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On X-ray channeling in a vibrating capillary

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ABSTRACT

A novel study on a different use of polycapillary optics is presented. The scope of this study is to achieve an efficient radiation collimation due to handled beam profiling that avoids the typical one based on total external reflection into the capillary channel. For this purpose a vibration is applied to a monocapillary in order to emulate a "virtual roughness" on the channel internal wall surface. The transmission properties of such a system for different vibrational states are discussed.

1. Introduction

Polycapillary optics is a well known device for X-ray microscopy and analysis. Consisting of hundreds of thousands of thin glass capillaries (inner diameter in the micron scale), this optics enables transmitting and shaping an X-ray beam within a large energy bandwidth, from 5 keV to 60 keV (for presently available technology).

The phenomenon behind its operating principle is the total external reflection (TER) of X-ray radiation. The beam is typically collected within a large acceptance angle at one end of the lens. Then, only the incoming fraction with the incident angle (to be defined for each capillary of complex polycapillary optics geometry) respect a capillary inner wall smaller than the critical value θ_c, which depends on both the lens reflective material and the photon energy [1–3], is transmitted by multiple reflections without essential absorption.

A number of studies on the use of single straight monocapillaries has been carried out [4], but until now they have been applied to synchrotron radiation sources to enhance the flux beam, because of their very low acceptance. In the case of conventional X-ray tubes, they have been used to shape and study the beam profile, always in a static mode and collimating the radiation by TER. A new application frontier for imaging purposes could be represented by the introduction of a dynamic optical system that would change the TER effects allowing the beam shaping to be controlling.

During the development of polycapillary optics both technology and applied tools an important role has been played by the mathematical modeling and simulation of the radiation propagation behavior inside the channels [5]. The channeling phenomenon through polycapillary optics depends on many variables and, therefore, every model focuses only on some of these parameters [6,7].

One of the first aspects to be examined for advanced polycapillary optics is till known as the effect of the surface roughness for the channels internal walls [8–10]. During past years many works have been produced by simulating and observing the influence of the radiation energy and the roughness on the interaction between the beam and the surface wrinkles [7].

Starting from these studies the roughness has been considered a suitable feature to the collimation effects. However, the difficulties in controlling the capillaries internal profile during the manufacturing process prevent a systematic study on the roughness-channeling efficiency correlation.

In the presented study a monocapillary is put in a vibrating state in order to emulate a virtual roughness. This is possible because at the beam propagation velocity the deformation due to the vibration appears stationary to the radiation. The first results on X-ray radiation transmission through a vibrating monocapillary are reported. The effects of the vibration on the transmitted beam

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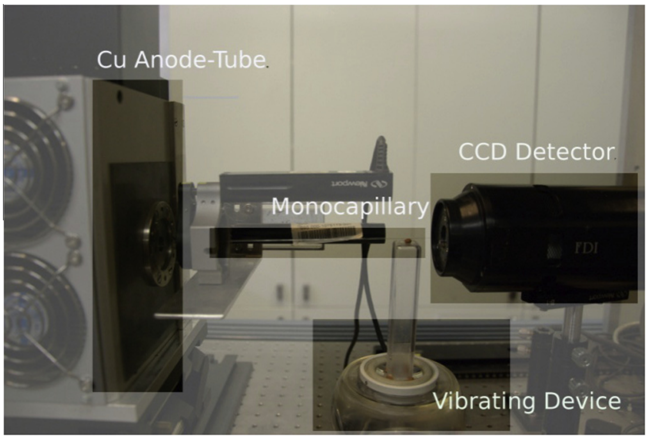

Fig. 1. Experimental layout. From left to right: x-ray source, monocapillary above the vibrating system, and CCD detector. The monocapillary, fixed in the left extremity and free on the right, can be simulated with a simple "fixed beam" model.

are observed at different frequencies and amplitudes by means of a CCD detector, and related radiation distributions behind the optics are compared. Then, a mathematical simulation of an approximated version of the system has been done in order to understand the experimental results. The vibration was applied to the source instead than the capillary to simplify the modeling process.

2. Experimental layout

The experimental layout could be distinguished into three main parts: source, vibrating system and detector (Fig. 1).

The source, a Cu-anode Oxford X-ray tube (50 W), is combined with a monocapillary (diameter $\Phi = 1$ mm, length $l = 150$ mm) placed at a distance of ~60 mm from it. By this way, the optics collects a 16 mrad angle.

The detector is a Photonic Science CCD camera, with an active area of 14.4×10.8 mm^2 and a spatial resolution given by the pixel size of 10.4×10.4 µm^2, placed at 20 mm from the monocapillary exit.

The vibrating system is basically composed of a common loudspeaker that generates the vibration, and a rigid plastic bar connecting the speaker membrane and the free output extremity of the monocapillary.

The speaker vibrating motion is controlled by a signal generator. A sin-waved signal combining different frequencies (10, 50, 100, 250, 500, 1000, 2500, 5000, 10,000 Hz) and different amplitudes (0.1, 0.5, 1, 2.5, 5 V) was used. For every combination two images have been collected, both in static and vibrating state, for an acquisition time of 200 ms. Then, the images have been processed by ImageJ software.

3. Theoretical evaluation

According to the capillary material (SiO_2 glass in our case) and X-ray photon energy (8 keV for Cu K_α), TER critical angle equals to

$$\theta_c[\text{mrad}] \approx \frac{30}{\omega[\text{keV}]} \sim 4\ [\text{mrad}]$$

However, this implies that only half of the channel length works in TER regime, therefore, only part of the 16 mrad acceptance angle of the beam initially captured will propagate through the capillary.

To validate the results the ray-tracing problem has also been simulated with a FEM (Finite Element Method) software using the Comsol 5.0 shell. The optics's channel was reproduced as a glass cylinder (150 mm length, 0.9 mm internal radius), the source – as a Math point (dimensionless spot) at 60 mm from the optics entrance end, and the detection was performed at a plane surface placed at 20 mm from the capillary exit.

This simulation did not run for dynamic capillary vibration but for different source position as explained in Section 4.

During the simulation the source emits n rays randomly distributed inside a cone with the aperture angle equal to the acceptance angle and the axis parallel to the channel axis. Then the simulation solves the ray-tracing six coupled equations

$$\frac{d\boldsymbol{k}}{dt} = \frac{\partial\omega}{\partial\boldsymbol{q}}$$

$$\frac{d\boldsymbol{q}}{dt} = \frac{\partial\omega}{\partial\boldsymbol{k}}$$

where $\boldsymbol{k}$ is the wave vector, $\boldsymbol{q}$ is the position vector and ω is the angular frequency of electromagnetic wave. In the areas where the refractive index is constant the equations of motion can be reduced to the followings

$$\frac{d\boldsymbol{k}}{dt} = 0$$

$$\frac{d\boldsymbol{q}}{dt} = \frac{c|\boldsymbol{k}|}{n}$$

Each reflected ray direction is estimated solving the equation

$$\boldsymbol{n_r} = \boldsymbol{n_i} - \boldsymbol{2}\cos(\theta_{\boldsymbol{i}})\boldsymbol{n_s}$$

where $\boldsymbol{n_r}$ and $\boldsymbol{n_i}$ are the unit vectors of reflected and incident rays and $\boldsymbol{n_s}$ is the vector normal to the channel surface at the point of

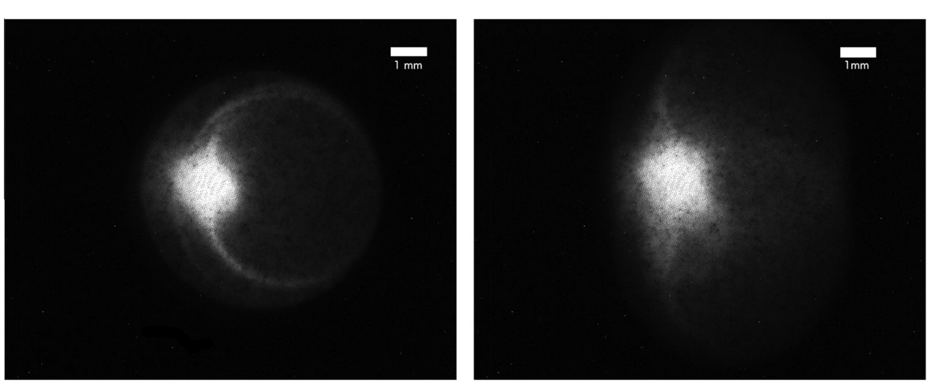

Fig. 2. (left) Static mode image. Inside the halo, the central spot and the circles are evident. (right) Vibrating mode image, in 50 Hz regime. The pattern shows a similar central spot, a more diffuse halo and enlarged "multireflection" circle.