High power soft x-ray source based on a discharge plasma

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Abstract. We report on a gas discharge plasma as a light source for laboratory based soft x-ray microscopy in the water-window spectral range. At 2.88 nm wavelength the source produces a radiant intensity of up to $4 \times 10^{13}$ photons/(sr pulse) narrowband line emission. Employing a matched grazing incidence collector, a photon flux at the specimen of $\sim 10^7$ photons/(\textmu m$^2$/s) can be obtained at 1000 Hz repetition rate. This allows for imaging of thick hydrated biological samples at an exposure time below 10 s. Images are presented using this source in a first laboratory scale microscope. Image quality and exposure times are promising in view of commercializing laboratory transmission x-ray microscopy.

1. Introduction

Full-field transmission x-ray microscopy is a striking method for investigating thick hydrated biological samples. To achieve an adequate signal-to-noise ratio, a radiation dose of $10^8$ photons/\textmu m$^2$ at the sample is required [1]. Tomographic imaging enables to fully tap the potential of x-ray microscopy. In order to acquire the desired amount of images within an appropriate period of time, exposure time for a single image has to amount below ten seconds. This demands a photon flux of at least $\sim 10^7$ photons/(\textmu m$^2$/s) at the sample. To realize a commercial synchrotron-independent microscope, compact sources capable to deliver that flux are needed. In this paper a gas discharge plasma is presented as an alternative light source for laboratory microscopy in the water-window spectral range.

2. Pinch plasma as a compact source for x-ray microscopic imaging

Here the hollow cathode triggered pinch plasma is under investigation, which has also been discussed as a source for EUV-lithography [2]. At present this concept is advanced to efficiently emit 2.88 nm line radiation at high average power. The gas is heated in a pulsed high current discharge of 12 to 20 J electric energy. Part of this energy is reemitted by the $1s^2\text{-}1s2p$ transition of helium-like ions in the nitrogen plasma. The source produces a radiant intensity of $2\times10^{13}$ photons/(sr pulse line) at 12 J and $4\times10^{13}$ photons/(sr pulse line) at 20 J. Radiant intensity was measured using transmission grating spectrometers calibrated at synchrotron facilities. The lateral diameter of the plasma column is 1175 \textmu m. Spectral bandwidth of the emission line is estimated to be less than $\Delta\lambda/\lambda=1/550$ [3], which is sufficient for high resolution zone plate imaging. Efficient operation of the source at a repetition rate of 1000 Hz is demonstrated [3] leading to a power input of 12 kW to 20 kW.
3. Setup
The source-collector-module consists of the source peripherals, the electrode system where the radiation is generated, a polycapillary as presented in [4] providing vacuum separation between source and collector chamber, an ellipsoidal grazing incidence collector with central stop and a 200 nm titanium filter virtually limiting the spectrum to the 2.88 nm emission line. Distance between source and collector focus is 600 mm.

The polycapillary consists of divergent 50 µm capillaries with a length of about 20 mm covering a solid angle of $15 \cdot 10^{-3}$ sr from the source. The transmission for the 2.88 nm line amounts 0.33. A transmission of 0.7 as theoretical limit is aimed for. Conductance of the structure can be estimated to be ~0.01 l/s. In figure 1 vacuum level ratio between source and collector chamber calculated for differential pumping at 300 l/s and a microscopic image of the capillaries are shown. At the source side of the polycapillary pressure amounts about $10^{-2}$ mbar, which allows to obtain a vacuum level of $10^{-6}$ mbar in the collector chamber for this pumping speed. The titanium filter is placed between collector and intermediate focus and can also be used to separate the vacuums of collector chamber and microscope.

At present a non matched gold coated grazing incidence collector, designed for different tasks is employed. Collection solid angle amounts 1.56$\cdot 10^{-3}$ sr and theoretical magnification is 0.67.

4. Results
Without polycapillary and spectral filter a central photon flux of $5.1 \cdot 10^3$ photons/($\mu$m$^2$ pulse) collectible in-band radiation is detected. In figure 2 an image of the intermediate focus and a profile plot across the focus are shown. The image is acquired using a Ce:YAG converter crystal at the focal plane and a CCD-camera. The focus is large in comparison to the focus in an LPP microscope due to the relatively large source volume. Only the very center of the spot is used for sample illumination. A good level of illumination homogeneity is achieved.

In figure 3 microscopic images of dried rat embryonic fibroblast cells are shown. The images are taken using the presented source-collector-module and a microscope with zone plate optic and back thinned CCD camera, described in [5]. A resolution below 40 nm is achieved with the setup [5], which corresponds to the diffraction limit of the zone plate having an outer zone width of 30 nm.

Both images are exposed at 12 Joule pulse energy with polycapillary and titanium filter installed. The left image is exposed 15 seconds at repetition rate of 600 Hz in order to demonstrate exposure times for biological samples attainable with the non-matched collector. The right image is taken at low repetition rate. It is rich in contrast and resolves small features.
5. **Outlook**
Ray tracing simulations of source and collector are carried out in order to estimate possible photon flux at the specimen. The collector is modelled as a nickel coated grazing incidence ellipsoidal mirror with a collection solid angle of $1.48 \times 10^{-3}$ sr and a magnification of 0.37. The apertures of collector and zone plate are matched. The simulation shows that applying this collector, at a repetition rate of 1000 Hz a flux of $2 \times 10^7$ photons/$\mu$m$^2$ s collectible in-band radiation can be achieved. A factor 0.5 for the transmission of polycapillary and spectral filter is taken into account. Future activities aim for applying this matched collector and for improving the brilliance of the source in order to finally achieve a photon flux of $\sim 10^8$ photons/$\mu$m$^2$ s at the sample.

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