Phase contrast imaging in partially coherent X-ray radiation

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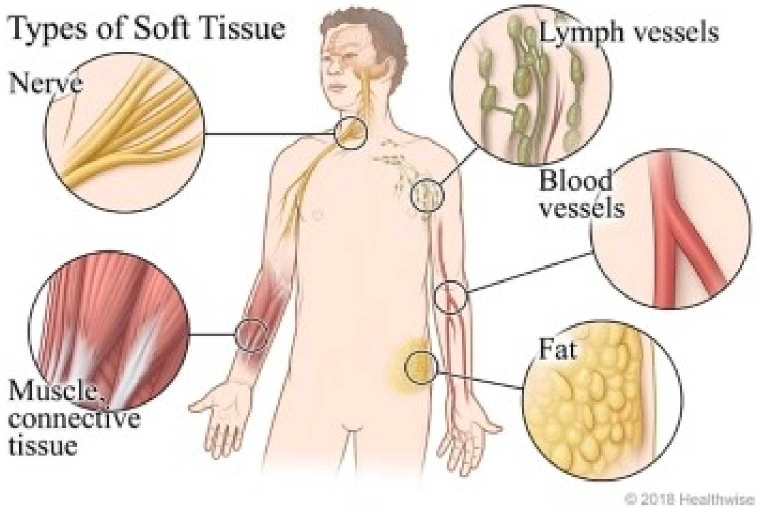
Motivation

The improvement of medical diagnostic and imaging methods is one of the most urgent problems. In this area wide use has been found for X-rays due to their peculiar interaction with biological tissues, in particular, the high penetration capability.

Problem of soft tissues imaging of human body: early cancer diagnostic; cardiovascular diseases; neurological diseases; respiratory diseases.

The main problems in area of early diagnosis and medical imaging:

- reducing the radiation dose;
- increase of spatial resolution;
- increase of contrast for soft tissue imaging.



The development of technologies based on X-ray phase-contrast imaging (PCI), is presented as one of the most promising methods of medical diagnostics.

From synchrotrons to conventional sources

X-ray phase contrast imaging, initially developed using the high intensity of synchrotron sources, should be adapted for use with conventional X-ray sources.

X-ray image formation in partially coherent radiation is of interest, especially in the context of the use of compact sources

The main types of compact X-ray sources:

- Microfocus X-ray tubes;
- Compton backscattering sources;
- Sources using accelerated ion beams;
- Sources using transition radiation;
- Laser-plasma sources…

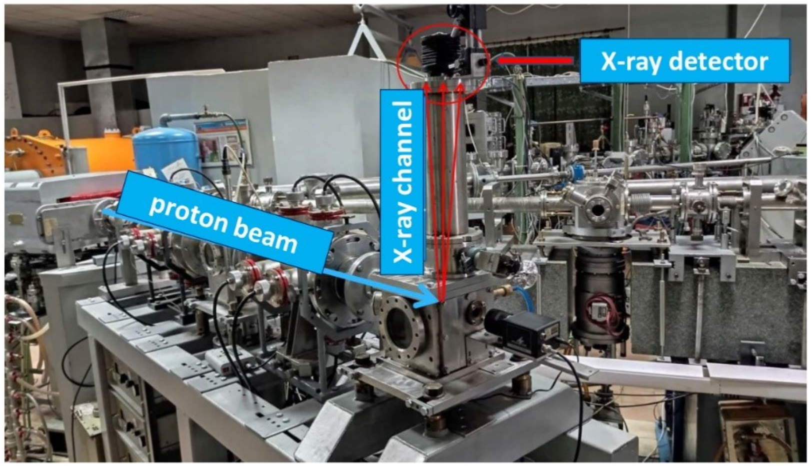
Reviews

Olivo, A., Castelli, E. **X-ray phase contrast imaging: From synchrotrons to conventional sources**. *Riv. Nuovo Cim.* **37**, 467–508 (2014). https://doi.org/10.1393/ncr/i2014-10104-8

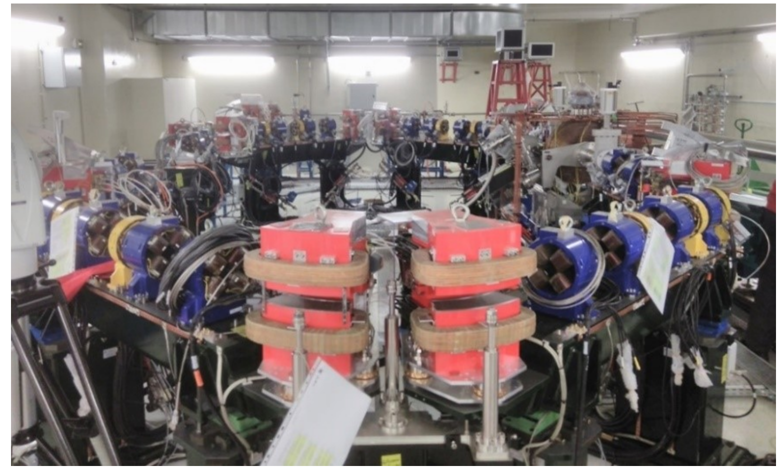
Quenot L, Bohic S, Brun E. **X-ray Phase Contrast Imaging from Synchrotron to Conventional Sources**: A Review of the Existing Techniques for Biological Applications. *Applied Sciences*. 2022; 12(19):9539. https://doi.org/10.3390/app12199539

X-ray sources based on compact accelerators

Development of X-ray phase contrast methods based on compact accelerators for use in medicine and materials science.



IAP NASU X-ray source



ThomX ICS source at IJCLab

Peculiarities & Differences	
Proton beam (2 MeV)	Electron beam (20-50 MeV) and laser pulse
Isotropic radiation of characteristic line	Narrow radiation of hard photons
Continuous regime	Pulsed regime of laser system
Intensity is limited by the beam current	High flux of radiation

Phase-contrast X-ray imaging

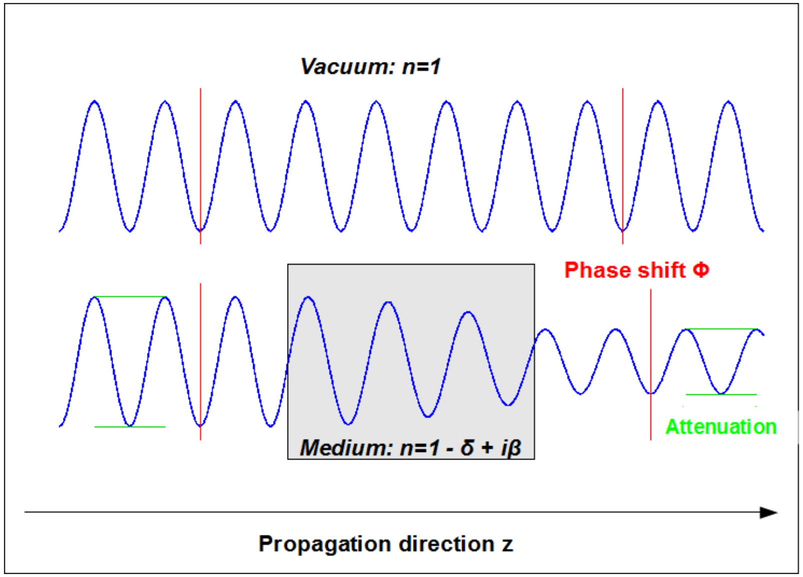
Phase-contrast X-ray imaging (PCI) is a general term for different technical methods that use information concerning changes in the phase of an X-ray beam that passes through an object in order to create its images.

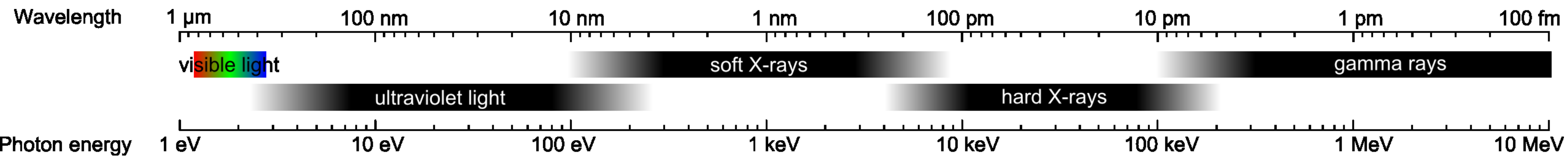
$$\Psi(z) = E_0 e^{inkz} = E_0 e^{i(1-\delta)kz} e^{-\beta kz}$$

the phase shift

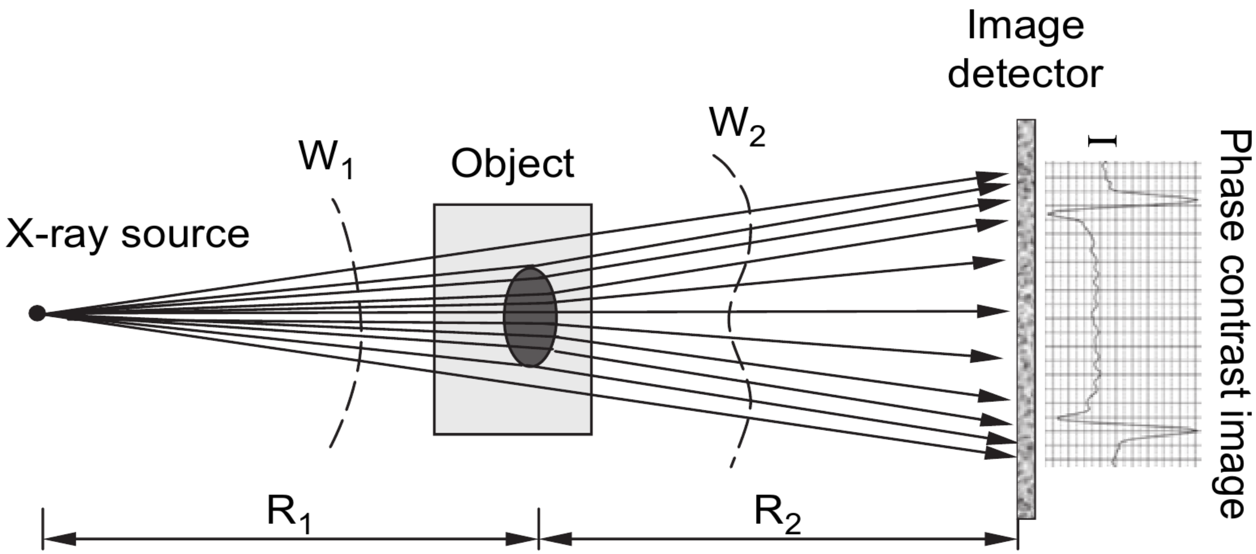
an exponential decay factor decreasing the amplitude of the wave

$\delta \propto k^{-2}$ $\beta \propto k^{-4}$





PCI propagation-based method

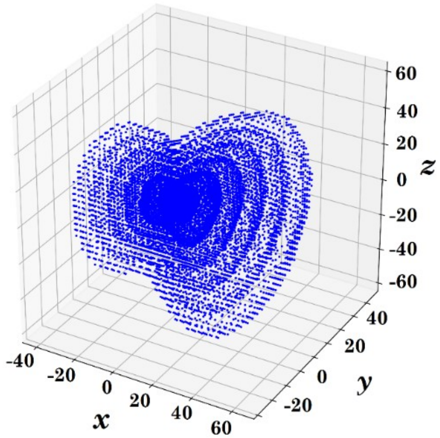


$$I_\omega(x, y, z = \Delta) \approx I_\omega(x, y, z = 0)\left[1 - \frac{z\lambda}{2\pi}\nabla_\perp^2 \phi_\omega(x, y, z = 0)\right].$$

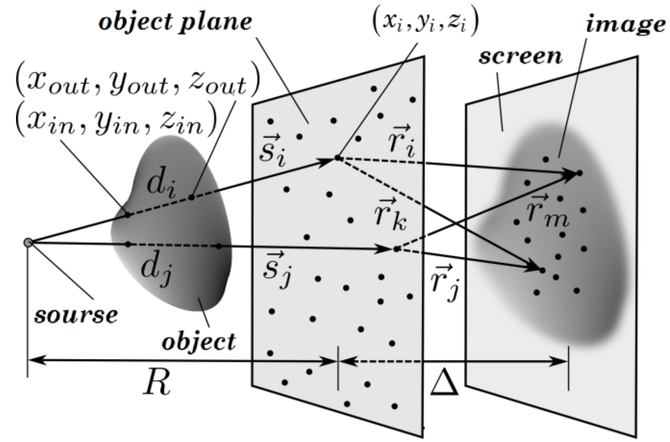
The solution of the direct problem of forming an X-ray phase contrast image is proposed as a way to find answers to a number of topical issues of practical implementing phase contrast on compact radiation sources.

Formation of X-ray phase contrast image by propagation-based method

Test object: three-dimensional, multilayer, optically inhomogeneous, arbitrary shape



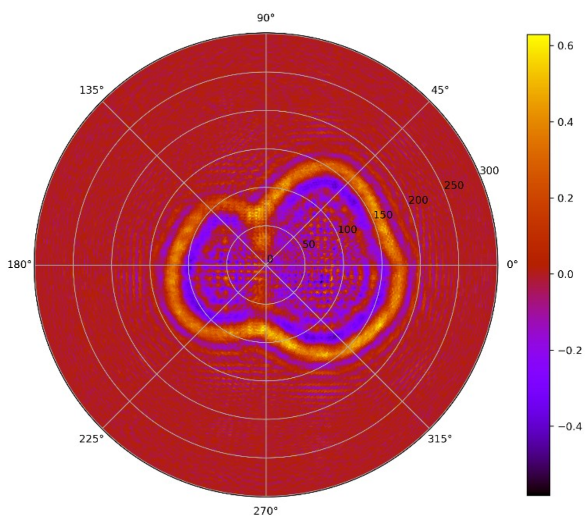
Modeling based on Fresnel-Kirchhoff theory



$$\psi(x_{scr}, y_{scr}) = \frac{1}{i\lambda} \iint_{-\infty}^{\infty} \frac{\exp(ik(r+s))}{rs} \times$$

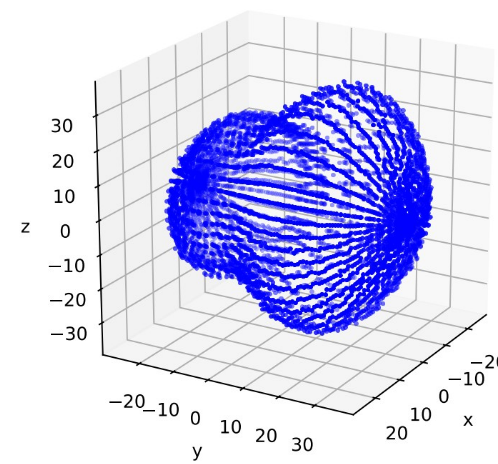
$$\times \left[\frac{\cos(\vec{n}, \vec{r}) + \cos(\vec{n}, \vec{s})}{2} \right] \exp(i\varphi) \exp(-k\gamma) dx_i dy_i$$

$$\varphi(x, y) = -\frac{2\pi}{\lambda} \int \delta(x, y, z) dz$$



PCI images of the six-layer object

Contours of image at different angles allow to reconstruct the object shape



Partially coherent radiation

The terms of mutual intensity and complex degree of coherence of radiation are widely used to description of the case of partially coherent radiation.

According to the key Van Zittert–Zernike theorem, the mutual intensity for points on the observation plane P_1 and P_2, irradiated by an incoherent source σ:

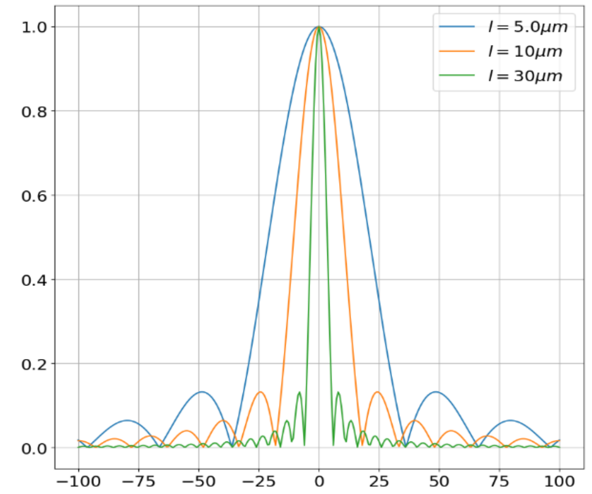
$$J(P_1, P_2) = \int_\sigma I(S) \frac{\exp(ik(R_1 - R_2))}{R_1 R_2} dS.$$

Here R_1 and R_2 are the distances from the point S on the source surface to the observation points P_1 and P_2, $I(S)$ is the surface intensity density of the source.

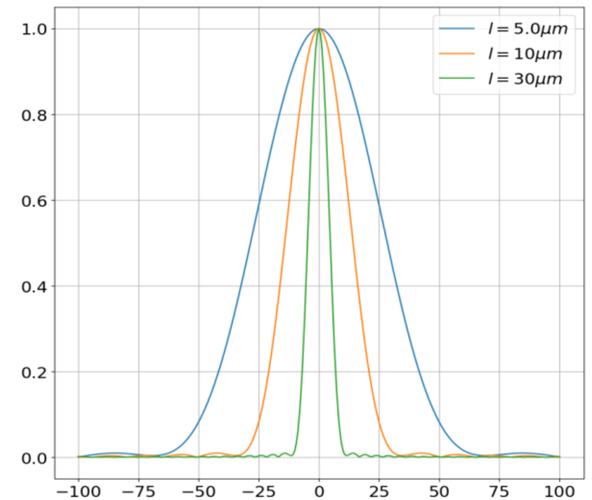
$$I(P_{1,2}) = J(P_{1,2}, P_{1,2}) = \int_\sigma \frac{I(S)}{R_{1,2}^2} dS$$

The complex degree of coherence of radiation:

$$\mu(P_1, P_2) = \frac{1}{\sqrt{I(P_1)}\sqrt{I(P_2)}} \int_\sigma I(S) \frac{\exp(ik(R_1 - R_2))}{R_1 R_2} dS,$$



Coherence degree of homogeneous source

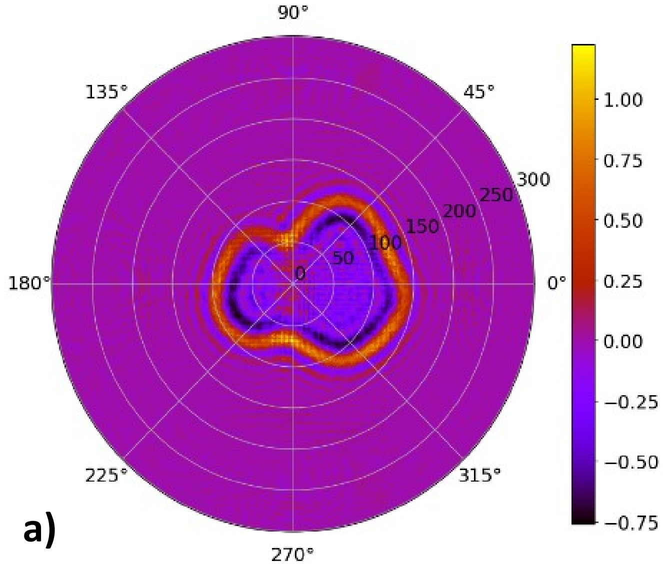


Coherence degree of Gaussian source

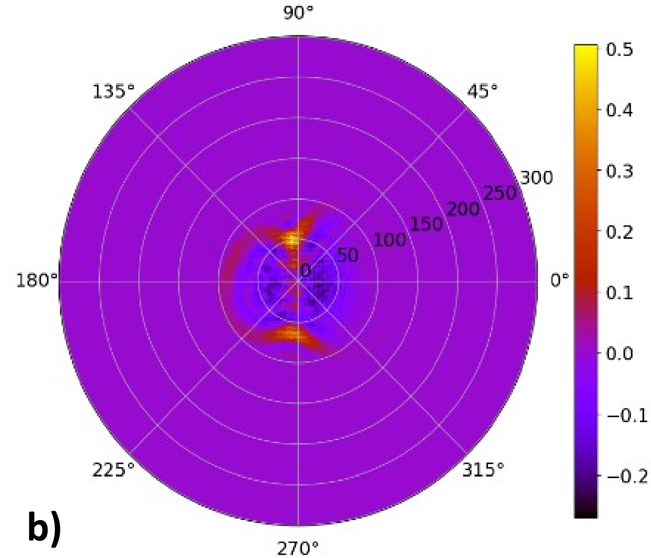
Intensity propagation of partially coherent radiation

$$I(Q) = \iint \sqrt{I(P_1)}\sqrt{I(P_2)}\mu(P_1, P_2) \frac{\exp(ik(R_1 - R_2))}{R_1 R_2} K_1 K_1^* dP_1 dP_2$$

Phase contrast imaging in partially coherent radiation



a)



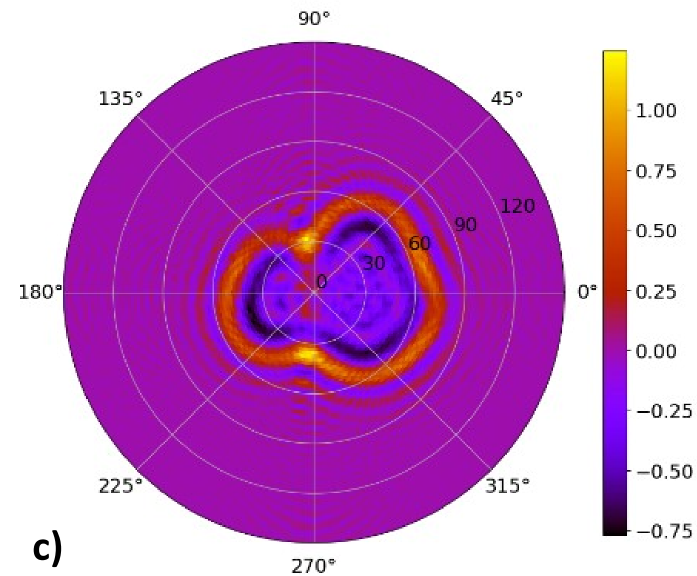
b)

Phase contrast images of the object at a distance $1.5\,m$ from the screen for wavelength $0.15\,nm$:

a) $\mathrm{R} = 1\,\boldsymbol{m}$, $\rho = 0\,\boldsymbol{\mu m}$;

b) $\mathrm{R} = 1\,\boldsymbol{m}$, $\rho = 2.5\,\boldsymbol{\mu m}$;

c) $\mathrm{R} = 5.6\,\boldsymbol{m}$, $\rho = 2.5\,\boldsymbol{\mu m}$.



c)

Summary

- The development of technologies based on X-ray phase-contrast imaging is presented as one of the most promising methods of medical diagnostics.
- X-ray phase contrast imaging should be adapted for use with conventional X-ray sources. Particularly X-ray sources based on compact accelerators and image formation in partially coherent radiation are of interest.
- Solution of the direct problem of forming an X-ray phase contrast image is a way to practical implementing phase contrast on compact radiation sources.

Thank you for attention!