Characterization of an x-ray phase contrast imaging system based on the miniature synchrotron MIRRORCLE-6X

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Purpose: The implementation of in-line x-ray phase contrast imaging (PCI) for soft-tissue patient imaging is hampered by the lack of a bright and spatially coherent x-ray source that fits into the hospital environment. This article provides a quantitative characterization of the phase-contrast enhancement of a PCI system based on the miniature synchrotron technology MIRRORCLE-6X.

Methods: The phase-contrast effect was measured using an edge response of a plexiglass plate as a function of the incident angle of radiation. We have developed a comprehensive x-ray propagation model based on the system’s components, properties, and geometry in order to interpret the measurement data. Monte-Carlo simulations are used to estimate the system’s spectral properties and resolution.

Results: The measured ratio of the detected phase-contrast to the absorption contrast is currently in the range 100% to 200%. Experiments show that with the current implementation of the MIRRORCLE-6X, a target smaller than 30–40 μm does not lead to a larger phase-contrast. The reason for this is that the fraction of x-rays produced by the material (carbon filament and glue) that is used for mounting the target in the electron beam is more than 25% of the total amount of x-rays produced. This increases the apparent source size. The measured phase-contrast is at maximum two times larger than the absorption contrast with the current set-up.

Conclusions: Calculations based on our model of the present imaging system predict that the phase-contrast can be up to an order of magnitude larger than the absorption contrast in case the materials used for mounting the target in the electron beam do not (or hardly) produce x-rays. The methods described in this paper provide vital feedback for guiding future modifications to the design of the x-ray target of MIRRORCLE-type system and configuration of the in-line PCI systems in general. © 2011 American Association of Physicists in Medicine. [DOI: 10.1118/1.3622606]

Key words: x-ray phase contrast imaging, miniature synchrotron, MIRRORCLE, x-ray generation

I. INTRODUCTION

Phase contrast imaging (PCI) has first been introduced in optical microscopy1 and later in transmission electron microscopy (TEM-PCI)3 and x-ray imaging (X-PCI).3,4 Medical application of X-PCI could provide a number of possibilities for label-free soft-tissue imaging, e.g., for contrast-agent-free angiography (cardiovascular), mammography (oncology),5,6 white matter lesions detection (neuroimaging), cartilage analysis (orthopedics), etc7–9 There are a number of different methods to measure X-PCI.10–13 In-line X-PCI is the most simple and straightforward method, as it requires only small modifications to the standard (transmission) imaging geometry. It does, however, require a coherent x-ray field of sufficient brilliance for which a (bench-top) synchrotron is needed. Competing methods are crystal-based X-PCI,4 which is usually limited to the use of synchrotron radiation, gratings-based X-PCI14 and aperture-based X-PCI,15 which can operate with conventional x-ray sources, but require modifications to the imaging geometry.
The requirements with respect to the size and brilliance of the x-ray source that are imposed by in-line X-PCI for medical imaging are incompatible with off-the-shelf x-ray sources. Large-scale synchrotron radiation facilities offer high brilliance but are far too large and far too expensive to comply with hospital infrastructure requirements. Microfocus x-ray tubes, on the other hand, are small but lack sufficient brilliance. The development of bench-top sized high-brilliance x-ray sources is thus of great importance for advancing in-line X-PCI for medical applications. Miniature synchrotron x-ray sources\textsuperscript{16,17} are among the emerging technologies\textsuperscript{18,19} that might provide the right combination of size, brilliance, and x-ray energy that is required for an effective implementation of in-line X-PCI.

We carried out a series of measurements using a prototype miniature synchrotron x-ray source, the MIRRORCLE-6X.\textsuperscript{20} The maximum contrast levels achievable with the current system in the X-PCI regime were compared to the corresponding contrast levels of the absorption image. Here we report on these measurements and on a model of the imaging system that includes the x-ray source characteristics, the imaging geometry, and the detector characteristics. In particular, the design of the electron target in the present types of sources appears to be crucial in obtaining high contrast levels, and several design improvements are deduced from the analysis we present here.

II. MATERIALS AND METHODS

II.A. MIRRORCLE-6X

The imaging system investigated here is based on the compact synchrotron x-ray radiation source called MIRRORCLE-6X. The synchrotron ring of the MIRRORCLE-6X contains an electron beam accelerated to a total energy of 6 MeV. A small metallic target can be suspended on a beryllium or carbon filament inside the electron orbit to produce white spectrum Bremsstrahlung radiation ranging from 0.001 to 6 MeV.\textsuperscript{22} A cone beam of hard x-rays leaves the synchrotron ring through a beryllium exit-window.

For the experiments presented in this paper, the MIRRORCLE-6X was operated with an electron injection current of 75 mA and an injection frequency of 400 Hz. Spherical targets composed of tungsten with a diameter of 10, 20, and 40 \(\mu\text{m}\) were used for x-ray generation. Each target was suspended inside an epoxy droplet attached to a carbon filament of 7.6 \(\mu\text{m}\) in diameter. Analysis of the acquired data, supported by simulations, shows that a significant part of the radiation is generated by the epoxy surrounding the target and the part of the target mounting wire that is exposed to the electron beam (roughly \(~1\ mm\) in diameter). This, so-called compound source model, has a profound influence on the effective source size and its spectral characteristics and will be investigated in Sec. III C.

The absorbed radiation dose was measured at 1 m distance away from the source during each acquisition. Typical values for the measured dose are in the range of 2 to 3.5 mGy/min. Using the conversion factor proposed by Yamada,\textsuperscript{21} we can estimate that the brightness of the MIRRORCLE-6X was on the order \(10^{10} - 10^{11}\) photons/(s-mrad\(^2\)-0.1% band). It has to be noted, however, that the conversion between the measured dose in mGy/min and the brightness is uncertain and relies heavily on the accuracy with which the spectral characteristics of the system are known.

II.B. X-ray detector

A BaF\(_{2}\) : Eu\(^{2+}\) photo-stimulable phosphor imaging plate (IP) was used as x-ray detector in combination with a FCR XL-1 image plate reader (Fujifilm, Tokyo, Japan). It was shown\textsuperscript{23} that the properties of the imaging plate are highly uniform over its surface and that the response is linear relative to the radiation dose up to \(4 \times 10^6\) photons/100 \(\mu\text{m}^2\) providing a wide dynamic range.

The full width at half maximum (FWHM) of the detector’s point-spread-function (PSF) is in the range of 170 \(\sim\) 200 \(\mu\text{m}\).\textsuperscript{23,24} The quantum efficiency (QE) of the IP is given to be almost 100% for energies below 20 keV and drops to about 50% or less for energies above 35 keV.\textsuperscript{25,26}

As the properties of IPs may vary between the different models, the PSF and its spectral characteristics were estimated by us independently. The PSF of the IP used in our experiment was estimated from the acquired reference beam-images using the “noise method.”\textsuperscript{27,28} The PSF was found to be approximately Gaussian shaped with a FWHM of 260 \(\mu\text{m}\). The images were sampled by the reader with a pixel pitch of 150 \(\mu\text{m}\). Further discussion of the detector’s spectral characteristics is given in Sec. III B.

II.C. Geometry of the setup

For in-line X-PCI, the standard transmission imaging geometry with a divergent beam is used (Fig. 1). The specimen is mounted between the x-ray source and the detector with source-object distance \(R_1\) and object-detector distance \(R_2\), providing a magnification \(M = (R_1 + R_2)/R_1\).

The phase-contrast image of the specimen has an interferometric nature and is observed as an intensity fringe located around the inhomogeneities in the projected refractive index of the object. Given certain propagation distances \(R_1\) and \(R_2\), the magnitude of the recorded phase-contrast image depends on the wavelength of the x-ray radiation and the contrast transfer function (CTF) of the imaging system.

![Fig. 1. Top-view of the imaging setup. The sample is positioned between the x-ray source (S) and the detector (D) allowing for magnified imaging. Object-source distance is \(R_1\), and object-detector distance is \(R_2\). The sample is mounted on a rotation stage in order to record phase-contrast images of the rotated edge at an angle \(\Theta\).](image-url)
Therefore, the major instrumental factors that define the contrast of the X-PCI system of a given total length are its spectral characteristics and the spatial resolution as dictated by the source size, the detector PSF, and magnification.

The experiments were carried out in the high magnification regime with $M$ in the range from 12 to 14.5 in order to reach the highest possible resolution in the object plane considering the limited resolution $PSF_{det}$ of the BaFBr:Eu$^{2+}$ detector. In such a regime, the effective resolution of the imaging system is primarily limited by the source $PSF_{src}$.

II.D. Measurements

A thin plexiglass plate blocking part of the x-ray beam is often used as a standard specimen in the investigations of the performance of X-PCI systems. The observed image in this case is a transmission image of the plate combined with the intensity fringe of the phase-contrast image that stretches along the plexiglass-air transition (Fig. 2). The image of such a specimen can be easily modeled, simplifying the analysis of the system performance.

The magnitude of the phase-contrast image fringe of the plexiglass plate is highly sensitive to the orientation of its edge with respect to the direction of the beam, as the projection of the edge feature changes. In our experiment, the plexiglass plate (thickness 1.95 mm) is mounted on a rotation stage. Series of images can be easily recorded for a range of angles of incidence for every system setting (Fig. 1).

II.E. Image processing and analysis

Since the plexiglass plate is homogeneous, it can be presented as a one-dimensional object simplifying the analysis. Several steps have to be taken before the raw measurements can be compared to the results of the model. First, a simple flat-field correction is carried out by dividing each acquired image by a reference beam image. Next, using the Radon transform, the image is integrated in the direction of the edge, resulting in a one-dimensional edge profile [Fig. 2(b)]. The orientation of the edge can be found as the angle for which the Radon transform of the image yields the highest maximum derivative.

The ratio between the phase contrast and transmission contrast of the edge [Fig. 2(b)] can be estimated for each image by measuring the fraction of the amplitude of the phase fringe $B-A$ to the intensity drop due to absorption of the plexiglass plate $A$. The ratio $(B-A)/A$ was used as an estimate of the sensitivity of the phase imaging system and is referred to in the text as the phase-contrast enhancement (PCE).

II.F. Calibration of the angle of incidence

The phase and transmission image of the plexiglass plate both depend on the angle with which the radiation is incident on it. This results in a high sensitivity of the phase-contrast enhancement to the angle of incidence. For that reason, each experiment consists of a series of images taken for a range of object orientations of approximately ±3 deg around zero rotation angle (Fig. 1). A variable angular step size in the range from 0.1 to 1 deg was used to provide denser sampling around 0 deg orientation. Considering the fact that the projected phase map of a thin plate must be symmetrical relative to the rotation angle 0 deg, the correction for a small misalignment in the object orientation could be done after the data acquisition.

III. MODEL

The MIRRORCLE-6X is a highly polychromatic x-ray source (spectrum 0.001–6 MeV), which requires an accurate account for polychromaticity during the analysis of the imaging process. The corresponding numerical model, outlined below, represents the three main stages of the image formation, namely: interaction of the polychromatic x-ray field with the object, propagation of the electromagnetic field to the x-ray detector, and the model of the detection process based on the estimated spatial resolution and the spectral characteristics of the x-ray detector and the x-ray source.

III.A. Object interaction and field propagation

The interaction of the x-ray field with the specimen is straightforward in the current experiment. The plexiglass plate satisfies the condition of the thin-body approximation;
where $\mu(x)$ is a linear attenuation map of the specimen and $\phi(x)$ is a phase map. The linear attenuation $\mu(x)$ is calculated using the mass attenuation coefficients from the NIST database and the known projected mass of the specimen. For the x-ray energies above the absorption edges of the material, and

$$\phi(x) = -i\alpha e N_x d(x),$$  

(2)

where $\alpha$ is the wavelength of the electromagnetic field, $e$ the classical electron density, $N_x$ is the electron density of the material, and $d(x)$ the projected thickness map.

The propagation of each monochromatic component of the electromagnetic field from the object plane to the detector plane is described by Fresnel diffraction. A computationally efficient Fourier formulation of Fresnel diffraction can be written as

$$\psi_x(x, R_z) = \frac{1}{M} \text{IFT} \left[ \exp \left( \frac{i\alpha R_z |u|^2}{4\pi M} \right) \text{FT}[T(x)] \right],$$  

(3)

where FT and IFT represent, respectively, the forward and inverse Fourier transforms and $u$ denotes the spatial frequency. In this equation, the geometric magnification $M$ of the system is accounted for. The constant phase prefactor is dropped for the sake of readability as it is irrelevant for the calculation of the intensity image.

The total intensity of the field at the detector plane $I_d(x)$ will be calculated as a superposition of all propagated monochromatic components

$$I_d(x) = \int |\psi_x(x, R_z)|^2 S(E) \, dE,$$

(4)

where $S(E)$ is the effective intensity spectrum of the imaging system.

Due to the finite size of the incoherent x-ray source, the detected image is formed as a superposition of intensity fields $I_d(x)$ produced by each point of the x-ray source independently. Considering that the source size is negligible relatively to the propagation length of the field, the result of the superposition is described as a convolution of the point-source intensity field $I_d(x)$ with a point-spread-function $\text{PSF}_d(x)$ representing the source size and shape

$$I(x) = \text{PSF}_d \left( \frac{x}{M} - 1 \right) * \text{PSF}_d(x) * I_d(x),$$  

(5)

where $I(x)$ is the image recorded at the detector plane, $\text{PSF}_d(x)$ is a point-spread-function of the x-ray detector. The factor $M^{-1}$ is introduced to account for magnification of the projected source size at the detector plane.

Expression (5) completes the model described above, which allows us to simulate the in-line X-PCI image of a known “2-D specimen.” The characteristics of the imaging system are included in the model as the effective spectrum $S(E)$, the imaging geometry as expressed by $R_1$ and $R_2$, and the source and detector point-spread-functions $\text{PSF}_s(x)$, $\text{PSF}_d(x)$. Accurate estimation of these functions is absolutely crucial for the modeling process and will be described in Secs. III B and III C.

### III.B. System spectral characteristics. Detector efficiency

The first step in modeling the imaging process is to estimate the effective spectrum of the system. The effective spectrum $S(E)$ is a product of the emission spectrum of the MIRRORCLE-6X $S(E)$, the energy dependent transmission of the imaging system $T_s(E)$, and the energy absorption efficiency $EAE(E)$ of the detector

$$S(E) = S_s(E) T_s(E) EAE(E).$$  

(6)

The emission spectrum $S_s(E)$ of the MIRRORCLE-6X was calculated using Monte-Carlo simulations based on the GEANT4 toolbox (Fig. 3). The energy dependent transmission of the system $T_s(E)$ is defined as the fraction of x-rays of a certain energy emitted by the source which reach the detector plane in the absence of an object. In the calculation of the system transmission $T_s(E)$, the absorption of

![Fig. 3. Spectra of tungsten spheres of 10, 20, and 40 μm in diameter were computed using GEANT4 package. A monochromatic, spatially uniform electron beam with a total energy of 6 MeV was assumed in the calculation. Estimation of the effective spectrum was done considering computed efficiency of the BaFBr:Eu detector and the transmission through 5 m of air.](image-url)
x-rays by the beryllium exit window of the MIRRORCLE and the air between the exit window and the detector is accounted for.

The energy absorption efficiency \( EAE(E) \) of the detector is defined as a fraction of x-ray intensity of a certain energy which is converted to a detector signal. It is given by

\[
EAE(E) = \left( \frac{\mu_{en}(E)}{\mu(E)} \right) \left( 1 - e^{-\mu(E)d} \right),
\]

(7)

where \( 1 - e^{-\mu(E)d} \) is the quantum detection efficiency (QDE), i.e., the fraction of x-ray photons which interact with the scintillator, \( d \) the thickness of the scintillation layer of the detector, and \( \mu(E) \) the linear attenuation coefficient of BaFBr. The energy-absorption coefficient divided by the linear attenuation coefficient \( \frac{\mu_{en}(E)}{\mu(E)} \) is the average fraction of energy transferred in each interaction with the scintillation layer. Both coefficients \( \mu_{en}(E) \) and \( \mu(E) \) are well documented.\(^{38}\) The effective spectrum of the 5 m long imaging system with the 40 \( \mu \)m tungsten target and the BaFBr:Eu detector is depicted in Fig. 3(b).

Calculation shows that the total intensity of the target is not linearly dependent on the volume. The photon fluxes of the 40 and 20 \( \mu \)m tungsten spheres were found to be, respectively, 26.2 and 4.5 times higher than that of the 10 \( \mu \)m target. This can be explained by self-absorption in the target. The same phenomenon contributes to beam hardening, taking place in the 20–40 keV regime, when the bigger target is used [Fig. 3(a)]. Such hardening of the emitted radiation lowers the sensitivity of the PCI system because the magnitude of the observed phase effect is proportional to \( \lambda^2 \) as can be seen from (3) and (4). On the other hand, high energy radiation might be more suitable because of the higher transmission through a particular object of interest.

It is apparent, therefore, that target size is an important characteristic of the x-ray source, which influences the sensitivity of the system to the phase effect, defines the source point-spread-function \( PSF_{src} \), and determines the total brightness of the system.\(^{39}\) The configuration of the target can be optimized using Monte-Carlo simulations considering the characteristics of the complete imaging system in each particular case.

**III.C. Compound target model: spectrum**

The results of the Monte-Carlo simulations for the spectrum of the x-ray source, based on tungsten spherical targets [Fig. 3(a)], correspond well with the measurements of the MIRRORCLE-6X brightness.\(^{20}\) However, we have found that the so-called compound target model of the x-ray source leads to a consistent interpretation of the phase-contrast data that were obtained in our experiments.

It is known that in the MIRRORCLE-6X the tungsten target is suspended in a small droplet of epoxy attached to a thin carbon filament of 7.6 \( \mu \)m in diameter. The whole construction is exposed to an electron beam of approximately \( \sim 1 \) mm in diameter (Fig. 4).

It was assumed that the interaction between the spherical tungsten target, the epoxy droplet, and the carbon filament is negligible during the x-ray production. Spectra of the compound target model were calculated as a superposition of independently simulated spectra of the source components. Calculations were made considering spherical tungsten targets of 10, 20, and 40 \( \mu \)m, a 70 \( \mu \)m sphere of epoxy, and a carbon cylinder of 7.6 \( \mu \)m in diameter exposed to an electron beam with Gaussian profile and a FWHM of 1 mm.

Monte-Carlo simulations show that the epoxy droplet and the carbon filament contribute a comparable or even larger fraction to the emission spectrum as the smallest tungsten target [Figs. 5(a), 5(d), 5(g)]. The fraction of the effective spectrum that is produced by the tungsten sphere is 33% for a 10 \( \mu \)m target, 62% and 89% for, respectively, a 20 \( \mu \)m and a 40 \( \mu \)m target. This indicates that there is a profound influence on the phase enhancement of the imaging system depending on the tungsten target size.

**III.D. Compound target model: source point-spread-function**

The point-spread-function of the compound target model \( PSF_{src} \) is determined as a sum of the relatively isotropic cross section of the tungsten target embedded in the epoxy droplet and the highly anisotropic profile of the carbon filament exposed to the electron beam. In each experiment, the edge and the filament are both vertically oriented with a small unknown misalignment angle \( \gamma \) between them (Fig. 4). The tungsten target is attached to the side of the filament and may also rotate around it due to the torsion of the filament. These factors are defining the projection of the x-ray source onto the image plane (and therefore the \( PSF_{src} \) in each measurement. The design of the target forces us to introduce several fitting parameters into the compound target model to find a consistent interpretation of the measured data. To reduce the number of fitting parameters, it was decided to neglect the fraction of the \( PSF \) resulting from the epoxy droplet. Effectively, we attributed its contribution to the emitted x-ray field to the small spherical target embedded in it. The first parameter is a fraction \( f \) of the x-rays that are not...
produced in the tungsten target but in the carbon filament. As a result, the image observed with the detector is the weighted sum of the image produced by the radiation from the target \( I_t \) and the filament \( I_w \).

\[
I = (1 - f) \ I_t + (f) \ I_w.
\]

Images \( I_t \) and \( I_w \) will be distinct due to two principal phenomena. First, the carbon filament and the target are emitting different x-ray spectra (Fig. 5); therefore, the phase effects in images \( I_t \) and \( I_w \) are not exactly the same. Second, the point-spread-functions of the target \( PSF_{src,t} \) and the filament \( PSF_{src,w} \) are different due to the shape of the targets. If we assume that the x-ray production is homogeneous over the volume of the target and neglect absorption of x-rays inside the target, the shape of its \( PSF_{src,t} \) is equivalent to the projection of its volume. Because the image of the homogeneous

Fig. 5. Normalized spectral characteristics (dose per solid angle unit) of the compound target components with 10 \( \mu \)m (top), 20 \( \mu \)m (middle), and 40 \( \mu \)m (bottom) tungsten sphere.
plexiglass plate can be considered as a one-dimensional edge profile, the point-spread-function is projected onto a line perpendicular to the direction of the edge. We approximate the one-dimensional target \( PSF_{src,t} \) as a normalized projection of a sphere with radius \( R_t \).

\[
PSF_{src,t}(x) = \begin{cases} 
\frac{3}{4} \left( R_t^2 - x^2 \right) & x < R_t \\
0 & x \geq R_t
\end{cases}
\]  

(8)

The projected \( PSF \) of a cylindrical filament with radius \( R_f \) is likewise

\[
PSF_{cylinder}(x) = \begin{cases} 
\frac{2}{\pi} \sqrt{R_f^2 - x^2} & x < R_f \\
0 & x \geq R_f
\end{cases}
\]  

(9)

Generally, there is a small angle \( \gamma \) between the direction of the filament and the edge of the plexiglass plate (Fig. 4). This extends the \( PSF_{src,w} \) by the projection of the profile of the electron beam along the filament onto a line perpendicular to the edge. If we assume that the electron beam has a Gaussian-shaped intensity distribution along the filament with a FWHM of \( h \), the projection of the beam \( PSF_{beam} \) is also Gaussian-shaped with a FWHM of \( h \sin \gamma \). Therefore, the full \( PSF_{src,w} \) of the filament is

\[
PSF_{src,w}(x) = PSF_{cylinder}(x) \ast PSF_{beam}(x, h \sin \gamma).
\]  

(10)

The mounting of the target on the side of the filament (Fig. 4) causes a potential misalignment of the centers of the filament and the sphere. This causes an arbitrary spatial shift \( \Delta x \) between the intensity images \( I_t \) and \( I_w \).

The observed phase-contrast edge profile \( I(x) \), taking all described effects into account, is given by

\[
I(x) = (1-f) \frac{x}{M-1} \ast PSF_{src,t}(x) + f \frac{x}{M-1} h \sin \gamma \ast PSF_{det}(x) * I_w(x).
\]  

(11)

IV. RESULTS

In the current paper, we present the phase-contrast enhancement in four series of 43 measurements of a 1.95 mm thick plexiglass plate.

![Image](image_url)  

(a) \#137: \( \Theta = 0.20^\circ, f = 0.78, \Delta x = -16 \mu m, h \sin \gamma = 73 \mu m \)

(b) \#156: \( \Theta = -0.90^\circ, f = 0.75, \Delta x = -6 \mu m, h \sin \gamma = 59 \mu m \)

(c) \#159: \( \Theta = -0.20^\circ, f = 0.81, \Delta x = -24 \mu m, h \sin \gamma = 87 \mu m \)  

Fig. 6. On the left: three profiles (crosses) measured at different angles of incidence \( \Theta \) with magnification \( M = 14.3 \), system length \( R_1 + R_2 = 5.41 m \), a 10 \( \mu m \) tungsten spherical target. Note the extra wiggle depicted with a small arrow in (a) and (c). The dashed lines are the modeled results for an ideal spherical target \( f = 0 \), and the solid lines are the results for the compound target model with the indicated parameters. Right: the total \( PSF \) of the imaging system (source and detector contributions) estimated with a Wiener filter (crosses). The dashed lines show the \( PSF_{src} \) of the spherical target alone and the solid lines represent the simulated total \( PSF \) of the imaging system using the fitted parameters for the compound target model [Eq. (10)].
As described in Sec. II C, each series of images is taken for a range of edge orientations (\(\pm 3\) deg) relative to the direction of the x-ray beam. Examples of the acquired profiles are depicted in the Figs. 6(a)–6(c). The figures show a large discrepancy between the measured edge profiles and the results of simulations based on a simple spherical target model.

Introduction of the compound target model, described in Sec. III C, allows for a very accurate simulation of the measured data, but it requires fitting of the parameters \(f\), \(h \cdot \sin(\gamma)\), and \(\Delta x\) that represent the misalignment between the orientation of the plexiglass edge and the components of the x-ray source.

The source point-spread-function \(PSF_{src}\) was estimated using Wiener deconvolution of the acquired images with the profile resulting from the model based on the fitted parameters. It is shown in Figs. 6(a)–6(c) that the estimated \(PSF_{src}\) corresponds to the \(PSF_{src}\) of a compound target model.

IV.A. Stability of fitting

Results of fitting the compound model parameters to the data acquired in three experimental data collection sets are presented in Figs. 7(a)–7(c). The sets consist in total of 31 measurements taken in the orientations range \(\pm 3\) deg, with magnification \(M = 14.3\), system length \(R_1 + R_2 = 5.41\) m, using a 10 \(\mu\)m tungsten target. A typical integration time was 600 s per image.

A considerable variation of the parameters throughout the series is apparent; however, linear trends in their variation can be found when the experimental data are divided into the three sessions in which the images were acquired (#131–141, 143–157, and 158–162) [Figs. 7(a)–7(c)]. This may be explained by the two resets of the setup that took place exactly after measurements #141 and #157 were taken. A linear change in the parameters, which are describing the compound target, may be explained by a drift of the suspended target during the measurement.

Such drift will of course not be relevant if the target \(PSF_{src}\) is isotropic, which can potentially be achieved by reduction of the carbon filament fraction that is exposed to the electron beam in the MIRRORCLE-6X or by increasing the volume of the spherical part of the target.

Figure 7(d) demonstrates that a reasonable match between the experimental values of the phase-contrast enhancement and the modeled values can be achieved using only the average values of the fitted parameters. The compound target model shows that the phase-contrast enhancement \(PCE\) of the current system is decreased in the performed experiment by a factor of 2 to 5 compared to the system with the same geometry but using an ideal 10 \(\mu\)m spherical tungsten target.

Another illustration of the results obtained with the compound target model is given in Fig. 8. The experimental series are acquired with magnification \(M = 12.8\), system length \(R_1 + R_2 = 5.31\) m, and a 10, 20, and 40 \(\mu\)m tungsten target. The compound target model uses values for \(f\) obtained in Monte-Carlo simulations of the x-ray emission by the target components Sec. III C, and the other two parameters \((\Delta x, h \cdot \sin(\gamma))\) are found by least-squares fitting.

![Graphs showing results of fitting the parameters of the compound target model to three sets of measurements.](image)

Fig. 7. (a)–(c) The result from fitting the parameters of the compound target model to three sets of measurements. The solid lines indicate trends in the data over time per measurement series. (d) The measured (crosses and circles) and modeled (lines) phase-contrast enhancement as a function of angle of incidence. The crosses indicate measurements done at negative angles of incidence. The solid line is the result for \(f = 0\) and the dashed lines are the results for two typical sets of values from (a), (b), and (c). Measurements done with \(M = 14.3\), \(R_1 + R_2 = 5.41\) m, and a 10 \(\mu\)m tungsten spherical target.
The predicted PCE based on an ideal spherical target is too large for the small targets by approximately a factor of 2 compared to the experimental data (Fig. 8). The results of the compound target model, on the other hand, are very close to the experimental data. They do not only reproduce a generally lower PCE in all three experiments but also indicate that the PCE may be higher with a larger target depending on the angle of incidence.

Namely, the 40 μm tungsten target dominates the other emitting components of the MIRRORCLE-6X (providing 89% of radiation according to the Monte-Carlo simulations). That is why it can produce a better performance compared to the smaller targets due to an effectively sharper point-spread-function. This also explains why the experiment that involves the bigger target is less influenced by the anisotropy of the MIRRORCLE-6X source (Fig. 8).

IV.B. Phase-contrast enhancement of MIRRORCLE-6X

The increase of contrast at a sharp plexiglass edge due to the phase-contrast effect of the MIRRORCLE-6X was observed to be between 100% and 200% in the current implementation. However, an accurate measurement of the phase-contrast enhancement was found to be particularly unstable. The instability can be attributed to the anisotropy in the resolution of the system caused by the radiation emitted from the various components comprising the x-ray source.

According to calculations, if no (or almost no) radiation is produced by the components other than the target, the current system based on the MIRRORCLE-6X will yield a PCE of 400% to 500% [Fig. 7(d)]. That could be potentially achieved using constructions made of carbon nanomaterials. Effective reduction of the x-ray source size below 30–40 μm can in principle be achieved without any modifications in the MIRRORCLE-6X design. A system of double bend Laue monochromators would be required for patient imaging to select the appropriate x-ray spectrum and to limit the source size. A choice of x-ray detector with a higher resolution (≤50 μm) will permit using a geometry with lower magnification which yields even higher levels of PCE.

Using the conversion factor by Yamada to estimate the brightness from the measured radiation dose shows that the MIRRORCLE-6X should be capable of yielding the brightness on the order of $10^{10}$–$10^{11}$ photons/(s·mrad$^2$·0.1%·band), which means that monochromatized beams with fluxes ranging from $10^8$ photons/(s·mrad$^2$) to $10^{11}$ photons/(s·mrad$^2$) should be possible, depending on the bandwidth of the monochromator.

Other X-PCI techniques than in-line X-PCI can be potentially designed with the MIRRORCLE-type sources. For instance, gratings-based X-PCI or aperture-based X-PCI implementations seem to be promising since they can tolerate a significantly larger source size. A transition to a digital detector and addition of the monochromator is of course inevitable for these techniques.

V. CONCLUSIONS

The performance of an X-PCI prototype based on the MIRRORCLE-6X x-ray source was characterized using the edge response of the system. The phase-contrast enhancement factor was measured in a series of experiments as the ratio between the phase and absorption contrast produced by the plexiglass plate. It was found to be particularly sensitive to the edge orientation due to the anisotropy of the x-ray source point-spread-function. The observed PCE values were found to be between 100% and 200% in different configurations of the system.

The role of the x-ray source target size was investigated using Monte-Carlo simulations using the Geant4 software package. Calculations show that the target size has a considerable influence on the low-energy part of the emission spectrum (10–40 keV of a total 0.001–6 MeV). Even more important, the components used for mounting of the spherical target in the present design may emit up to 70% of the total radiation in case of a 10 μm spherical tungsten target, down to 10% for the 40 μm targets.

As a result, the same or higher performance in terms of PCE values was observed in experiments when a 40 μm target was used instead of 10 or 20 μm targets. The emission produced by the components of the mounting cannot be fully avoided in the current implementation of the system due to the limited focusing of the electron beam in the synchrotron ring. This factor determined a minimal diameter of the tungsten target that could be effectively used in the MIRRORCLE-6X to 30–40 μm.

Calculations demonstrate that after achieving a significant reduction of the radiation emitted by the target...
mounting, the PCE levels of the MIRRORCLE-6X can be improved by a factor of 2 to 5 by allowing to use smaller targets.

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