as a guide, a conservative estimate of the number of electrons with exit energies higher than 400eV, would be of the order of 2%. Therefore, the reduction in field strength in the anode region is not considered significant.

Figure 3.6 illustrates the PHDs obtained at various MCP voltages and Figure 3.7
Figure 3.6. The PHDs obtained with EM MCP at various bias voltages for an ion beam energy of 500eV. The initial (dotted line) and the final (dashed line) LLD settings of the flight electronics are also shown.

the average gain increase with voltage. The tests were performed using a 500eV ion beam at a rate of 500-700 pulses/s. The MCP is in the saturated mode from the lowest specified operation voltage (-2400V). The initial discriminator threshold on the CIDEL was set at 2.5 $10^5$ e$^-$ but severe noise pick-up problems (see Chapter 4) forced the selection of the maximum available discriminator setting of $5 \times 10^5$ e$^-$. For the latter setting the MCP could be operated with no loss of real events for all
voltages above 2500V. For the CID EM tests the MCP voltage was set at -2700V

![Graph showing average gain increase with bias voltage for the EM MCP.](image)

Figure 3.7. The average gain increase with bias voltage for the EM MCP.

which corresponded to ~2550V across the chevron pair. At this bias voltage and
with the above LLD threshold, the MCP gave a PHD with resolution of 74%
FWHM, modal gain of 4.3 \(10^6\) e/ion and a background rate of 2-5 pulses/s.

3.5.2 Performance of the Flight Model MCPS

The FM plates had been in storage for about a year, before they were integrated
on the CID FM. Consequently, the MCP stack resistance was measured at 1.15GΩ,
or 575GΩ per plate, corresponding to a 15% increase in six months, on the
assumption that both the EM and FM plates had the same resistance when they were
delivered and that they underwent the same rate of increase during the first six
months in storage. It should be noted, however, that according to Fraser (1989), an
anomalously low resistance pore can cause up to 50% resistance differences between
geometrically identical MCPS of the same batch. Figure 3.8 illustrates the PHDs
Figure 3.8. The PHDs obtained with the FM MCP at various voltages, for a 500ev ion beam. The initial (solid line) and the final (dashed line) LLD settings of the flight electronics are also shown.

produced by the FM MCP at various voltages using the same reference beam as for the tests of the EM plates. The gain was almost half that of the EM plates, i.e. the average gains at 2700V were $4.95 \times 10^6$/ion and $2.85 \times 10^6$/ion for the EM and FM plates respectively. The FWHM of the PHD remained above 100% up to $\sim 2950$V. The lower gain, itself, did not represent a significant problem, since the only thing that needed be done, was to operate the FM MCP at a voltage 50-100V higher than
that required for the EM one. The only penalty would be the reduction of the available MCP power supply voltage range that could be used in-flight to compensate for the loss of gain due to mcp ageing. Since the planned duration of the mission was just one year, this was not considered a significant drawback.

A matter of greater concern, however, was the increased noise of the FM plates. With the ADC LLD set at $2.5 \times 10^5$, the background count rate was high (over 80 pulses/s) at any voltage above -2700V while, at lower voltages, there was loss of real events. Taking into account that after a week's operation the noise had not subsided, it was decided that, prior to delivery, the CID FM plates would be swapped with the CID EM ones. All the CID FM calibration tests, however, were performed with the original FM plates. This was done in order to protect the mcps, that were going to be used in the mission, from gain reduction stemming from excessive charge abstraction. For the laboratory tests, the FM MCP was operated at -2800V which, with the test electronics' LLD set at $-1.4 \times 10^6$, resulted at a noise background of 6-15 pulses/s.

3.5.3 MCP Efficiency

At the time the mcp tests took place, there was no available facility for the determination of the mcp detection efficiency for different ion species. As it has already been discussed in Chapter 2, the absolute efficiency of mcp detectors is closely related to the mcp open area. Therefore, for the rest of this work it is assumed that the detection efficiency of the MCP is the same for all detected particles and that it has a value of $\sim 60\%$ (the minimum OAR of the MCP front surface) which is in accordance with the consensus that the mcp efficiency is closely related to the OAR.
The assumption of constant detection efficiency, however, is valid only if there is no loss of valid events due to the mcp gain dropping below the LLD threshold. Excluding mcp ageing, there are two other possible causes for gain changes: 1) It has been found that the mcp gain increases monotonically with the ion energy (Hellsing et al., 1985; Oberheide et al., 1997). As the mcp gain tests were performed using 500eV ions, there is a possibility that at lower particle energies a part of the PHD could be lying below the discriminator threshold. 2) As it has been discussed in Chapter 2, the mcp gain reduces at high count rates. The tests described below, were performed using the modified CID EM (CID EMM), which is discussed in section 3.7.4.

3.5.4 Gain Dependence on Particle Energy

Figure 3.9 illustrates the average gain variation with ion energy at various MCP voltages. As the front surface of the MCP is negatively biased the impact energy of the ions is the sum of the MCP voltage and the incoming particle energy. The gain increases with energy, with the maximum gain always obtained for the highest beam energy tested (800eV). The gain increase is steeper at the lower operating voltages. The deviations from a monotonically increasing curve at low ion beam energies (50 - 100eV) should be attributed to gain reduction due to increased count rate. All the above tests were performed using count rates of 6000-12000 counts/s.

In the worst case, i.e. for 20 and 100eV ions and a MCP bias voltage of -2600V, the relative gain is ~60% of that obtained with 800eV ions. Taking into account the discriminator threshold of $5 \times 10^5 e^{-}$ and the relative gain at 500eV (~80%), the
Figure 3.9. The average gain variation with ion energy at various MCP bias voltages.

The gain is normalised to 100.

minimum MCP gain should be higher than $5 \times 10^5 / 0.75 = 6.7 \times 10^5$. For the CID EM mcp stack, which was eventually transferred to the CID FM, the above requirement is fulfilled for every voltage above 2500V (Fig. 3.6).

3.5.5 Gain Variation with Count Rate

As it has been shown previously, the mcp gain reduces at high count rates. The manufacturers, of the plates tested, state (Philips, 1991) that for electron currents averaging, in the output, more than 10% of the strip current, the mcp will start going
into count rate dependent gain reduction. Another MCP manufacturer (Hamamatsu, 1991) suggests that count rate dependent gain depression starts for currents of 5-6% of the MCP strip current. The maximum pulse current which can be abstracted is found empirically to be between 10 and 30% of the available conduction current (Fraser 1989 and references therein). One way of estimating the achievable count rate before gain reduction occurs is presented below:

The magnitude of the conduction current is:

\[ I (A) = \frac{\text{MCP bias voltage (V)}}{\text{MCP stack resistance (\Omega)}} \]

Accepting the 10% limit, the magnitude of the pulse current is 0.1 I.

The output count rate, CR, is given by:

\[ CR = 0.1 \frac{I (A)}{\text{average gain per pulse}} \times 1.602 \times 10^{-19} \left( \frac{\text{C}}{\text{e}^-} \right) \]

For the CID FM MCP at a bias voltage of -2700V (I = 2.57 \times 10^{-6} A and average gain = 4.95 \times 10^6 e/\text{ion}) the expected maximum achievable count rate, before gain reduction occurs, is \( \sim 324000 \text{ pulses sec}^{-1} \) or \( \sim 210000 \text{ pulses sec}^{-1} \text{ cm}^{-2} \) for 14mm diameter plates.

The following tests were performed long after the STRV 1A was launched, with the test MCP having a stack resistance of 1.8G\( \Omega \) (67% higher than before). Increased resistance means lower standing currents for the same bias voltages and consequently, lower achievable count rates. Figure 3.10 illustrates the modal gain reduction with count rate at MCP bias voltages from 2700V to 3000V using a 30eV
Figure 3.10. The modal gain reduction with count rate for various MCP bias voltages. The ion beam energy was 30eV.

The reduction is greater for higher bias voltages as the increase of the standing current is not adequate to counter the gain increase. In particular, increasing the MCP bias voltage from 2700V to 3000V yields a standing current increase of \(~10\%\) (from 1.5\(\mu\)A to 1.67\(\mu\)A) whereas the average gain is increased by \(~284\%\) (from \(1.28 \times 10^6\) to \(4.91 \times 10^6\)).

The plot in Figure 3.10 suggests that the gain reduction becomes apparent at count rates that are much lower than those predicted by the 10\% criterion. This is probably due to the fact that the electric field between the MCP front surface and the
Accelerator has a focusing effect on the incoming particles, thus reducing the active area to a fraction of the available MCP surface. Calculation of the number of activated MCP channels, however, is difficult. From the computer simulations (MCP front face bias voltage -3000V, Accelerator at ground, ion energies 45 - 70eV) the active area is about 14.5mm$^2$. If the 10% criterion is used, together with the assumption that the pulse current is 10% of the conduction current of the activated pores when the gain is reduced by 15%, the illuminated area is calculated as 8.1mm$^2$ at 2900V and 4.76mm$^2$ at 3000V. Furthermore, since in the most probable situation each pore in the front MCP activates 3 pores in the rear MCP (Eberhardt, 1981), the active area of the front MCP becomes a third of those calculated above. It should be noted, however, that count rate dependent gain depression effects not only the illuminated pores but also the neighbouring quiescent pores up to a radial distance of ~1.5mm (Edgar et al., 1992).

3.6 Ion Beam Characterisation

Plasma analyzers are usually calibrated with plasma sources producing a broad monoenergetic parallel beam of particles. Although such a source was not available, the aperture of the ion gun, described in Chapter 2, was 10 times wider (10mm against 1mm for the CID aperture) than that of the CID. Therefore, with appropriate beam focusing, we expected that the ion beam it produced would be adequate for our purpose. The following tests were aimed at the determination of the beam focus voltage which produced the optimum beam profile.
3.6.1 Test Procedure

The step sequence described below was followed in all ion beam mapping tests:

- Set the MCP voltage at operating level (2700 - 2800V).
- Switch on the ion gun power supply, set the beam energy voltage and the bias voltage at 100V below the selected beam voltage.
- Set the focus voltage at 50% of beam energy voltage.
- Set the Deflector voltage at 105% of beam energy.
- Increase the ion gun filament current until counts are recorded.
- Move ion gun in the X-axis (horizontal axis) until the maximum count rate position is found.
- Repeat above step for the Y-axis (vertical axis).
- The ion gun is now assumed to be aligned with the sensor.
- Set filament current for a count rate of 1000 - 1200cps.
- Set Deflector voltage at 50% of beam energy, thus, rendering the ion energy too high for the analyzer's passband and allow one hour for the ion flux to stabilise.
- Set Deflector voltage at 105% of beam energy.
- Perform a beam scan by moving the ion gun in the X and Y axes. The range of ion gun movement was always greater than or equal to the diameter of the ion gun aperture.

3.6.2 Test Results

The maximum count rate, for the same filament current and the same Deflector voltage, was always obtained with the focus voltage set at ~65% of the beam energy. Figures 3.11 illustrates the count rate variation with respect to the ion gun position as a three dimensional plot whereas Figure 3.12 is a contour plot of the
Figure 3.11. 3D plot of the count rate variation as a function of the distance between the ion gun and CID axes. The ‘Counts’ axis is normalised to 100.

The same data, obtained for a 500V beam voltage and a focus voltage of 325V. The graphs are incomplete due to overheating of the X-axis motor. The X-Y table movements were controlled from the same computer program which ran the CID data acquisition and thus, the motors were powered continuously. Since the scanning was arranged so that for each Y-axis position the full range of X-axis positions was acquired, the most likely motor to overheat and cease moving was the one providing the horizontal movement. In view of this problem, the tests had to follow the more
time-consuming route of using two separate programs, one for the ion gun movements (using the keyboard’s arrow keys) and one to acquire the data at each point of a coarser grid.

Of greater importance, however, was the fact that the assumption that the sensor axis (Z-axis) coincided with the ion gun’s at the point where the maximum count rate was obtained, did not seem to hold true. In fact, the recorded count rates
Figure 3.13. Count rate variation with the ion gun moving along the Y-axis, for X-axis positions of -5mm (empty squares), 0mm (stars) and 5mm (filled squares). The 0,0 position corresponds, within 1mm, to the position where the ion gun and the CID are aligned.
increase with radius from the centre of the plot, from a minimum of ~15%-30% of maximum to a value that ranges from 45% to 100% of maximum at about 0.87r. Tests at different focus voltages yielded similar results. Figure 3.13 illustrates scans in the Y-axis for three different X-axis positions: -5mm, 0mm and 5mm, where the 0mm position corresponds, within 1mm, to the centre of the ion gun aperture. The focus voltage was set at 50% (250V) of the beam energy.

Three probable causes were investigated:

i) \textit{Existence of stray fields.} This was ruled out as: a) Most of the high voltage connection points were well insulated and the rest were situated well behind (30 - 40cm) the area of importance, namely the 77mm gap between the ion gun and the analyzer; and b) usually, the effect of a stray field is to attract or repel (depending on charge polarity) all the particles towards a single direction, whereas here the response was symmetric with respect to the ion gun axis.

ii) \textit{The observed distribution being an inherent characteristic of the ion gun used.} This would mean that either the beam density increased radially outwards (assuming a predominantly parallel beam), or that the beam intensity increased with angle (assuming a focussed beam) at least within the angular acceptance range of the CID.

Immediately after these tests were performed, the analyzer had to be removed from the vacuum chamber so that another instrument could be tested. It was the detector for the Toroidal Imaging Mass-Angle Spectrograph (TIMAS) instrument that was later flown aboard NASA's POLAR spacecraft. The TIMAS detector comprised a chevron pair of annular mcps and a wedge and strip imaging anode. Dr. D. Walton, manager of the TIMAS project at MSSL, kindly agreed to perform a short series of ion gun beam focussing tests. For these, the ion gun was placed 4 - 5mm away from the front face of the mcps, which was biased at -3450V, the ion
beam energy voltage was set at 900V and the detector was set to acquire 2000 events. The proximity of the ion gun aperture to the mcp front face and the highly negative bias of the latter meant that the ions, after exiting the ion gun, would follow trajectories almost parallel to the gun axis. Thus, the ion beam could be mapped at the point of exit from the ion gun, albeit without detailed information about its angular distribution; i.e. the angle between the ion path and the gun axis. Figure 3.14 illustrates the beam trace in polar co-ordinates, from the centre of the TIMAS anode, for a focus voltage of 400V. The abscissa is the diameter of the beam. The box below the main plot illustrates the intensity per radius pixel, normalised to maximum, integrated over all angles. The TIMAS anode resolution was measured at 6-6.5 pixels/mm. From intensity plots like this, the effect of focus voltage on the beam diameter can be clearly seen. At low voltages, up to 400V, the beam diameter was ~65pixels (Fig. 3.14) or ~10mm. From there on, it gradually reduced to a minimum of ~12pixels or 1.85-2mm at 700V and then it started increasing again. At a focus voltage of 600V or ~67% of the beam energy voltage (which is only 2% higher than the voltage where the CID obtained the maximum count rate) the beam diameter is ~5mm, whereas, in the CID beam measurements (Figs 3.11 and 3.12) the beam diameter is ~13 - 14mm, with the maximum occurring at a radial distance of ~6mm. Therefore, the ion beam was diverging. The determination of the angular distribution of the beam, however, is a more difficult task, since the TIMAS detector's angular resolution is relatively low, the beam trace being covered in 3 - 4pixels. The beam intensity variations with radius (Fig. 3.14) don't show the dramatic effects observed with the CID. They are more likely to be an effect of the statistical nature of the ion production, as well as, of the fact that the TIMAS
Figure 3.14. Image of the ion beam trace obtained with the TIMAS detector. Individual resolution pixels are plotted with respect to their distance from the centre of the detector in polar co-ordinates. The panel below the main plot shows the intensity variation with radial position integrated over angle. The panel at the left of the main plot window shows the intensity variation with angle integrated over radius.
detector was set to acquire a fixed number of events instead of accumulating counts at a set time interval.

iii) The CID angular response. As the analyzer was a new and as yet untested instrument, the only data available about its angular response was from the computer simulations. It was thus, possible that the ions, with trajectories parallel or nearly parallel to the sensor's axis, were detected less efficiently than those coming at higher angles; in other words, the angular response of the instrument was the inverse of the expected.

This was deemed to be the more likely cause.

In order to establish the actual CID response, an ion beam with small angular spread was required, as with the ion gun aligned to the CID, the sensor detected particles within a cone of ~3.2°. It was decided, that this would be achieved by fitting a collimator to the ion gun. The collimator would have two axial holes 2mm in diameter separated by 12mm. The advantages of using a collimator were: a) By reducing the ion gun front aperture (2mm diameter instead of 10mm) it would be far easier and less time-consuming to align the CID with the ion gun; b) with a distance between the centres of the CID and the ion gun collimators of 86mm, the maximum angle accepted by the analyzer, when aligned to the ion gun, was ~0.9°. This allowed the determination of the response of the sensor at distinct angles. Tests with the TIMAS detector showed that at least 95% of the events were recorded within 13 pixels yielding a beam diameter of ~2mm. The FWHM of the beam, however, was measured at 1.2 - 1.5mm only. The beam distribution appeared to be uniform, i.e. similar numbers of events were recorded in either side of the beam centre. The maximum count rate using the CID, was now obtained for a focus voltage of ~70%
of the beam energy. The beam mapping at that focus voltage, however, showed that

Figure 3.15. 3D plot of the apertured ion beam mapping data collected with the CID FM. The focus voltage was set at 70% of the ion beam energy. The 'Counts' axis is normalised to 100.

the peak of the distribution was very narrow (Fig 3.15) with the 90% of the maximum count rate being obtained only within 0.125mm from the centre of the beam trace. Since the CID can only provide information about the total number of events without any positional details, it is difficult to translate the ion gun mapping data to their respective point of occurrence. In addition, the obtained distribution represents a convolution of the instrument response and the distribution of the beam, which cannot be deconvolved as there are no independent measurements of either
the beam width or the CID detection efficiency variation with radial distance from
the centre of the aperture. Closer examination of Figure 3.15, however, shows that
the half maximum of the distribution is obtained within a radial distance of ~0.4mm
from the centre and that it almost goes to zero at a radial distance of ~1mm. Thus,
we can assume that the beam is parallel, with the maximum half angle calculated at
~0.7°. Figures 3.16a and b, illustrate the distribution of accumulated events along
the X and Y axes respectively. The obtained Y-axis distribution agrees very well

![Graphs showing data for X and Y axes](image)

Figure 3.16a and b. A subset of the data shown in Fig. 3.15. The count rate variation
along the X-axis (a) and Y-axis (b) (stars). The solid lines indicate the expected
distribution for a uniform parallel beam with a 1mm diameter and a sensor with
constant detection efficiency.

with the distribution that would result if the source produced a 1mm diameter
parallel beam of constant density and if the instrument response was constant with
radius. The same is also true for positive x values of the X-axis distribution. For
negative x positions, the number of accumulated events drops more rapidly in
agreement with the apparent asymmetry in Figure 3.17. In fact, this figure reveals
three areas where the number of events is less than their neighbours on the same contour, at approximately $120^\circ$ to each other (as indicated by the straight lines). Thus, it is likely that they represent the effect which the three spokes of the Accelerator have on the in-coming particles. If that were true, then the double thickness spoke would have to be the one lying almost parallel to the X-axis.

![Contour plot](image)

Figure 3.17. Contour plot of the data in Fig. 3.15. The straight lines show the nearly $120^\circ$ angular distance between the apparent asymmetries. The contours show the number of events as a percentage of the maximum and are spaced at 10% increments.
For a proper calibration of an instrument, however, it is preferable for the test beam to have constant density in an area larger than the area of the instrument's aperture, to minimise the risk of source-instrument positioning errors. In order to achieve uniform coverage, beam mapping tests were performed at various focus voltages, requiring that the count rates remained above 90% of the maximum. Figure 3.18 illustrates the beam trace at a focus voltage of 50% of the ion energy obtained with the modified engineering model of the CID (discussed in section 3.7.4). Here, the count rate is fulfilling the 90% requirement, even though there are some anomalies in the beam trace which can be attributed to several factors. Apart from

Figure 3.18. Contour plot of the ion beam mapping data obtained with the CID EMM for an ion focus voltage of 50% of the ion energy. The contours show the number of events as a percentage of the maximum and are spaced at 10% increments.
the response of the sensor, there are the errors in the assumed position of the ion gun, beam density fluctuations and the error in the alignment of the ion gun and the sensor axes. The latter could be of the order of $1^0 - 2^0$ which should be enough to produce some asymmetry of the beam profile in the X-axis.

![Figure 3.19](image)

**Figure 3.19.** The count rate variation as a function of ion gun focus voltage measured by the TIMAS detector. The large negative bias of the front MCP surface of this detector, ensures that all ions exiting from the gun will hit the detector. Thus, the measured count rate variation is proportional to the ion gun's total output variation with focus voltage.

The uniform illumination of the sensor's front aperture by reducing the focus voltage, however, has a very important downside. Figure 3.19 illustrates the count rates observed with the TIMAS detector for the same beam energy and filament
current at various focus voltages. There is a steep reduction in the ion gun’s output
either side of the observed maximum. This meant that the count rates recorded by
the CID would be very low for focus voltages much lower than the optimum (70%).
In practice, with the optimum focus voltage, the CID FM was recording a maximum
of ~1400 counts/s.

3.7 CID Calibration

During calibration, the data acquisition procedure was similar to the in-flight
envisaged one, with the deflector voltage starting at the maximum setting and then
being stepped down through its full range while acquiring data for a pre-set time
interval at each step. From the data obtained with the full energy range sweep, a
reduced voltage range, big enough not to lose any valid events, was determined. The
data acquisition time interval and the ion beam energy were kept constant during an
energy sweep.

3.7.1 CID EM Tests

Figure 3.20 represents one of the very first energy spectra obtained for a beam
energy of 600 eV, an acquisition time per step of 65 ms and with the ion gun aligned
with the CID EM. At first glance, the results appeared quite satisfactory. The
distribution had the expected shape, showing that the sensor was acquiring events
only within a specific voltage range which was relative to the test beam energy.
Looking at the FWHM points of the distribution, the CID EM started recording
events when the Deflector voltage was at ~668 V and stopped when the Deflector
voltage was at ~ 590 V, just below (less than 1.7%) the corresponding nominal beam
energy of 600 eV. The 668 V Deflector voltage corresponds to a 1st RPA voltage of

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Figure 3.20. An early energy spectrum obtained with the CID EM. The nominal ion energy was 600eV.

about 607 V, with the fixed voltage divider set-up so that 1st RPA voltage = 0.909 X Deflector voltage. Thus, the 1st RPA functioned as expected. The lower limit of the distribution, however, was higher than expected. Indeed, the FWHM was ~12%, about 15% less than that predicted by the simulations results. The difference, albeit not of great significance at this stage, could be due to either or both of the following reasons: a) the angle of the cone of the Deflector was too small, thus, resulting in reduced deflection capability for voltages below the corresponding ion energy; and b) at low Deflector voltages, the accelerating field set-up between the Deflector and the Accelerator, was failing to direct the particles towards the MCP.
When it came to testing the sensor response at beam energies below 40eV, using the custom made ion source, the FWHM of the spectra increased with reducing ion energy. In particular, the FWHM was ~28% at 40eV and gradually increased up to ~69% at 10eV, the lowest energy tested. This was proof that the particles were being successfully deflected by the Deflector cone and that it was the accelerating field that did not produce the expected results. There was, however, an even more worrying aspect in the CID EM low energy response. Figure 3.21 illustrates the distribution obtained for a 25eV ion beam. Looking at the FWHM Deflector voltages, the lower voltage is still close to the corresponding beam energy, but the upper one is at ~35V, resulting in a resolution of ~31% (FWHM). As we have already seen, the sensor was supposed to be set-up such that the 1st RPA was at
~91% of the Deflector voltage. Based on the experience from the CID EM tests at high energies, whenever the 1st RPA reaches in value the ion energy (at a Deflector voltage of ~28V in this case), the count rate should fall below half the maximum. Here, however, the 28V Deflector voltage corresponds to the peak of the distribution, while at half maximum, the 1st RPA voltage is ~32V or ~28% higher than the ion energy. The ion source power supply variation was never more than 0.5V (or 2% of the 25eV beam), hence it is not the main source of error.

The situation became even more complicated when the angular response tests were performed. Figure 3.22 illustrates the count rates (normalised to maximum) obtained with the CID EM at the full range of accepted angles. The ion gun was fitted with the collimator and the beam energy was 500eV. In this plot, the count rate was obtained with the Deflector set at the voltage that corresponded to the maximum number of counts in the energy spectrum, obtained with the instrument aligned to the source, for a 500eV beam. The number of particles detected, increased with absolute angle value up to about 3.5° and then reduced again down to zero at about 5.5°. Although the range of angles was very close to the expected from the collimator geometry, the count rate remained below half maximum between -2° and 2°. Thus, the tests emphatically confirmed what was already suspected from the beam mapping tests; there was a hole in the sensor's angular response.

Since the above described sensor characteristics constituted a severe deviation from the computer simulation results, it was important that the whole process of instrument manufacture and assembly be investigated. It turned out that the technician who assembled the voltage divider, had used an older configuration in which the 1st RPA and the Accelerator received ~54.5% and ~9.1% of the Deflector
voltage respectively. The voltage divider, together with the rear MCP face bias

![Graph of count rate variation with angle](image)

Figure 3.22. Normalised count rate variation with angle of incidence for the CID EM.

resistor, were assembled as a separate unit fully enclosed in a cylindrical aluminium container wherefrom, once integrated to the sensor, only the total resistance value of the Deflector - 1st RPA - Accelerator circuit could be measured.

Figure 3.23 illustrates the computer simulated performance of the sensor as angle versus energy and Figure 3.24 the energy response integrated over all angles. The bias voltage values used, were 110V, 60V, 10V for the Deflector, the 1st RPA and the Accelerator respectively. As in the laboratory tests, the half maximum on the higher energy part of the distribution is quite close to the corresponding Deflector voltage (Fig. 3.24) while the other half maximum point is at ~87eV resulting in an
Figure 3.23. Scatter plot of successful ion trajectories relative to ion energy and angle of incidence from simulations of the CID EM.

Figure 3.24. Simulated energy response of the CID EM integrated over angle.
energy resolution of ~25% (FWHM). The variation of the energy response with angle of incidence (Fig. 3.23) sheds some light to the peculiar angular response of the instrument (Fig. 3.22). The energy range, over which the particles succeed in reaching the detector, increases with angle of incidence and, moreover, the number of detected particles, of the same energy, increases with angle. Witness to the latter effect, is the fact that the half maximum of the distribution (integrated over angle) in Figure 3.24 occurs at ~87eV even though there are, virtually, no events up to almost 2°. As the angular response tests were performed without varying the Deflector voltage, due to the limited vacuum chamber time available, we cannot verify that the CID EM energy resolution varied with angle. There are, however, strong indications to that fact. Figure 3.25 illustrates an energy spectrum obtained under similar conditions to those for the distribution in Figure 3.20 but for the ion gun which was now fitted with the collimator. The resolution now is ~9.4% FWHM or ~77% of the previously obtained one. With all the other settings being unchanged, it is very likely that the reduced range of accepted angles caused the reduction in the energy range of the accepted particles. The conical field of view of the CID covers the ion gun’s 10mm diameter aperture for a half angle of 3.2° while 0.7° is enough when the collimator is used.

The reduction of resolution at energies below 20eV is partly due to the fact that the beam emitted by the custom-made ion source had a wider angular spread. Since, however, all the voltages are scaled with respect to the Deflector bias one would expect the resolution to remain constant (independent of the particle energy) and close in value to the one predicted by the simulations. Even at 25eV, close to the middle of the low energy range (0 to 40V was specified for the flight sensor), the measured FWHM is ~22% higher than predicted (31% against 25%). Hence there
Figure 3.25. Energy spectrum obtained for a 600eV ion beam and with the ion gun fitted with the collimator.
should be another factor causing the observed resolution variation. For reasons discussed in the next section, the likeliest candidate is the Accelerator grid.

3.7.2 CID FM First Tests

With the delivery date drawing ever closer, it was necessary to proceed with the flight model manufacturing even before the CID EM low energy and angular response tests were performed. The CID FM was identical to the EM but for the voltage divider configuration which now was set-up as it was originally planned, i.e. 1st RPA at 100/110 and Accelerator at 0V with respect to the Deflector voltage. It was anticipated that the more intense accelerating field on the CID FM, caused by keeping the Accelerator at 'ground', together with the increased resolution (13 - 14% was predicted), would improve the angular response and bring it closer to the performance of the simulated instrument (Fig. 3.5).

Figure 3.26 illustrates the energy response of the CID FM for a 500eV beam, obtained with the ion gun aligned to the sensor. The 1st RPA was operating properly, with a sharp cut-off at ~513V (564V Deflector voltage) or 2.6% higher than the nominal beam energy. The double peak feature of the spectrum, however, was not expected. At first, it was thought that, as the secondary peak appeared at the lower Deflector voltages, it represented a more intense occurrence of the effect observed in the EM sensor response; i.e. a sensitivity of the instrument to higher energy particles (beam energy higher than Deflector bias) with incidence angles up to 2° (Figs 3.22, 3.23 and 3.24).

The FWHM of the main peak in Figure 3.26, however, is only ~4.7%, a third of what was expected. In addition, the secondary peak varied in height with ion energy.
Figure 3.26. The energy response of the CID FM for a 500eV ion beam. The sensor was aligned to the ion gun.
Figure 3.27. The energy response of the CID FM for a 200eV ion beam. The sensor was aligned to the ion gun.
Figure 3.27 shows an energy spectrum obtained for a 200eV beam. Here the FWHM is $\sim12.7\%$ for the whole distribution and $\sim5.7\%$ for the low energy (rightmost) peak. Most importantly, however, the height of the valley between the two peaks is $\sim48\%$ of the main peak whereas it was only $\sim2\%$ in Fig. 3.26. Thus, it appeared that there was an energy dependent hole in the observed distribution. At Deflector voltages close to the ion beam energy, or at particle energies around the middle of the acceptance window, most of the particles didn’t reach the MCP.

The most obvious difference between the actual instrument and the computer simulation model, was the shape of the Accelerator grid. In the simulations the Accelerator was assumed to be an ideal mesh with the same potential over its entire surface and 100% transmission. The cartwheel-like grid used, is a poor implementation of the above grid. The large gaps between the three spokes are certain to allow significant field penetration. Figure 3.28 illustrates the simulated field distribution within a sensor with an ideal mesh. The shape of the equipotentials

Figure 3.28. The simulated distribution of equipotentials within a sensor with an ideal Accelerator mesh.
in the region between the 1st RPA and the Accelerator is essential in the
determination of the successful particle trajectories. As shown in Figures 3.26 and
3.27, the energy spectra have three main features, namely two peaks and a valley
between them. Each feature corresponds to a specific part of the sensor energy
passband, therefore, the effect of the 1st RPA-Accelerator field on the incoming
particles can be analysed as follows:

1) **Ions with energies in the lower part of the sensor’s energy passband.** They
undergo the highest and earliest deflection, reaching close to the sensor wall
surrounding the Deflector, which is at Deflector bias. From there, they are
accelerated from the converging (relative to the sensor axis) part of the Deflector -
Accelerator field (convex equipotentials at radial distances >R/2) towards the axis.
The ever flattening equipotentials close to the Accelerator have the same effect on
all the trajectories; namely, they reduce the angle between the particle trajectory and
the sensor axis.

2) **Ions with energies in the middle part of the sensor’s energy passband.** They are
deflected closer to the cone and thus, they undergo most of their acceleration from
the diverging part of the 1st RPA-Accelerator field. As the radius of curvature of
the equipotentials increases at radial distances of more than R/2, the particles cross
the Accelerator plane still retaining a radially outward velocity component and their
detection depends on the effectiveness of the converging Accelerator-MCP field to
direct them towards the MCP.
3) Ions with energies in the upper part of the sensor’s energy passband. Most of these ions follow paths similar to the middle energy particles. However, due to the shape of the equipotentials between the edge of the Deflector and the Accelerator, they are most likely to cross the Accelerator plane at smaller radial distances thus, allowing more time for the MCP field to guide them towards the detector. The picture is different for the particles with energies close to the upper limit of the energy window, which reach very close to the flat base of the Deflector, where the field is almost parallel to the sensor axis. Their paths are similar to these of the low energy particles, only this time the ions almost bounce upon the sensor walls surrounding the region between the 1st RPA and the Accelerator. As the walls are at the same bias voltage as the Deflector, the particles acquire a radially inward velocity component due to the shape of the field in this region.

To determine what happens if the ideal mesh is removed, however, is more difficult. Since, at that time, there was no 3D version of the simulation software, a test for a sensor where there was no Accelerator grid was performed. Figure 3.29 illustrates the resulting potential distribution. The exclusion of the Accelerator mesh allows some field penetration from the MCP side. The field equipotentials are now convex equipotentials as far as the middle distance between the Deflector and the MCP. Additionally, the shape of the field, at radial distances >R/2, should have a converging effect, more intense than in the ideal case, on the deflected particles. Thus, this simulation did not offer any evidence for the behaviour of the CID FM. As the delivery time was getting ever closer and the only thing we had to go by was the simulations results of the ‘meshed’ instrument, it was decided that a cross wire stainless steel mesh with 100X100 lpi, 0.001 in wire thickness and 81%
transparency should be fitted on the front face of the Accelerator grid. As the Deflector and the Accelerator were glued together prior to integration in the instrument, a new Deflector cone was required. As it turned out, at the mechanical workshop there was no one available to produce it until about two months after the official delivery date. Thus, we opted for the next best solution of fitting the mesh behind the Accelerator and as close as possible (2mm) to it.

Figure 3.30 illustrates the modified CID FM response for a 500eV ion beam. The obtained distribution is quite similar to that of the instrument without the mesh (Fig. 3.26). The response of the modified instrument for a 200eV beam (Fig. 3.31) is similar to that for 500eV ions, but a lot worse than that in Figure 3.27. Thus, the most likely explanation for the instrument behaviour is that the Accelerator grid fails to act as a well defined ‘ground’ plane. Consequently, the
Figure 3.30. The energy response for a 500eV ion beam of the modified CID FM.

Figure 3.31. The modified CID FM energy response to a 200eV ion beam.
field required to direct the particles towards the detector is controlled by the biasses applied on the 1st RPA, the Deflector and the sensor walls surrounding it and the MCP front face. As the potential distribution (Fig. 3.29) was obtained for a front face MCP bias of -3000V and a deflector bias of 100V, it is more representative of the 200eV (Fig. 3.27) distribution than that for 500eV (Fig. 3.26). The CID FM body assembly at the region between 1st RPA and MCP, has the following sequence (Fig. 3.1): 1st RPA - 0.4mm insulator - 4mm conductor at Deflector voltage - 1mm insulator - 0.127mm Accelerator grid at 'ground' - 3mm conductor at 'ground' - 4mm insulator - 3mm conductor at front MCP bias (-2800V) - 0.254mm front MCP contact at -2800V - MCP stack. Even if we assume that there is no Accelerator grid, in the region close to the 1mm gap between the Deflector voltage biassed conductor and the 'grounded' one, the field distribution depends on the applied Deflector voltage. In particular, the MCP generated field has a constant value of 280V/mm, which means that for Deflector voltages lower than 280V the field configuration is more or less as in Figure 3.29 and the hole in the experimental data should be attributed to the field distortion caused by the Accelerator grid. For higher Deflector voltages, however, the field in the above region would gradually become more parallel to the sensor axis and thus, less effective in reducing the radial velocity component of the deflected particles. As it has already been discussed, the detection of the medium energy particles is the one most dependent on the converging properties of the field. Therefore, at Deflector voltages above 280V, the energy distribution should have a deeper and wider valley between the high and low energy peaks.

As would be expected from the above reasoning, the inclusion of a mesh 2mm behind the Accelerator made matters worse. Not only did it prevent the MCP field to
Figure 3.32. The distribution of equipotentials within a sensor with a 'grounded' mesh fitted 2mm behind the Accelerator grid.

attract particles towards the detector, but it allowed some penetration from the Deflector side (Fig. 3.32). Thus, the particles crossing the Accelerator plane at radial distances >R/2 would be further accelerated towards the sensor walls (the field equipotentials at distances >R/2 are concave). This should explain why the response obtained with the CID FM (with the mesh) for 200eV ions (Fig. 3.31) is similar to that obtained for 500eV ions with (Fig. 3.30) or without (Fig. 3.26) the mesh. The Deflector field penetration is likely to affect the detection efficiency of the sensor. In particular, the shape of the field in the vicinity of the Accelerator grid directs the particles towards its spokes thus, increasing the effective spoke width. The only positive effect of the inclusion of the mesh was that now the instrument response remained constant throughout the energy range of the sensor. Finally, it was decided that the instrument would be calibrated and flown in its current configuration.
3.7.3 Modified CID FM Calibration

The calibration tests were focussed on the determination of the angle and energy response as well as the geometric factor of the instrument. For the latter, the Faraday cup, connected to an electrometer, would provide absolute measurements of the ion beam current. The ion gun produced current, however, was near the lower limit of the electrometer current range. This forced us to operate it with the focus voltage set at 70% of the beam energy, where the maximum count rate was obtained. The possible errors, in the ion gun - sensor alignment and in the position of the centre of the CID collimator relative to the axis of rotation, would be overcome by acquiring data over a grid of X - Y positions covering the whole of the aperture area. It was found that the X - Y table motors were getting overheated and ceased moving before the completion of a whole run. Consequently, the data acquisition procedure had to be modified as follows:

1. Turn on the ion gun, set filament current as high as possible, without risking destruction, set beam energy voltage at 900V, set focus voltage at 630V and allow one hour for beam stabilisation.

2. Turn on MCP voltage at required level (-2800V).

3. Turn on Deflector voltage at a level 5% higher than the ion energy selected.

4. Optimise count rate by moving the ion gun (in 125 μm steps).

5. Set the data acquisition time (from 1-10s)

6. Acquire a full energy spectrum.

7. From this spectrum, determine a smaller Deflector voltage range, wide enough not to lose valid events.

8. Rotate the sensor by -6° clockwise looking at the rotary table from above, which represents the maximum expected half angle plus 2° (polar angle test).
9. Adjust the ion gun position to maximise count rate. If no counts are detected, rotate the sensor anti-clockwise at 1° steps until events obtained. When counts detected, optimise count rate and acquire a spectrum.

The acquisition of a full spectrum at each angular step, would enable to check any energy range variations with angle.

10. Continue to acquire energy spectra at 1° steps, always anti-clockwise, until no counts are detectable.

11. Return sensor to its original position (aligned to the ion gun).

12. Repeat above procedure for ion energies of 500eV and 200eV.

13. Rotate sensor body (Z-axis of rotation) by 60° clockwise (azimuthal angle test) from the front of the sensor looking aft and repeat the above steps.

The 60° sensor body rotation was the minimum azimuthal angle step available, due to the way the sensor was mounted on the rotary table.

14. Rotate the sensor body by 60° (120° in total) and repeat process until a full 360° rotation is completed.

3.7.3.1 CID FM calibration Results

The above test procedure, where the energy sweep was performed with the ion gun positioned for maximum count rate, had one intrinsic inadequacy; i.e. the count rate depended on the selected Deflector voltage setting. The time available did not permit the acquisition of more than two or three energy spectra per angle of incidence, as most of the time was spent trying to locate the maximum count rate ion gun position. Thus, it was chosen to acquire data, with the ion gun positioned for maximum count rate, at Deflector voltages corresponding to the two peaks of the energy spectrum (obtained with the CID aligned to the source). If the total number
of events, in the distribution with the lower total, were more than 90% of the other, the averaged total would be used in the calculations. If the lower total were less than 90%, then the distribution with the highest total of events would be used. In Figure 3.33, for instance, where the illustrated distributions were obtained for a 500eV beam at a nominal angle of $4^\circ$, only spectrum (b), obtained with the ion gun positioned for maximum count rate at the main peak, would be used.

![Figure 3.33. The energy response of the CID FM for a 500eV beam at a nominal incidence angle of $4^\circ$. The count rate was optimised at the secondary peak (a) and at the main peak (b).](image-url)
Figures 3.34 a, b and c illustrate the angular response of the sensor for a 500eV ion beam with the sensor body rotated by 0°, 60° and 120° respectively (similar results were obtained from the tests at 200eV and at 900eV). The ordinate in each of the graphs represents the normalised total number of events at each angular step. The angular response tests at 180°, 240° and 300° weren’t performed due to lack of time. However, since the polar angle range (-5° to 5°) effectively yields the angular response of the sensor for two diametrically opposite azimuthal angles, the tests at 180°, 240° and 300° would only help to provide better statistics. The apparent differences in the response among the three graphs (Fig. 3.34) were expected, albeit not at such high a degree. The angular stepping was performed in the X-Z plane and the Accelerator was lying in the X-Y plane, where the rotation of the CID body was performed. Hence the number of events (for similar angular positions of opposite sign) would depend on the proportion of the ‘illuminated’ semicircle area that was taken up by the Accelerator’s spokes. If it is assumed that the Y-axis divides the Accelerator area into two semicircles, then the maximum event variation would occur when the double-width spoke together with a single-width one, lay on the same side of the Y-axis. Assuming that the particle trajectories are uniformly distributed over the whole of the semicircle area, then the difference in events due to the physical size of the spokes would be ~12%. This value, however, could be a lot different from the measured one as it does not take into account the fact that the effective spoke width is larger due to the shape of the field in the region between the Deflector and the Accelerator. From the data used in Fig. 3.34, the total number of events for positive angles is 9.4% higher than that for negative angles at 0°, 55.3%
lower at 60° and 38.6% lower at 120°. The above values, however, incorporate the

Figure 3.34. The angular response of the CID FM integrated over energy for azimuthal angles of 0° (a), 60° (b) and 120° (c). The angle steps corresponded to a nominal 1° of rotation and were always taken from -5° to 5°. The ordinate is normalised to one.

CID FM energy response variations with angle. Since the data acquisition was optimised for maximum count rates at the peaks of the energy distribution, the variation in the maximum obtained count rates, for similar angular positions of opposite sign, should be more representative of the instrument's angular response. Figures 3.35 a, b and c correspond to Figures 3.34 a, b and c respectively, but for
the ordinates which now show the normalised maxima obtained at each angular step. The level of asymmetry is reduced significantly. In this case, the difference between the total number of events, either side of the middle step, is calculated as 6.6% at 0°, 16.4% at 60° and 17.2% at 120° with the higher total always occurring on the left of the middle step in Figure 3.35 (negative angles). In view of the above differences and assuming that the 6.6% difference could be attributed to other factors, such as slight errors in the angular positions and ion gun output variations, it seems very likely that the Accelerator spokes positions relative to the Y-axis were as follows: a) the double thickness spoke was on the opposite semicircle from that of the single thickness spokes (with respect to the vertical axis) at 0°; and b) the double thickness spoke was lying on the same semicircle (the one most illuminated at positive angles) as one of the single thickness ones at 60° and 120°. This is, marginally, achievable only when the double thickness spoke is aligned with the Y-axis at 0°. As has been already discussed, the beam mapping data suggests (Fig 3.17) an Accelerator grid position where the spokes are orthogonal to the above. Even if we assume that for some unknown reason the X and Y axes had been transposed during the beam mapping tests, there is another fact pointing to a different factor affecting the instrument response. In particular, looking for number of events differences at the Deflector voltage (~542V) corresponding to the main peak of the energy spectrum obtained with the CID aligned to the ion gun, the picture is completely different. At 0° the difference is still ~6.1% in favour of the negative angles. However, at 60° and 120° the differences are ~30% and ~17.9% but in favour of the positive angles respectively. If the event variations were totally due to the spokes’ positions relative to the Y-axis, the differences should be in favour of either the negative or the
positive angles irrespectively of the incoming ions' energy. It is clear, therefore, that

![Angular Response Graphs](image)

Figure 3.35. The angular response of the CID FM relative to the maximum count rate obtained at each angle step, for azimuthal angles of 0° (a), 60° (b) and 120° (c). The angle steps corresponded to a nominal 1° of rotation and were always taken from -5° to 5°.

there exists another geometrical asymmetry causing the sensor angular response to be energy dependent.
3.7.3.2 Investigation of the Energy Response Variation with Angle

Figures 3.36 (negative angles) and 3.37 (positive angles) illustrate the normalised energy spectra obtained, using a 500eV ion beam, with the CID body rotated by 0° (leftmost column), 60° (middle column) and 120° (rightmost column). Each row corresponds to the same angular step (same nominal angle) with the angle of incidence increasing from top to bottom. Studying the above figures, the following picture emerges:

**CID FM body at 0°**

The energy response remains almost constant with angle, the range of Deflector voltages (where there is particle detection) is always ~470 - 555V and the low energy (high Deflector voltages) cut-off always occurs at ~550V (corresponding to a 500V 1st RPA voltage). There is, however, a slight increase of the high energy peak (low Deflector voltages) at positive angles (fig 3.37).

**CID FM body at 60°**

In this case the greatest variability of the energy response is found. The effective Deflector voltage range is fairly constant but, at negative angles, the cut-off point (the voltage where the number of recorded events drops below 50% of maximum) goes down with angle, as does the height of the low energy peak. At positive angles, it is the high energy peak that reduces with angle while the low energy one remains at the same voltage range with a cut-off at ~550V.
Figure 3.36. Energy spectra obtained at each negative angle step. The absolute angle increases from top to bottom (steps 4 to 0) for azimuthal angles of 0° (leftmost column), 60° (middle column) and 120° (rightmost). The ordinate is normalised to the maximum count rate obtained for the same azimuthal angle.
Figure 3.37. Energy spectra obtained at each positive angle step. The angle increases from top to bottom (steps 6 to 10) for azimuthal angles of 0° (leftmost column), 60° (middle column) and 120° (rightmost column). The ordinate is normalised to the maximum count rate obtained for the same azimuthal angle.
CID FM body at 120°

The response is similar to that for a CID body rotation of 60°, but with the low energy peak always being comparable to the high energy one at negative angles. In contrast, the high energy peak is always comparable to the low energy one at positive angles.

Excluding the Accelerator grid, the only component that is crucial for the energy response of the sensor is the Deflector. The cone is glued on a 1mm-long cylindrical insulator which in turn, is glued on the centre of the Accelerator grid. As all this was done by hand, it is possible that the cone has a radial displacement from the sensor axis of the order of 0.1mm. Another possible error is for the cone axis to be at an oblique angle to the sensor axis. A 0.01mm height difference of the layer of glue would result at an angular displacement of ~0.57° and a radial displacement of the tip of the cone of ~0.02mm. If it is assumed that the displaced cone axis lies on the X-Z plane (horizontal plane), with the cone tip being closer to the rear aperture side which accepts the ions at negative angles, this would result in a 1st RPA-Deflector field asymmetry relative to the sensor axis. Assuming that the Deflector bias is kept constant, the sensor energy response should be the following:

Low energy particles (energy less than the corresponding Deflector bias) at negative angles. They enter a stronger retarding field which leads to increasingly higher losses with angle. The result is a low energy response curve which is less steep than what is usually expected in an RPA spectrum.

High energy particles (energy higher than the corresponding Deflector bias) at negative angles. The field is more effective for lower energies thus, the high energy peak of the spectrum should be close to the corresponding deflector bias.
Low energy particles at positive angles. They enter a weaker field which is more effective in deflecting the very low energy particles. Thus, the low energy peak should be just above the 1st RPA bias and the response curve quite steep at the low energy part.

High energy particles at positive angles. As the field is not strong enough to deflect them away from the axis, most of them will hit the Deflector. The high energy peak of the spectrum will be very small.

The above analysis is in good agreement with the results obtained with the CID body rotated by $60^\circ$ (middle column in Figs 3.36 and 3.37). It can also predict the sensor response at $0^\circ$ (leftmost column in Figs 3.36 and 3.37) on the assumption that the cone displacement is mainly along the Y-axis. The response at $120^\circ$, however, is rather harder to explain. The similarity of the low energy response to that at $60^\circ$ suggests a cone displacement predominantly along the X-axis. On the other hand, the high energy response, almost identical for both positive and negative angles, points to a cone aligned to the sensor axis. Further investigation would require a big amount of precious computer time and without much gain as it would just help to emphasise the obvious. For best angular response results, the cone axis has to coincide with the sensor axis.

3.7.3.3 Total Angle and Energy Response

Figures 3.38 and 3.39 illustrate the total number of events (normalised to 1) per energy level (as a percentage of the Deflector voltage) and per angle step respectively. A few weeks after the CID FM had been delivered, a 3D version of the
Figure 3.38. The energy response of the CID FM integrated over angle.

Figure 3.39. The angular response of the CID FM integrated over energy and azimuthal angle.
simulation software was made available. Figures 3.40 and 3.41 illustrate the energy response, with angle and integrated over all angles respectively, for a sensor with the same configuration as the CID FM. The maximum accepted angle (Fig. 3.40) is \( \sim 4.3^\circ \) and the event loss is present throughout the range of accepted angles. The integrated energy response spectrum (Fig. 3.41) is quite similar to that obtained experimentally (Fig. 3.38) with the main differences being the slightly wider energy range. In particular, there is very good agreement in the width of the main (low energy) peak (FWHM 6.7\% from the simulations and 6.8\% experimentally), less so in the secondary peak (5.5\% simulated against 3.2\%). Finally, assuming the response to be step-like, the FWHM of the whole distribution is calculated as 14.2\% in the simulations, against \( \sim 13\% \) from the laboratory tests. The difference is mainly due to the larger error in the 1st RPA potential (\( \sim 4\% \) against \( \sim 3\% \)). There is also a sizeable difference (simulations: 27\% of maximum; experiment: 10\% of maximum) in the depth of the hole of the distribution which should be attributed to the Deflector cone misalignment. The agreement in the angular response, even though it does not appear equally good (the maximum accepted angle is \( \sim 4^\circ \) in the simulations against \( \sim 5^\circ \) in the experiments; a difference of 25\%), is satisfactory when the following considerations are taken into account:

a) The maximum anticipated error in the rotary table movements is \( \sim 2.8\% \) of one degree (1 rotary motor step). It should be noted, however, that, due to the weight of the base plate, the final angle reached was on average \( \sim 95\% \) of what was specified.

b) Another major factor is the angular distribution of the ion beam. If the rotation axis passed through the centre of the CID FM collimator, the displacement (along the X-axis) of the front aperture centre from the ion gun axis, at an angle of \( 5^\circ \), would be \( \sim 0.46\)mm. During the angular response tests, the maximum count rate at
Figure 3.40. Scatter plot of the successful trajectories relative to their angle of incidence and energy obtained from a 3D simulation of the CID FM.

Figure 3.41. Integrated energy response of the CID FM obtained from a 3D simulation.
$5^\circ$ (steps 0,10 assuming that the rotation per angle step is the nominal $1^\circ$) was obtained with the ion gun moved along the X-axis by 0.625mm yielding an axial distance (along the Z-axis) between the rotation axis and the collimator centre of $\sim1.8$mm. If, however, the error in the collimator position were less (0.5mm expected), it would mean that the sensor was recording events within a cone of double the expected half angle ($0.6^\circ$ instead of $0.3^\circ$). The last argument is supported by the slight flaring out of the angle response curve between steps 0 and 1 as well as between steps 9 and 10 (Fig. 3.39).

Figure 3.42. 3D plot of the normalised number of events, obtained with the CID FM per energy level and per polar angle integrated over azimuthal angle.
Figure 3.42 illustrates the sensor response with energy and angle of incidence. The axis labelled 'Total No. of Counts' represents the sum of the events recorded at each angle and particle energy over all the azimuthal angles used (the angles at which the sensor body was rotated). The ion energy was derived from the Deflector voltage range and corresponds to the range of energies accepted by the sensor when its Deflector bias is kept at 500V. The angular range has been derived from the angular steps after accounting for the above mentioned errors. The field of view has a half angle of $3^\circ \pm 0.5^\circ$ at FWHM.

![Graph showing sensor response with energy and angle of incidence.](image)

**Figure 3.43. Energy response of the CID FM for a nominal ion energy of 20eV.**

At low energies the energy response measured with the custom-made ion source, varies with particle energy. In particular, it retains its usual shape down to $\sim 15$eV (Fig. 3.43; ion energy 20eV), while below that energy the secondary peak disappears and the FWHM of the distribution increases as the particle energy reaches closer to the lower limit of the measurable range. Fig. 3.44 illustrates the distribution obtained for 10eV nominal ion energy (the response suggests $\sim 11$eV) having a resolution
$\Delta E/E \sim 12\%$ FWHM, while at a nominal energy of 5eV (Fig. 3.45) the resolution is $\Delta E/E \sim 22\%$. The low energy tests were performed using the CIDEL FM which swept through the range of 0-40V in 127 steps of $\sim 0.31V$. Thus, the disappearance of the second peak is most likely due to the fact that at low voltages the energy

![Energy response of the CID FM for a nominal ion energy of 10eV.](image)

Figure 3.44. Energy response of the CID FM for a nominal ion energy of 10eV.
Figure 3.45. Energy response of the CID FM for a nominal ion energy of 5 eV.
range between the two peaks becomes smaller than the voltage steps and cannot be resolved. The $\Delta E/E$ increase is probably due to the fact that the beam energy spread becomes increasingly comparable to the beam energy.

3.7.4 The Modified CID EM

Several months after the CID FM delivery, but over one month before the actual launch of the STRV 1A, a new cone was finally manufactured and integrated with an Accelerator that featured a mesh on its front face. This new assembly was inserted to the CID EM (now called CID EMM), which also had its voltage divider circuitry changed so as to match the specifications of the CID FM (1st RPA bias = 100/110 of Deflector bias, Accelerator at 'ground'). The instrument calibration time available was only one week thus, the tests were limited at high energies; i.e. the energies where there was satisfactory output by the ion gun ($\geq 200$eV). The focus voltage of the ion gun was set at 50% of the beam voltage used (as we have already seen, at this focus voltage the count rate remains above 90% of maximum for radial distances, between the source and instrument axes, of up to $\sim 0.5$mm) thus, doing away with the highly time consuming task of locating the highest count rate gun position every time the CID - ion source angle was changed. Figures 3.46, 3.47, 3.48 illustrate the obtained sensor response in the same manner as in Figures 3.38, 3.39 and 3.42 respectively. The energy resolution is $\sim 12\%$ FWHM which is just over 20% less than that suggested by the simulations (Fig. 3.4; $\Delta E/E \sim 15\%$ FWHM). This is partly due to the assumed voltage difference between Deflector and 1st RPA (10% in the simulations, 9.1% actual) and partly due to the Deflector being less
effective than predicted by the simulations, in diverting particles with energies just

Figure 3.46. The energy response of the CID EMM integrated over angle.

Figure 3.47. The angular response of the CID EMM integrated over energy and azimuthal angle.
Figure 3.48. 3D plot of the, normalised, number of events, obtained with the CID EMM, per energy level and per polar angle integrated over azimuthal angle. above its bias. Like that of the CID FM, the field of view has a half angle of $\sim 3^0$ FWHM.

3.7.5 The Geometric Factor

The CID records a number of pulses a given time when the detector is viewing in a particular direction and when its energy passband is centred on a particular energy.
The relation between counts and the distribution function is (Johnstone et al., 1987):

\[ N = \int dt \int v \cdot A G(v) f(v) \, dv \quad (3.1) \]

where \( N \) is the number of counts, \( v \) is the particle velocity, \( A \) is a vector whose magnitude is the aperture area and whose direction is along the inward normal, \( f(v) \) is the particle distribution function and \( G(v) \) is the detector response function. The latter has the property that \( G(v) = G(v/v_0) = G(v') \), where \( v_0 \) is the centre velocity in the passband, i.e. the shape of the response is independent of the centre velocity. The integral is taken over all phase space. Then,

\[ v \cdot A G(v) \, dv = v_0^4 [ v' \cdot A G(v') \, v'^2 \, dv' \, d\Omega ] \quad (3.2) \]

The detector response function \( G(v) \) is assumed to be non-zero in a comparatively small region of the characteristic range over which the distribution function varies, i.e. \( f(v) \) remains constant over the whole of the detector response (Vasilyunas, 1971, calls it 'differential' behaviour).

We can now rearrange and rewrite equation 3.1 in the following way:

\[ f(v_0) = N/(v_0^4 \lbrack GF \rbrack T) \quad (3.3) \]

where \( T = \int dt \) is the accumulation time (it is assumed that time variations during the accumulation period can be ignored) and \( [GF] \), the geometric factor, is a
property of the sensor independent of $v_0$, which can be obtained from the calibration and is defined as:

\[ [GF] = \int v' \cdot A \, G(v') \, v'^2 \, dv' \, d\Omega \]  

(3.4)

3.7.5.1 Calculation of the Geometric Factor

The density of the beam is obtained by measuring the beam current with the Faraday cup whose collecting area is $A_F$:

\[ \int f(v) \, dv = I_b / e \, v_b \, A_F \]  

(3.5)

Each measurement gives a value:

\[ (v_b' \cdot A) \, G(v_b') = e \, v_b \, A_F \, N_b / I_b \, T \, v_0 \]  

(3.6)

The last two equations above, are obtained on the assumption that the ion beam is sufficiently narrow i.e. the spread of velocities about the bulk velocity is very small compared to the bulk velocity itself (Vasilyunas, 1971, calls it ‘integral’ behaviour). In which case, the sensor response function is assumed not to vary significantly over the range of $v$ that $f(v)$ is appreciably different from zero.

The geometric factor can be obtained from a summation over a series of calibration measurements:

\[ [GF] = \left( \frac{e \, A_F / I_T}{v_0} \right) \sum N_b \, v^2 \, \Delta v' \, (\sin \theta) \, \Delta \theta \, \Delta \phi \]  

(3.7)
where \( \theta \) is the polar angle, \( \Delta \theta \) the polar angle step and \( \Delta \phi \) the step in azimuthal angle.

The velocity passband of the analyzer is narrow enough to allow us to approximate

\[
\frac{v}{v_0} = 1 \quad v' = 1
\]

with an error of less than 5%, in addition \( \Delta \phi \) and \( \Delta \theta \) are constant (60° and 1° respectively). The Deflector voltage step was kept constant at \( \Delta V = 6V \pm 10\% \) (for a 500eV ion beam) therefore, \( \Delta v' = \Delta v/v_0 = 0.5 \Delta E/E_0 = 0.5 \Delta V/V_0 \) is also constant. 

Thus equation 3.7 becomes:

\[
\text{[GF]} = \left( e \frac{A_p}{I_b T} \right) \Delta \phi \Delta \theta \Delta v' \sum N_b \sin \theta \quad (3.8)
\]

where the summation is taken over the complete series of measurements covering the response of the analyzer (561 data points in total for the CID FM and 510 data points for the CID EMM).

During the current measurement, the electrometer readings not only fluctuated constantly but were susceptible to extraneous noise sources. The beam current value that looked most likely was 1fA ± 80%. After the completion of the calibration tests and risking filament burn-out, a spectrum was obtained with the sensor aligned to the ion gun and an electrometer reading of 5fA ± 50%. As the shape of the response of this final spectrum was quite similar to the ones obtained with lower beam currents, it is conceivable to assume that application of its maximum count rate
value to a suitably normalised total response of the sensor would yield a realistic GF value. Effectively, the higher current measurement yields a multiplier of 5.8 for each data point or a 16% higher GF than the calculation based on the lower beam current value. As the Faraday cup was apertured, the collecting area value used, was the area of the front aperture (2.8mm diameter) i.e. \( A_F = 6.16 \text{mm}^2 \).

Another problem arises from the existence of \( \sin \theta \) which is zero at the position where the count rates usually reach their maximum value. For the calculation of the GF it has been assumed that there is an error of 0.1° in the initial position of the sensor (ion gun aligned to the CID). Johnstone et al. (1987) get around this problem by making the azimuthal angle step inversely proportional to \( \sin \theta \), namely, \( \Delta \phi = \Delta \phi / \sin \theta \) where \( \Delta \phi' \) is constant, effectively making the volume element \( \Delta v' \) constant. Thus, equation 3.8 becomes:

\[
\text{[GF]} = (e A_F l_b T) \Delta \phi' \Delta \theta \Delta v' \sum N_b
\]  
\[ (3.9) \]

Using equation 3.8 the GF is calculated as:

\[
\text{[GF]}_{CIDFM} = 2.22 \times 10^{-4} \text{mm}^2 \text{sr}
\]  
\[ (3.10) \]

while using equation 3.9 with the assumption that the solid angle step is constant i.e. \( \Delta \Omega = \text{sensor field of view} / \text{No. of angle steps} = 2.4 \times 10^{-3} \text{ sr} / 33 \), we get \( [GF]_\Delta \Omega = 2.57 \times 10^{-4} \text{mm}^2 \text{sr} \) which is ~16% higher. The computer simulations results yield \( [GF]_c = 2.73 \times 10^{-4} \text{mm}^2 \text{sr} \) which, adjusted for mcp efficiency (60%), gives \( [GF]_c = 1.64 \times 10^{-4} \text{mm}^2 \text{sr} \). The range of energies used in the simulations, however, was a lot wider than
the CID acceptance window (only the ratio of successful trajectories over the total number of particles is used in the calculation) thus the simulation derived GF is possibly about 20-30% lower.

A simple calculation of the GF, ignoring the absolute value of the beam current, can be made as follows:

FWHM half angle field of view = 3°, i.e. Field of view = 8.61 \(10^3\) sr.

Aperture diameter = 1mm, i.e. aperture area = 0.785 mm\(^2\).

Mcp efficiency = 0.60

Grid transmission factor = 0.72 (mesh transmission \(\times\) Accelerator grid transmission = 0.81 \(\times\) 0.89)

\(\Delta E/E\) of main peak = 6.7 \(10^2\)

\[
[GF] = 8.61 \times 10^3 \times 0.785 \times 0.60 \times 0.72 \times 6.7 \times 10^2 = 1.96 \times 10^4 \text{mm}^2\text{sr}.
\]

(3.11)

This is 12% lower than the GF value in 3.10. However, that GF includes the effect of both peaks and hence should be higher.

For the CID EMM the calculated GF values are:

\[
[GF]_{\text{CID EMM}} = 3.52 \times 10^4 \text{mm}^2\text{sr}
\]

(3.12)
using equation 3.8 while equation 3.9 yields $[GF]_\infty = 4.47 \times 10^4\text{mm}^2\text{sr}$. If equation 3.11 is used, only the $\Delta E/E$ needs be changed to $12 \times 10^2$ and the resulting value is $[GF] = 3.51 \times 10^4\text{mm}^2\text{sr}$ i.e. almost identical to the value obtained using equation 3.8.

Figure 3.49 shows the integrated energy response of both the CID FM and CID EMM. The area under the CID FM curve is about 62% of the CID EMM one. Thus, the expected GF for the CID FM should be:

![Figure 3.49. Comparison of the integrated energy response of the CID FM (solid line) and EMM (stars).](image-url)
\[ \text{[GF]}_{\text{CID FM expected}} = 0.62 \quad \text{[GF]}_{\text{CID EMM}} = 2.18 \times 10^{-4} \text{mm}^2 \text{sr} \]

(3.13)

which is, within 2%, the value obtained from the FM calibration. In conclusion the degree of confidence in the GF values obtained should be much higher than suggested by the uncertainty of the ion beam current measurements. However, the CID FM GF value looks the more optimistic, since in its calculation, in equation 3.13 a) it is assumed that both instruments would record the same maximum number of events; and b) no account is taken of the fact that, unlike the CID EMM, most of the particles do not cross the Accelerator mesh at right angles and thus, the transparency of the mesh is reduced.

3.8 The Bessel Box

Bessel boxes are very simple electrostatic analyzers with a straight line geometry acting as bandpass ion energy filters. The basic concept is a can with two holes, one on top and one on the bottom representing the entrance and the exit apertures, together with a beam stop with diameter equal or slightly larger than that of the apertures' in the centre of the device (Fig. 3.50). Low energy cut-off is achieved by applying a DC voltage \( \Delta V \) on the end caps against the central cylindrical part of the box. The apertures are at a voltage lower by \( \Delta V \) than the main body and the beam stop. The charged particles entering the box are forced to pass a potential barrier before reaching the exit aperture. A central beam stop prevents high energy particles with axial trajectories from passing the filter and results in a high energy cut-off. The particles with energies between the two limits are first deflected around the central
stop and then focussed towards the exit aperture by the field within the cylinder. Depending on their energy they either exit the box, or hit the walls (Fig.3.51). The passband of the filter is thus centred at a value (expressed in volts) slightly greater than the voltage at the middle of the cylinder. By sweeping the cylinder and the cap voltages, while maintaining a constant difference between them, the Bessel box can be used as an energy analyzer with resolution better than 1eV. This design not only predates the CID by about 20 years, but it is a lot simpler too.

The similarities of the two designs are the front aperture (1st RPA on the CID), being at a lower potential than the cylindrical structure and the beam stop (Deflector on the CID). Excluding the grid supporting the central stop (at the cylinder potential on the Bessel box; at ground on the CID) the CID could be considered as half a Bessel box with the other half replaced by the MCP detector.

There are, however, a few differences between the Bessel box and the CID. The former sweeps the energy spectrum with a constant energy bandwidth $\Delta E$ (i.e. the energy resolution increases with particle energy), irrespective of the particle energy. The latter instrument sweeps having a constant $\Delta E/E$. In addition, the fact that simulations of similar designs did not produce adequate results, suggests that for the Bessel box: a) the trajectories of the incoming particles must be at angles of more than $4^0$ to $5^0$, although this could be achieved with the introduction of a focussing lens before the entrance aperture (Lindau et al., 1973); and b) the GF, not only is probably even smaller (for similar values of angular acceptance) than that of the CID, but it decreases with increasing particle energy. The Bessel box GF can be increased (at the expense of resolution) by altering the voltage difference between the apertures and the main body. Another possible is the
Figure 3.50. Diagram of a Bessel box with cylindrical symmetry operating as an energy bandpass filter. The selected energy, $E_p$, is slightly higher than the cylinder voltage $V_p$. The energy resolution, $\Delta E$, scales linearly with $\Delta V$ (Stalder et al., 1994).

Figure 3.51. Ray tracing results for a Bessel box with angular acceptance of $\pm 14^0$ and for kinetic energies of 100.1 eV (a), 101.4 eV (b) and 102.7 eV (c). The Bessel box was at 100 V and the entrance and exit apertures at 90 V. (Stalder et al., 1994).
geometry limitations. It seems that, as the CID shares the characteristic of constant fractional energy resolution with the curved plate analyzers (CPAs), the Bessel box shares the CPAs' resolution dependence on their geometry characteristics. It should be noted, however, that the simulations for a voltage difference of ~50% between 1st RPA and Deflector indicated a ΔE/E of ~25%. Thus, there could be geometry limitations (Deflector cone half angle, 1st RPA - Deflector distance relative to sensor inner diameter) for the CID energy resolution too.
CHAPTER 4

The Mission

4.1 The Spacecraft

The STRV 1A (Fig. 4.1) and STRV 1B spacecraft were built by DERA in order to serve: a) as low-cost platforms upon which the in-orbit performance of new technologies would be tested, prior to their application to much more expensive operational missions; and b) to provide a base from which to produce economically future small spacecraft. In particular, the satellites had been optimised to address the following three major hazards facing most spacecraft once in orbit:

1) Radiation damage to solar cells and microelectronics.
2) Electronic anomalies caused by charging and arcing at high (geostationary) altitudes.
3) Erosion of important satellite surfaces by atomic oxygen at the low altitudes used by Earth observation spacecraft.

The shape of the spacecraft, a cube measuring 450 x 450 x 450mm with a mass of 50-53kg, was determined by: a) the need to utilise the full volume available within the launch vehicle's (Ariane 4) fairing; and b) the desire to simplify the construction and assembly processes. Both satellites had Carbonfibre/PEEK structural components and thermoplastic skinned aluminium honeycomb panels. They were powered by GaAs body mounted solar arrays with an average output of 31-33W while 16 NiCd cells provided a total of 46Whr power storage.
Figure 4.1. The STRV 1A spacecraft during integration. The main antenna, the neutralizer, the Langmuir probe and the CID can be seen on the +Z face of the satellite. The cap on the CID had a nozzle through which, the sensor was purged with nitrogen.
4.2 Orbit

The launch expenses, especially for a low-cost programme, constitute a significant part of the total budget of a mission. A highly cost effective means of putting a small payload into orbit, is to incorporate it as an auxiliary payload to an already designated launch. The Ariane Structure for Auxiliary Payloads (ASAP) was utilised to inject the two STRVs, as piggy back to INTELSAT-702, into orbit. The theoretical disadvantage of the orbit parameters being determined by the primary passenger, doesn’t apply here, since, the Geostationary Transfer Orbit (GTO), provided by Ariane for virtually all standard communications satellites, is almost ideal for the complement of experiments carried aboard the spacecraft.

Ariane 44LPW64 was launched on 17 June 1994 and placed the two microsatellites into a GTO with an apogee of 35953km, a perigee of 297.8km, an inclination of $7^\circ$ and an orbit period of $10.5h$. Both spacecraft are spin stabilised around the Z-axis (almost perpendicular to the sun vector) with a spin rate of 5-6rpm. The spin was provided by the Ariane third stage and its rate is controlled by a magnetorquer.

The GTO is challenging in several respects. Near perigee, surface materials are subject to erosion from the action of neutral atomic oxygen, which is produced from the dissociation of molecular oxygen by UV sunlight. Further up, the spacecraft encounter the Van Allen belts of trapped high energy particles, in addition to penetrating cosmic rays, and a variety of radiation effects threaten components and systems degradation. Finally, at altitudes near the apogee of the orbit, surface charging is a likely hazard, since it can result in electrostatic discharge (ESD) and cause upsets in sensitive circuits.
4.3 Experiments Carried

For the sake of completeness, all the experiments, carried aboard the two spacecraft, are mentioned below but with varying degrees of detail.

4.3.1 Atomic Oxygen Experiment (AOE) - STRV 1A

It was developed by the University of Southampton to measure the rate of erosion of a selected number of typical spacecraft materials due to the action of atomic Oxygen. Such information is of increasing importance since the expected lifetime of low altitude satellites is constantly being extended. The AOE relies on the way that atomic Oxygen changes a conducting material (silver) into its non-conducting oxide. As the surface of a thin strip of silver turns to oxide, the resistance increases correspondingly. Hence, the rate of erosion can be measured by a simple electrical circuit. The performance of different materials can be assessed by covering silver strips with a coating of the material in question. The longer the silver underneath remains uncorroded the better the performance of the material that covers it.

4.3.2 Battery Recharge Experiment (BRE) - STRV 1A

This was a power system experiment, devised by the European Space and Technology Centre (ESTEC), studying a new and more effective means of controlling the charging of a spacecraft battery. It involves very careful monitoring of the temperature of the selected cells of the battery, as well as their terminal voltages. When charging is taking place the temperature tends to fall, whereas it rises when the process is complete and more energy is dissipated within the cells. Therefore, by measuring the rate of change of the temperature with time the completion of charging can be accurately determined, as confirmed by a change to a positive value. It was anticipated
that the BRE would provide a power saving of ~30% by minimising the waste inherent in overcharging.

4.3.3 Solar Cell Technology Experiment (SCTE) - STRV 1B

This was an investigation of the extent to which 47 new types of solar cell or solar cells employing advanced or improved cover glasses, manufacturing techniques or coatings, can withstand the damage caused by particle radiation. The results of the SCTE can prove very important for the design of future spacecraft, since the solar arrays have always been oversized to account for radiation damage.

4.3.4 BMDO/JPL Experiments - STRV 1B

The payload of STRV 1B included four experiments commissioned by the Ballistic Missile Defence Organisation (BMDO) and constructed by the Jet Propulsion Laboratory (JPL). They comprised the investigation of the performance of novel Infra-Red detectors and a neural network chip in the radiation environment, the demonstration of a SRAM chip as a radiation mass spectrometer and a series of cryocooler related investigations.

4.3.5 Cosmic Ray Effects and DOsimetry Experiment (CREDO) - STRV 1A

It employs arrays of pin diodes with pulse height analysis to give energy deposition and linear energy transfer (LET) spectra with 40% accuracy. CREDO also provides directional information from two orthogonal arrays, with axes along and perpendicular to the spin axis. Large area arrays (4cm²) are utilised for high LET (100 to 20000 MeV g⁻¹ cm²) and single diodes for low LET (>2 MeV g⁻¹ cm²) at high fluxes (inner radiation
belt). Six radfets of various sensitivity and at various shielding depths (two external) are used to measure the accumulated dose.

4.3.6 Radiation Dose Rate Sensor Experiment (RDRS) - STRV 1A

This experiment is closely associated with CREDO. The RDRS has been designed to protect sensitive equipment against high dose transient radiation events; i.e. intense solar flares. In this flight, the sensor would be examined for the generation of false triggers as a function of trigger threshold.

4.3.7 Radiation Environment Monitor (REM) - STRV 1B

The REM, supplied by ESTEC, comprises two 300μm silicon diode detectors with different areas and shielding configurations so as to have selective sensitivity to either protons or electrons. The “proton detector”, which has an area of 150mm$^2$, a shielding of 3mm aluminium and 0.75mm Tantalum (Ta reduces considerably the penetration of electrons and γ rays), is sensitive to protons with energy $>35$MeV. The “electron detector” has a 25mm$^2$ area, 3mm aluminium shielding and is sensitive to protons with energy greater than 25MeV and electrons with energy greater than 2MeV. When energetic particles pass through the detectors, the atoms in the Silicon lattice get ionised. The amount of the generated charge depends on the type of particle its path length through the detector and its energy. The REM electronics measure the charge pulses and record the impact in one of 16 counter channels according to pulse amplitude (energy deposit).
4.3.8 Charge Alleviation Experiment (CAE) - STRV 1A

When a body is immersed in a plasma it tends to collect charge and adjust its potential with respect to the plasma. This process continues until the net current measured by the charges arriving and leaving the body equals zero. At this time the potential difference between the body and a plasma sheath around it, is such that positive or negative charges are preferentially attracted or repelled so that the net current to the body is zero. As a satellite is an isolated body its electrostatic potential is simply determined by current balance considerations. Charge build up revealed by increasing potential \( V \) will be controlled by the resultant capacitance \( C \) and conductance \( G \) values such that

\[
C \frac{dV}{dt} = \sum I = J A + G V
\]

\[= 0 \quad \text{for equilibrium},\]

where \( J(V) \) is the net current density at the surface of the body \( A \). Determination of \( J \), however, is very difficult as it is a non-linear and non-local function of \( V \) (Wrenn, 1993).

Absolute charging infers that the whole satellite acquires a potential different from the 'space potential' (assumed to be zero in a neutral plasma with \( n_e = \sum n_i \)). While differential charging refers to the situation where a surface element assumes a potential difference with respect to the main structure and other surface elements of the spacecraft.

Photo-emission due to solar illumination (the dominant factor for the current balance of surfaces in space) charges a surface positively, but the emitted electrons have very low energy and further escape is prohibited as soon as the surface reaches a potential of a few volts.
In eclipse, photo-emission is suppressed from the whole satellite while, at other times, some elements may be in shadow either continuously or for only part of a spin. It is in these circumstances that surface charging becomes a real hazard. The plasmasheet region of the magnetosphere frequently features fluxes of relatively energetic electrons which, in the absence of cold plasma, can cause exposed surfaces to be charged up to negative potentials exceeding breakdown thresholds thus, precipitating electrostatic discharge (ESD). The possible magnitude of the charging process is well illustrated by the absolute charging of \(-10\text{kV}\) observed on ATS-5 (Rosen, 1976; DeForest, 1972). Wrenn (1993) however, states that, although discharge to space (‘blow-off’) can occur, the large potential differences which could induce surface breakdown (‘flashover’) or bulk breakdown (‘punch-through’) and serious ESD are effectively prohibited.

The geosynchronous orbit (GEO) at \(6.6\ R_e\) is particularly susceptible to surface charging problems as it is usually outside the cold plasma confined to the plasmasphere and it almost always traverses the plasmasheet on the night side. Rosen (1976) in a review of environmentally induced anomalies of spacecraft in GEO, shows that most of the anomalies occurred in the midnight to dawn satellite local time sector, coincident with the occurrence of large magnetic storms. The magnetosphere is a dynamic system which responds to changes in the solar wind and the interplanetary medium via magnetohydrodynamic coupling. Energetic electrons are frequently injected from the tail as part of the substorm process and then drift towards dawn (Fig. 4.2). ESD is induced by surface charging; large discharge current transients, when triggered, can
Figure 4.2. Schematic view, on the geomagnetic equatorial plane, of electron and proton injection events during the growth phase of a substorm (Rosen, 1976).
conduct or radiate throughout the spacecraft and cause upsets in sensitive circuits.

The STRV's GTO is well suited to a study of the charging process, since most of the orbital period is spent near apogee, although this only applies when apogee is between midnight and 06hr local time. Substorms are more likely at times of high geomagnetic activity, as monitored by the Kp index, with their occurrence frequency peaking within a couple of years of solar maximum. As the launch date (June 1994) was near the minimum of solar cycle 22 (1995/6), only a small number of charging events was expected to be observed.

The operation of an ion thruster on a satellite disturbs the current balance which is the one of the main reasons for the long delayed acceptance of ion engines for spacecraft propulsion. In particular, there has been uncertainty about thruster-spacecraft interactions including such potential problem areas as the emission of electromagnetic interference (EMI), the deposition of sputtered material emanating from the thruster onto sensitive spacecraft surfaces (such as solar cells), direct impact of the beam onto such surfaces and a varying thrust vector direction. In reality, the operation of a thruster depends upon the practicability of an associated neutralizer which, by producing a cold plasma, would: a) prevent the spacecraft charging negatively and thus inhibiting emission of the beam; and b) neutralize the ion beam emitted by the thruster. The operation of such a neutralizer could have a wider application as a means of natural charging alleviation. Schmidt et al, 1995, have reported that indium ion emitters have been successful in reducing the Geotail spacecraft potential from about 50-70V down to about 2V. In the following sections, the basic principles of ion propulsion, the neutralizer flown aboard STRV 1A as part of the CAE and the instruments used as diagnostics tools for the neutralizer operation are presented.
4.3.8.1 Electrical Propulsion

Most satellites, once placed in orbit, require some form of propulsion in order to perform orbit maintenance and repositioning and attitude control while interplanetary spacecraft require some form of on-board propulsion capability.

To date, in the majority of cases, chemical thrusters have been used. In these, a gas is exhausted through a nozzle to produce the necessary thrust. This gas can be cold, supplied by a high pressure storage vessel, or heated by a chemical reaction with the latter producing the best performance in terms of the speed achievable (up to 4.7km/s; Fearn, 1996).

It can be shown, by equating the rate of change of momentum to the force applied on the spacecraft by its propulsion system and integrating over time, that

\[ \Delta V = u_{\text{eff}} \ln \left( \frac{M_o}{M_f} \right) = u_{\text{eff}} \ln \left( \frac{M_o}{M_o - \Delta M} \right) \] (4.2)

where \( u_{\text{eff}} \) is the effective exhaust velocity, \( \Delta V \) the velocity increment required to conduct a manoeuvre, \( M_o \) and \( M_f \) the mass of the spacecraft at the start and end of the manoeuvre and \( \Delta M = M_o - M_f \), which is the mass of propellant consumed. Equation 4.2 (so called rocket equation) illustrates the importance of obtaining as high a value of \( u_{\text{eff}} \) as possible. For a given \( \Delta V \), a low \( u_{\text{eff}} \) must be compensated by a large increase in \( \Delta M \) and therefore in the size of the vehicle.

For small \( \Delta M \) equation 4.2 simplifies to

\[ \Delta M = \Delta V \frac{M_o}{u_{\text{eff}}} \] (4.3)
showing that a tenfold increase in $u_{\text{eff}}$, as is possible with the use of electrical propulsion, leads to a reduction of the required propellant mass by the same factor. Another often used Figure of merit is the specific impulse $I_{sp}$. This is defined as the ratio of thrust $T$ to the total rate of use of propellant $m$ expressed in terms of weight at sea level. Thus,

$$I_{sp} = \frac{T}{m \, g} = \frac{m \, u_{\text{eff}}}{m \, g} = \frac{u_{\text{eff}}}{g}$$

(4.4)

where $g$ is the acceleration due to gravity at sea level.

4.3.8.2 Operating Principles of the UK Kaufman-Type Ion Thrusters

These thrusters (shown schematically in Fig. 4.3) have been developed by DERA in collaboration with AEA’s Culham laboratory and more recently with the Aerospace Corporation in the USA.

The propellant gas, originally (before the 1980s) mercury but changed to xenon mainly due to surface contamination concerns, is fed to the cylindrical discharge chamber via an axial hollow cathode and a bypass distributor mounted on the soft iron backplate. This gas is ionised in a D.C. discharge between the cathode and a concentric anode cylindrical anode. Six solenoids, equispaced around the outside of the discharge chamber, apply an azimuthally symmetric divergent field which enhances significantly the efficiency of the discharge process. The field lines inside the chamber link an inner cylindrical soft iron pole and a larger diameter outer pole. The tip of the inner polepiece surrounds a non-magnetic baffle disc, which separates the cathode region from the main discharge plasma. The design ensures that the primary electrons from the
Figure 4.3. Schematic of the UK Kaufman-type ion thrusters (Fearn, 1996).

cathode, passing through the annular gap between the baffle and the inner polepiece, gain the correct amount of energy to achieve optimum ionisation within the discharge chamber.

The resulting highly ionised plasma drifts towards a set of closely spaced grids at the downstream end of the chamber. The ions are extracted and accelerated, by the electric fields applied between the grids, to velocities typically in the range 30-50km/s. The positive space charge of the emerging ion beam is neutralized by electrons emitted from an external cathode, which is essentially identical to that in the discharge chamber. The neutralizer is fed with xenon at a low flow rate, typically, less than 0.04mg/s. The plasma is created by a discharge between its tip and a nearby ‘keeper’ electrode. Since the innermost grid and the chamber are biased at the potential through which the ions are accelerated (usually 1000-2500V) an earth screen
surrounds the whole device to prevent electrons from the neutralizer and from the space plasma from being attracted to the thruster body.

4.3.8.3 The STRV 1A Neutralizer

The STRV neutralizer, mounted on the +Z face, utilises a hollow cathode (Fig. 4.4) sub-system which is a hybrid of standard T5 (the ion thruster co-developed by DERA and the Atomic Energy Authority Culham Laboratory) components. It is constructed from a small tantalum tube of approximately 3.5mm outer and 2.8mm inner diameter.

A tungsten tip with a 0.3mm central orifice is welded into the downstream end of the tube. A small cylindrical plug made of porous tungsten is then inserted into the tube.

Figure 4.4. Schematic of the hollow cathode described in text (Wallace, 1996).
and butted up against the tip. A layer of alumina is flame sprayed onto the tube, a heater wire wrapped on top of this and encapsulated in a further coat of alumina. A multi-layer molybdenum heat shield is then wound around the assembly and disc shaped shields are positioned coplanar with the tip. The complete assembly is contained within a stainless steel tube of 11.5mm diameter.

The cathode is operated by first heating it until the tip temperature is \( \sim 1000^\circ \text{C} \). Shortly before this temperature is reached a small flow of xenon gas is introduced through the cathode tube and a high voltage (600V) is applied to the 'keeper' electrode which is positioned 2.4mm away. Electrons emitted from the cathode are accelerated towards the 'keeper' and ionise the xenon gas. As soon as a discharge has been initiated (approximately 3-5 minutes after applying the heater power) the heater can be turned off, since the cathode is heated by the bombardment of xenon ions from the plasma existing in the tip to 'keeper' region and the 'keeper' voltage is reduced to \( \sim 20 \text{V} \) although, depending on the gas flow rate, the emission current being extracted and the condition of the cathode, the keeper voltage could be set up to 50V.

The rate of cold plasma production, depends upon the degree of ionisation achieved by the discharge and the gas flow rate which can was controlled between 0.2 and 1 cc/min. Assuming maximum flow rate and 100% ionisation, a maximum of 4.5 \( 10^{17} \) ions/s, or 72mA of either electron or ion current, can be produced (Wrenn, 1993).

4.3.8.4 The Langmuir probe (LP)

In order to measure the neutralizer plasma, a LP was mounted adjacent to the neutralizer aperture. It is a simple planar collector of 10mm diameter surrounded by a 60mm diameter guard ring. By sweeping through its voltage range (-12 to 28V with
respect to spacecraft ground) in 10s the LP current measurements would provide information about the temperature and density of the xenon plasma.

4.3.8.5 The Surface Charge Detector (SCD)

The SCD was a novel instrument that utilised the Pockels effect to measure the surface potential of the spacecraft. In the Pockels effect, a change of polarisation occurs when light passes through a uniaxial crystal subjected to an electric field. Light from the SCD laser diode is measured after passing through the electric field generated between an exposed kapton sheet and spacecraft ground. The kapton sheet is isolated from the rest of the spacecraft thus, the electric field across it is a measure of the amount of charge deposited on the surface. The SCD was mounted on the -Z surface of STRV 1A.

4.3.8.6 The CID

The CID experiment comprised the sensor which has already been discussed, the CIDEL and a guard plate surrounding the sensor body at the spacecraft surface level (the guard plate outer diameter was 12cm). The CID would provide environmental monitoring and if the ion concentration of the xenon plasma were high enough, information about the neutralizer ion production and its efficiency in reducing the satellite potential. The sensor was mounted on the +Z face, pointing parallel to the spin axis, with the sensor body protruding some 70mm from the surface.
4.3.8.7 Brief Description of the CIDEL

a) The digital circuit

Figure 4.5 is a block diagram of the main features of the digital circuitry. The CIDEL used three 8bit registers, one for each of the three addresses (29,30,31) allocated to the unit. The STRV Data Interchange Bus (SDIB) lines were connected to the CIDEL through a 37way D-type connector and from there to the register selected by an address decoder. Registers 30 (high byte) and 31 (low byte) were used for data output to the SDIB. The timer was using the 1.5MHz system clock of the spacecraft, after reducing the frequency to 500kHz, to set the data acquisition time intervals. The timer could be set, through bits 5 to 7 of the address 30 register, to eight different time intervals ranging from 0.512 to 65.536ms.

b) The voltage generators

Figure 4.6 is a block diagram of the main features of the analogue circuitry. The MCP power supply was a Cockroft-Walton chain which can provide negative voltages in the range of 2400 to 3300V at fifteen 60V steps as well as a low voltage (130V) for calibration testing at atmospheric pressure.. The MCP supply was controlled through bits 0 to 5 of the address 29 register. Where bits 0-3 were used for selection of the MCP output level, bit 4 was the HV gate (enabling the high voltages) and bit 5 was used for the low voltage selection (0 = set MCP to -130V).

The Vsweep was another Cockroft-Walton type power supply providing the Deflector voltage in either of two ranges; 0 to 40V in 127 linear steps or 40 to
Figure 4.5. Diagram of the main parts of the CIDEL digital circuitry.

Figure 4.6. Diagram of the main parts of the CIDEL analogue circuitry. The safe plug was used to disable HV generation.
1500V in 127 quasi-logarithmic steps. Register 31 was used for controlling $V_{sweep}$ (bits 0 to bit 7 for range selection). The $V_{front}$ power supply (controlled through bits 0 to 4 of register 30) provided the voltage bias (-22 to 8V in 32 linear steps) for the guard plate, the sensor body and the front aperture of the collimator as well as the voltage reference for the $V_{sweep}$ supply. During laboratory tests it was found that the sensor body, which was insulated from the spacecraft, was picking up radiated noise. In order to filter out the noise, the $V_{front}$ output was capacitively coupled to ground via a 100nF capacitor.

Four analogue monitors, one for each power supply and one for checking the temperature inside the CIDEL housing, served as diagnostics means. All four monitors had the same output range of 0 to 4.5V.

c) The event counting circuit

The counting chain consisted of an A111 amplifier and a D400 counter both manufactured by Amptek. The A111 is a charge sensitive preamplifier providing low level discrimination (maximum threshold at $8 \times 10^{-14}$ C or $5 \times 10^5$e) and pulse shaping, which has been developed especially for instrumentation employing mcps and other low capacitance charge producing detectors operating in the pulse counting mode. In view of the noise problems encountered during testing and with the MCP average gain being about one order higher, the LLD was set to its maximum available setting. The output pulse has an amplitude of 4.7V and a pulse length of 350ns, thus the counting ability of the A111 is about $2.5 \times 10^6$ cps. The D400 is a hybrid quad 8bit binary counter and 3-state latch. Two of its counters were connected in series to give 16bit capacity. When two or more of its counters are latched, the D400, by design, sets the LSB of the next counter to 1 when the MSB of the previous counter goes from 0 to 1. Figure 4.7
shows the relation between the number of events and the D400 output. For the CIDEL D400 counter configuration, a subtraction of 256, every time the MSB of the low byte was set to 1, was required in order to obtain the actual number of events. This D400 counting peculiarity had not been taken into account by the DERA data compression software writer. Hence all the CID data compression algorithms were made redundant. The only way available to save on-board computer storage space, was to reduce the number of steps used in the energy sweeps. Both the A111 and the D400 had a radiation resistance of >10^6 Rads.

Figure 4.7. The Amptek D400 counter output versus the number of events.
4.3.8.8 CIDEL Calibration

It was focussed on determining the output at each step of the three programmable power supplies (MCP, Vsweep, Vfront) and verifying the accuracy of the pulse counting circuit. During the CIDEL benchtests, all the voltage outputs were connected to a dummy load box which contained resistive loads that closely represented those of the CID, as well as test points from where the output levels were measured by digital volt meters. The readings of the latter were fed to a PC which also stored the nominal voltage settings they corresponded to.

The current drawn by the unit, under maximum load, was 19mA which, for the nominal spacecraft supply voltage of 28V, translates to a power consumption under maximum load of 532mW. The MCP output was always lower than the nominal setting by about 0.5 to 1% up to 3000V and by 1% to 2% up to the maximum setting of 3300. The Vsweep analogue monitor range depended upon the Vfront setting. Figure 4.8 shows the Vsweep's low range output versus analogue monitor output for each one of the 32 Vfront levels and Figures 4.9 and 4.10 illustrate the Vsweep's high range output versus monitor reading and selected voltage step respectively. The A111 LLD threshold was verified using a signal generator and the same capacitor as in Chapter 3, as was the accuracy of the data acquisition timer (Fig. 4.11). During thermal vacuum testing at the DERA Farnborough facilities, the MCP supply absolute output was found to increase for temperatures below -2°C (Fig. 4.12). The CIDEL manufacturers (after keeping the FM unit for about ten days) claimed that it was corrected but there was no time available to repeat the thermal vacuum test. However, even if the problem still existed, it would rarely appear, since the temperature inside the spacecraft was expected to remain above 0°C for most of the spacecraft lifetime.
Figure 4.8. The Vsweep low range output versus the Vsweep monitor output. The monitor output depended on the Vfront setting. The 32 curves show the Vsweep monitor output range for Vfront settings of -22V (leftmost curve) to 8V (rightmost curve).
Figure 4.9. The Vsweep high range output versus the Vsweep monitor output.
Figure 4.10. The V_sweep output versus the selected step number.
Figure 4.11. The CIDEL counter output versus the CIDEL timer acquisition interval setting for a 10kHz signal.
Figure 4.12. The MCP supply output variation with temperature for a nominal setting of -2400V when going down in temperature (stars) and when going up in temperature (diamonds).

From the calibration results, the following formulae were derived for conversion of the monitor outputs to actual voltage and temperature values:

- \( V_{\text{front}} \) (V) = \((V_{\text{front monitor}} \times 6.8) - 22.12 \pm 0.1\)
- \( V_{\text{sweep}} \) low range = \(15.42 \times (V_{\text{sweep monitor}} - (k \times 0.0625)) - 0.3 \pm 0.09\)
  
  where \( k = 0 \) to 31 for \( V_{\text{front}} \) settings of -22 to 8V

- \( V_{\text{sweep}} \) high range = \((V_{\text{sweep monitor}} - 0.19) \times 333.56) + 40.0 \pm 4\%\)
- \( MCP \) (V) = \(-717.39 \times MCP \text{ monitor} \pm 1\%\)
• Temperature (°C) = (Temperature monitor X 15) - 17.9 ± 2

It is worth noting, however, that the monitors were used only to provide information about the general condition of the CIDEL. Since during data acquisition the monitor readings weren’t recorded, the Vsweep levels corresponding to each data point were taken from look up tables created during calibration testing.

4.3.8.9 CID Operation Algorithm

The chosen cycle of operation was to set the sweep (Deflector) voltage to a selected upper value and then scan downwards in energy at a constant step (depending on the data compression required, the energy sweep step was usually between 1 to 6 steps of the Vsweep supply). After selection of the sweep voltage, the CIDEL allows a predetermined time for the voltage to settle and then starts the timer and acquires events for the selected timer period. The counter is cleared each time the timer is started. The on-board data handling system (OBDH) controls every step of the scanning process; no part of the CID operation is automatic. The normal cycle of data acquisition is as follows:

1. Switch on instrument low voltage.
2. Enable HV, set MCP at the chosen operating voltage level and wait 10s.
3. Set Vfront voltage and wait 30ms.
4. Set data accumulation period.
5. Set Vsweep starting level (the highest level was reduced to step 247 or ~1250V as it was found that a voltage breakdown occurred within the CID at ~1330V).
6. CIDEL waits 100ms then starts timer and accumulates events.
7. OBDH reads count total (high and low bytes).
8. Set next Vsweep level (downwards) or go to 10
9. CIDEL waits 30ms then starts timer and accumulates events - then go to 7 or continue.

10. Switch off low voltage.

The flight software was written in such a way that one command from the ground station would be enough to run the CID until the next uplink.

4.3.8.10 Command Programmable Quantities

The instrument was operated via OBDH command number 185. There were eight programmable quantities via six parameter bytes.

1. MCP bias voltage.

2. Vfront bias voltage.

3. Time interval (the dwell time at each Vsweep step).

4. Maximum Vsweep step. Fixed during the same command.

5. Minimum Vsweep step. Fixed during the same command.

6. Data compression. The amount of Vsweep steps between Vsweep voltage settings.

7. Wait time between spectra. Variable between 0 (continuous operation) and 37.5 minutes.

8. Number of spectra collected per command. Variable between 1 and 151.

4.4 First In-Flight Operations and Results

During either launch or the early orbit phase of the mission, the STRV 1A battery suffered a failure of at least one cell. This seriously degraded the capacity and therefore, the performance of the battery. During the first month of the mission, operations of the STRV 1A spacecraft were very difficult. The reduced battery capacity meant that any magnetorquer manoeuvres had to be very short in duration and
also had to be performed in sunlight, so that the power could be provided by the solar cells. Unfortunately, at that time the perigee, the most effective point part of the orbit to perform a manoeuvre, was in eclipse. The fact that the magnetorquer could not be used to maximum effect combined with a large nutation, presumably imparted to the spacecraft during separation from the ASAP ring, led to a drifting solar aspect angle (SAA) which, in turn, resulted to the loss of communication between spacecraft and ground control for one month in August 1994. STRV 1A was re-acquired on August 30 1994 and although control was achieved, a full spacecraft check-out indicated that the battery capacity was still reduced.

4.4.1 The Neutralizer

The battery problem had a knock-on effect to the operation of the neutralizer. At start-up, with the heater coil on, the neutralizer draws almost 3A for approximately 2 to 8 minutes, then the current requirement drops to 1.5-2A for the 30 minutes of the neutralizer planned operation. This amount of power consumption was considered too much for the state of the battery, especially as the neutralizer was planned to be operated during eclipse. Thus, it was decided that neutralizer operations, if there were to be any, should be left for the final stages of the mission.

That decision meant that the LP also would not be operated for about a year. The delay in the LP operation was considered unfortunate as far as the CID was concerned, as it was hoped that the LP data could serve as a reference for an in-flight calibration of the CID measurements.

4.4.2 The SCD

During the final stages of the STRV project, it was demanded by the Intelsat design
team that the spacecraft should undergo an additional sinusoidal vibration test at 4g, an acceleration level that represented a 400% increase on that specified by Arianespace (0.8g). The fully integrated flight model of the spacecraft had to be used. The SCD fell victim of this test as the sensing crystal broke free, causing severe damage to the crystal surfaces. As a result, the instrument was launched without being calibrated, which possibly explains the problems experienced in-flight. There is a lack of repeatability in the obtained data, which makes it very difficult to establish any charging events. This meant that there would be no cross-reference if any spacecraft charging events were indicated by the CID yielded data.

4.4.3 The CID

The CID was first switched-on on July 15 1994, one month after launch, allowing it a much longer period for outgassing than it is usually specified. The initial results confirmed that communications between the instrument and the spacecraft computers were in order. Subsequently, a programme of instrument checks were made, checking the temperature and the sweep and bias voltages. A series of sweeps with the MCP voltage off confirmed that there was no noise pick-up from other operating equipment. The HV was applied to the MCP without evidence of breakdown. The Vfront, however, couldn’t supply voltages below -11.4V, i.e. a 50% reduction on the available range of negative Vfront voltages of 0-22V. The same problem had occurred during the first integration of the CID FM on the spacecraft and the cause had been found to be insufficient electrical insulation between the guard plate, which was in contact with the CID body and the thermal blanket surrounding it. The problem was then solved by adding insulating material (kapton) in the areas that the two surfaces were making contact. It seems that, either during the final integration before launch or the launch
itself, the insulation got degraded. The -11.4V CID bias voltage, although less than planned, was considered adequate for most purposes. For all subsequent CID operations it was decided that a) the Vfront would be commanded to output -22V so that the maximum available bias was supplied to the CID body-front collimator aperture-guard plate and b) the first spectrum would be the readings of the analogue monitors so as to check the health of the instrument and the validity of the collected data.

The first real data was collected during MCP gain tests, involving varying the MCP voltage between -2400 and -2760V with different, but always negative, CID body and guard plate biases and full energy sweeps in the low range (0 to 40V). From these tests, it was decided that the MCP operating voltage would be set at the nominal level of -2640V (about -2620V actual according to the CIDEL laboratory test results). As it has been shown in the previous chapter, this voltage level could lead to some loss of events during observation of low energy ions (<100eV) at high count rates, but as it was the beginning of the mission it was thought that MCP gain preservation should be given priority.

At this point contact with STRV 1A was lost. When communications were re-established, tests similar to the above gave similar results but for the negative bias of the Vfront which was now reduced to the range of -7.5 to -8.5V. Figure 4.13 is an
energy spectrum acquired at the low sweep range with the MCP set at -2640V, the Vfront at -22V (about -8.4V actual) and the data acquisition interval at 65.5ms. The dotted line indicates the channel that corresponds to the Vfront voltage. The sharp counts peak seen in this channel is due to cold ions being drawn into the instrument by the bias potential and indicates that the spacecraft was in the plasmasphere at that time. Away from this peak the counts are more or less steady and are probably produced by highly energetic particles. The reason for this reduction is not known. The fact that the Vfront output remained at that level for the next two years, rules out erosion of the insulator as well as degradation of the power supply performance. As every CID
operation was preceded by a readout of the voltage monitors, the only uncertainty relative to the Vfront output is its variation within the period of execution of the same command (usually 1-2 orbits).

![Graph showing data variation](image)

Figure 4.14. Eight orbits of data in channel 1, showing the background level variation.

As: a) there was not going to be any neutralizer operation in the foreseeable future; and b) the amount of data acquired by the CID in an orbit could be easily accommodated by the on-board computer memory, it was decided that the instrument would be operated over the whole of each orbit with a data compression of $-3.72$
(acquiring data in one of every four \( V_{\text{sweep}} \) channels). Figure 4.14 shows eight orbits of data at channel 1. The \( V_{\text{front}} \) was \(-8.5\) V, which corresponds to channel 27. Since, below channel 27 there should be no recorded low energy ion events, \( V_{\text{sweep}} \) channels 0-21 (allowing for a \( V_{\text{front}} \) drift to \(-7.5\) V) could be used for the determination and subsequently, correction for background events. The very good

![Graph](image-url)

Figure 4.15. The background maximum level variation of the CID (top) and the fluxes of \( >2\text{MeV} \) electrons recorded by GOES-7 (bottom) over a period of 60 days.
correlation between the spacecraft’s crossings of the radiation belts and the increase in background event rates as well as the very good agreement between the CID recorded maximum count rates and the GOES-7 measured daily fluxes of >2MeV electrons over a period of 60 days (Fig. 4.15) lead us to believe that the main source of background flux is highly energetic electrons. Indeed, the 2mm Al shielding provided by the CID body, wouldn’t be enough to protect the MCP (sited above the spacecraft surface) against electrons with energies >1MeV. Bühler et al. (1998) who, by taking advantage of the CID high temporal resolution and in conjunction with REM data studied a coronal mass ejection, found that the CID sensitivity extends to electrons with energies <1MeV. It should be noted, however, that since the high count rates (up to several thousand counts per 65.5 ms) occur in both the inner and outer belts, the CID must also be sensitive to highly energetic ions.

For most of the CID data collected (excluding the radiation belt data), the count rates vary between ~50 to 35000 counts/s; levels that, according to the MCP tests, described in Chapter 3, could lead to only marginal, if any, event loss due to count rate dependent gain reduction.

4.5 Review of the CID In - Flight Performance

After about six months of operation, the instrument started failing to turn on during time-tagged routine operations, but could be ‘manually’ turned on with uplinked commands. After investigation by DERA officials, it was determined that the CIDEL needed more time than it was allowed to read the commands sent to it by the on-board computer. The cause of this problem was, probably, radiation induced drift in the characteristics of a CIDEL electronic component. The solution was modification of the start-up software so as to allow more time between commands.
Another intermittent problem, particularly in the second year of operation, was the appearance of spurious events in the acquired spectra. This contamination caused high count rates at a particular energy. As the energy channel, where the excess events appeared, changed with time, it appeared that there was beating between the energy sweep and regular noise pulses. On many occasions the onset of the spurious events was found to agree with the turn on of the SCD but other sources of noise contamination cannot be excluded. Contamination was evident also during neutralizer operations as will be discussed in a following subsection.

Eventhough the MCP gain tests were to be carried out every month, they first took place almost after one year of operation (it has to be noted, however, that since October 1994 the MCP bias was set at -2700V). These showed that the observed count rates were dependent on the MCP bias voltage implying degradation of the detector’s gain. Investigation of the problem, however, is complicated by the fact that a) the background events do not show the same saturation effect and b) a number of these tests were upset by the above mentioned contamination effects. As the MCP gain investigation hasn’t been completed, the absolute value of flux measured by the CID incorporates an as yet undetermined error margin.

The CID operations were officially terminated in March 1997.

4.6 CID Data Analysis

With the exception of the qualitative data for radiation belt studies, the CID provided data on plasmaspheric ions, plasmapause location and neutralizer operations.
4.6.1 Data Analysis Technique

The technique used for the derivation of density from the raw data was as follows (Rodgers, 1996): The average counts of the bottom four energy channels (the raw data are given as counts per accumulation period per energy level) are assumed to be a measure of the radiation background level at the end of the sweep. Interpolation between this and the background at the end of the previous sweep, yield a background value which is subsequently subtracted from the counts at each energy bin. Using the GF value obtained during calibration, the flux is then calculated as:

\[
\text{Flux (m}^2 \text{s}^{-1} \text{J}^{-1}) = \frac{4\pi \times 10^4 \text{ No. of counts}}{e \text{ GF } \Delta t}
\]  

where \(e\) is the electron charge in Q, \(\Delta t\) is the accumulation interval and \(\text{GF}\) is the geometric factor in cm\(^2\) sr. The value used in the data analysis was:

\[
[\text{GF}] = 2.74 \times 10^{-6} \text{ cm}^2 \text{ sr.} 
\]

This was derived from the GF obtained during calibration \(2.22 \times 10^{-6} \text{ cm}^2 \text{ sr}\) and the assumption that at low energies (i.e. in the low sweep range) there should be enough field penetration from the MCP side of the Accelerator mesh to guide the incoming ions away from the wires and through the mesh gaps thus, improving the geometric factor value from \(2.22 \times 10^{-6}\) to \(2.22 \times 10^{-6} / 0.81\) (the combined transmission factor of the Accelerator grid and mesh) = \(2.74 \times 10^{-6} \text{ cm}^2 \text{ sr}\).

The density is obtained by summing the moment contributions of each energy bin between 5eV and 15eV.
density (m^3) = \sum_{E_a=5V}^{15V} \frac{\Delta E_a \ e \ Flux}{\sqrt{2} E_a \ e \ / \ m_i}

(4.7)

where \(\Delta E_a = E_{a+1} - E_a\) and \(m_i\) is the proton mass.

4.6.2 Plasmaspheric Measurements

At the top of the ionosphere, ions with velocities exceeding escape velocity travel out into space. The terrestrial magnetic field, however, keeps them bound to the earth and forces them to travel along the magnetic field lines. As the particles gyrate, their gyrocentres bounce between mirror points in each hemisphere. In addition, the particles execute a drift motion across field lines, principally under the influence of crossed electric and magnetic fields (ExB drift). Figure 4.16 illustrates typical drift paths. The electric field has two main components, the cross-tail field and the corotation field caused by the rotation of the earth’s dipole field. At low \(L\) values the corotation field dominates and the drift paths are closed. A corotation boundary exists, dividing closed drift paths which circle the earth from open ones which terminate at the magnetopause. Within the corotation boundary, the ions are trapped and substantial densities can build up over time forming the plasmasphere.

The density of ions along a magnetic field line (a flux tube) increases until there is equilibrium between the number of ions arriving from the ionosphere and of those returning to it. Since the gyroradius increases as the magnetic field becomes weaker, the density required to achieve equilibrium is smaller for magnetic field lines that stretch to higher radial distances. Chappel et. al (1970) using data from the OGO 5 ion mass spectrometer, found a density dependence with radial distance of \(1/L^4\).
Figure 4.16. The equatorial flow lines of the flux tubes within the magnetosphere. The dashed lines show the flow directions of flux tubes dominated by convection and the dotted lines show the flow directions of flux tubes dominated by corotation. The closed solid line represents the boundary between these two types of flow (Chappel et al., 1970).
Figure 4.17 illustrates the calculated densities over one orbit (perigee to perigee). There is good agreement with the $1/L^4$ model (dotted line; the model was $n = 4.8 \times 10^3 / L^4$). Figure 4.18 is a summary plot of the same data. The plasmaspheric distribution can be seen below 10eV from 14UT to 18UT and from 22UT to 24UT.

The outer boundary of the plasmasphere, the plasmapause, is in practice hard to define. Simply defining the plasmapause to be where the density falls below a threshold is inadequate, since the density falls anyway with $L$. Chappell et al., 1970, defined plasmapause as the region where the density falls by more than one order of magnitude (i.e. where the density distribution shows a 'knee'). This definition, however, becomes unclear by the fact that the corotation boundary moves due to changes in the cross-tail field. If it goes to lower $L$, trapped particles begin to be lost (convecting towards magnetopause) but it can move outwards again before the flux tubes have emptied. Therefore, there can be several discontinuities in the density versus $L$ profiles, due to field lines filled to different degrees. In addition if a spacecraft observes a dense ion population when returning to the plasmasphere, this could be either a re-crossing of a distorted plasmapause or a detached cloud of plasmaspheric ions drifting outwards.

The procedure used in finding the plasmapause was as follows:
The density profile was checked for sudden deviations which result in a fall of more than an order of magnitude. These positions are then checked by reference to the summary plot to ensure that there had been no data contamination. If the falls were
Figure 4.17. The ion density calculated over one orbit of CID data. The dotted line is the density calculated with a $L^4$ model (Rodgers, 1996).

Figure 4.18. Summary plot of the data shown in Fig. 4.17. Also shown are the background levels, middle panel, and the model magnetic field, $B$, and $L$ values, bottom panel (Rodgers, 1996).
deemed real, subsequent peaks were assumed to be ions outside the plasmasphere. In Figure 4.17 the plasmapause was identified at 16.5hrs and at 22.5hrs. Although the gaps (caused by the density falling below 1cm$^{-3}$) are indicative of how this procedure relied upon human judgement. It was more likely to go wrong where the plasmapause occurred near the peak of the outer radiation belt, as, despite noise removal, the cold ion peak was virtually undetectable. A further obstacle was the reduced resolution of the points when the CID operated in the environmental mode (full energy sweep, one in every four points stored) in contrast to the plasmaspheric mode (Low energy sweep, either one every two points stored or all 128 points stored).

Figure 4.19 illustrates the plasmapause points relative to L and local time. Although approximately one year's data have been used, there is a gap of a few hours around 9hrs local time. The solid line shows the mean plasmapause, calculated by binning the data in 1hr local time bins. The mean plasmapause lies furthest from the earth (L = 5.6) around 21hrs and closest (L = 3.2) near 9hrs. A reduced set (due to lack of Kp data) of the data used in Figure 4.19 has been used in Figure 4.20 to illustrate the mean plasmapause positions for four Kp ranges. The L value of the plasmapause position is generally larger for low Kp and smaller for high Kp. Ninety eight plasmapause crossings have been used in Figure 4.21 to illustrate the mean plasmapause position dependence on the solar wind velocity being greater or less than 400km/s. Although the statistics could be better, the plasmapause can be seen to extend further when the solar wind velocity is low.
Figure 4.19. Scatter plot of all plasmasphere positions relative to L value and local time. Plasmaspheric measurements are shown as crosses. Low resolution ones are shown as stars. The dotted lines represent L values from 1 to 7. The solid line shows the mean plasmapause position (Rodgers, 1996).

Figure 4.20. Mean plasmapause positions relative to L value and Kp index. Four Kp ranges are indicated: 0 to 1 (solid line), 1+ to 2 (dashed line), 2+ to 3 (dot-dash) and 3+ to 4 (dot-dot-dot-dash) (Rodgers, 1996).
4.6.3 Neutralizer Operation Measurements

In August 1995 the problems associated with the lack of battery capacity changed dramatically when, after suffering a complete battery discharge due to increasingly long eclipse duration, the condition of the battery improved to a level where operation of the neutralizer was possible.

The sequence of a neutralizer run is as follows:

The cathode heater is turned on. This was done outside the standard neutralizer sequence because the current drawn by the heater, when cold, exceeded the current
limit of a cut-out. This phase lasts about two minutes by which time the total spacecraft bus current has dropped to about half.

- The neutralizer automatic sequence begins. The heater remains on and the valve between the xenon tank and the plenum tank (Fig. 4.22) is pulsed every few seconds.
- When operating pressure is reached, the valve pulsing is slowed down to once every several tens of seconds.
- Electrical discharge begins. On-board software detects the increase in current and stops current to the heater. The neutralizer is then in its working state.
• At the end of the run no further gas is admitted to the plenum tank and pressure in
the tank decays exponentially.

Each neutralizer run lasted about thirty minutes and most of the runs were
performed near perigee. Figure 4.23 shows bus current and plenum tank pressure for a
typical run which took place on orbit 417. The current and pressure measurements
were taken every 10s. The initial current peak corresponds to the heater turn-on. After
about 2 minutes, when this current has fallen considerably, the effect that the pulsing of
the valve to the plenum tank has on the current level can be clearly seen. The irregular
switching between two current levels, is the result of beating between the valve pulses
and the current measurements. During this period the tank pressure rises to a peak of
400mbar. The smaller peak near sample 70 indicates the start of the discharge. At
sample 160 measurements stop.

The general consensus for the CID observations during neutralizer runs is that the
measurements appear to be dominated by induced noise. The background noise is
plotted against time in Figure 4.24. Also plotted on the same timescale is the bus
current. At the start of the neutralizer run (again on orbit 417), the noise follows the
current closely. The noise exhibits a sudden second peak which resembles the peak in
the current (indicating the onset of discharge) but occurs at a later time. The cathode
heater has been identified as a significant source of RF noise (Wallace, 1996). Since the
noise was high enough to drown out any real signal, analysis of the CID data collected
during neutralizer runs has ceased.
Figure 4.23 Bus current and Plenum tank pressure during the neutralizer run on orbit 417 (Wallace, 1996).

Figure 4.24. Background event levels (diamonds) and bus current during the neutralizer operation on orbit 417. The units along the time axis are minutes (Rodgers, 1996).
CHAPTER 5

Concluding remarks

The first and general remark should be that the instrument was a success. The time from drawing board to FM delivery was 20 months but, judging from the man-hours actually spent on the instrument, this time could be reduced down to less than 5-6 months including the mcp quoted delivery time of 12 weeks from order. The CID passed all the pre-flight tests although, the CIDEL had a HV output problem during the thermal vacuum tests which should be attributed mainly to: a) the unit using as many non-military standard components as possible; and b) the need to achieve low weight without high cost. In addition, the instrument was operated continually for about 32 months, up until the mission was ended. The only operational problem was an intermittent HV failure to switch on, which was attributed to the high radiation dose imparted to a CIDEL component. However, the fact that the OBC didn't wait for a data acknowledge signal between commands must have had played a role too.

5.1 Instrument Response

Figure 5.1 shows the CID EMM energy response, integrated over angle, with reference to the ratio of the ion energy over 1st RPA voltage. The error in energy, \( \Delta E/E = \Delta V/V \), is \(-3.5\%\) for \( V=100\% \) of ion energy and with \( \Delta V \) taken to be the difference between the voltage where the minimum number of events is recorded and
the voltage where the number of recorded events drops below 90% of maximum. The

Figure 5.1. The CID EMM energy response (normalised to 1) integrated over angle. The abscissa is the 1st RPA voltage as a percentage of the ion energy. The straight lines indicate the mean number of events per data point (horizontal line) and the point where the ion energy, in volts, is equal to the 1st RPA voltage (vertical line).

straight lines show that there is good agreement (<0.5%) between the point where the number of events drops below the mean number of events per data point (horizontal line) and the 1st RPA voltage being equal to the particle energy (vertical line). This would give a fractional energy error of <1.5%. If we assume that the 1st RPA is a
circular aperture of radius $R$, held at a voltage $V_1 = (100/110)V_0$, between two uniform fields $E_1$ and $E_2$ then the maximum voltage deviation on the aperture plane, which at the centre of the hole is $V_1(0)$, is given by (Szilagyi, 1988)

$$\Delta V = V_1 - V_1(0) = (E_2 - E_1) \frac{R}{\pi}$$

(5.1)

and further assuming that the 1st RPA potential is effective up to the middle point of the collimator (5mm away) and the Deflector - 1st RPA field is that between the 1st RPA plane and the plane of the base of the Deflector cone (separated by ~4mm) then the maximum voltage deviation (worst case) is $\Delta V = 0.025 V_0$ or $\Delta V/V_1 = 2.8\%$. Thus it seems that the CID can achieve good energy resolution (much better than the FWHM energy response suggests) albeit at the expense of event counting efficiency.

The GF of the instrument is quite small. The physical GF (PGF) of a collimator with circular apertures is given by (Heikkila et al., 1970):

$$\text{PGF} = R^2 \pi^2 \left[ 1 - \frac{2}{1 + \sec \theta} \right]$$

(5.2)

where $R$ is the radius of the aperture and $\theta$ is the acceptance half angle. For the CID ($R = 0.5\text{mm}$, $\theta = 5.54^\circ$) the corresponding PGF equals $5.78 \times 10^{-3}\text{mm}^2\text{sr}$, which, after taking into account the combined grid transparency and the MCP efficiency, takes the value of $2.53 \times 10^{-3}\text{mm}^2\text{sr}$. This value is more than 7 times the CID EMM calibration yielded GF. The computer simulations had shown that only ~30 to 35% of the eligible particles actually pass through the rear collimator aperture. In some cases, however,
the energy range of the particles in the simulation was wider than it should have been and the trajectory tracing software, which uses generation of random numbers to select the particle trajectories, was more likely to select the higher elevation angles. Even accepting the simulation yielded losses, however, an extra 40% of the particles is being lost between 1st RPA and MCP. Assuming no noise, or a constant background event level, and using equations 4.5 and 4.7, the minimum detectable density is ~ 50cm$^3$ for a rate of 10counts / 65.5ms. This minimum count rate value is imposed by the requirement that the count rate must drop by one order of magnitude at both ends of the acquired spectrum. An instrument using a particle detector should be able to measure densities at least one order of magnitude lower than that. Otherwise, it would be difficult to justify the risks involved in flying particle detectors (extra HV supplies, detector performance degradation with time of operation) on non-imaging instruments.

5.2 CID In-Flight Performance

Since the main task of the instrument was to serve as a diagnostic tool for the neutralizer operation, it had to be positioned on the +Z face of the spacecraft. The ion velocity, in the spacecraft rest frame, was almost at normal angles to the CID axis. Ambient plasma measurements could only be achieved by negatively biasing the sensor body, thus, making it impossible to verify the mass discrimination ability of the sensor. In addition, the fixed $V_{\text{sweep}}$ step of 0.31-0.32V in the low range, being larger or equal to the thermal energy of the ions, resulted in a small number of data points per spectrum. The agreement of the ion density measurements with L-models is encouraging as are the derived L values for the plasmapause position.
The CID failed as a diagnostic means during neutralizer operations due to increased noise pick-up. The author, however, using a limited CID data set, found a few occasions where the noise level is much lower than the actual signal. Figure 5.2 shows five spectra, about 5 minutes apart. The number of events and the FWHM of the spectrum are both larger than the usual yield from ambient plasma particles. The voltage corresponding to the peaks drifts from about 10V to 8V which may be indicating spacecraft charging due to the neutralizer operation. Further analysis would

![Figure 5.2. Surface plot of five CID spectra (collected at 5 minute intervals) where the count rates are higher than usual.](image)
require data that at present are not available (i.e. exact time and date of neutralizer operations, LP measured densities). It would be advisable, therefore, that the whole CID data set be searched for similar occurrences by DERA researchers.

5.3 CID Miniaturisation Potential and Possible Design Improvements

Figure 5.3 lists the CID FM specifications. With a total experiment weight of less than 0.6kg it is already a lot lighter than the Faraday cup RPA flown aboard the WIND spacecraft (Ogilvie et al., 1995). The latter instrument weights 5kg and uses nine grids, one modulator grid, one suppressor grid, three grids to shield the modulator from the plasma and four grids to shield the modulator from the two semicircular collector plates. The CID FM is also lighter than the projected mass of a ‘light’ instrument (1.8kg) based on the design of the WIND Faraday cup (Lazarus et al., 1993). It should be noted, however, that, since in a RPA instrument the retarding potential has to have the same magnitude as the particles’ energy, the above Faraday cup RPAs are designed for solar wind measurements which require retarding potentials of the order of 9kV. Therefore, most of the mass is allocated not to the sensor but to the DPU and the other electronics systems (electrometer, power supplies). The ‘light’ sensor’s projected mass is ~0.3kg. The CID FM mass was 0.190kg, but incorporation of the resistor chains in the electronics housing would allow a mass reduction of ~30% and similar reduction in the sensor’s length. Subject to possible geometry limitations affecting the ion optics, the sensor inner diameter can be reduced by about 50%. This would allow either a similar reduction in outer diameter, thereby reducing the volume of the sensor by three quarters, or allowing an increase of the sensor housing wall thickness for better radiation shielding, at the expense of increased mass.
<table>
<thead>
<tr>
<th>Sensor length</th>
<th>137mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sensor diameter</td>
<td></td>
</tr>
<tr>
<td>inner</td>
<td>12mm</td>
</tr>
<tr>
<td>outer</td>
<td>28mm</td>
</tr>
<tr>
<td>Sensor mass</td>
<td>0.190kg</td>
</tr>
<tr>
<td>Electronics mass</td>
<td>0.350kg</td>
</tr>
<tr>
<td>Total mass of experiment</td>
<td>0.594kg</td>
</tr>
<tr>
<td>Power consumption (maximum)</td>
<td>0.562W</td>
</tr>
<tr>
<td>Energy range</td>
<td></td>
</tr>
<tr>
<td>low</td>
<td>0.3eV to 40eV in 128 steps of ~0.315 eV</td>
</tr>
<tr>
<td>high</td>
<td>40eV to 1500eV in 128 semi log steps</td>
</tr>
<tr>
<td>Energy resolution</td>
<td>ΔE/E (FWHM)</td>
</tr>
<tr>
<td>Geometric factor</td>
<td>2.22 x 10^{-4} mm^2 sr</td>
</tr>
<tr>
<td>Field of view half angle (FWHM)</td>
<td>3° ± 0.5°</td>
</tr>
</tbody>
</table>

Figure 5.3. The CID FM specifications.

There are still important obstacles that need to be overcome before a CID type instrument is selected for solar wind measurements. The MCP front face voltage, which provides focusing and post acceleration to the incoming particles, is small compared to the particle energies in the range measurable by a Faraday cup. A means
of increasing the field between MCP and Accelerator needs to be used to avoid a GF reduction and noise by secondary electrons. Inclusion of a ring spacer at Deflector voltage behind the Accelerator would probably be enough. Shortly after the instrument design was finalised, it was found that the CID axis - sun vector angle would always be greater than $\sim 70^\circ$. Hence the light rejection ability of the CID did not need to be checked. Hole patterns (Enloe et al., 1995) drilled on the inner surfaces, to serve as light dumps, and surface blackening (i.e. Ebanol C; Moore et al., 1995) would need to be used, but the in-line design is always suspect for light rejection. Similar to the Faraday cups on the WIND spacecraft, a segmented anode could provide limited angular information. Another solution, albeit requiring an ingenious mechanical design to make it practically possible, is the use of a particle mirror. The charged particle mirror is itself a differential energy analyzer. Particles with energy much higher than the mirror voltage hit the biased mirror surface which lies behind a grounded grid. Particles at the selected energy window, defined by the angular acceptance of the following aperture and the shape and bias of the mirror grid, are directed towards the detector. Finally, particles with lower energies are deflected at angles outside the field of view of the sensor. A particle mirror has been incorporated on the Thermal Ion Dynamics Experiment (TIDE; Moore et al., 1995) which was flown aboard the POLAR spacecraft. TIDE (Fig. 5.4) includes an RPA immediately after the mirror. The RPA provides a sharp low energy cut-off and the mirror a more gradual cut-off on the high energy end. The mirror shape has a focussing effect on the incoming particles thus increasing the instrument's geometric factor. With the use of the mirror, TIDE needs only to reject reflected EUV. This is achieved first by an immersion lens, focussing the
Figure 5.4. Schematic of the ion trajectories within the TIDE instrument (Moore et al., 1995).

particles exiting the dual RPA grid lying between two grounded grids, and a deflector which directs the particles off-axis and to the TIDE mcp detector (through 'S' shaped trajectories).

The CID GF could be improved by increasing the angular acceptance and/or using a separate retarding grid behind the rear aperture of the collimator, which, in principle, can be achieved without error in the derivation of the particle energy. The CID could use the 'cone in a can' design (Enloe, 1994), where the entrance aperture (Fig. 5.5) is at the apex of a grounded cone protruding into the hole of a cylinder biased at the retarding potential. The equipotential surfaces (Fig. 5.6A) within the cylinder are approximately nested spheres. As the retarding field is approximately
Figure 5.5. A RPA design which exhibits better energy resolution than its planar counterparts. a) grounded aperture; b) biased retarding structure; c) particle detector (Enloe, 1994).

Figure 5.6. A) The computer simulated potential distribution in the ‘cone in a can’ design. B) The energy resolution of the instrument for particles of $0^\circ$ and $20^\circ$ (Enloe, 1994). Antiparallel to the particles' trajectories, the design minimizes errors in the apparent mean energy due to the angle of incidence of the particles. The differential I-V characteristic (fig. 5.6B) shows almost identical energy resolution for angles of incidence of $0^\circ$ and $20^\circ$.  

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The CID could also do with a reduction of the apparent losses of events from particles that go through the 1st RPA. Fine-tuning the Deflector shape and possibly the shape of the walls surrounding the Deflector, as well as maintaining the Accelerator grid at an even lower potential should help. The good agreement between the CID EMM response and the sensor simulation results shows that the design can be optimised on screen, with very high probability that the actual instrument's response will show similar improvement.

It has to be said, however, that the competition, that even a miniaturised CID type instrument will have to face, is very stiff. The compact thermal ion detector (Enloe et al., 1995) measures 6cm diam. x 2.6cm (Fig. 5.7), uses a RPA and a mcp detector and offers imaging capabilities for ions up to about 200eV. In this instrument, the ions, after crossing the RPA, they are turned by almost 180° by the electrostatic potential structure (Fig. 5.8a and b) established between the grounded sensor body and the mcp front face (biased at -1900V). In addition, an array of Bessel boxes, micromachined by means of anisotropic wet etching <110> silicon (Stalder et al., 1994), with a size per box of 2.6mm in length and 0.8mm in width, has already been tested and work for a two dimensional version is on-going. Compared with the size of a typical Bessel box (10cm in length and 5cm in diameter) micromachined arrays offer huge size reductions. A large array of Bessel boxes with 10cm² open area would have a diameter of 15cm, a weight of
Figure 5.7. Cross section of the thermal ion sensor. a) aperture; b) retarding grid; c) insulating washer; d) insulating post; e) grounded grid; f) grounded sleeve; g) mcp stack; h) back wall/light baffle; i) centre pin and j) anode plate (Enloe et al., 1995).

Figure 5.8. a) Equipotential structure within the sensor and b) particle trajectories for orbital velocity (5eV) O⁺ (Enloe et al., 1995).
0.050kg (excluding power supplies) and would be capable of analysing particles up to 50keV.

In common with every other instrument, the CID would greatly benefit from miniaturisation of the electronic components; the mass of the CIDEL was almost double that of the sensor. In particular, Application Specific Integrated Circuits (ASICs) could help in reducing the power and weight requirements of an instrument package (Cushing and Lindelef, 1993). Caution should be exercised, however, as this miniaturisation in spacecraft electronics, although desirable in terms of reduced spacecraft resources, may increase the risk of radiation damage and reduce reliability (Barnes et al., 1993).

Overall the CID was proved reliable in-flight and its design offers potential for much better performance and miniaturisation. Hopefully, the intrinsic qualities of the design will be realised when a CID type instrument is selected for a future mission.
Figure 5.9. The CID experiment’s sensor and electronics unit.
Acknowledgements

Firstly, I wish to thank Professor Alan Johnstone for his guidance and for giving me the opportunity to work on such an interesting project. Secondly, I would like to thank Andrew Coates for undertaking the supervision of a somewhat patience testing student during the last stages of this thesis. Special thanks and large amounts of gratitude go to Dave Walton who helped me learn everything I needed to know about lab testing, to Ady James whose willing support saved me a lot of valuable time and to David Rodgers for the latter reason. I would also like to thank Ady James, Dave Walton, David Rodgers, Mick Edgar, Chris Alsop, Mat Trow, Jon Lapington and Roger Woodliffe for useful discussions on detector physics throughout my years at MSSL.

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I also think it appropriate to thank the DERA Space Department for providing the finance to design and built a new instrument and for financing the analysis of the CID flight data (eventhough I was excluded from the latter work).

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Applied Optics, 18, p. 1418.


ADDENDUM

A.1 Scientific requirements

As it has already been mentioned, the instrument was selected to fly aboard the STRV 1A satellite in a GTO. The orbit would take the satellite from the topside of the ionosphere (~300-400km) where the ion density is of the order of $10^5\text{cm}^{-3}$ and the temperature is of order of a few thousand degrees K, through the plasmapause (ion density typically $\sim 10\text{cm}^{-3}$ but can be as high as $100\text{cm}^{-3}$) to a geocentric distance of more than 6 Earth radii where the ion density is, typically, less than $1\text{cm}^{-3}$ and the temperature can be much higher than at low altitude (from a few $10^4$ °K to about 10keV). The aim of the instrument was: a) to observe the effect of the neutralizer operation on the spacecraft potential; and b) to monitor the environment under ambient conditions.

A.2 Design principles

A.2.1 Sensor energy range

The above aims, orbit characteristics and the expected energy range of the neutralizer produced ions ($<7\text{eV}$) meant that the instrument would spend most of its
operational time measuring ions with energies less than 10eV (hence the name Cold Ion Detector).

The measurement of cold ions, however, is made difficult by the fact that, due to the emission of photoelectrons, the surface of the spacecraft can get charged positively up to about 6V, even within the plasmasphere. Consequently, as this repelling voltage is in most cases higher than the plasmaspheric ion energy, cold ions can only be measured by a sensor with a negative body bias so as to negate (at least) the spacecraft surface potential effect. In the case of the CID, however, since the STRV 1A velocity vector would be at an angle of ~83° relative to the CID axis, it would give a near perpendicular energy component (at a range of 0.1 - 0.7eV) to the plasmaspheric ions thus, making necessary the use of a negative sensor body bias even in the absence of positive spacecraft charging. It was decided that a sensor body bias of up to -22V relative to the spacecraft ground should be adequate for our purposes (more than 3 times of either the expected level of charging or the maximum expected energy of the neutralizer ions and more than 2 times the energy of the cold ions outside the plasmasphere). Furthermore, a guard plate would be placed around the sensor body, at spacecraft surface level and at sensor body bias, to increase the effect of the attracting field. The maximum body bias combined with the maximum expected energy (~32eV in total) of the cold ions meant that the sensor should be scanning the range of 0-40eV.

As it has been discussed in Chapter 4, under certain conditions (spacecraft in eclipse and outside the plasmasphere, i.e. eclipse near apogee) the spacecraft could charge negatively up to 10keV or more. The level of charging, however, depends on solar activity and, since the launch would take place near the minimum of the solar cycle, it was not very likely that such high levels of charging would occur. Additionally, as
RPAs need to utilise voltages greater than the energy of the measured particles, the size and, consequently, the mass of both the CID sensor and electronics would need to be increased considerably. With consideration of the above factors, it was decided that the instrument should be scanning at a, much easier to accomplish, range of 40-1500eV. It should be noted that ATS-5 was occasionally charging negatively at 1000-1500V in eclipse and at 50-100V in sunlight (De Forest, 1972).

**A.2.2 Sensor design principles**

In addition to the requirements detailed in Chapter 3 (which determined the overall size of the sensor and the electronics unit), the CID needed to have a geometric factor suitable for measurements throughout the designated orbit. In particular, as the particle density would vary from about $10^5\text{cm}^{-3}$ at perigee to about $1\text{cm}^{-3}$ near apogee, the sensor should ideally have a dynamic range of about 5 orders of magnitude.

The upper value of the geometric factor, however, was limited by the count rate that the mcp detector could cope with. As the count rate increases, the charge extracted from the mcp channel wall cannot be replenished by the conduction current before the next pulse arrives. Thus, the mcp gain gradually reduces. The mcps chosen for the CID (14mm diameter, 25μm pores, 2mm thickness for ease of handling and better rigidity) had a quoted resistance of 300-450MΩ per plate. In the worst case the mcp stack resistance would be 950 MΩ (including the 50MΩ rear mcp face bias resistor). From the gain versus voltage curves for a single plate which were published by the plate manufacturers, it was estimated that a voltage of 2400V the mcp stack gain would be about $10^7$e⁻ per pulse with a resolution of 70% FWHM. Using the above values and the
10% criterion for mcp gain reduction, the highest count rate obtainable would be about 1000 mm⁻² s⁻¹ or 95000 s⁻¹ for the 95mm² active area of the front mcp.

Equation 4.7 (assuming an instrument with energy resolution of 15% FWHM, a particle energy of 20eV and a particle density of 10⁵ cm⁻³) provides a flux value which, when substituted in equation 4.5, together with the count rate calculated above, yields a maximum value for the CID geometric factor of about 5.6 10⁻⁴ mm² sr.

The geometric factor of the sensor is determined: (i) by the characteristics of its geometry (angular acceptance and area of entrance aperture which define the physical geometric factor); (ii) by its energy resolution; and (iii) by its detection efficiency (the amount of particles detected relative to the amount of all the particles eligible for detection). The instrument’s angle of view was required to: a) provide relatively accurate information about the incoming particles’ direction of motion; and b) to reduce the risk of mcp exposure to sunlight. A field of view with a half angle of 5.5° was thought to be sufficient for the following reasons:

1. Since the sensor would be mounted with its axis parallel to the spin axis of the spacecraft (perpendicular to the ecliptic plane), it would be at an angle of about 12° to the Earth’s magnetic dipole axis. Therefore, it would be viewing within the 10⁰-20⁰ range (Sojka et al., 1984) of proton pitch angles outside the plasmasphere (the distribution of pitch angles is near isotropic within the plasmasphere).
2. The application of a negative bias on the sensor body would mean that the sensor would be detecting particles over a solid angle greater than the one defined by its collimator geometry.
The field of view was implemented via a collimator comprising two circular apertures (1mm diameter) placed 10mm apart. The field of view had a conical shape with a half angle of 5.740 and the physical geometric factor was calculated (eq. 5.2) as $\sim 6.2 \times 10^3$ mm$^2$ sr. Combination of the PGF value with the mcp detection efficiency (0.6) and the expected energy resolution of the instrument (15%), yielded an expected geometric factor for the CID of $5.58 \times 10^{-4}$ mm$^2$ sr.

A.3 Functional description of the instrument operation

The description of the instrument operation is done here with reference to Fig. A.1 (from the particle entrance at the top to the signal output at the bottom of the diagram). The reader, however, is encouraged to refer also to Fig. 3.1a&b. For clarification, it is assumed: a) that the instrument electrodes are at fixed voltages $V_1$ for the 1st RPA and $V_0$ for the Deflector, with $V_1 < V_0$; and b) that it is immersed in a region where there is unidirectional flow of ions with energies starting much lower than the one corresponding to $V_1$ and ending much higher than the one corresponding to $V_0$. The thickness of all the insulating ring spacers used followed the 1kV/mm rule (two neighbouring components with a potential difference $\Delta V$ (volts) should be separated by $\Delta V/1000$ mm). The inner diameter of all metal spacers is equal to the sensor inner diameter, as they actually constitute the sensor. The inner diameter of the insulating spacers is larger than the sensor inner diameter to avoid surface charging due to ion impact. Finally, the term ground, as used here, means the reference for the bias of the retarding electrodes.
Collimation & 1st RPA retardation area

The particles enter the sensor through the collimation area. This comprises two thin metal discs kept at an axial distance $A$ by a cylindrical metal spacer with inner diameter equal to the sensor inner diameter. The discs have had concentric circular apertures of diameter $D$ cut in them. This configuration constitutes a cylindrical collimator whose field of view is a cone with half angle $\alpha = \arcsin(D/A)$. In other words, a light ray (or a charged particle moving in the absence of fields) entering through the front aperture will exit through the rear aperture, only if its direction of motion is at an angle $0 < \theta \leq \alpha$ with the collimator axis. Thus, the collimator selects particles according to their angle of incidence.

In this design, the rear aperture also serves as a retarding potential electrode (1st RPA). Hence, it is positively biased (at a voltage $V_1$ for this illustration) with respect to the rest of the collimator components which are kept at ground, thereby creating an ion retarding field between the two apertures. The rear aperture, or 1st RPA, is insulated from the rest of the collimator by an insulating ring spacer.

The combined effect of the collimation and of the retarding field is that ions of energy $E$, charge $Q$ and angle of incidence $\theta$ can make it through the collimator only if: $\theta \leq \alpha$ and $(E/Q) \cos \theta > V_1$ (only the axial energy component is effective in overcoming the retarding potential). Particles with energy per charge less than $V_1$ are repelled. Thus, the 1st RPA voltage defines the low energy cut-off level.
Deflection & Re-acceleration area

The ions which pass through the rear aperture enter the Deflection and (subsequently) Re-acceleration area. This comprises the 1st RPA, the Deflector (a cone-shaped electrode mounted centrally with the cone pointing towards the 1st RPA), the sensor wall surrounding the cone and the Accelerator (a grid behind the Deflector upon which the Deflector was suspended via an insulator). The cone base diameter is large enough to preclude a direct path from the rear aperture to the sensor's mcp particle detector.

The Deflector and the sensor wall surrounding it are always kept at a voltage ($V_0$ here) higher than that of the 1st RPA ($V_1$ here). The Accelerator is always at ground. The complex electric field of this area has a dual effect. In the vicinity of the rear aperture - Deflector area the particles are slightly retarded in the axial direction. At the same time, they are accelerated radially outwards (the half angle of the conical electrode is less than $45^\circ$; a half angle of $\approx 35^\circ$ gave the best results in computer simulations). The particles, with axial energy sufficiently low to allow them to reach a radial distance greater than the Deflector radius, are accelerated towards the next sensor area. The higher energy particles hit the Deflector surface. In the deflection & re-acceleration area, therefore, a second energy selection is performed. Only this time it is the particles with high energies that are cut-off. The combined effect of the two electrodes (1st RPA and Deflector) is that only particle energies within a passband that depends on the voltages $V_0$ and $V_1$ are accepted (i.e. the instrument has a differential energy response). Use of two separate power supplies (or a single power supply and a voltage divider incorporating a variable resistor) for the Deflector and 1st RPA.
Collimation & 1st RPA retardation area

Selection of ions according to angle of incidence and energy (Low energy cut-off)

Deflection & Re-acceleration area

Selection of ions according to energy (Upper energy cut-off)

Ion focussing area

The particles are accelerated and focussed towards the MCP front face

Ion detection area

The ion impact on the front MCP face creates an electron avalanche. The resulting electron cloud charge is collected by the anode

Figure A.1 Functional diagram of instrument design.
voltages would allow variable energy resolution, thus, giving the sensor a wide dynamic range.

**Ion focusing area**

This area comprises the Accelerator (at ground), a metal spacer (at ground), an insulating spacer, a metal spacer (at front mcp face voltage), the front mcp face contact (a thin gold-coated metal ring with a solder tag; at front mcp face voltage) and the front mcp face (at a high negative voltage i.e. >2.5kV). The field between the Accelerator and the front mcp face, focuses the particles towards the centre of the mcp, increases their energy in order to improve the mcp detection efficiency and prevents energetic electrons from reaching the mcp detector.

**Ion detection area**

It comprises the mcp stack, the rear mcp face contact (a thin gold-plated metal ring; at a voltage of about 150-300V), an insulating spacer and the anode (a gold-plated metal disc at virtual ground). The ion impact at the front mcp face generates secondary electrons which are accelerated by the voltage difference between the mcp front and rear faces and multiplied through impact with the mcp channel walls. The cloud of electrons exiting the mcp is accelerated towards and collected by the anode. The anode signal is then fed to the counting electronics, usually consisting of a charge sensitive preamplifier, a shaping amplifier and a pulse counter.

**A.4 CID method of operation and measurement capabilities**

The whole sensor could be biased relative to the spacecraft so that the sensor could
operate at space potential or it could be biased negatively in order to draw in ions and increase the sensitivity. The energy bandpass of the sensor could be swept through the full energy range of the instrument from 0.3eV to 1500eV by varying the voltage applied to the two internal electrodes. At each step the flux would be measured by recording the number of counts per accumulation period detected by the microchannel plate. This would provide the energy spectrum of the ions over this range, from which the density (using the geometric factor value obtained), temperature and the spacecraft potential (as the sensor body bias was referenced to the spacecraft ground, a spacecraft potential different from the plasma potential would register as a shift in the particle energy) could be obtained.

The CID would provide neutralizer operation diagnostics in the following way: The instrument would be operating prior, during and after the neutralizer operation with the maximum negative sensor body bias. If the spacecraft were positively charged prior to the neutralizer operation, then a gradual increase in measured particle density and/or energy during and after the neutralizer operation would indicate the effectiveness of the operation. If the spacecraft was initially negatively charged, then an effective neutralizer operation would be indicated by a reduction in the measured particle density and energy after the operation and, possibly, by an increase in the measured particle density during the neutralizer operation.

The CID, however, had its limitations. Firstly, even if the instrument achieved the expected geometric factor value of $5.58 \times 10^4$ mm$^2$ sr, the minimum practically measurable particle density would be $\sim 25$cm$^3$ (with a 10-15% error, assuming the fluctuation of the number of counts recorded per distribution is given by the Poisson
value $1/N^{1/2}$). This could possibly be a major handicap for measurements during neutralizer operations outside the plasmasphere. Secondly, as the instrument would need to operate with a body bias of about 20-70 times the thermal energy of most of the plasmaspheric ions, the width of the peak of the distribution (from which the particle temperature would be determined) would be reduced to a level that the energy resolution of the instrument would not be narrow enough to resolve the true width. Finally, at altitudes near perigee, the instrument would be measuring mostly hydrogen ions (about 10% of the constituents). The atomic oxygen atoms (about 90% of the constituents) would be imparted an energy of about 10eV at almost right angles to the CID axis by the spacecraft velocity (~10.5km/s). Therefore, the body bias of the sensor would not be sufficient to draw them into the sensor. Since the oxygen density can be as high as a few $10^6$ cm$^{-3}$, it would require a (most unwelcome) further reduction of the geometric factor. Thus, this was not considered too big a problem.

A.4 Summary of the CID performance

A.4.1 Laboratory calibration results

A.4.1.1 MCP results

Both pairs of mcps showed a resistance increase with storage time. The pair used in the CID EM had a stack resistance of 1.05GΩ while the one used in the CID FM had a resistance of 1.15GΩ. More importantly, the EM mcps gave almost double the electron gain of the FM ones for the same voltage and with much better resolution. After calibration and just prior to the CID FM delivery the plates were swapped between the two instruments. The mcp gain was dependent on the particle energy, with the gain at 20eV being about 85% of that at 500eV for the same mcp voltage.
High count rate tests showed a rapid reduction of gain long before the pulse current reached the value of 10% of the standing current, indicating that at low ion energies there is strong focusing of the beam towards a small area at the centre of the mcp. For the mcp pair flown, the tests indicate (for an ion energy of ~20eV and a mcp voltage of 2700V) a worst case maximum count rate of ~300000 s⁻¹.

A.4.1.2 CID EM results

This instrument’s voltage divider was supplying the 1st RPA with ~55% of the Deflector voltage and the (three-spoke, cartwheel like) Accelerator with ~9% of the Deflector voltage. The CID EM energy response was ~12%FWHM at ion energies above 100eV but gradually increased with decreasing ion energies up to ~70% at 10eV (the higher ion energy spread at low energies cannot account for such a high increase).

The CID EM angular response exhibited a hole for angles up to 2°. There is evidence, however, that the angular response depends on the particle energy.

A.4.1.3 CID FM results

This instrument’s voltage divider was supplying the 1st RPA with ~91% of the Deflector voltage and the (initially three-spoke, cartwheel like) Accelerator was kept at ground. The CID FM exhibited a hole in the energy distribution with two peaks at either end of the passband and a trough in the middle, mostly due to the Accelerator grid failing to act as a well-defined ground plane. For beam energies above 300eV the high-energy peak was about half the size of the low-energy one, while the smaller peak gradually increased in size for beam energies below 300eV. Subsequent inclusion of a steel mesh 2mm behind the Accelerator grid removed the latter effect.
The angular response of the sensor was $6^\circ \pm 1^\circ$ FWHM. The calibration tests showed an asymmetry in energy response at different azimuthal angles, which was probably due to a slight misalignment between the Deflector cone axis and the sensor axis. The calibration-derived geometric factor was $2.22 \times 10^{-4}$ mm$^2$ sr, although at energies below 100eV field penetration from the mcp side should improve the steel mesh transparency to almost 100% making, thus, the geometric factor $2.74 \times 10^{-4}$ mm$^2$ sr.

A.4.1.4 CID EMM results

This instrument had the same voltage configuration as the CID FM but now the steel mesh was attached on the back of the Accelerator grid. The CID EMM energy response was very close to the one obtained by computer simulations. The energy resolution was $\sim 12\%$ FWHM, the angular response was similar to the CID FM one (but without the asymmetries at different azimuthal angles) as was the CID EM field of view ($\sim 6^\circ$ FWHM). The CID EM geometric factor was calculated at $3.52 \times 10^{-4}$ mm$^2$ sr. Fig. A.2 illustrates the main properties of the tested instruments.

More testing is required to establish the limits of energy resolution achievable, as simulations of the CID EM showed that a 45% electrode voltage difference results in an energy resolution of 25% (i.e. smaller than the voltage difference), while for a voltage difference of 10% the resolution is 15% (i.e. larger than the electrode voltage difference). The light rejection properties of the design should also be investigated.
<table>
<thead>
<tr>
<th></th>
<th>CID EM</th>
<th>CID FM</th>
<th>CID EMM</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Electrode Voltage</strong></td>
<td>45%</td>
<td>9.1%</td>
<td>9.1%</td>
</tr>
<tr>
<td><strong>ΔV/V_{Deflector}</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Energy Resolution</strong></td>
<td>12% E&gt;100eV</td>
<td>6.7% (main peak)</td>
<td>12% E&gt;15eV</td>
</tr>
<tr>
<td><strong>ΔE/E (FWHM)</strong></td>
<td>40-70% E&gt;10</td>
<td>40-70% E&gt;10</td>
<td>40-70% E&gt;10</td>
</tr>
<tr>
<td><strong>Field of View</strong></td>
<td>2.5° - 4°</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Half angle (FWHM)</strong></td>
<td>The response had a</td>
<td>3° ± 0.5°</td>
<td>3° ± 0.5°</td>
</tr>
<tr>
<td><strong>Geometric Factor</strong></td>
<td>N/A</td>
<td>2.22</td>
<td>3.52</td>
</tr>
<tr>
<td><strong>10^{-4} mm^2 sr</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure A.2. Properties of the three CID versions tested.

**A.4.2 CID in flight performance**

The instrument operated for nearly three years with the only problems being an occasional reluctance of the mcp voltage to turn on and a poor insulation of the sensor body from the spacecraft that reduced the maximum achievable negative sensor body
bias to \( \sim 8 \text{V} \). The data acquisition time was always kept at 65.5ms. Figure A.3 illustrates the main attributes of the CID experiment as flown aboard STRV 1A.

The sensor provided particle density measurements throughout the plasmaspheric regions covered by the STRV 1A orbit, which are in good agreement with L models. Its geometric factor, however, was too low for measurements outside the plasmasphere or near the plasmapause. Indeed, neither real events have been found at the sensor high-energy range, nor an orbit where valid data exists for particle densities below \( 80 \text{cm}^{-3} \). Using the density 'knee' criterion for the determination of the plasmapause position, however, gave satisfactory results as it gave good correlation between the plasmapause position and the kp index and it depicted the equatorial bulge.

The limited protection against particles with energies \( >2 \text{MeV} \), that the external aluminium body afforded the mcp detector, prevented measurements within the radiation belts. It has, however, helped researchers study a substorm, making good use of the better temporal resolution of the CID relative to that of the high energy particle detectors.

Severe noise pick up during neutralizer operations (probably due to the inadequate sensor body insulation) prevented the CID from measuring neutralizer produced ions.
<table>
<thead>
<tr>
<th>Attribute</th>
<th>Value or Range or Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Technique</td>
<td>Retarding potential analyzer</td>
</tr>
<tr>
<td>Species detected</td>
<td>Ions</td>
</tr>
<tr>
<td>Energy range</td>
<td></td>
</tr>
<tr>
<td>Low</td>
<td>$0 &lt; E/q &lt; 40V$ in 128 0.31V steps</td>
</tr>
<tr>
<td>High</td>
<td>$40 &lt; E/q &lt; 1500V$ (1300V in flight)</td>
</tr>
<tr>
<td></td>
<td>in 128 semi-logarithmic steps</td>
</tr>
<tr>
<td>Density range</td>
<td>$50 &lt; n &lt; 3 \times 10^3 \text{ cm}^{-3}$</td>
</tr>
<tr>
<td>Temporal resolution</td>
<td>Full energy sweep $8 &lt; t &lt; 25s$</td>
</tr>
<tr>
<td>Sensor bias</td>
<td>$-22 &lt; V_f &lt; 9V$ (-8V in flight)</td>
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<tr>
<td>Sensor length</td>
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<tr>
<td>Inner sensor diameter</td>
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<td>Outer sensor diameter</td>
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<tr>
<td>Sensor mass</td>
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<tr>
<td>Electronics mass</td>
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<tr>
<td>Total mass of experiment</td>
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</tr>
<tr>
<td>Power</td>
<td>0.562W (max)</td>
</tr>
<tr>
<td>Telemetry rate</td>
<td>580 bits/s (max)</td>
</tr>
</tbody>
</table>

Figure A.3. Main attributes of the CID experiment