Polycapillary Optics: a Potential New Approach for Soft X-Ray Imaging and Tomography in Fusion Device

A. Romano[1], D. Pacella[1], S. Dabagov[2,4], F. Murtas[2], L. Gabellieri[1], D. Mazon[3], D. Hampai[2], L. A. Grosso[1], V. Piergotti[1], G. Rocchi[1], A. Sibio[1], B. Tilia[1]

[1]*Euratom-ENEA Association, C.R. Frascati, Via E. Fermi, 45 - 00044 Frascati, Rome, Italy*
[2]*Istituto Nazionale di Fisica Nucleare, Via E. Fermi 40, 00044 Frascati, Rome Italy*
[3]*Association Euratom-CEA, CEA Cadarache, DSM/IRFM 13108 St Paul lez durance Cedex, France*
[4]*P. N. Lebedev Physical Institute RAS, Leninsky Pr. 53, 119991 Moscow, Russia*
e-mail: afra.romano@enea.it

Introduction

Soft X-ray (SXR) emissions reveal a lot of information about the processes occurring into the Magnetic Fusion Plasmas (MFP), but the environmental conditions (highly radiative background, high magnetic fields, optical limitations and so on) prevent the installation of X-ray detectors directly into, or close to, the machine. Therefore, we have investigated the possibility of transporting the SXR radiation far from the machine, Polycapillary lenses appear promising both for application to SXR imaging and for tomography. Tests have been performed, in the SXR range 5÷25 keV, for characterizing the polycapillary lenses for distances much larger than the optical focal length both on the detector and the source sides. Polycapillary lenses offer a large flexibility in designing optical systems, good efficiency and high selectivity for SXR radiation.

Polycapillary lenses and laboratory set-up

Polycapillary X-ray lenses are composed of several hundreds thousands of hollow glass fibers (capillaries) bundled together to form a single structure and then bent and shaped to form a lens. X-ray photons propagate down each capillary remaining confined within hollow inner cavity. As known, below the critical angle θ_c (a few mrad) we deal with efficient reflection of X-rays from the surface (total external reflection), where the angle θ_c that is inversely proportional to X-photon energy (keV):

$$\vartheta_c(\mathrm{mrad}) \approx \frac{30}{E(\mathrm{keV})}.$$

Polycapillaries can be used in focusing (full lens) and collimating (half lens, pillar) mode. However, the geometry of bending for polycapillary units is defined by the appropriate curvature set R_i limited by the following condition

$$R_i \leq \frac{d_i \cdot \vartheta_c^2(\mathrm{mrad})}{2}$$

where d_i is the i-th layer capillary diameter (a few μm) [1, 2].

The experiment to investige the properties of such lenses, has been set at the Laboratori Nazionali di Frascati (LNF INFN) in the framework of the collaboration between ENEA Frascati, INFN Frascati and CEA Cadarache [3]. Two radiation sources, 50 W Cu or Mo X-ray tube (Oxford Apogee 5000) with a source spot size of about 50 μm, and three different detectors were used for this purpose. In particular, a scintillator with an effective working area of about 1 inch^2 for the alignment of the polycapillary lens with respect to X-ray source; a Silicon Drift Detector (SDD) with a 30 mm^2 working area for the measurements of the spectra and, finally, the C-MOS imager (Medipix 2) as a 2-D detector [4].

Characterization and imaging properties of polycapillary lenses

Full and half lenses have been characterized to study their properties at large distances, compared with the focal distances. The output focus of the full lens has been determined by scannig of the "detector-lens" distance. The exit beam behind the lens has a Gaussian spatial distribution, with the peak on the optical axis, while the beam intensity at the optics entrance is fairly uniform. This is an expected feature of the lenses, due to the rapid decrease in the radiation transmission by single capillaries and the increase in absorption. This is a consequence of the different curvature: it varies from zero for the central channel to the maximum value at the edge [1]. We adopted the half width at half maximum (σ) as the measurement of the cross dimensions for exit beam. The values of σ along the two directions (x and y) perpendicular to the optical axis (z) are plotted in figs. 1 and 2, respectively for the full and half lenses and σ is given in the units of pixel size of the Medipix2 detector (55 μm).

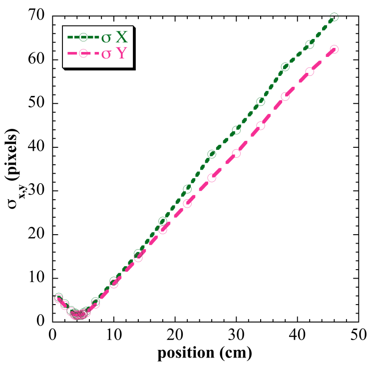

Figure 1 Divergence of the full lens, in the directions perpendicular to the optical axis (z)

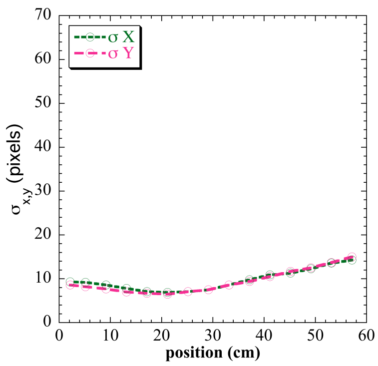

Figure 2 Quasi parallelism of the half lens, in the directions perpendicular to the optical axis (z)

The spot broadening is linear with the distance (fig. 1); the total geometric divergence results approximately of 2.6°, with a small difference between x and y axis, like a sort of weak astigmatic aberration. The output beam is almost parallel even at long distances (fig. 2) for the half lens.

It shows a weak convergence up to 22 cm and then a slight divergence of about 0.3°. The beam at 60 cm is only 40% wider than at the exit of the lens.

The imaging properties of a full lens have been tested by using the X-ray tube with a Mo anode: voltage and current have been set at 25 kV and 150 μA respectively. A radiography has been done, at first, putting the samples (needle, wire, mesh) just in front of the detector, to check the structure, contrast and dimensions, as reference. The image produced by the lens is obtained putting the samples just before (roughly 5 mm) the optics. A plastic foil with holes of about 400 μm has been used as a sample (see its radiography in fig. 3) to test the high resolution imaging proprieties of the full lens. Apart from the bright small spots in correspondence of the holes, there is also a larger circular spot in the centre of the image because the plastic foil is not fully opaque to this X-ray spectrum. In fig. 4, we can observe that the geometry of this sample is perfectly reproduced. There is only a decrease of the intensity at the lens edges but it might be corrected. By means of a spectroscopic detector, the decrease of intensity towards the periphery is found to be progressively stronger at higher energy. This can be explained by the fact that the effective area of the peripheral capillaries reduces for X-ray photons of higher energy.

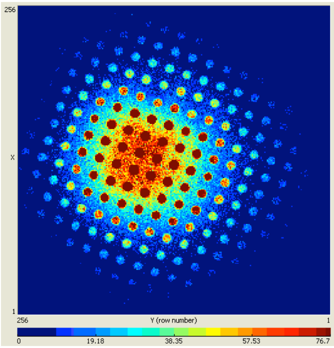

Figure 3 Radiography of a plastic foil with holes

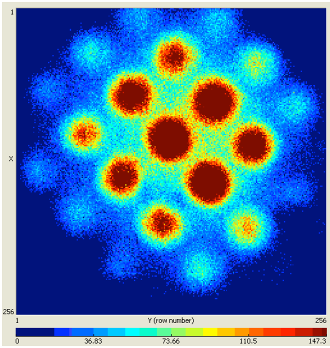

Figure 4 Image with a full lens of a plastic foil with holes

A rectangular mesh made of Nickel wires of 100 μm diameter and pitch 1.3 mm has been used to estimate the resolving power of the full lens finding a value of about 100. The imaging properties have been also tested for half-lens.

We have also quantified the effective transmission of the full lens used in laboratory for this tests, i.e. the ratio between the outcoming SXR flux and the effective incoming one, taking into account the condition on the angle of incidence for the X-ray photons. The measured transmission is 6%, because this used lens was degraded by humidity and dust. The transmission is about 30% for a new polycapillary lens.

Possible applications in MFP

These preliminary studies confirm the potentialities of the polycapillaries as optics for advanced SXR diagnostics in MFP. A comparison with the traditional pinhole allows the evaluation of the advantages of the polycapillary lenses as X-ray optic. First of all polycapillaries are extremely selective for the X-ray band which they are optimized for. Second, they have a smaller entrance angle, so the line of sight is much more defined, without loosing luminosity because it is compensated by the active area of the lens, much higher that for pinhole. In particular, the luminosity for a full lens is estimated to be about 3.6×10^{-5} $mm^2\cdot sr$ and it is comparable or even greater than the pinhole. Polycapillaries offer a large flexibility in designing optical systems to get the radiation from the plasma. Full lens, with an entrance angle of a few degrees and located at meters far from the source, allows 2-D imaging of the plasma selected portion. Half lens allows the collection of radiation from a larger geometrical entrance cone (aperture of a few degrees), while the cylindrical lens gathers radiation from a well defined line of sight, having a divergence of only few milliradians. These lenses in particular could be thought for a tomography array. Cylindrical lenses with large area (diameter ~5 mm) offer a greater luminosity, while long and thin cylindrical lenses (diameter ≤ 1 mm) could be bent to form a fan-in array. Half and cylindrical lenses produce an almost parallel output beam (0.17°), with the advantage to move the detector far away, even meters away. Full lens produces a divergent beam, with an image magnification that offers the advantage of using large area detectors, placed at large distances.

Conclusions

X-ray imaging properties have been demonstrated for polycapillary full-lens, with a resolving power at least of about 100 and for distances much longer (15 times) than the focal distance. Efficiency is found progressively lower at the edge, as expected, and dependent on photon energy. Half-lens revealed as an excellent light collector, having an output beam with a very low divergence (quasi parallel). These preliminary results demonstrate the capabilities to transport almost parallel SXR beams. Thanks to this optics, the detector could be moved far from the lens thus reducing the level of background radiation. Polycapillaries represent therefore a potential tool for either SXR 2-D imaging or tomography. All that is particularly attractive in case of harsh radiative environmental conditions, as in MFP. Tests under neutron irradiation are indeed planned in the near future.

References

[1] S.Dabagov, Physics-Uspekhi, **46** (10), 1053-1075 (2003).

[2] P.J. Schields et al., Powder Diffr. **17** (2), 70-80 (2002).

[3] D. Hampai *et al.*, Nucl. Instr. Meth. B 244, 481-488 (2006).

[4] X. Llopart *et al.*, IEEE Transact. Nucl. Sci., **49** (5), 2279-2283 (2002).