

Prototype of the Imaging High-throughput XUV Monochromator on Base of Spherical Multilayer Mirror

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The until now used XUV diagnostics of tokamak plasma have a limited time and spatial resolution and allow mostly only the global or average parameters of the high-temperature plasma to be estimated. Study of spatial and temporal changes of the plasma parameters is very important in the effort to understand the physics of the plasma density and temperature fluctuations, which are probably responsible for an anomalous transport of the energy and particles in the plasma edge. This calls for development of an XUV diagnostic instrumentation with an improved quality allowing contactless space and time resolved measurements consequently.

The test of the experimental limits of an advanced diagnostic technique using the multilayer disperse elements in a conditions of a low intensity XUV source like a high temperature tokamak plasma is one of the main goals of our diagnostic activities on the CASTOR tokamak. The multilayer mirror (MLM) spectroscopy technique combined with convertor-channeltron detector makes possible an absolute measurement of the most intensive ultra-soft x-ray spectral lines of the low-Z impurities in wide plasma density range [1].

During recent years, the technology of curved multilayer mirrors for ultra-soft x-ray focusing optics had some applications that have further increased the diagnostic potential of the MLM-based spectroscopy and that nowadays allows:

- separation and detection of the spectral lines of the low-Z plasma impurities (B,C,N,O),
- imaging of the weakly plasma emanation regions.

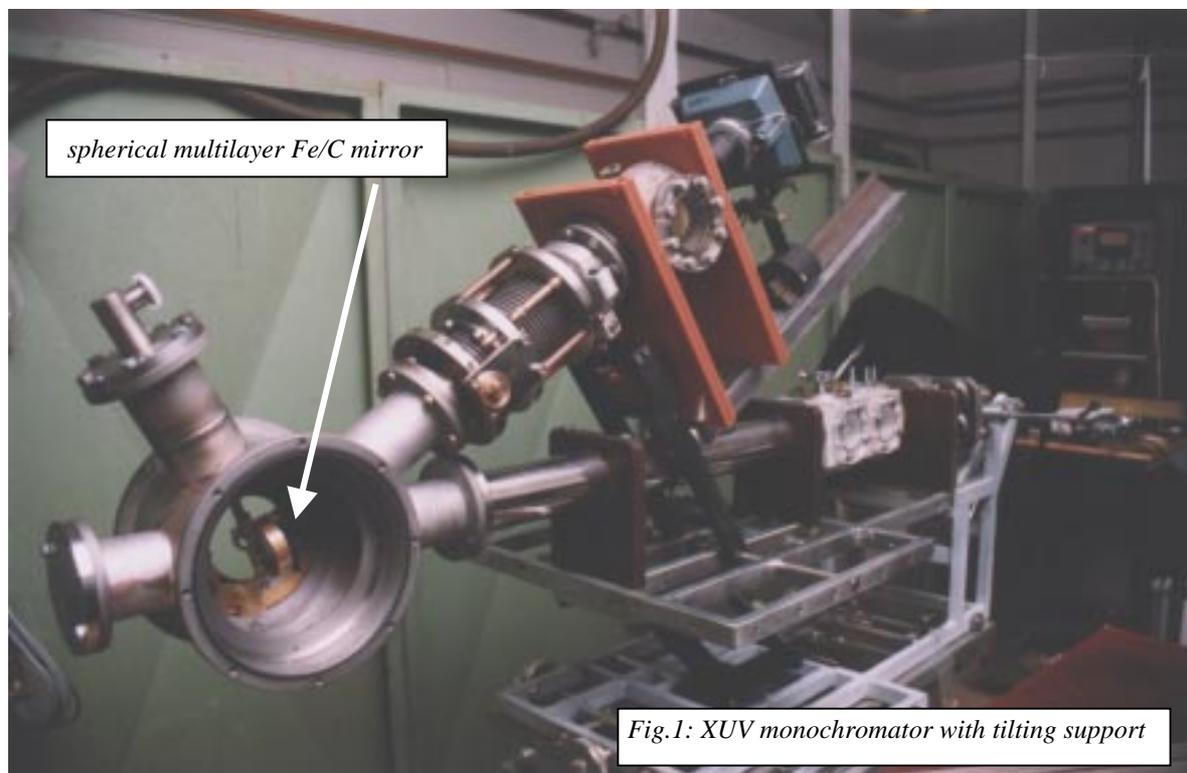
The conception of the XUV monochromator and data acquisition involves:

- measurements of the Carbon line C^{4+} (4.03 nm) emission with a time resolution 10 μ sec in a regime of "one-chord detection",
- the time and spatial evaluation of the radial distribution of the C^{4+} line emission from the plasma area of 80 x 46 mm with space resolution better than 1 mm during one tokamak discharge in an "imaging regime".
- the modelling of light impurities emission in tokamak CASTOR by use of the ionisation and radiation code with respect of the particles transport phenomena. (The code uses fitted electron density and temperature profiles and calculates radiation profiles associated with the main lines of each charge state of the impurity under consideration. It is however necessary to assume ad-hoc the transport coefficients in order to obtain reasonable results.)

In the frame of our current research programme we have fabricated the prototype of a high-throughput XUV monochromator based on spherical multilayer mirror (Fig.1) and nowadays the completed apparatus was tested on CASTOR tokamak in the regime of low-time resolved measurements of the Carbon C^{4+} (4.03 nm) line.

XUV monochromator design for CASTOR

The relatively high reflectivity and small difference in the meridional and sagittal focal length for near normal incidence angle makes the MLM spherical mirror to be both the dispersive and the imaging element of the presented XUV monochromator [2,3].



The **spherical multilayer Fe/C mirror** with the diameter 50 mm, the curvature of 1000 mm and the number of periods equal to 100, is tailored for detection of the spectral line of Carbon C⁴⁺(4.03nm). The mirror reflection R=1.24 % and spectral resolution $\lambda/\delta\lambda=81$ is calculated at 4.027 nm wavelength and at appropriate Bragg angle 74.2 deg. The reliability of calculated data for chosen wavelength of 4.027 nm is confirmed by good coincidence of both: experimental and calculated data for several emission characteristic lines of different elements. The experimental data shown in the Table 1 are slightly corrected if an angular divergence of the probing beam is taken into account. The unhomogeneity of the Fe/C layers-period at a diameter of 40 mm is less than 1%. The major mirror characteristics are consulted with the manufactory: The Budker Institute of Nuclear Physics, Novosibirsk, Russia.

Table 1: The characteristics of the spherical multilayer Fe/C mirror

Wavelength Å	Experimental data			Calculated data		
	Θ_{\max} , ded.	Refl., %	$\lambda/\delta\lambda$	Θ_{\max} , ded.	Refl., %	$\lambda/\delta\lambda$
8.34	11.5	4.7	95	11.52	4.60	83.4
9.89	13.8	3.6	94	13.75	3.70	94
13.33	18.6	1.7	90	18.58	1.76	81
14.56	20.3	1.3	79	20.35	1.35	80
17.59	24.7	5.2	73			
40.27				74.2	1.24	81

According our previous measurements, the brightness of the Carbon C⁴⁺(4.03nm) line is about 5.2×10^{17} photon/m².sec.sr in CASTOR. Due to the increase of the effective reflection surface of the spherical mirror by two orders in the comparison to the previous used flat mirror configuration, the expected number of detected photons (and consequently number of generated photoelectrons) could be approximately in two orders higher too. Really, the input (S1) and output (S2) aperture are about of 1000 mm² and are placed at the distance L=1500mm; so the "étendue": $S1.S2/L^2=10^{-1}$ is 2-3 order higher than the "étendue" of our flat MLM spectrometers [1].

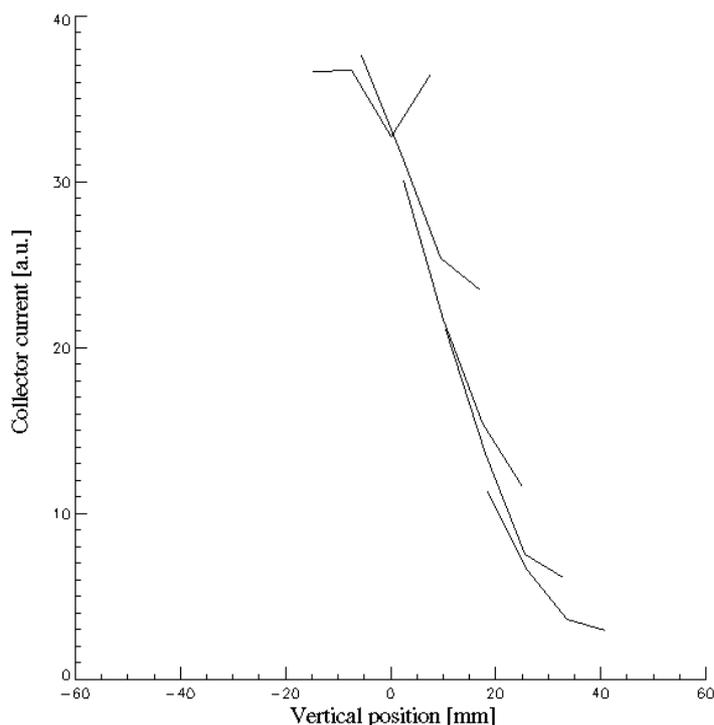
Because the expected count-rate is higher than 10^6 impuls.sec⁻¹ in a regime of one-chord detection, we use a two-step microchannel plate (MCP) detector. The effective dead time of the whole MCP is about 6.10^{-8} sec. Therefore, in the case of homogenous photons flux up to $10^7 - 10^8$ photon/100 mm² on the whole active detector area and supposing that the individual microchannels work independently, the gain remains constant during the irradiation.

The imaging properties of the spherical mirror monochromator system have been analysed in geometrical optics approximation using a ray-tracing procedure. The calculated space resolution in meridional plane is better than 0.1 mm (!), while the experimentally observed space resolution is about 1 mm. This value was evaluated in visible light on an optical stand.

The high throughput XUV monochromator represents an additional huge volume connected to the tokamak vacuum system through the large surface slot. The intensive differential pumping is needed to avoid an undesirable influence on the tokamak discharge regime.

Experimental proof of the XUV monochromator

- As a first experimental test of the complete monochromator system, we have proved to image the plasma vertical profile in visible integral spectra during the total period of a plasma discharge in simple reflection mirror mode. The image of a plasma has been created at a ground-glass and successfully recorded by CCD camera. Unfortunately, the back-ground lightness due to the mirror surface strongly affects the quality of the picture. As the monochromator system could be tilted, the plasma has been imagined at different view angles and the final result has been created by processing of different picture expositions. In this way, the apparatus back-ground lightness has been almost eliminated during the acquisition processing of the image. The very preliminary results indicate the maximum of the visible light emission near to the plasma column axis, as we expected.
- The first effort to detect the vertical distribution of the Carbon C⁴⁺(4.03 nm) line emission was realized by microchannel plate detector equipped by four anode-collectors. The width of the collector was 2mm and the space between the collectors was 0.5 mm. The MCP detector was screened by 0.24 μm thick Ag filter that hold visible and ultraviolet radiation back. This set-up collects photoelectrons that correspond to the radiation from 26 x 46 mm of plasma (the spatial resolution in vertical direction is about 6 mm). The four signals are recorded during the one plasma discharge. In Fig.2, the rough signals of the collector currents as a function of the "vertical position in plasma" are seen. The different plasma profile sectors have been imagined onto the collector set-up again by a tilting of the monochromator. The clear maximum of the x-ray emission is located a little bit lower than the geometrical axis of the tokamak chamber is located. Similar location of the hot core plasma has been confirmed by the other diagnostic tools at CASTOR yet earlier.



The signals were time smoothed due to the acquisition electronic system that was available. For better time resolution, a new electronic unit will be installed to form the electron pulses on MCP output of 10^{-8} sec duration in a logic pulses (5V, 10^{-7} sec) available for high count rate.

Fig.2: Collector current signals detected at 12.ms of the discharge shown as a function of the vertical position

There are many problems calling for urgent measures and changes in XUV monochromator design to cope with the snare in x-ray imaging optics and consequently to improve our experimental technique. A systematic test of the apparatus set-up with use of an only single spherically curved multilayer mirror to form a large plasma volume image in Carbon C^{4+} (4.03 nm) line onto a one- or two-dimensional detector array will naturally continue according our tokamak plasma diagnostic programme.

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