PPPL-5364

Testing a novel SXR imaging diagnostic in reactor-relevant conditions in the DIII-D tokamak

L. Delgado-Aparicio, B. Grierson, A. Bortolon, A. Nagy, N. Pablant, K. Hill,
M. Bitter, B. Stratton, R. Maingi, R. Nazikian, and P. Efthimion

March 2017

Prepared for the U.S.Department of Energy under Contract DE-AC02-09CH11466.

Princeton Plasma Physics Laboratory
Report Disclaimers

Full Legal Disclaimer

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, nor any of their contractors, subcontractors or their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or any third party's use or the results of such use of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof or its contractors or subcontractors. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

Trademark Disclaimer

Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof or its contractors or subcontractors.

PPPL Report Availability

Princeton Plasma Physics Laboratory:

http://www.pppl.gov/techreports.cfm

Office of Scientific and Technical Information (OSTI):

http://www.osti.gov/scitech/

Related Links:

U.S. Department of Energy

U.S. Department of Energy Office of Science

U.S. Department of Energy Office of Fusion Energy Sciences

Testing a novel SXR imaging diagnostic in reactor-relevant conditions in the DIII-D tokamak

L. Delgado-Aparicio, B. Grierson, A. Bortolon, A. Nagy, N. Pablant, K. Hill, M. Bitter,
B. Stratton, R. Maingi, R. Nazikian, and P. Efthimion
[1]PPPL, Princeton, NJ, 08540, USA

1. Target of opportunity

We are proposing the installation of a multi-energy SXR detector for testing impurity control strategies on reactor-relevant conditions in DIII-D. In-lieu of the large uncertainty of the NSTX-U recovery timeline we are proposing a temporary installation of this diagnostic, which was originally conceived for NSTX-U. The proposed hardware leverages the x-ray diagnostic advances from the DOE 2015 Early Career Research Proposal Award (L. Delgado-Aparicio, PPPL). This novel diagnostic has the capability to measure the x-ray emissivity in multiple energy ranges simultaneously and to infer profile measurements of core electron temperature (T_e) and impurity density (n_Z). The x-ray detector could be installed in DIII-D during the summer of 2017 before the beginning of the FY18 campaign. A collaborative multi-institution team at DIII-D (GA, MIT, PPPL), in which we would participate, will conduct the impurity transport studies.

2. Objective

We propose to collaborate on the diagnosis, study and control of high-Z impurity transport and accumulation in the core of advanced confinement regimes in DIII-D. This new hardware would provide relevant measurements of both high-Z impurities generated from plasma-wall interactions (e.g. Ni, Mo), and those purposely introduced by means of gas-puffs (e.g. Ar), an impurity granule injector (e.g. SiC) or a laser blow-off (e.g. Si, Ca, Mo, W). Additionally, we can provide measurements of the plasma position and profiles of the electron temperature $T_e(R,t)$, regardless of the magnetic field and plasma density. The maximum detector frame rate is 500 Hz so we expect time and space resolutions of the order of 2 ms and 1 cm, respectively.

3. Background

With the selection of tungsten for the divertor in ITER, understanding the sources, transport and confinement of high-Z impurities is crucial to ITER success. Controlling impurity transport to avoid accumulation in the core is necessary to achieve and maintain high fusion performance in the presence of high-Z plasma-facing components (PFCs). Two outstanding issues confront the quantitative understanding of high-Z impurity accumulation in machines with metal PFCs. First, is the degree to which the metal wall material is screened by the scrape-off-layer (SOL) and boundary plasma before reaching the separatrix. Second is the transport of such impurities after they cross the separatrix and reach the core region, where they are subject not only to a Z-dependent neoclassical or turbulent transport but also to the effect of externally applied 3D resonant magnetic perturbations (RMPs). This proposal is focused on the latter issue of core impurity transport. Through controlled injections of known amounts of high-Z impurities in the trace limit ($\Delta Z_{eff}/Z_{eff} << 1$), the changes in the impurity diffusivity and convective velocity profiles will be determined under various conditions of electron vs. ion heating and RMP scenarios. The x-ray emission from low-charge states of high-Z impurities will be measured at the edge (e.g. pedestal region) while the emission from higher charge-states with higher photon energy will be measured simultaneously at the core. Therefore, the new proposed diagnostic will measure the dynamical evolution of the spectrally resolved x-ray emission from multiple charge states across the plasma cross section and will permit a robust evaluation of the cross-field impurity neoclassical and turbulent transport from the top of the pedestal to the plasma center.

4. Unique PPPL diagnostic capability for T_e, n_Z, ΔZ_{eff} and the birth of runaways

With recent advances in x-ray detector technology it is now feasible to record spatially resolved x-ray photons in multiple energy ranges from highly charged ions in tokamak plasmas [1,2]. This system has been tested successfully at Alcator C-Mod using a ~24 cm^2 Pilatus2 detector (see Fig. 1). The novel

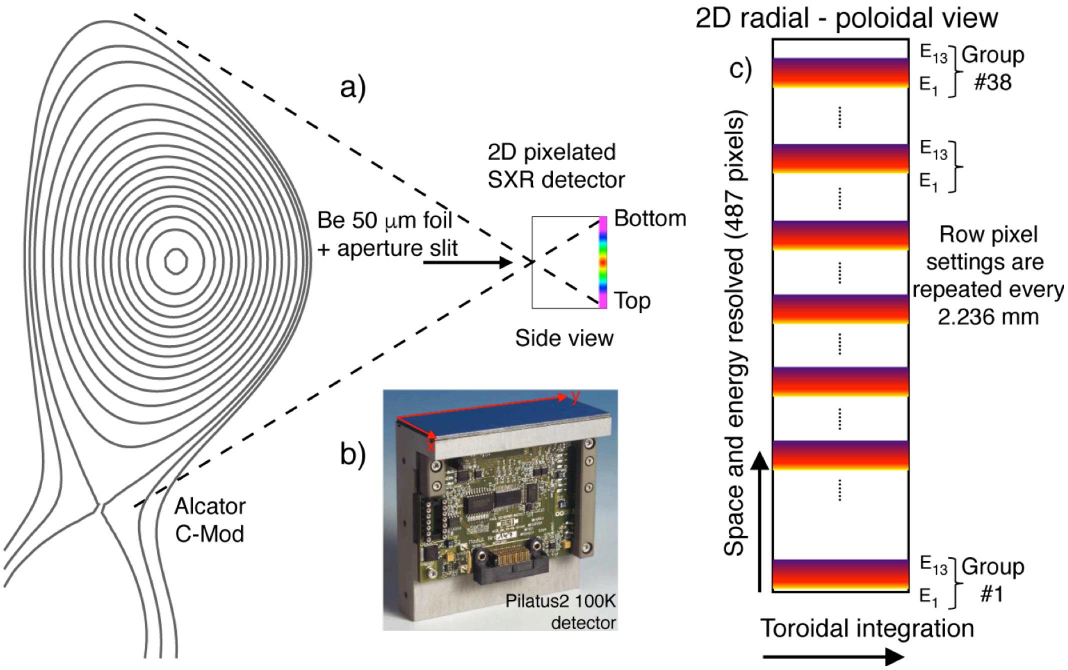

Fig. 1. a) Detector setup at Alcator C-Mod at MIT with the PILATUS2 detector shown in b). Inset (c) shows a vertical arrangement of energy thresholds, which repeats every 13x172 μm and is optimum for a 1D radial view.

configuration of pixelated detectors tested at MIT is shown in Fig. 1-c). Here, an entire row of pixels would be effectively used for each energy value, which will result in larger signal-to–noise ratios. Since the x-ray emissivity is uniform along the toroidal magnetic field, the pixels in adjacent rows sample nearly the same plasma volume separated by few millimeters in the plasma core. It is therefore possible to obtain coarse spectral resolution by setting the pixels in adjacent rows to varying energy thresholds, E_1, E_2, . . . , E_{13}, etc. (from 4 to 16 keV), and then repeat the pixel grouping vertically. In principle, a larger number of pixels can be set to the higher energy thresholds to compensate for the decrease of the photon intensity with energy.

A broadband multi-energy soft x-ray (ME-SXR) imaging diagnostic provides therefore a unique opportunity for measuring simultaneously the x-ray emissivity in multiple energy ranges, allowing the users to infer a variety of important plasma properties. In particular, the energy resolved measurements are used to produce simultaneous measurements of impurity concentrations (n_Z and ΔZ_{eff}) and the electron temperature (T_e) from the absolute image intensity at different energy bands. This capability will be used to optimize neoclassical and turbulent impurity screening and their Z-dependence; particular attention will be given to regimes with an increased turbulent diffusion or outward convective pinch due to a thermal electron heating (e.g. RF impurity pump-out) using ECRH. Moreover, there is a unique opportunity for obtaining coarse information on the radial profiles of the velocity distribution function from non-thermal electrons during the formation of runaway tails. Non-thermal Bremsstrahlung emission ($10<E<100$ keV) will be measured during routine experiments aiming at the study runaway electron birth and their mitigation using pellets or gas puffs.

5. Methodology

The proposed x-ray system will routinely monitor the radial time history profiles of the high-Z emission at multiple energy ranges in all DIII-D scenarios (see tangential system proposed in Fig. 2). The new PILATUS3 detector shown in Figure 2-a) was designed for PPPL and has separable front- and back end electronics. The x-ray detector allows the user to set distinct energy thresholds with energy response widths of approximately 0.5 keV and independent of the energy of the threshold set. The ability to set an energy threshold at an arbitrary value with constant energy resolution is a significant improvement over metallic foil systems [3]. Each pixel of the detector has a maximum counting rate of nearly 10 MHz per pixel and customizable energy thresholds for each of the ~100,000 pixels. Example of pixel-map configurations for tangential imaging are shown in Figs. 2-c), -d) and -e). The proposed diagnostic in DIII-D will thus provide an unprecedented flexibility in the tangential configuration of an imaging x-ray detection system.

The first goal after obtaining the local multi-energy emissivities is to provide simultaneous measurements of $T_e(R,t)$ as well as the fractional impurity density (e.g. n_{Ni}/n_e or n_{Mo}/n_e) during routine operations at DIII-D. These measurements will be done by modeling the slope of the continuum and line-radiation from ratios of the available 1D-Abel inverted radial emissivity profiles over different energy ranges, with no *a priori* assumptions of plasma profiles, magnetic field reconstruction constraints, high-density limitations or need of shot-to-shot reproducibility. Of particular interest for our group during routine operations is to: a) asses the inter-ELM evolution of $T_e(R,t)$ as well as n_Z/n_e at the top of the pedestal which may shed light on the process regulating and stabilizing ELMs, and b) understand the radial dependence of poloidal asymmetries and its role for off-axis impurity peaking, especially when the use of off-axis torque may bring a concomitant increase of the Mach numbers in the outward lower temperature plasma. It is therefore indispensible to sample both the edge and core plasma since transport will shift the charge state distribution and x-ray emission (see Figs. 3 and 4).

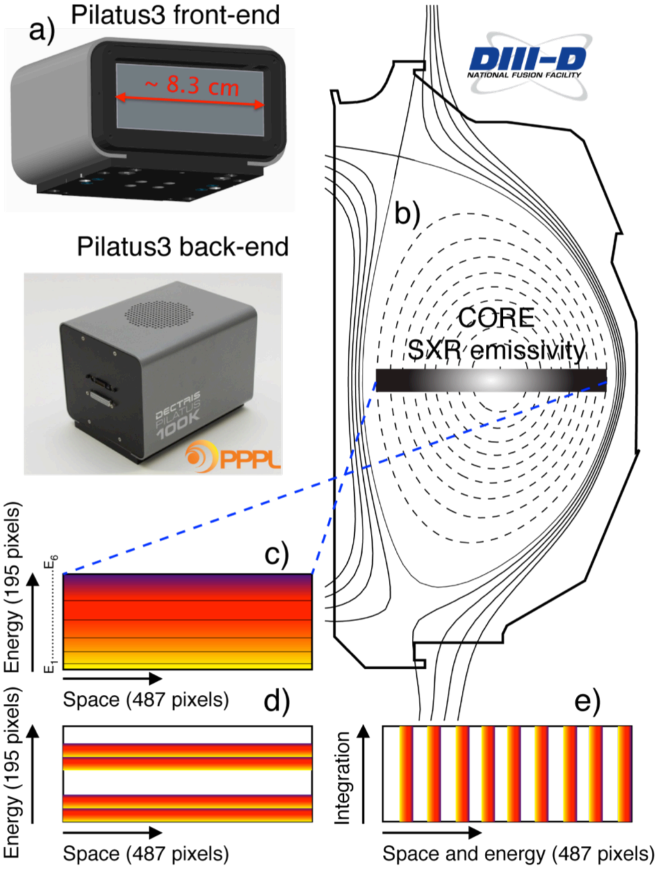

Fig. 2. a) Separable Pilatus3 front end and back-end electronics. b) Cross section of DIII-D highlighting mid-plane core region for the proposed x-ray system. Three distinct pixel maps will result in imaging schemes with c)-d) high- and e) medium-spatial resolution, respectively.

Our x-ray system is also world leading in its ability to study transport of high-Z impurities injected at the edge of the plasma - either by gas-puffs, granules or laser-blow-off (LBO) with resolution sufficient for impurity transport and exhaust studies. A number of unique DIII-D capabilities will benefit from routine operation of our diagnostic: a) the existing impurity granule injector (or powder dropper) is being upgraded to allow single injections of a variety of granules, and b) the new LBO system developed by our MIT-PSFC collaborators (Drs. Nathan Howard, J. Hughes and M. Greenwald) will be also installed the FY18 campaign. The new PILATUS3 x-ray cameras have been procured and will be calibrated at the DECTRIS laboratories in Switzerland in mid-April 2017. This calibration will cover the x-ray energies between 1.6 and 20 keV to resolve the medium- (e.g. Ar, Ca, Ni) to high-Z (e.g. Mo, W) emission. The

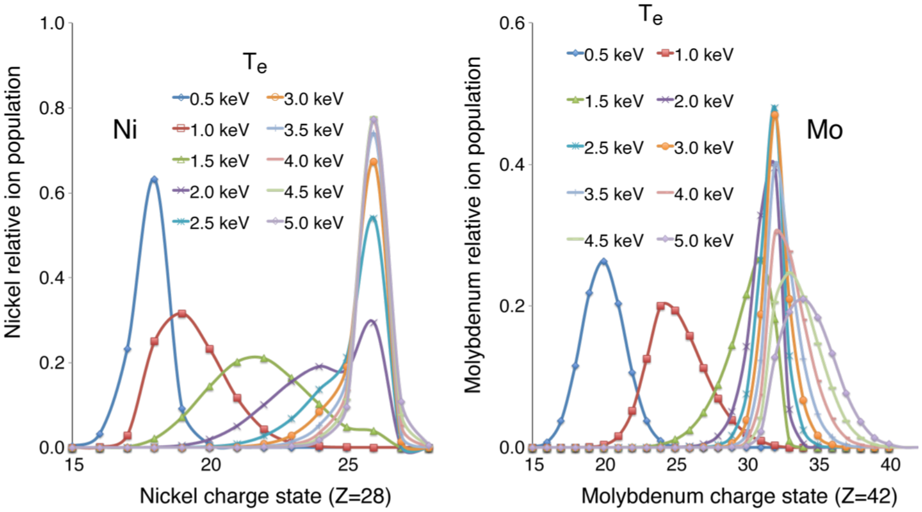

Fig. 3. a) Ni and b) Mo charge state distributions as a function of T_e from 0.5-5 keV.

response curves shown in Fig. 4 are few examples of pixel settings that can be used to measure the x-ray radiation from intrinsic to extrinsic impurities. While DIII-D will be asked to identify the machine access and the support for design and fabrication, PPPL will provide the Be vacuum window, the SXR detector, shield box and cooling systems. A full-time on-site postdoc and students can be trained by our x-ray group to operate the systems, perform spectral analysis and participate in transport modeling.

6. Deliverables

By exploiting novel SXR imaging tools for high-Z impurity monitoring, this proposal seeks to contribute answering basic impurity transport questions in a variety of scenarios, which include:

a) Optimize neoclassical and turbulent impurity screening; attention will be given to regimes with an increased turbulent diffusion or outward convective pinch due to electron heating (e.g. RF impurity pump-out) using ECRH.

b) Ameliorate high-Z core accumulation with fast ELM pacing using RMP fields, D_2 pellet injection and low Z granule injection.

c) Study high-Z impurity transport in RMP-ELM-suppressed plasmas, extending previous DIII-D work with low and medium Z to reactor relevant PFC materials.

d) Compare low- vs high-torque scenarios and confirm the dependence of medium- and high-Z impurity asymmetries on Mach numbers.

e) Determine the reduction in Ware pinch and impact of elevated safety factor on impurity accumulation when operating non-inductively for steady-state optimization.

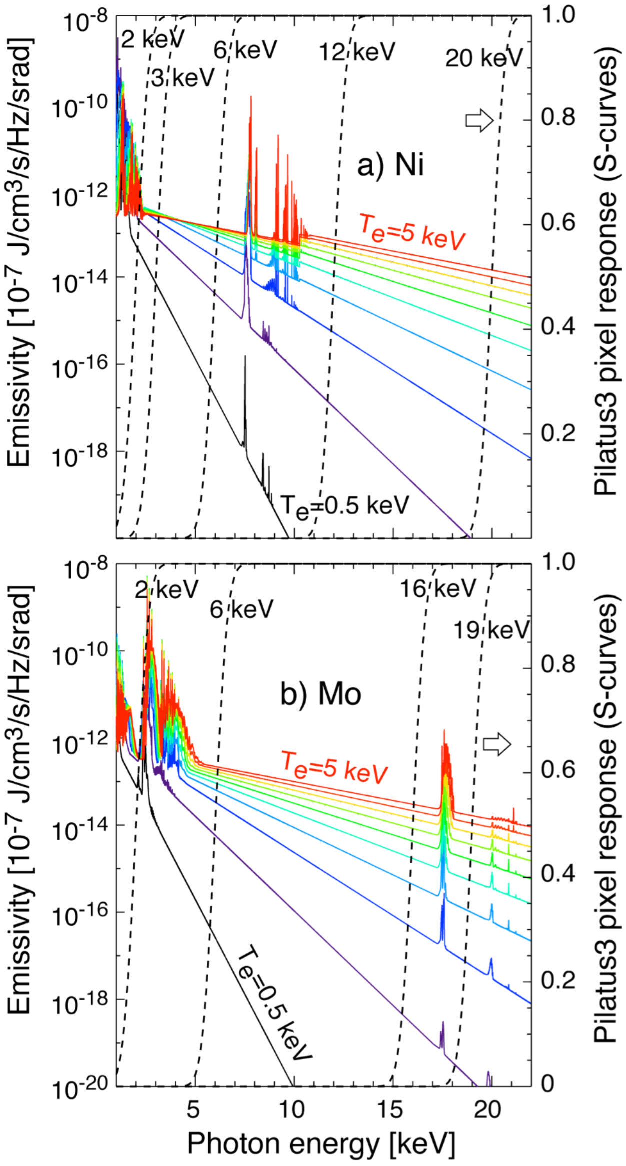

Fig. 4. a) FLYCHK Ni- and b) Mo x-ray spectra at ten temperatures from 0.5 to 5 keV. Indicated with the dotted lines are the pixel energy response curves.

One key goal of this proposal is also to evaluate the effectiveness of control-actuators for reducing high-Z impurity accumulation and radiation losses. Examples of such actuators include applied magnetic perturbations, low- vs high-frequency ELM pacing, on- vs off-axis NBI and ECRH heating. The objective of this final thrust is begin to develop an integrated real-time active-control approach aimed for long-pulse scenarios, optimizing the effect of available actuators for reducing plasma dilution, radiative losses and avoiding the formation of poloidal impurity asymmetries and radiation-induced instabilities. The results from this collaborative research will be presented at physics meetings such as APS, EPS and IAEA-FEC conferences, as well as ITPA transport meetings. This new multi-energy SXR capability should be explored also as a burning plasma diagnostic in-view of its simplicity and robustness. Therefore we also foresee making several presentations in diagnostic meetings like HTPD, ECPD and ITPA.

7. References

[1] L. F. Delgado-Aparicio, *et al*., Rev. Sci. Instrum., **87**, 11E204, (2016).
[2] L. F. Delgado-Aparicio, *et al*., PPPL-Report 4977, (2014).
[3] L. F. Delgado-Aparicio, *et al*., Plasma Phys. Controlled Fusion, **49**, 1245, (2007).