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Recent progress of phase-contrast imaging at Tsinghua Thomson-scattering X-ray source

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ABSTRACT

Due to its small spot size, a Thomson-scattering X-ray source can produce high spatial coherent X-ray pulse, which is the prerequisite for phase-contrast imaging. In this paper, we will introduce the recent progress of phase-contrast imaging at Tsinghua Thomson-scattering X-ray source (TTX). Since the generation of first hard X-ray pulse at TTX in 2012, we have demonstrated the capacity of in-line phase contrast imaging using a refill of gel ink pen. And then, a Monte Carlo simulation tool for in-line phase-contrast imaging based on Thomson-scattering X-ray source has been developed. Taking advantage of this code, we calculate the typical requirement of photon numbers for in-line phase-contrast imaging based on this type of X-ray source. After the upgrade of infrared laser system and control program, the total photon yield of TTX has been increased to $\sim 2 \times 10^7$ photons/pulse at X-ray central energy of 25 keV and 50 keV with RMS jitter less than 6% and 4% respectively. A new run of experiments about in-line phase-contrast imaging and phase-contrast computed tomography (CT) have been carried out at TTX.

1. Introduction

Different from the conventional X-ray imaging that is based on the difference in absorption cross-section among different materials, phase-contrast imaging takes advantage of the difference in phase-shift cross-section for imaging. From the wave point of view, the interaction between X-rays and objects being imaged consists of two processes, i.e. attenuation and phase-shift. In order to describe the two processes, the complex refractive index n of materials would be comprehensive, which can be written as [1]

$$n = 1 - \delta + i\beta \tag{1}$$

where the imaginary part β is related to the linear attenuation coefficient μ with $\mu = \frac{4\pi}{\lambda}\beta$, and λ is the wavelength of X-rays, while the real part δ is related to the phase-shift φ as [2]

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

Here, we assume the X-ray go straight through the material along the z-axis. Usually, the ratio of δ/β is almost 10^2–10^3 for low-Z elements, so the poor contrast problem encountered in soft tissues and organic materials imaging can be resolved by phase-contrast imaging with extremely high sensitivity. When being used in medical soft tissues imaging, phase-contrast imaging can make it possible to remove the contrast media and/or reduce the radiation dose [3,4].

Up to now, there are several kinds of methods that can achieve phase-contrast imaging, such as Fresnel zone plate technique [5], X-ray interferometry method [6], diffraction-enhanced technique [7,8], grating based method [9,10], and propagation-based technique [11,12]. Compared with others techniques, in-line phase contrast imaging, i.e. the propagation-based technique, is the simplest and more easily to implement, because no extra instrument, such as crystal, grating, or Fresnel zone plate, is required. There are only two significant requirements for in-line phase-contrast imaging, i.e. partially coherent X-ray beams and a significant distance between the sample and the detector. The wave-front of a coherent X-ray beam is distorted in proportion to the phase-shift imposed by the sample after passing through the sample, and the propagation of the distorted wave-front between the sample and detector will give rise to Fresnel diffraction fringes in the image. In the point-like source case, typical of micro-focus X-ray source, the final

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intensity recorded by X-ray detector is related to the phase-shift as follows [12–15]

$$I(x,y) = I_0\left(1 - \frac{\lambda R_2}{2\pi M}\nabla^2\varphi\right) \tag{3}$$

where I_0 is the intensity that would have reached the detector plane in the absence of the sample, R_1 is the source-to-sample distance, R_2 is the sample-to-detector distance, $M = (R_1 + R_2)/R_1$ represents the image magnification, ∇^2 is the two-dimensional Laplace operator, and the other parameters are defined as before. According to Eq. (2), the interface between different materials will be distinguished from the background visibly, since the change of phase-shift at the interface is discontinuous and the change of intensity at the interface will be magnified by the Laplace operator of this phase-shift. This effect is often known as edge-enhancement, and has been used widely for merging dynamics [16] and complex multiphase flow phenomena [17].

Almost up to ten years ago, the X-ray sources that could be used for phase-contrast imaging were limited to synchrotron facilities and micro-focus X-ray tubes. However, as the development of state-of-art laser system and high-brightness electron beam generation, Thomson-scattering X-ray sources have drawn much attention among scientists, since they can provide X-ray pulse characterized by quasi-monochromaticity, continuous tunability of X-ray energy, high spatial coherence, ultra-short pulse length, straightforward polarization control, and relatively high brightness [18–24]. Several experiments and theoretical studies about phase-contrast imaging based on Thomson-scattering X-ray source have been carried out at different laboratories around the world [25–38].

In 2012, the first hard X-ray pulse was generated at the Tsinghua Thomson-scattering X-ray source (TTX) [39], and then, a demonstration experiment using a refill of gel ink pen was carried out to verify the capability of in-line phase-contrast imaging, from which clear edge-enhancement effects were observed [32]. In this paper, we will review the recent progress of in-line phase-contrast imaging at TTX, especially the progress after the first demonstration experiment. This paper is organized as follows. In Section 2, we will introduce the simulation tool development and the typical photon number requirement for in-line phase-contrast imaging based on a Thomson-scattering X-ray source. TTX beamline, beam parameters, and the recent photon yield measurement will be introduced in Section 3. Finally, in Section 4 we will introduce the results of recent phase-contrast imaging and phase-contrast CT experiments carried at TTX.

2. Simulation tool development

In order to plan a phase-contrast imaging experiment and to choose the optimal experimental parameters that will produce the best image quality, it is necessary to have reliable software for phase-contrast imaging simulation. Since in-line phase-contrast imaging can be rigorously described by Fresnel diffraction theory, Bruno Golosio et al. developed a simulation code by calculating the Fresnel-Kirchhoff diffraction integrals [31]. Although this method can obtain the exact results, it is proved to be computationally-intensive to solve these integrals, particularly for two-dimensional imaging. And samples of complicated geometry are difficult to handle, since their transmission functions cannot be described analytically. Here, we develop a simulation tool based on a Monte Carlo method to simplify the geometric modeling.

2.1. Theory

As it is well known, the Monte Carlo method treats the X-rays as particles when dealing with the interaction between X-rays and the sample, and the attenuation process is easy to handle. However, in-line phase-contrast imaging requires the phase-shift information that should be calculated using wave optics theory. To solve this contradiction, we divide the imaging process into two individual processes. First, X-rays will undergo refraction when passing through sample regions characterized by different refraction indices, which will cause the phase-shift of X-rays since the refraction angle is related with the phase-shift gradient according to Ref. [7]. Second, interference between the wave-front that has undergone phase-shift and the unperturbed wave-front propagating in the downstream of the sample will occur, which will cause the Fresnel diffraction fringes in the detector. The first process can be achieved using Monte Carlo method by adding a refraction physical process, and taking advantage of the results from the first process, interference can be realized by wave optics theory in the second process. However, when the resolution of imaging system is not too high (e.g. $\geq 20\,\mu m$ for typical values of 30 keV, $R_1 = 192$ cm, and $R_2 = 80$ cm), the second process can be neglected. A. Peterzol et al. show that the Fresnel-Kirchhoff diffraction theory is equivalent to the ray-tracing approach when the following condition is satisfied [40]:

$$\frac{\pi\lambda R_2 M}{[2FWHM(g)]^2} \ll 1 \tag{4}$$

where $FWHM(g)$ characterizes the full-width at half-maximum (FWHM) of function g which represents the overall point spread function (PSF) of the imaging system.

At the Tsinghua Thomson-scattering X-ray source, the limited imaging space ($R \sim 3.0$ m), and the limited resolution of imaging plate ($\sim$25 μm/pixel) make the above condition satisfied, so in-line phase-contrast imaging based on TTX can be simulated by ray-tracing method. Based on the Monte Carlo software Geant4 [41], we add a refraction physical process to the interaction between X-rays and the sample to realize the simulation of in-line phase-contrast imaging based on TTX. To conduct a simulation, all we need to do is to provide the refraction index information of the sample when constructing the class of detector geometry. It must be pointed out that, when the resolution of the imaging system is improved so that Eq. (4) cannot be satisfied, the second process, i.e. the interference process, must be taken into account. Silvia Peterl et al. [42] and Silvia Cipiccia et al. [43] have realized the interference process based on other Monte Carlo software as EGS and FLUKA respectively.

2.2. Description of the Thomson-scattering X-ray source

Although several simulation codes about in-line phase-contrast imaging have been developed using the Fresnel diffraction theory or a ray-optical approach, none of them can describe the characters of a Thomson-scattering X-ray source correctly. In the work of B. Golosio et al. [27], a Thomson-scattering X-ray source is modelled as a superposition of independent point sources and the source distribution is modelled as a Gaussian function. However, point source model, i.e. isotropic distribution, cannot reflect the real situation, because the spatial distribution of scattered X-rays follows the differential Thomson-scattering cross-section in the lab frame, which can be written as [44]

$$\frac{d\sigma}{d\Omega} = \frac{r_e^2}{\gamma^2(1-\beta cos\theta)^2}\left(1 - \frac{sin^2\theta cos^2\phi}{\gamma^2(1-\beta cos\theta)^2}\right) \tag{5}$$

where $r_e = 2.82 \times 10^{-15}$ m is the classical electron radius, $\beta = v/c$ is the speed of electron relative to the speed of light, γ is the relativistic Lorentz factor, θ is the polar angle with respect to the z-axis (the electron moving direction), and ϕ is the azimuthal angle in the $x-y$ plane which is associated with the polarization of laser. Meanwhile,

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