X-ray Imaging for Plasma Position Control in the Ignitor Experiment

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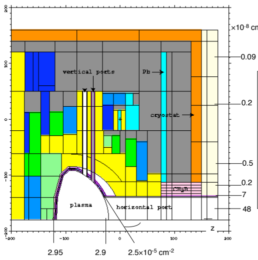
Abstract

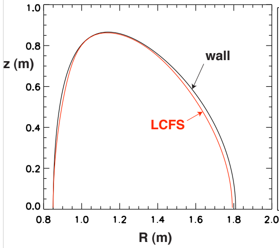
In burning plasma environments, traditional magnetic measurements may be expected to fail because of the high neutron and gamma radiation background. Light extraction and detection will also be more difficult than in present day tokamaks. In general, it will not be possible to keep detectors in the proximity and in direct view of the plasma. In this work we propose a diagnostic system for plasma position control using a multilayer mirror (MLM) as the dispersing element for the soft X-ray radiation emitted from the plasma outer region, and a Gas Electron Multiplier (GEM) detector. In the proposed layout, the radiation of the lower and/or upper region of the plasma is diffracted by cylindrical MLMs at shallow Bragg angles, and is collected by 2D detectors placed outside the machine horizontal port. GEM detectors are suitable for radiation in the 0.2-8 KeV range, and they are characterized by a very high counting rate. This system should measure the plasma position and detect any plasma movement with sufficient time resolution to be used for real-time feedback control of the vertical plasma position.

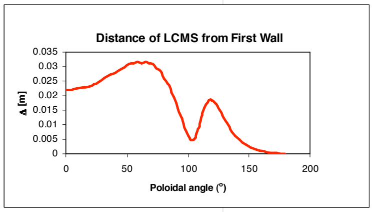


S. Rollet et al., *Fus. Eng. & Des.* **51**, 599 (2000).

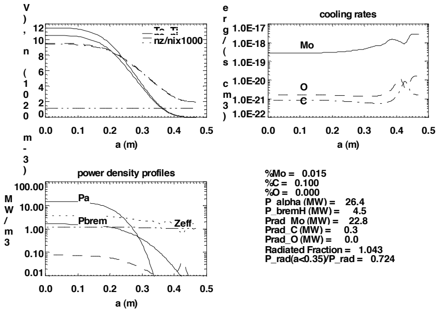
For a high performance shot (3.3 × 10^{19} n/s):
~10^{15} n/(cm^2 s) @ First Wall
~10^{13} n/(cm^2 s) @ port flange

The plasma LCMS in Ignitor is almost everywhere close to the first wall, which acts as an extended limiter. This configuration has the advantage of spreading the thermal heat loads over a relatively large area, thus reducing the peak values. On the other hand, small errors in the position of the plasma column, of the order of 5 mm, or its sudden displacement, can produce "hot spots", or lead to the loss of vertical control.



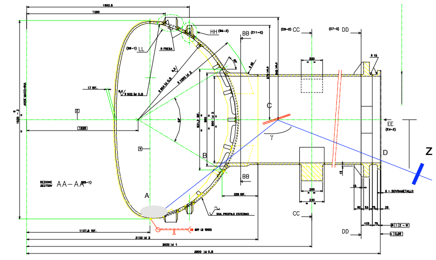


The tiles covering the plasma chamber are made of TZM, a syntherized form of Mo. Thus, the radiation emitted from the edge plasma can be expected to be dominated by this element, even if only a very small fraction of Mo ions (of the order of 10^{-5} times the electron density) enter the plasma.



%Mo = 0.015
%C = 0.100
%O = 0.000
P_alpha (MW) = 26.4
P_bremH (MW) = 4.5
Prad_Mo (MW) = 22.8
Prad_C (MW) = 0.3
Prad_O (MW) = 0.0
Radiated Fraction = 1.043
P_rad(a<0.35)/P_rad = 0.724

The use of a curved diffracting element serves the double function of selecting the radiation spectral range and of focussing it on a detector that can be located outside the plasma chamber, not in direct view of the plasma.



A	(1137, 866)
B	(1705, 400)
C	(2193, 0)
D	(3800, 400)
γ	127°
θ_s	26.7°

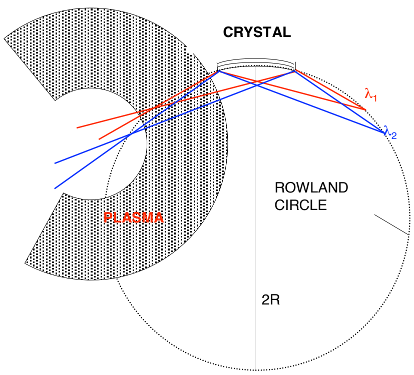
In order to observe the bottom of the plasma, the mirror needs to be located about 1.6 m inside the port. The reflection angle is such that the X-rays can clear the lower edge of the port and be collected by a detector placed outside the machine vacuum.

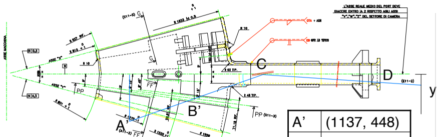
We want to observe the radiation in the range between 25 and 40 Å (500-300 eV). For this application, the instrument spectral resolving power can be poor, just enough to discriminate the edge radiation from the one at higher energy emitted by the core plasma along the line-of-sight.

In the toroidal plane, a rectangular crystal (or MLM) bent to a radius of curvature 2*R* determines a Rowland circle of radius *R*. X-ray photons of wavelength λ incident on the crystal at an angle

$$\theta_B = \sin^{-1}\left(\lambda/2d\right)$$

relative to the diffracting planes are focused on the Rowland circle. Photons of different wavelengths are focused at different positions and a position sensitive detector located on the Rowland circle allows the simultaneous measurement of the spectrum in a given wavelength range.





A'	(1137, 448)
B	(1705, 192)
θ_B	12.2°

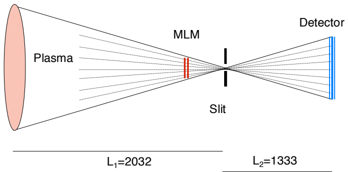
The port geometry determines, in the toroidal plane, the maximum Bragg angle for the radiation to be channeled out of the port: $\theta_B \cong$ 12.2°

Assuming a distance between the MLM and the detector of approximately 2 m, for $\lambda \cong$ 35 Å, the radius of curvature 2*R* of the MLM and the interplanar spacing 2*d* need tp be:

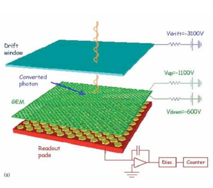
$$2R = \frac{d}{\sin(\theta_B)} \cong 10\,\mathrm{m}, \qquad 2d = \frac{\lambda}{\sin(\theta_B)} \cong 165\,\text{Å}$$

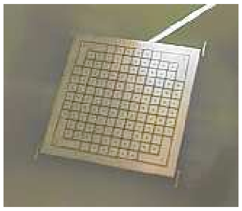
Clearly, this kind of spacing requires the use of multilayer mirrors rather than natural crystals. MLM can be made of different materials, for example a combination of Ni/C, for which the reflectivity can be very good, of the order of 10% in the range of interest [1].

With cylindrical mirrors, in order to obtain some spatial resolution of the observed plasma is necessary to introduce a slit along the line-of sight (spherical mirrors are not suitable, but toroidal ones may be a possibility). Since we want to keep the dimension of the detector within the limit of what is commercially available, the slit will need to be placed between the MLM and the detector to get a reduction of the source. With the following arrangement about 15 cm of plasma can be imaged on a 10 cm wide detector.



A detector suitable for this application is a GEM (Gas Electron Multiplier) [2], since it can be made with a large surface area (10x10 cm), it operates at high counting rates (<1 MHz/pixel), its spatial resolution in the two directions, x and y, can be adjusted as needed, its intrinsic energy discrimination can provide a primary means of background rejection.





The throughput of the instrument can be calculated as:

$$L = \frac{\eta}{4\pi}\frac{R_i l_c h_f h'_D \sin\theta_B}{2R\sin\theta_B - D_{cf}} \approx 4\times10^{-11}\ \mathrm{sr\cdot m^2}$$

This should provide a sufficiently fast signal (<1 ms) for the control system (see Poster NP1.00010).

[1] P. Gorenstein, Private Communication

[2] D. Pacella, R. Bellazzini, A. Brez, G. Pizzicaroli, M. Finkenthal, *Nucl. Instr. Meth. A* **508**, 414 (2003)

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