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L. F. Delgado-Aparicio,1, J. Maddox,1 N. Pablant,1 K. Hill,1 M. Bitter,1 J. E. Rice,2 R. Granetz,2 A. Hubbard,2 J. Irby,2 M. Greenwald,2 E. Marmar,2 K. Tritz,3 D. Stutman,3 B. Stratton,1 and P. Efthimion1

1Princeton Plasma Physics Laboratory, Princeton, NJ, 08540, USA
2Massachusetts Institute of Technology, Cambridge, MA, 02141, USA
3The Johns Hopkins University, Baltimore, MD, 21218, USA

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Plasma Science and Fusion Center
Massachusetts Institute of Technology
Cambridge MA 02139 USA

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Multi-energy SXR cameras for magnetically confined fusion plasmas

L. F. Delgado-Aparicio,1,a) J. Maddox,1 N. Pablan,1 K. Hill,1 M. Bitter,1 J. E. Rice,2 R. Granetz,2 A. Hubbard,2 J. Irby,2 M. Greenwald,2 E. Marmar,2 K. Tritz,3 D. Stutman,3 B. Stratton,3 and P. Efthimion1

1) Princeton Plasma Physics Laboratory, Princeton, NJ, 08540, USA
2) Massachusetts Institute of Technology, Cambridge, MA, 02141, USA
3) The Johns Hopkins University, Baltimore, MD, 21218, USA

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A compact multi-energy soft x-ray (ME-SXR) camera has been developed for time, energy and space-resolved measurements of the soft-x-ray emissivity in magnetically confined fusion (MCF) plasmas. Multi-energy soft x-ray imaging provides a unique opportunity for measuring, simultaneously, a variety of important plasma properties \(T_e\), \(n_e\), \(\Delta Z_{\text{eff}}\) and \(n_{e,\text{fast}}\). The electron temperature can be obtained by modeling the slope of the continuum radiation from ratios of the available brightness and inverted radial emissivity profiles over multiple energy ranges. Impurity density measurements are also possible using the line-emission from medium- to high-Z impurities to separate the background as well as transient levels of metal contributions. This technique should be explored also as a burning plasma diagnostic in-view of its simplicity and robustness.

I. MOTIVATION

Thanks to important advances in the x-ray detector technology, especially, the manufacturing of two-dimensional hybrid pixel array x-ray detectors of large areas and high single-photon count rate capabilities of 2-10 MHz per pixel, it is now possible to record spatially resolved x-ray photons through direct x-ray detection at multiple energy ranges from highly charged ions from tokamak plasmas1–5. The CMOS hybrid pixel technology developed by CERN6 and The Paul Sherrer Institute7, and commercialized by DECTRIS Ltd.8, was originally conceived for synchrotrons but has been used in the fusion community since 2005 as the diagnostic of choice for x-ray crystal imaging spectrometers. Since these detectors have a variable lower energy threshold for photon detection that can be adjusted independently on each pixel, they provide an unprecedented flexibility in the design of a multi-energy x-ray imaging system. In this paper we describe, in particular, an x-ray imaging system for tokamak and stellarator plasmas which are important in magnetic fusion energy research.

X-ray imaging at multiple energy ranges provides a unique opportunity for measuring, simultaneously, a variety of important plasma properties. The energy resolved measurements can be used to produce images of impurity concentrations \((n_Z, \Delta Z_{\text{eff}})\) - from the absolute image intensity at different energy bands - and the electron energy distribution function, both thermal \((T_e)\) and non-Maxwellian \((n_{e,nM})\), from the variation of emissivity with x-ray energy. Impurity density measurements can be obtained using the line-emission from medium- to high-Z impurities with the goal of discriminating the background as well as transient levels of metal contributions in reactors with metal plasma facing components (PFCs). Selecting an appropriate detector response would eliminate the contamination introduced by line-emission, thus facilitating the temperature measurements in Ohmic and RF-heated scenarios (e.g. ICRH and LHCD).

II. PHA AND MULTI-FOIL METHODS

Previous attempts to develop this capability in the soft x-ray (SXR) energy range have lacked temporal, spatial or energy-resolution. Single-chord pulse-height-analyzers (a.k.a. PHA\(^{9–11}\)) are naturally restricted since they are line-integrated measurements with limited spatial localization (e.g. one spectrum per instrument and with very poor profile definition and slow time resolution). The typical spectra obtained consist of an exponentially decreasing continuum due to Bremsstrahlung and radiation recombination emission, and distinctive x-ray peaks from line-emission from impurity ions\(^{9–11}\). Because the continuum is a well-known function of \(T_e\), an average core electron temperature \((T_e)\) along a line-of-sight can be derived from the measured spectrum. Medium-Z impurity concentrations can also be derived from the intensity of the impurity peaks by use of theoretical plasma-electron-excited x-ray production rates. The complexities associated with using arrays of cooled Si(Li), HgI2 and Ge x-ray detectors\(^{9–11}\) have nowadays been lifted by using individual silicon-drift-detectors (SDDs\(^{12–17}\)). Nonetheless, the time- and space-resolution are still very limited.

A better spatial coverage at the expense of a lack of energy resolution can be gained using multiple x-ray detector arrays filtered using different metallic foils\(^{18–19}\). By using multiple foils with different cut-off energies \((E_C)\) and several detectors with identical plasma views, it is possible to probe the same plasma volume at multiple energy ranges (see Fig. 1 and refs.\(^{18–27}\)). The electron temperature calculated using the multi-foil technique in NSTX was obtained by modeling the slope of the continuum radiation from ratios of the available 1D-Abel inverted radial emissivity profiles over different energy

\(^{a)\}l.delgado@pppl.gov\)
ranges, with no a priori assumptions of plasma profiles, magnetic field reconstruction constraints or need of shot-to-shot reproducibility. The inferred temperature profiles exhibit a shorter time resolution (< 1 ns) in comparison to that of the Thompson scattering [compare Figs. 1-b) and -c)]. This technique has been used to obtain fast temperature measurements in the NSTX, avoiding the time and magnetic-field limitations and requirements imposed by Thompson scattering and electron cyclotron emission (ECE). This multi-energy capability has shown remarkable flexibility and could be used also for impurity transport and the study of slow macroscopic MHD phenomena.  

III. NEW MULTI-ENERGY IMAGING CAPABILITY

The novel imaging diagnostic technique discussed hereafter combines the best features from both PHA and multi-foil methods. This diagnostic employs a pixelated x-ray detector in which the lower energy threshold for photon detection can be adjusted independently on each pixel of the detector. A first proof-of-principle diagnostic system was deployed at the Alcator C-Mod tokamak at MIT in 2012 with good results. In a much recent installation a multi-energy camera was operated in a radial/poloidal configuration [see Fig. 2-a)] and used in various regimes which include low- and high-density Ohmic plasmas, L→H transitions, laser blow-off impurity injections as well as RF heating and current drive experiments. A 1 mm tall slit was placed after the Be vacuum 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, along the toroidal field is uniform. The measured profiles are spatially resolved in a direction per-
pendicular the toroidal magnetic field. At the heart of the new proposed system is a PILATUS28 x-ray detector depicted in Fig. 2-b) that has been the detector of choice for designs of x-ray crystal imaging spectrometers, which our x-ray group at PPPL installed in C-Mod in C-Mod since more than 95% of the plasma facing components are made out of pure molybdenum and/or TZM, an alloy that contains 99% Mo, 0.5% Ti and 0.08% Zr. The average molybdenum ion charge for a core electron temperature of interest \(T_e,0 \sim 1-4 \text{ keV}\) is \((Z)_{Mo} = 32\), with a broad ion fraction of \(\sim 50%\) for Z=32, and 20% and 30% for Mo31+ and Mo33+, respectively. Argon, on the other hand, is an extrinsic impurity commonly used for diagnostic purposes. For the temperatures of interest between 1-4 keV, Ar16+ and Ar17+ are the main line-radiators in the photon energy of interest.

The spectra depicted in Fig. 3 shows the Mo and Ar continuum- and line-emissivities as a function of photon energies between 1 and 25 keV, for electron temperatures between 1 and 10 keV, an electron density of \(1.0 \times 10^{14} \text{ cm}^{-3}\) and impurity concentrations of \(10^{-6}\), as calculated by the FLYCHK code. The dotted lines indicate the different detector responses for neighboring pixels using thirteen energy ranges between 4 and 16 keV. Choosing a detector response with cutoff energies below 6 keV [see Fig. 3-c and -d] can be used to calculate Ar and Mo impurity concentrations. However, preselecting a detector response between 6 and 15 keV will help eliminating

The new configuration of pixilated detectors is shown in Fig. 2-c). Here, an entire row of pixels would be effectively used for each energy value, since by skipping pixel rows only redundant spatial information would be discarded. Since the x-ray emissivity is uniform along the toroidal magnetic field, the pixels in adjacent rows sample nearly the same plasma volume. It is therefore possible to obtain coarse spectral resolution by setting the pixels in each row to varying energy thresholds, \(E_1, E_2, \ldots E_{13}\), etc. (from 4 to 16 keV). The configurations of pixilated detectors can be optimized based on the Shannon-Nyquist sampling and interpolation theory, since the observed spectra are typically oversampled. In principle, a larger number of pixels can be set to the higher energy threshold to compensate for the exponential decrease of the photon intensity with energy. The diagnostic envisioned for C-Mod had a spatial and temporal resolution of 1-2 cm and 10-20 ms, respectively.

**IV. SPECTROSCOPY**

The x-ray spectrum emitted by a hot plasma is characterized by a set of continua that falls off exponentially with increasing photon energy and decreasing electron temperature \((\propto \exp(-E/T_e))\), see Fig. 3. Emission lines peculiar to medium and high-Z impurity charge states are also visible above this continuum. Bremsstrahlung (free-free) and radiative recombination (free-bound) are the two dominant emission processes contributing to the continuous x-ray radiation and can be expressed as,

\[
\frac{d\mathcal{P}_{ff}^{ij}}{dE} \propto \frac{n_e^2}{T_e^{3/2}} \frac{n_i}{n_e} n_{ij} Z_{ij}^2 G_{ff}(Z, T_e, E) \exp(-E/T_e) \tag{1}
\]

\[
\frac{d\mathcal{P}_{fb}^{ij}}{dE} \propto \frac{n_e^2}{T_e^{1/2}} \frac{n_i}{n_e} n_{ij} Z_{ij}^2 \beta_{ij}(T_e, E) \exp(-E/T_e) \tag{2}
\]

where, \(n_i/n_e\) is the impurity concentration, \(n_{ij}/n_i\) is the ion charge state distribution, \(G_{ff}\) is the free-free Gaunt-factor and \(\beta_{ij}\) represents recombination from all quantum states. Line (bound-bound) radiation is the third mechanism occurring in magnetically confined fusion plasmas. The power radiated per unit energy by an impurity ion, \(i\) in a charge state, \(j\) can be expressed as,

\[
\mathcal{P}^{ij}_{L} \propto \frac{E_L}{n_e^2} \frac{n_i}{n_e} \frac{n_{ij}}{n_i} \langle \sigma v(T_e, E) \rangle_{ij} \tag{3}
\]

where \(\langle \sigma v(T_e, E) \rangle_{ij}\) is the total cross section averaged over a Maxwellian velocity distribution.
the “contamination” of the continuum introduced by the line-emission and facilitating the temperature measurements during Ohmic and RF-heated plasmas.

The number of Bremsstrahlung x-ray photons emitted by a local volume-element and detected by a photon counting detector is given by,

$$N_e \propto \frac{C n_e^2 Z_{eff}}{T_e^{1/2}} \int_0^\infty \frac{e^{-E/T_e}}{E} T_{Be} T_{Air} A_{Si} S_{det} dE$$  \hspace{1cm} (4)$$

where, the constant factor $C$ includes the geometry of the detector (e.g. ‘etendue’) and a line-averaged Gaunt-factors which are taken to be constant, the transmission product of air and the Be-filter ($T_{Be} T_{Air}$), the x-ray absorption in the silicon detector lattice ($A_{Si}$), and the detector electronic response curves ($S_{det}$) shown in Fig. 3.

The dependence of the integrand in eqn. (4) with various detector settings at three plasma temperatures of 1, 2 and 5 keV is depicted in Fig. 4. Notice the strong non-linear temperature sensitivity for the integrand for each of the detector threshold energies.

V. FIRST RESULTS

The first data obtained with the multi-energy camera at MIT was during error-field-induced locked-mode experiments which were aimed at delaying the locked mode-onset using ion cyclotron resonance heating (ICRH). The time history of the total SXR counts in the camera frame during the Ohmic and ICRH-heated phases are is shown in Fig. 5-a). Details of the line-integrated profiles across C-Mod cross section in thirteen different energy ranges for $t=0.640$ s - before the ICRH heating phase - is shown in Fig. 5-b). The rapid decrease in x-ray counts for sight-lines which are not aligned with the core is due to the strong temperature and density sensitivity of the soft x-ray emission. The broadening seen at low-energies are likely not due to continuum emission but the strong recombination edge of Ar which is stronger at lower temperatures away from the magnetic axis. This detector has demonstrated an unprecedented flexibility in the configuration of an imaging x-ray detection system having a dynamic range spanning nearly 5 orders of magnitude. The strongest signals obtained during these experiments were up to $5 - 6 \times 10^5$ counts/sec/pixel, far from the its maximum count-rate of $2 \times 10^6$ counts/sec/pixel.

In order to check the consistency of the Maxwellian electron energy distribution function and the possible line-emission contamination, the ME-SXR signals should be routinely plotted as a function of the characteristic cut-off energies. If these basic assumptions are valid, the trace found should have an exponential dependence on energy as predicted by the ideal\(^{21}\) and numerical solutions of eqn. (4) as is shown in Fig. 6-a). The multi-energy soft x-ray-inferred line-averaged electron temperature ($T_{e,0}$) using the data from the central sightline is of the order of 2.15 keV in agreement with the central value of the electron temperature measured with Thomson Scattering and ECE. As eqn. (4) suggests, the fitting routine to find local electron temperatures should be applied on the inverted local multi-energy SXR emissivities. However, the line-integrated brightness measurements in these L-mode discharges are heavily weighted along the line of sight by a strong density ($n_e^2$) and temperature dependence as shown in eqn. (4) and the data in Fig. 4. Moreover, the time-history of ($T_{e,0}$) during the Ohmic and ICRH-heated phases also shows the same trends as the core temperature ($R = 68$ cm) measured by ECE in Fig. 6-b). In most L-mode cases with peaked density and temperature profiles the line-integrated measurements are therefore a good proxy for the local emissivity.
at the distance of closest approach to the hottest and most dense plasma volume. However, in cases of strong inhomogeneities in the local plasma characteristics (e.g. caused by MHD activity and/or poloidal asymmetries due to centrifugal effects) or broader SXR emissivity profiles (e.g. H-modes), the limitations of the multi-energy fit using line-integrated signals - rather than the local emissivity - becomes apparent and a tomographic inversion will become imperative.

The space- and time-resolved electron temperature profiles inferred from the tomographically inverted ME-SXR emissivities are shown in Fig. 6-c) and shows the same Ohmic and ICRH heating features as the ECE data depicted in Fig. 6-b). A slightly more challenging scenario is one in which the electron heating is done by Lower Hybrid Current Drive (LHCD). LH waves pull non-Maxwellian tails with velocities up to 70% of the speed of light. In such scenarios the ECE radiation temperature and plasma temperature are different due to the downshift of the electron gyrofrequency, hence diffculting an ECE temperature estimates. An example of the electron temperature measurements during Ohmic and LHCD phases are shown in Fig. 7-a) showing heating up to 3.7 keV in the core; the SXR-inferred measurement agree well with ECE during the Ohmic phase before the LHCD pulse. The SXR-temperature measurements during the LHCD pulse are possible because the PILATUS2 detectors have a reduced sensitivity to non-Maxwellian part of the electron energy distribution function since their efficiency drops quickly beyond 10 keV. Moreover, first estimates of the background as well as transient levels of metal contributions are possible using the emission from molybdenum and tungsten computed by FLYCHK using arbitrary impurity concentrations \( (n_Z/n_e) \) and temperatures [see Fig. 7-b)]; tungsten atoms were introduced using laser-blow-off injection which reduced the core plasma temperature by nearly 1 keV. These are very preliminary results but indicate the potential to discriminate electron temperature and impurity concentration levels (both background as well as transient levels of metal contributions) in reactors with metal plasma facing components.
VI. CONCLUSIONS

ME-SXR imaging provides a unique opportunity of measuring, simultaneously, a variety of important plasma properties. PILATUS technology allows for individually selecting (64) energy ranges for all its 100 kpixels (minimum). In L-mode cases, the inferred “line averaged” \( T_{e,0} \) is in good agreement with the core temperatures measured by Thomson Scattering and ECE. Tomographically reconstructed emissivities in L- and H-modes will facilitate estimates of \( T_e \) and \( n_Z/n_e \) profiles towards the end goal of being able to separate simultaneously the background as well as transient levels of metal contributions (e.g. impurity transport experiments). This technique should be explored also as a burning plasma diagnostic in-view of its simplicity and robustness.

VII. FUTURE WORK

(a) Further improvements will include the use of new PILATUS3 systems sensitive to the Ar and Mo line-emission in between 2 and 4 keV [see Fig. 3-c and d].

(b) 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 per second in a single pixel can be accurately measured.

(c) Tests are being conducted to study changes in the detection efficiency for cameras embedded in a strong ITER-like magnetic field of \( B_{DC} \approx 2.5 \text{ T, } dB/dt \sim 3\text{T/s}. \) These cameras are also being tested against a 1 MeV neutron equivalent fluence of \( 10^{15} - 10^{16} \text{ neq/cm}^2 \).

(d) This compact x-ray system should be fully explored as a possible burning plasma diagnostic in-view of its simplicity and robustness. Traditional methods based on the slope of the continuum radiation can still be employed since the Tungsten (W) continuum extends from 15 to 55 keV. Intense line-emission from high-Z impurities from metal PFCs can be ‘filtered’-out from the continuum using appropriate energy thresholds.

(e) An appropriate alternative for high energies is CdTe, which will allows detection up to \( 100 \text{ keV with nearly 70\% efficiency. The latter is of interest of our community when radio frequency waves heat plasmas introducing non-Maxwellian “tails” in the distribution function, which are prone to generate hard x-rays.}

(f) Faster Si and CdTe detectors have recently become commercially available and could provide the future framework for rapid estimates of electron temperature and impurity accumulation prior tokamak disruptions.

(g) Two additional features are of interest in our community: a) the development of radiation hard detectors which can tolerate neutron equivalent fluences of \( 10^{17} \text{ neq/cm}^2 \), and b) SXR and HXR detectors with a dual-threshold capability to “scan” the continuum emission.

VIII. ACKNOWLEDGEMENTS

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