# Development of soft X-ray to VUV diagnostics for ITER

## A White Paper to the Department of Energy Office of Fusion Energy Sciences

**M. Finkenthal and D. Stutman**

*Plasma Spectroscopy Group*
*Department of Physics and Astronomy*
*Johns Hopkins University, Baltimore MD 21218*

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## Motivation

The diagnosis of the burning plasma in ITER will pose one of the most difficult challenges in the history of experimental data gathering. Among the basic measurements, the spectroscopy and imaging of the plasma emission in the range from tens of eV to tens of keV (soft X-ray to VUV) will play an essential role for machine control and operation, as well as for plasma performance evaluation and physics studies. The measurements enabled by soft X-ray to VUV diagnostics in tokamaks, range from monitoring the impurity content and distribution, to the characterization of MHD and transport and even to the assessment of the plasma current profile. In the first phase of ITER operation few other diagnostics can address these topics, therefore the soft X-ray to VUV measurements will be even more important.

All plasma parameter measurements are considerably more difficult in the environment of a burning plasma. As a general observation, we consider that a simple extrapolation of the techniques developed in large tokamaks (as it is more or less the case with the present ITER diagnostics) will not suffice for making useful and reliable measurements in burning plasmas. For instance, a major unresolved issue is in our opinion the viability and reliability of beam based diagnostics under ITER conditions. Also, new diagnostic ideas and tools have to be investigated, for at least two main reasons. The first is to provide *redundant or alternate techniques for some of the critical measurements*, such as the impurity density, $Z_{eff}$ profile, plasma position and shape, and current profile. The second reason is to provide solutions for *important measurements not covered under the present ITER diagnostic plan*.

The Johns Hopkins Plasma Spectroscopy Group proposes to investigate such new ideas and tools, focusing on the following areas:

i) Development and testing of new ideas for the *extraction* and *detection* of soft X-ray to VUV light in the burning plasma environment

ii) Design and prototyping of *robust* yet *modular* and *easily replaceable* soft X-ray to VUV spectroscopic and imaging devices

iii) Development of new *atomic data* and *modeling tools* for the analysis of the measurements obtained with these devices

Possible research directions in each of the above areas are briefly described in the following.

## I Development and testing of new ideas for the extraction and detection of soft X-ray to VUV light in the burning plasma environment

### I.a Extraction components

We propose first to investigate alternate ideas to the presently considered light extraction systems based mainly on multiple grazing reflections on single layer metallic mirrors. Even if the mirrors will survive in the harsh ITER environment, their reflective and polarizing properties will change in ways difficult to predict. Subsequently, this will render uncertain any previous intensity calibration. Since all ITER spectroscopic measurements are critically dependent on accurate and stable photometric calibrations, we propose to study alternate solutions to the above.

A first idea we propose to investigate is the use of *normal incidence, transmissive-diffractive optical elements* as an alternative to the grazing incidence reflective elements. The basic idea is to use diffraction of freestanding metallic structures like the *transmission grating*, in order to deflect a usable portion of the incident light out of the direct plasma view and into a particle and radiation shielded measurement region. *Fresnel zone plates* are other transmissive-diffractive structures of interest, which can in addition focus incident photons up to several keV energy. X-ray zone plates have been recently produced with up to 5x5 mm active area.

The advantage offered by this approach is that the active light-deflecting element is not an extended material surface, but an array of thin metallic wires. Thus even under heavy neutron, gamma and particle bombardment, and even with some plasma impurity deposition, there is a better chance that such a device will withstand the direct plasma view without significant alteration of its optical properties. Furthermore, even if slow efficiency degradation would occur, it will be easy to use interchangeable gratings in the beam path, since the sensitivity to misalignment at normal incidence is very low. Our group has already built and operated such a device on NSTX (Blagojevic *et al*., Rev. Sci. Instrum. **74**, p1988, 2003). Further protection of the grating, along with high spatial resolution in the plasma could be achieved using the multi grid-collimator designed by our group for in-vessel measurements (see Soukhanovskii *et al*., Rev. Sci. Instrum. **72**, p3270, 2001).

Another potentially important tool for light extraction can be *multilayer optics*. Although more sensitive to direct plasma effects, such as sputtering and deposition, multilayer mirrors can offer the advantage of large collection area combined with higher source intensity and strong background rejection. Our earlier assessment of the radiation hardness of these devices (Regan *et al*., Rev, Sci. Instrum. **68**, p757, 1997), as well as more recent ITER results, show good mirror reflectivity even after prolonged neutron irradiation. Although some shift of the diffraction peak may occur, it is not yet clear if this is a thermal or an irradiation effect.

## I.b Detection elements

As concerns soft X-ray to VUV light detection, we consider that new devices are also needed for the burning plasma environment. Most of the present designs for soft X-ray to VUV detection in ITER rely on transporting with grazing incidence optics and optical fibers the plasma light far from the machine and then measuring the signal with heavily shielded, highly sensitive detectors. This approach has two major limitations. The first is that it is very difficult to implement in this way wide-angle imaging diagnostics. The second limitation is that the transport of weak signals over long paths and the use of highly sensitive detectors are prone to interference and noise in the burning plasma environment.

For these reasons we consider important to investigate new radiation detection ideas, which may allow soft X-ray to VUV measurements in closer proximity to the burning plasma. One device concept we presently explore and which may lead to a class of viable detectors for burning plasmas is the ‘optical’ soft X-ray array. This consists of an efficient *X-ray converter* followed by high throughput *visible light wave guides* and *high quantum efficiency remote detectors* (JHU Advanced Diagnostic Proposal, August 2001). The basic idea behind this device is to first transform the short wavelength light into visible light using an efficient converter which conserves the initial photon statistic in the soft X-ray signal and then transport the visible light to remote detectors using low loss wave guides. This ensures that no information is lost or noise added throughout the light conversion and extraction process. The ‘optical’ array device could be applied either for directly measuring the plasma soft X-ray emission, or for the detection of light dispersed by various soft X-ray to VUV optical elements.

## II Development of new spectroscopic and imaging devices

Based on light extraction and detection ideas like those described, it might be possible to design novel spectroscopic and imaging systems enabling measurements essential to both machine operation and performance analysis. A main characteristic of the proposed systems will be robustness and mechanical simplicity, thus allowing easy replacement.

### II.a Soft X-ray imaging

Although *tomographic imaging* is proven to be a powerful diagnostic in present tokamaks, very limited X-ray imaging is considered under the current ITER diagnostic plan, due to the aforementioned obstacles with conventional techniques.

The low cost and the flexibility of the optical array we propose could allow extensive and highly resolved poloidal imaging at multiple toroidal locations. We believe such measurements could be vital for ITER, where due to the very long pulse and slow plasma evolution, the magnetic measurements relying on an integral of dB/dt will be prone to much larger errors than in conventional tokamaks.

Furthermore, this optical array idea could be extended to 2-D tangential imaging of the central plasma shape, for an assessment of the current profile using the technique perfected at the University of Wisconsin (Tritz *et al.*, Rev. Sci. Instrum. **74**, p2161, 2003). (The Wisconsin group has expressed interest in developing such a diagnostic for ITER.) In addition, due to the very energetic X-ray core emission in ITER, the accuracy of this technique could be improved by using iso-temperature surfaces to constrain the current profile, instead of the iso-emissivity surfaces. The iso-temperature surfaces in turn, could be determined by pulse height analysis of the optical array signals.

### II.b Multi-chordal soft X-ray to VUV spectrometry

Another class of measurements we estimate to be important for ITER operation is soft X-ray to VUV *imaging spectrometry*. For the main plasma its role would be monitoring the medium to high-Z impurity content and its spatial distribution. In the divertor it can serve in addition for low-Z impurity assessment. As a possible alternative to the measurements planned so far, we propose a simpler and more robust solution based on a transmission grating pinhole camera, such as the one above mentioned and demonstrated on NSTX (Blagojevic *et al.*, Rev. Sci. Instrum. **74**, p1988, 2003). This instrument imaged with a few Å spectral resolution and a/20 spatial resolution the 5-350 Å line and continuum emission from most of the plasma volume.

A similar diagnostic could be possible for ITER, using an ‘optical’ soft X-ray array as 2-D detector. Besides extensive spectral and spatial coverage, an essential benefit of this device in ITER conditions would be the accuracy and stability of the photometric calibration and alignment. In conjunction with detailed atomic physics modeling (see below), the accurate and space resolved measurement of the line and continuum intensity could enable a reliable estimate of the medium to high-Z impurity content and distribution in the main ITER plasma. Similar imaging spectrometers operating at VUV wavelengths could be deployed for space resolved spectroscopy of the ITER divertor.

## III Development of new atomic data and modeling tools

Along with the investigation of new diagnostic and instrumentation ideas, it will also be important to develop comprehensive atomic data and modeling tools for the simulation of the complex spectra measured by the proposed diagnostics from ITER.
Our objective is to develop *tools for the prediction of device/measurement specific emission patterns*. This will involve accurately calculating the emission from a mixture of high-Z impurities like tungsten and medium and low-Z impurities, in a wide range of temperatures encompassing both the main ITER plasma and the divertor region.The comparison of the predicted line and continuum intensities with those measured by a calibrated multi-chordal spectrometer like the transmission grating device, would then enable a precise characterization of the medium and high-Z impurity content and distribution in ITER.

Our previous work shows that the large scale atomic structure and collisional radiative calculations needed for such simulations can reliably be performed using the HULLAC suite of codes. The HULLAC predictions for the radiated power emitted by complex high-Z ions have been successfully confirmed by our group in several tokamak experiments [May *et al.*, Rev. Sci. Instrum. **70**, p375, 1999). Recently also the HULLAC/MIST simulations of NSTX soft X-ray emission enabled obtaining impurity and $Z_{eff}$ profiles which are in good agreement with the CXR measurements (Stutman *et al.,* Rev. Sci. Instrum. **74**, p1982, 2003).

We therefore propose to develop a HULLAC atomic database for the low, medium and high-Z elements and in the temperature range relevant for ITER and also to incorporate this database in a comprehensive impurity transport model adequate for burning plasma conditions.