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Testing novel multi-energy SXR imaging diagnostics in enhanced confinement scenarios in the MST-RFP

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1. Target of opportunity

We are proposing the installation of a multi-energy SXR detector to complement the x-ray diode-array suite at the Madison Symmetric Torus (MST) Reversed Field Pinch (RFP). In-lieu of the large uncertainty of the NSTX-U recovery timeline we are proposing a 0.5-1.0 year installation of this NSTX-U diagnostic at MST. 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) with no *a priori* assumptions of plasma profiles, magnetic field reconstruction constraints, high-density limitations or need of shot-to-shot reproducibility. The proposed hardware leverages the x-ray diagnostic advances from the DOE 2015 Early Career Research Proposal Award (L. Delgado-Aparicio, PPPL). The maximum detector frame rate is 500 Hz so we expect time and space resolutions of ~2 ms and <1 cm, respectively. The x-ray detector could be installed in MST in the summer of 2017. A collaborative multi-institution team (e.g. UW, PPPL), in which we would participate, will conduct the particle- and thermal-transport, as well as MHD stability studies.

2. Unique PPPL diagnostic capability for T_e, n_Z, ΔZ_{eff}, and $n_{e,fast}$

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) in combination with a 1 mm tall horizontal slit placed after a Be vacuum-wall filter. The orientation of the slit parallel to the toroidal magnetic field is possible because the electron density, electron temperature, and therefore the x-ray emission is uniform along the toroidal field. The measured profiles are thus spatially resolved in a direction perpendicular to the toroidal magnetic field. The novel configuration of pixelated detectors tested at MIT is shown in Fig. 1-c). Here, an entire row of pixels can 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. The configurations of pixelated detectors can be optimized based on the Shannon-Nyquist sampling and interpolation theory [3], since the observed spectra are typically oversampled. In principle, a

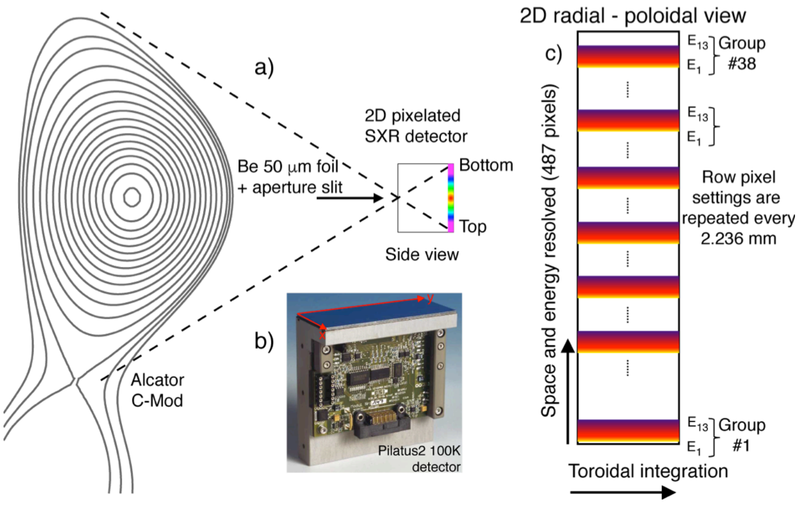


Fig. 1. a) Detector setup at Alcator C-Mod at MIT with the PILATUS2 detector shown in b). Inset (c) shows a vertical arrangement of energy thresholds, which repeats every 13x172 μm and is optimum for a 1D radial view.

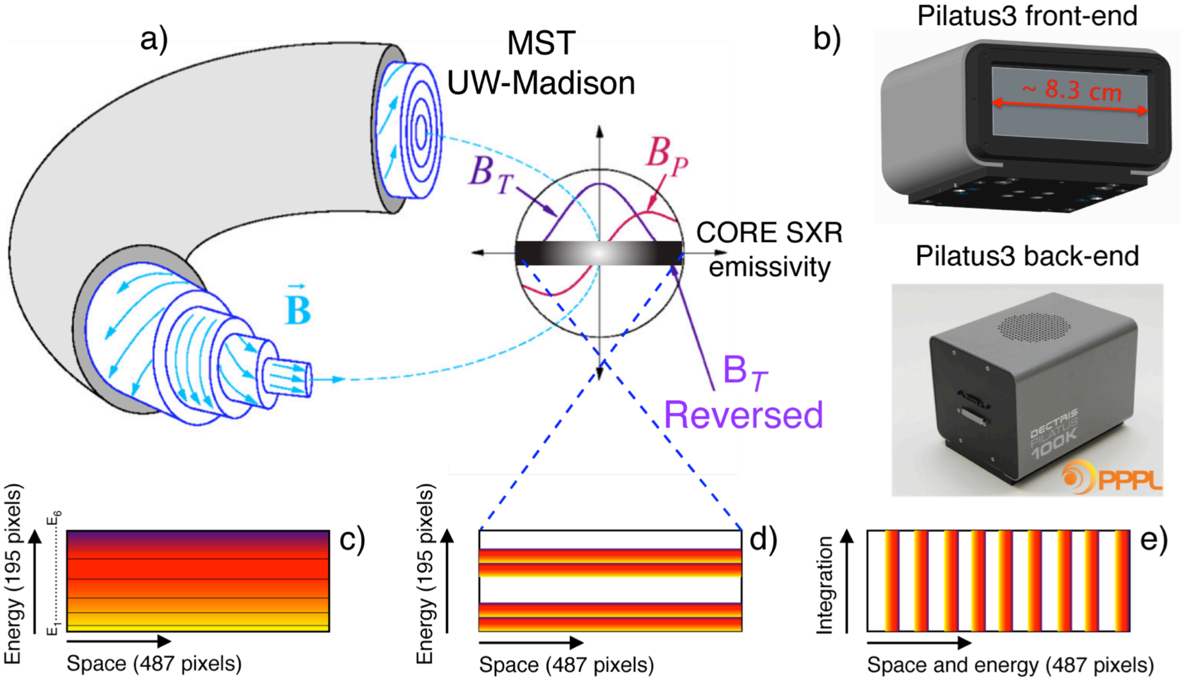


Fig. 2. a) Cross section of MST highlighting mid-plane core region for the proposed x-ray system. b) Separable Pilatus3 front end and back-end electronics. Three distinct pixel maps will result in imaging schemes with c)-d) high- and e) medium-spatial resolution, respectively.

larger number of pixels can be set to the higher energy threshold to compensate for the exponential 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.

3. Methodology and synergistic opportunity between MST and NSTX-U

The proposed x-ray system will routinely monitor the radial time history profiles of the medium-Z emission at multiple energy ranges in all MST 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 [4]. 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). Further improvements implemented on the new cooled PILATUS3 systems allows to be sensitive to the strong aluminum emission between 1.5 and 2.4 keV (see Figs. 3) as well as the characteristic Ar and Mo line- emission in between 2 and 4 keV. To account for the increase in signals, we will make use of the newly developed instant re-trigger technology, which detects pulse pile-up, retriggers the counting circuit, and effectively overcomes counter paralyzation. Photon rates of more than 10^7 photons/s in a single pixel can be accurately measured. The upper limit is bounded by the x-ray absorption of a 450 μm slab of silicon, which has 50% and 90% transmission coefficients at 17 and 35 keV, respectively. The proposed diagnostic in MST will thus provide an unprecedented flexibility in the tangential configuration of an imaging x-ray detection system worldwide.

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_{Al}/n_e or n_{Mo}/n_e) during routine operations at MST. 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 evolution of $T_e(R,t)$ as well as n_{Al}/n_e in the transition between standard, QSH and PPCD scenarios, and b) understand the radial dependence of classical aluminum, argon and molybdenum transport and their role for off-axis impurity peaking. The spatially-resolved profiles $T_e(R,t)$ and n_{Al}/n_e will be compared in low-temperature - *standard* - as well the high-temperature - *enhanced PPCD and QHA* - confinement scenarios. This capability can be used also to optimize classical impurity screening and their Z-

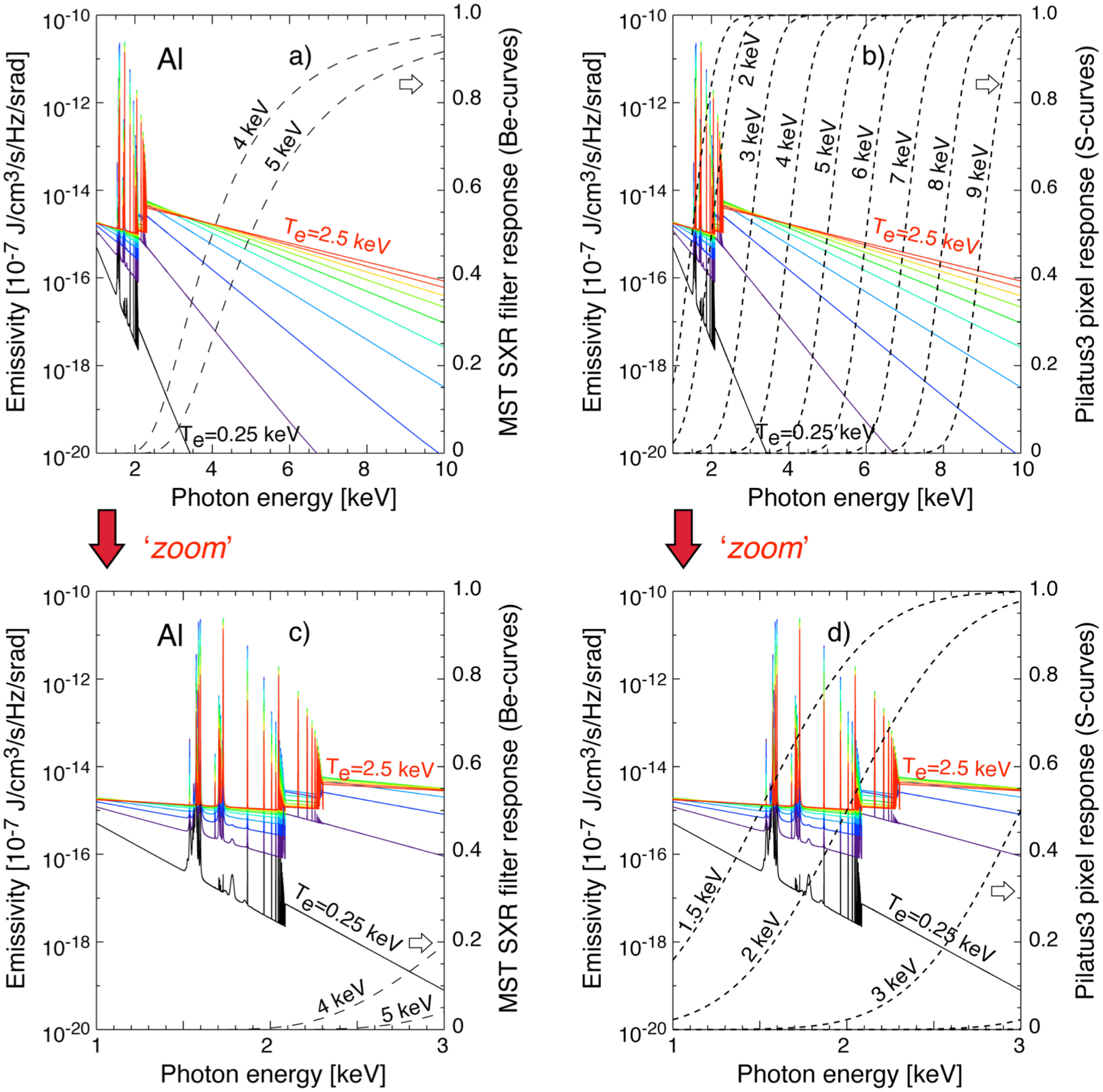
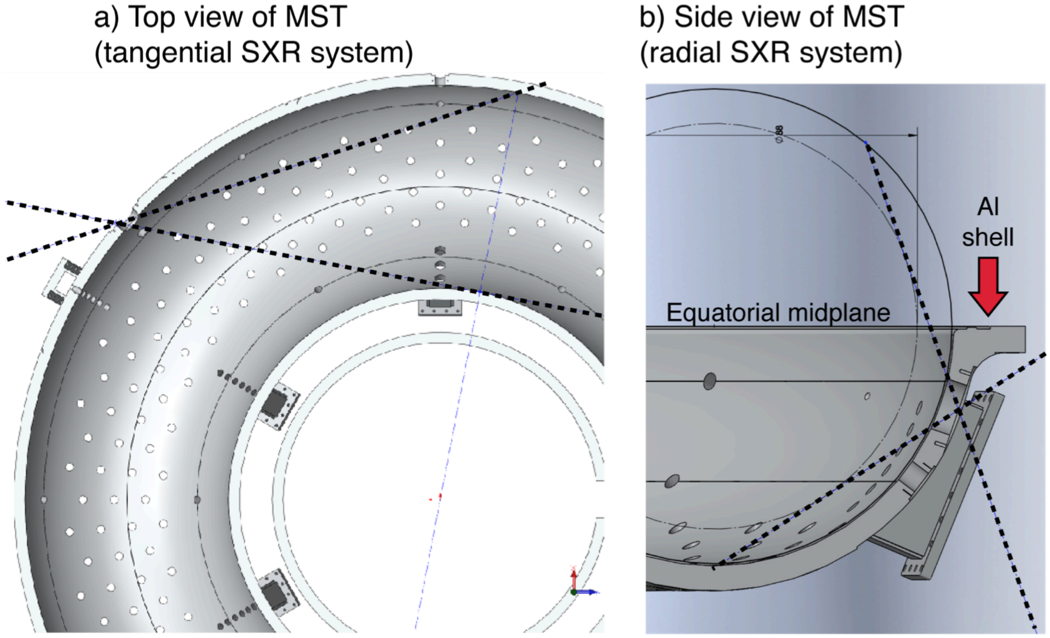


Fig. 3. a) FLYCHK Aluminum x-ray spectra at ten temperatures from 0.25 to 2.5 keV. Indicated with the dotted lines are the filter response curves for the present 2-foil system installed at MST.

dependence. Moreover, there is a unique opportunity for obtaining coarse information on the radial profiles of the velocity distribution function from non-thermal electrons during reconnection events or the formation of runaway tails. Non-thermal Bremsstrahlung emission can be measured during routine experiments aiming at the study electron energetization (e.g. differences in Te∥ vs Te⊥ before and after sawteeth-like events) and runaway electron birth and their mitigation using pellets or gas puffs. Several diagnostics and physics thrusts are listed in Section 5 of this paper.

The proposed methodology and goals are in-line with MST research program. In particular, with the research and development carried on by MST scientists on "*Integrated data analysis (IDA) to improve* T_e *and* Z_{eff} *measurement on MST and NSTX-U*" (see references [5,6]). This novel capability is being developed as an advanced data analysis technique, focusing specifically on improving measurement of the effective ionic charge (Z_{eff}) and electron temperature (T_e) profiles through the integration of data from multiple diagnostics. The benefit to the MST program lies in the ability of the new PILATUS3 detector to characterize the aluminum line-radiation present in MST; the strong line-radiation in comparison to Bremsstrahlung, arises from exposure of the aluminum first wall to the plasma. The He-like and H-like aluminum radiation lines (see Fig. 3) have been a persistent challenge in the interpretation of MST's x-ray data for many years, and an energy resolved x-ray detector will provide the resolution necessary to characterize them. The experienced gathered in MST with the line-emission from the aluminum wall and the PILATUS detectors will be *exported* over the NSTX-U scenarios when dealing with contamination from the metal molybdenum wall.

The x-ray spectra assuming a trace amount of Al-impurities at ten values of T_e from 0.25 to 2.5 keV highlights the challenges of using the MST's two-foil arrays [see Fig. 3-a)], and the benefits of the proposed system [see Fig. 3-b)]. Indicated in the former (with dotted lines) are also the filter response curves for the present 2-foil system installed at MST. In case a small amount of aluminum accumulates in the core of MST, the ability to infer temperature profiles using the (4 and 5 keV) two-foil ratio technique will be hindered. The new PILATUS3 detector allows, however, to pre-select multiple energy ranges [see Fig. 3-b)] and thus '*sample the continuum*' with much higher accuracy, thus facilitating electron temperature measurements with no *a-priori* assumptions of plasma profiles, magnetic field reconstruction constraints, or need of shot-to-shot


a) Top view of MST (tangential SXR system)

b) Side view of MST (radial SXR system)

Fig. 4. Sketches of possible a) tangential and b) radial views from radial port at 138° located 19° below the equatorial mid-plane. An identical port at 222° is also available. The tangential view is not optimized since is the low-field side emission is 'clipped' by the thick aluminum shell.

reproducibility. Moreover, the new cooled PILATUS3 capabilities will allow PPPL and UW scientists to use low-energy thresholds to '*bracket the He-like and H-like aluminum emission*' [see Figs. 3-c) vs –d)] and provide radial profiles of the impurity density. These synergistic activity and improved measurements of T_e and Z_{eff} will be available for general use by MST and NSTX-U researchers, and will have direct application to many research areas. The forward model of the detector and the x-ray signals will then be transferred to NSTX-U once the detector is operating again on NSTX-U, and subsequently used in the IDA effort to obtain improved T_e and Z_{eff} profiles. This collaboration will also directly benefit NSTX-U diagnostic development, as experience with the advanced x-ray detector on MST will help prepare for operation on NSTX-U.

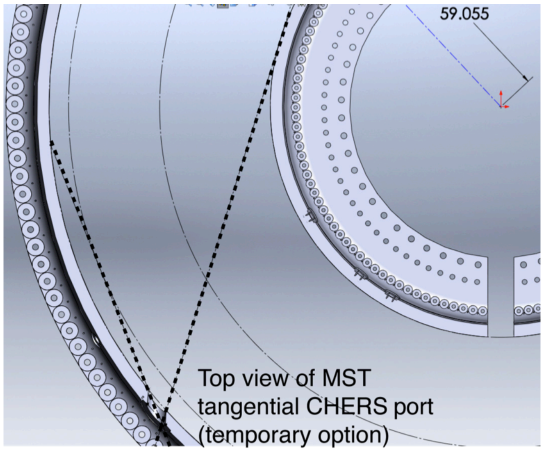


Fig. 5. Unique tangential view used by the tangential CHERS system. This option could be only temporary.

4. Timeline

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. Al, Ar) to high-Z (e.g. Mo) emission. The response curves shown in Fig. 3 are few examples of pixel settings that can be used to measure the x-ray radiation from intrinsic to extrinsic impurities. While MST will be asked to identify the machine access (see Figs. 4 and 5 for radial and tangential views) and the support for design and fabrication, PPPL will provide the Be vacuum window, the SXR detector and cooling systems. A full-time on-site UW-scientist and -students can be trained by our x-ray group to operate the systems, perform spectral analysis and participate in the stability and transport modeling.

5. Diagnostic and physics studies

By exploiting these novel SXR imaging tools this proposal seeks to contribute answering basic transport and stability questions in a variety of MST scenarios. PPPL and UW scientists have identified two diagnostic thrusts and a list of physics topics, which might be exploited by UW scientists and/or students.

a) DIAGNOSTIC EFFORT #1 (using 1D profiles @ 500 Hz with sub-cm resolution):
  - Complement MST's x-ray detection with multi-energy SXR brightness (line-integrated) and tomographically-inverted SXR emissivity (local).
  - High resolution $T_e(R,t)$ profiles and their comparison with Thomson Scattering (TS).
  - High resolution $n_{Al}(R,t)$ profiles and their comparison with those obtained by Charge Exchange Recombination Spectroscopy (CHERS).
  - Use 1D profiles as constraints for integrated data analysis (IDA) to improve T_e and Z_{eff} measurement on MST.

b) DIAGNOSTIC EFFORT #2 (using 2D profiles @ 500 Hz with cm resolution):
  - 2D $T_e(R,Z,t)$ profiles:
    i. Compare T_e-isotherms with magnetic flux surfaces.
    ii. Discuss technique for applications such as Ψ, q-profile and current density (J).
  - 2D $n_{Al}(R,Z,t)$ profiles.

c) Physics Thrusts:
  - *Formation and stability of the QSH:*
    i. Measure T_e and n_Z profiles.
    ii. Comparing good particle (n_e, n_{Al}) vs. intermittent thermal confinement (T_e).

    iii. Fast-ion confinement studies (e.g. controlling QSH phase & using NBI).
- *Impurity transport:*
    i. C vs Al, Ar, Mo classical transport
    ii. $n_{Mo}(R,t)$ profiles when using biasing electrode.
- *Non-thermal effects:*
    i. Spatial- and energy-resolved
    ii. Compare standard vs QSH vs PPCD scenarios
- *Particle energetization during reconnection events*
  (use two camera-views to resolve $T_{e\parallel}$ vs $T_{e\perp}$ before and after sawteeth-like events)

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.

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