# Edge-illumination X-ray phase contrast imaging: matching the imaging method to the detector technology

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ABSTRACT: X-Ray Phase Contrast Imaging (XPCI) has been arguably the hottest topic in X-ray imaging research over the last two decades, due to the significant advantages it can bring to medicine, biology, material science and many other areas of application. Considerable progress has recently been achieved, in terms of the first *in vivo* implementations at synchrotrons (notably at Elettra in Trieste), and of new XPCI methods working with conventional sources. Among the latter, edge-illumination (EI) is possibly one of the most promising in terms of mainstream translation, due to set-up simplicity, scalability and flux efficiency compared to other approaches. EI is indeed the only method working with a completely incoherent source: however, it was recently demonstrated that neither the ability to perform quantitative phase retrieval, nor the method's phase sensitivity are affected by the source's incoherence. Here its implementation with different detector technologies is discussed.

KEYWORDS: X-ray imaging; Phase-contrast; Edge-illumination.

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## Contents



## 1. State-of-the-art of edge-illumination X-ray phase contrast imaging

In X-ray phase contrast imaging (XPCI), contrast originates from refraction and interference effects rather than attenuation [1]. This overcomes the main limitation of conventional X-ray imaging – low image contrast arising from small attenuation differences, and as such has generated great interest, since benefits extend over a wide range of applications.

Following pioneering developments based around the use of perfect crystals, either in the arrangement of an interferometer [2] or used as "analysers" of micro-radian changes in the beam direction due to X-ray refraction [3], XPCI methods became much more widely studied since the mid-90s, based on the use of either synchrotron radiation [4], [5] or micro-focal sources [6], [7]. The use of these sources was made necessary by the stringent requirements that most XPCI methods impose in terms of source (especially spatial) coherence, a limiting factor that has effectively limited its widespread use in "real-world" applications [8].

Indeed, only in the mid '00s methods emerged that enabled for the first time the implementation of XPCI with low-brilliance sources. These are of two types: coherent methods, based on artificially increasing the coherence of a low brilliance source through appropriate collimators [9], [10] or truly incoherent methods [11], [12]. This paper focuses on the latter, since their implementation is made simpler by the fact that they do not require source gratings or other devices to collimate an incoherent source, and in particular on the edge-illumination (EI) approach [11], [13]. In fact, the approach described in [12] can effectively be considered a "de-coherenced" (and consequently less sensitive, see [14]) version of that described in [9]: in fact, it uses the same acquisition scheme (phase-stepping), rather than the sensitivity-enhancing edge-illumination one [13], [15]-[17], and indeed still requires the use of a source grating if the focal spot is increased.

EI was developed at the Elettra synchrotron in Italy in the mid '90s, and is based on pre-shaping the beam with an appropriate slit and aligning this pre-shaped beam with a sharp absorbing edge (figure 1a). Any phase-induced deviation of the shaped beam (X-ray refraction) would move part of it on or off the absorbing edge, consequently decreasing or increasing the detected number of photons i.e. creating a "differential" phase contrast profile [13], [16]-[17].

Since its introduction, the method has undergone a number of significant developments. It was shown that, by combining two images acquired in opposite edge illumination conditions (see figures 1a and 1b), phase and absorption signals could be separated and individually quantified [18]. The processing algorithm was inspired by Chapman *et al*'s "diffraction enhanced imaging" (DEI) approach [19]; this equivalence with DEI, already observed in the original EI paper [13], was more recently formally demonstrated [20]. Possibly the key, and arguably unique, feature of EI is its resilience against incoherence. While the robustness against temporal incoherence [11], [15] is shared at least with free-space propagation XPCI [7], [21]-[22]; that against spatial incoherence is arguably unique to this method [11], [15]. This robustness is easily understood by comparing figure 1c with figure 1d. Simplifying, if the source is spatially coherent, the beam profile will not be blurred, and its footprint on the detector mask can be described by a rectangular function (figure 1c). If, on the other hand, a source with finite size is used, this will blur the profiles of the shaped beams, so that their footprint on the detector mask will be better described by e.g. a Gaussian (figure 1d). However, the detected phase signal depends on the (vertical, in the drawings of figure 1) movement of the shaped beam: so long as this is "chopped" by an absorbing edge, a similar signal is detected in both cases. In the small refraction angle (i.e. weak phase variation) approximation, the signal is identical so long as the flat top of the Gaussian can be approximated with a straight line (which explains e.g. the possibly surprising result reported in figure 6 in ref. [15]).

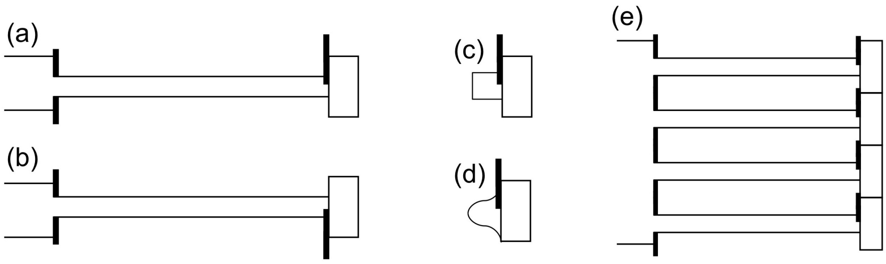


**Figure 1.** Schematic implementation(s) of the edge illumination XPCI method. (a) shows the standard synchrotron implementation, with the beam coming from the left-hand side being shaped by a slit (in black) and ultimately impinging on a sharp absorbing edge (also in black) placed in front of a detector. The object, not shown, would be placed immediately downstream of the shaping slit and scanned through the beam. (b) shows the "reverse" illumination condition which, combined with (a), allows quantitative phase retrieval (see text). (c) and (e) compare the spatially coherent (c) to the spatially incoherent (d) cases, and (e) represents the "replicated" version of (a) which adapt the concept to a 2D, area detector through masks. In this case, scanning is avoided. All graphs must be imagined to extend into the plane of the drawing. In all figures, "boxes" on the far right, immediately behind the second absorbing edge, represent detector pixels.

This robustness against spatially incoherent sources enabled some notable and apparently counterintuitive results, such as the ability to quantitatively retrieve the phase [23] and perform dark field imaging [24] with incoherent sample illumination. In particular, the latter signal (sometimes also referred to as "ultra-small angle scatter") has repeatedly been attributed in the past to "degradation of the coherent wavefront" (e.g. [25]).

This resilience against both temporal and spatial coherence makes the method easily adaptable to conventional sources, simply by replicating the above scheme as shown in figure 1e. Two-directional phase sensitivity can also be obtained by using appropriately shaped apertures [26]. The only caveat is to keep the beams physically separated, which also means that no interference occurs. The resulting large pitch of the masks makes the method particularly robust against environmental vibrations [27], without this affecting its phase sensitivity, which remains as high as in other (coherent) methods [17]. This is due to the amplifying effect that the edge has on phase sensitivity, which e.g. makes EI the most sensitive differential XPCI method when implemented with coherent sources [28], also at high energies [29]. The combination with a conventional X-ray source yields an extremely flexible method, which has been applied to, among others, cartilage imaging [30], mammography [31] and security [32], as well as adapted to different implementations such as microscopy [33], tomosynthesis [34] and CT [35], all with a common element of low dose delivery.

## 2. Matching the imaging method to the detection technology

Another key difference between EI and other methods is that, while in most XPCI approaches a detector with the appropriate spatial resolution (and where possible efficiency) is simply placed e.g. at the output of an interferometer, in EI it forms part of the "phase sensing" mechanism itself. This is achieved via a variety of means, including "masking" the detector as often done in lab-based implementations (figure 1e). Alternatively, the physical edge of the detector itself, or the separation between pixels, may be used as the phase sensing mechanism (figure 2). However, in the latter case, the sensitivity is reduced, due to its dependence on the sharpness of the edge-sensing mechanism [17], [36], which means it suffers from the fact that the point spread function (PSF) of a pixel is never perfectly sharp [15], [36]-[37].

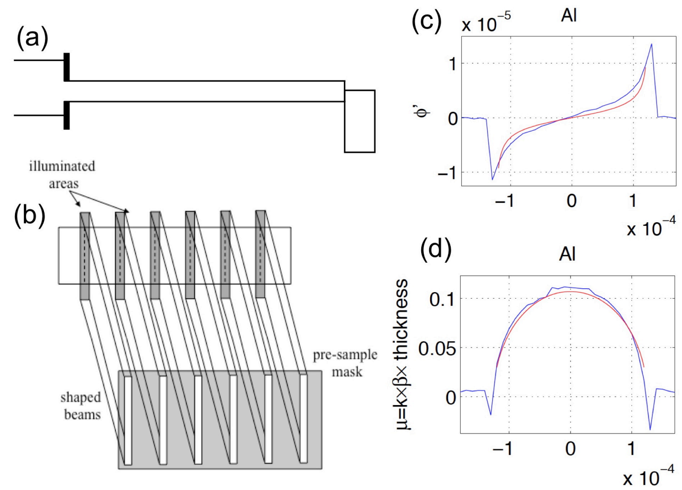


**Figure 2.** Alternative EI schemes. (a) is equivalent to figure 1a, but the edge has been removed and replaced with the physical edge of the detector itself. (b) shows yet another illumination scheme, where only a pre-sample mask is used and areas between pixels are illuminated. The unshaped beam hits the front of the pre-sample mask which shapes it into individual beamlets, each one of which hits the transition region between adjacent pixels (indicated with grey shading on the detector surface). In this case this is applied to a linear detector (PICASSO, see text)), but the extension to an area detector is trivial. (c) and (d) show phase and absorption profiles (respectively) retrieved from an image of a 200 μm Al monofilament (x-axis in meters) acquired with the scheme shown in (b). In both cases, the retrieved profile (in blue) is superimposed to the theoretical one (in red).

The detector used to obtain the results shown in Fig. 2 was PICASSO (Phase Imaging for Clinical Application with Silicon detector and Synchrotron radiation), developed by the Trieste medical physics group and based on the use of edge-on silicon microstrips equipped with single photon counting electronics. A full description of the device can be found in [38]. The irregularity of the pixel PSF has the additional complication that, also when used with almost ideal, direct conversion devices, it leads to significant artefacts both in the retrieved phase (figure 2c) and absorption (figure 2d) profiles if standard retrieval methods bases on sum/subtraction [18], [23] are used. This demonstrates the lack of quantitativeness of some previous attempts (e.g. [39]), and can be solved by "illumination curve" based retrieval approaches [20], [28], which however require a precise knowledge of the pixel PSF. Although EI XPCI was demonstrated to work with practically any detector technology (e.g. a-Si [11], a-Se [31], CMOS [32], and others), the sensitivity of the method to the PSF's sharpness means that direct conversion methods, which are typically characterized by a sharper pixel PSF, outperform other detection technologies when used with EI XPCI (hence the repeated use of a-Se e.g. in [17], [23]-[24], [30]-[31], [34]-[35]). Currently, the top performance for EI XPCI is therefore obtained when direct conversion methods are implemented jointly with photon counting capabilities, which in addition minimize the noise thus maximizing the contrast.

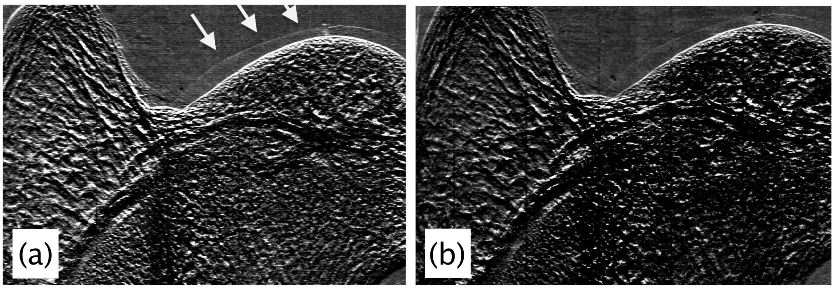


**Figure 3.** (a) EI XPCI image of a rabbit knee immersed in water acquired with the Pixirad detector and a Molybdenum spectrum at 26 kVp. The white arrows underline a sharp signal from the edge of the articular cartilage, the clear delineation of which would enable an easy detection of possible damage. The cartilage is still clearly visible in (b) which was acquired with the same setup but at 40 kVp, which opens the way to dose reduction strategies.

This is quite effectively demonstrated by the images in figure 3, obtained with the Pixirad detector [40]. Here cartilage is very clearly detected in water, with an image quality that has been improved even further compared to the already noteworthy results presented in [30].

## 3. Conclusions

EI is a flexible, incoherent XPCI method that is easily adapted to conventional sources. It allows low-dose imaging, short exposure times and is robust against environmental vibrations. At the moment, the phase sensing mechanism is implemented by illuminating edges of apertures in appropriately designed masks. It is possible to incorporate the sensing mechanism directly on the detector (or even use the detector itself), however care must be taken in the quantitative interpretation of the results. Regardless of the specific implementation of the sensing mechanism, the method works best with direct conversion, possibly photon counting detectors.

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## References

[1] R. Fitzgerald, *Phase-sensitive x-ray imaging*, 2000 *Phys Today* **53** 23.

[2] U. Bonse and M. Hart, *An X-ray interferometer*, *Appl. Phys. Lett.* **6** (1965) 155.

[3] E. Forster, K. Goetz and P. Zamumseil, *Double crystal diffractometry for the characterization of targets for laser fusion experiments*, *Krist. Tech.* **15** (1980) 937.

[4] A. Snigirev et al., *On the possibilities of x-ray phase contrast microimaging by coherent high-energy synchrotron radiation*, *Rev. Sci. Instrum.* **66** (1995) 5486.

[5] V. N. Ingal and E. A. Beliaevskaya, *X-ray plane-wave topography observation of the phase contrast from a non-crystalline object*, *J. Phys. D: Appl. Phys.* **28** (1995) 2314.

[6] T. J. Davis, D. Gao, T. E. Gureyev, A. W. Stevenson and S. W. Wilkins, *Phase-contrast imaging of weakly absorbing materials using hard x-rays*, *Nature* **373** (1995) 595.

[7] S. W. Wilkins, T. E. Gureyev, D. Gao, A. Pogany and A. W. Stevenson, *Phase-contrast imaging using polychromatic hard x-rays*, Nature **384** (1996) 335.

[8] A. Olivo and I. Robinson, *'Taking X-ray phase contrast imaging into mainstream applications' and its satellite workshop 'Real and reciprocal space X-ray imaging'*, *Phil. Trans. R. Soc. A* **372** (2014) 20130359.

[9] F. Pfeiffer, T. Weitkamp, O. Bunk and C. David, *Phase retrieval and differential phase-contrast imaging with low-brilliance x-ray sources*, *Nat. Phys.* ***2** (2006) 258*.

[10] R. Lanza, B. Horn and A. Damato "*Phase-contrast x-ray imaging*", *International Patent* **WO 09/058976** (7 May 2009).

[11] A. Olivo and R. Speller, *A coded-aperture approach allowing x-ray phase contrast imaging with conventional sources*, *Appl. Phys. Lett*. **91** (2007) 074106.

[12] Z.-F. Huang et al., *Alternative method for differential phase-contrast imaging with weakly coherent hard x-rays*, *Phys. Rev. A* **79** (2009) 013815.

[13] A. Olivo et al., *An innovative digital imaging set-up allowing a low-dose approach to phase contrast applications in the medical field*, *Med. Phys.* ***28** (2001) 1610*.

[14] R. Zhang, L. Zhang, Z. Chen, W. Peng and R. Li, *Sensitivity of a non-interferometric grating-based x-ray imaging system*, *Phys. Med. Biol.* **59** (2014) 1573.

[15] A. Olivo and R. Speller, *Modelling of a novel x-ray phase contrast imaging technique based on coded apertures*, *Phys. Med. Biol.* ***52** (2007) 6555*.

[16] A. Olivo and R. Speller, *Image formation principles in coded-aperture based x-ray phase contrast imaging*, *Phys. Med. Biol.* ***53** (2008) 6461*.

[17] P. C. Diemoz, C. K. Hagen, M. Endrizzi and A. Olivo, *Sensitivity of lab-based implementations of edge illumination x-ray phase-contrast imaging, Appl. Phys. Lett.* **103** (2013) 244104.

[18] P. R. T. Munro et al., *A quantitative, non-interferometric x-ray phase contrast imaging technique, Opt. Exp.* **21** (2013) 647.

[19] D. Chapman et al., *Diffraction enhanced x-ray imaging, Phys. Med. Biol.* **42** (1997) 2015.

[20] P. R. T. Munro, C. K. Hagen, M. B. Szafraniec and A. Olivo, *A simplified approach to quantitative coded aperture x-ray phase imaging, Opt. Exp.* **21** (2013) 11187.

[21] A. Olivo and R. Speller, *Experimental validation of a simple model capable of predicting the phase contrast imaging capabilities of any x-ray imaging system, Phys. Med. Biol.* ***51*** *(2006) 3015.*

[22] T. E. Gureyev et al., *Some simple rules for contrast, signal-to-noise and resolution in in-line x-ray phase-contrast imaging Opt. Exp.* **16** (2008) 3223.

[23] P. R. T. Munro, K. Ignatyev, R. D. Speller and A. Olivo, *Phase and absorption retrieval using incoherent x-ray sources, Proc. Natl. Acad. Sci. USA* **109** (2012) 13922.

[24] M. Endrizzi et al., *Hard x-ray dark-field imaging with incoherent sample illumination, Appl. Phys. Lett.* **104** (2014) 024106.

[25] F. Pfeiffer et al., *Hard-x-ray dark-field imaging using a grating interferometer, Nat. Mat.* **7** (2008) 134.

[26] A. Olivo et al., *A non-free-space propagation x-ray phase contrast imaging method sensitive to phase effects in two directions simultaneously, Appl. Phys. Lett.* **94** (2009) 044108.

[27] T. P. Millard et al., *Method for automatization of the alignment of a laboratory based x-ray phase contrast edge illumination system, Rev. Sci. Instrum.* **84** (2013) 083702.

[28] P. C. Diemoz et al., *X-ray phase contrast imaging with nanoradian angular resolution, Phys. Rev. Lett.* **110** (2013) 138105.

[29] A. Olivo, P. C. Diemoz and A. Bravin, *Amplification of the phase contrast signal at very high x-ray energies, Opt. Lett.* **37** (2012) 915.

[30] M. Marenzana et al., *Visualization of small lesions in rat cartilage by means of laboratory-based x-ray phase contrast imaging, Phys. Med. Biol.* **57** (2012) 8173.

[31] A. Olivo et al., *Low-dose phase contrast mammography with conventional x-ray sources, Med. Phys.* **40** (2013) 090701.

[32] K. Ignatyev et al., *Coded apertures allow high-energy x-ray phase contrast imaging with laboratory sources, J. Appl. Phys.* **110** (2011) 014906.

[33] M. Endrizzi et al., *Phase-contrast microscopy at high x-ray energy with a laboratory setup, Opt. Lett.* **39** (2014) 3332.

[34] M. B. Szafraniec et al., *Proof-of-concept demonstration of edge-illumination x-ray phase contrast imaging combined with tomosynthesis, Phys. Med. Biol.* **59** (2014) N1.

[35] C. K. Hagen et al., *Low-dose phase contrast tomography with conventional x-ray sources, Med. Phys.* **41** (2014) 070701.

[36] F. A. Vittoria et al., *Virtual edge illumination and one dimensional beam tracking for absorption, refraction and scattering retrieval,* *Appl. Phys. Lett.* **104** (2014) 134103.

[37] K. Ignatyev, P. R. T. Munro, R. D. Speller and A. Olivo, *Effects of signal diffusion on x-ray phase contrast images,* *Rev. Sci. Instrum.* **82** (2011) 073702.

[38] L. Rigon et al., *A single-photon counting "edge-on" silicon detector for synchrotron radiation mammography,* *Nucl. Instrum. Meth. A* **608** (2009) S62.

[39] F. Krejci, J. Jakubek and M. Kroupa, *Single grating method for low dose 1-D and 2-D phase contrast x-ray imaging,* *JINST* **6** (2011) C01073.

[40] R. Bellazzini at el., *Chromatic x-ray imaging with a fine pitch CdTe sensor coupled to a large area photon counting pixel ASIC,* *JINST* **8** (2013) C02028.