Development of X-ray sensors and optical light extractors for DEMO operation and control

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As discussed in the Greenwald report, the lack of sensors, light extractors and measurement techniques suitable for the reactor operation and control constitutes quite a serious issue. The requirements for reactor diagnostics can be broadly stated as:

- Capability to function *continuously* and *reliably* in an extreme radiation environment
- *Modularity* for ease of maintenance and replacement
- *Minimization of openings* in the reactor blanket (e.g., < 1-2% of total area)
- *Minimization of costs* (e.g. fraction of overall reactor cost comparable to that in fission)

While the issue of fusion reactor control and operation is very broad, we propose two research thrusts within our area of expertise.

I. Development of X-ray sensors and control techniques

The use of magnetic sensors for plasma position, shape and MHD control in a fusion reactor will be difficult. Due to radiation effects, very long pulse, and eddy currents in the blanket, magnetic sensors are near their limit of applicability already in ITER [1]. In a steady-state reactor operating continuously for months these problems will become much more severe.

Microwave diagnostics can address many of the reactor measurement issues. There are important measurements however, such as the plasma shape or MHD perturbations that will be difficult to perform using solely these techniques. The need to minimize openings and costs will also limit the number of waveguides and antennas. Lastly, measurements based on independent techniques may be required for safety related parameters such as the plasma-wall gap.

We propose that fusion reactors should make extensive use of hard X-ray measurement and control techniques. First, this would exploit the tens of MW 'bulk' emission of the burning plasma. Second, *energy-resolved* X-ray measurements in the range from a few to a few tens of keV could simultaneously provide a number of important plasma parameters:

-plasma position, shape and MHD perturbations, on time scales from dc to sub-ms
-T_e, n_z, n_e, and P_{rad} profiles (using external $\int ne\, dl$ constraints), possibly I_p [2] and T_z profile

In addition, X-ray measurements can be performed through relatively thick windows that would resist plasma exposure. Last but not least, one could use the low cost X-ray diagnostics to reduce the plasma exposure of more expensive and sensitive optical diagnostics, such as Thomson scattering, or MSE. This could be done by intermittently operating the optical diagnostic (e.g. only once every few minutes) and using the X-ray diagnostic to monitor the plasma parameters in between. As illustrated in Ref. 3, good accuracy can be maintained through periodic normalization of the X-ray measurement to the optical one.

The elements of the proposed research are:

(i) Development of X-ray sensors compatible with the fusion reactor environment

Here we envisage two sub-directions:

-*Proximity sensors* that work behind the blanket and can thus have a large, fan-shaped field of view. This solution is considered for ITER and requires the development of radiation hardened X-ray detectors that are insensitive to the intense neutron and gamma background. Such detectors can built using nano-dispersed high-Z photocathodes coupled to a photocurrent amplification mechanism [3].

-*Remote sensors* based on transporting the X-ray light away from the plasma and analyzing its spatial distribution, intensity and spectrum with conventional X-ray detector arrays. For X-ray extraction we propose to use total reflection on large planar mirrors, in a modular 'dog-leg' arrangement that will block the streaming neutrons and gammas (Fig. 1). Total reflection X-ray mirrors were early proposed for ITER. A relatively small number of X-ray modules as in Fig. 1 might suffice for DEMO control, since the device will operate in a fixed scenario where plasma parameter variations will be small. In addition, with some modifications this concept is of interest also for inertial fusion reactors.

(ii) Validation of the X-ray sensors

We envisage a progression of tests from present machines, to ITER, and to the fusion test facility (CTF/FDF). Inertial confinement or pulsed power fusion experiments could also be used.

(iii) Development of X-ray based plasma and MHD control techniques

In a first stage this can be done on the existing tokamaks using sensors based on conventional SXR detectors. In a later stage, the combination of the radiation hardened X-ray sensors and of X-ray based control algorithms could be tested in ITER, followed by the fusion test facility.

II. Development of alternate light extractors for optical diagnostics

Optical diagnostics such as MSE, impurity spectroscopy, Thomson scattering, and IR thermal imaging will likely remain essential for DEMO operation and control,.

To extract light for these diagnostics ITER will use metallic 'first' mirrors, followed by a 'dog-leg' optical train which prevents neutron streaming [1]. However due to plasma erosion and, in particular, deposition this solution encounters major difficulties. While in-situ cleaning and mitigation techniques are being explored, it is not clear if such techniques can be extrapolated to reactor conditions, due to the requirement for continuous operation and to the added complexity and cost. It is thus important to explore also alternate solutions for light extraction. We propose two research directions:

(i) Free standing diffractive optical elements

We explored with very promising results diffractive extractors based on free-standing optical elements, such as transmission gratings or focusing Fresnel zone plates [4]. Since for a diffractive element the light is deflected by a periodic array of slits instead of a solid surface, there is a better chance that it will maintain its optical properties during plasma and radiation exposure. Another important advantage of the diffractive solution is that it is scalable with about constant efficiency, in principle from the X-rays to the infrared. For instance, zone plate lenses for the infrared could be made out of tungsten, which would likely withstand the harsh plasma conditions encountered in divertor thermography.

(ii) Liquid metal mirrors

Liquid metal mirrors are used in astronomy for their high quality optical surface. For fusion reactors the attractiveness of a liquid mirror comes from the capability for continuous regeneration of the optical surface (e.g., through molten metal flow in capillary channels) and from the virtual elimination of plasma or radiation damage. Moreover, since the first wall temperature in DEMO will be several hundred degrees C it might be easier to maintain a molten metal surface than to cool a solid mirror. Recent results at NSTX suggest Li is an attractive candidate for liquid mirrors. The proposed mirror research is thus synergistic with that of liquid metal first wall.

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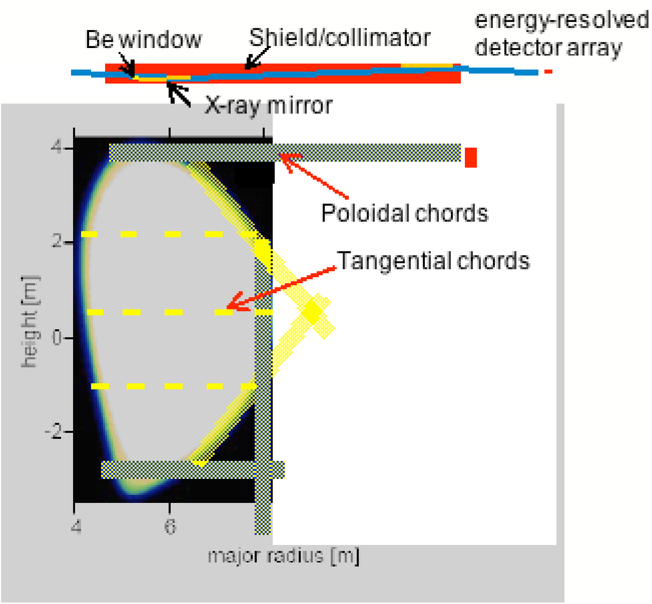

Fig. 1. Remote X-ray sensing for plasma operation and control in DEMO