Energy-sensitive X-ray Cameras for Thermal and Non-Thermal Plasmas: A 12-Year Technology and Physics Journey

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Soft (S) and hard (H) x-ray systems are a common diagnostic tool in low- and high-temperature plasma and fusion research, providing information on the plasma MHD stability (edge and core), confinement properties, impurity transport as well as radiated power. In high temperature magnetically confined fusion (MCF) plasmas, soft x-ray (SXR) arrays are often poloidally distributed around the plasma cross section, viewing the plasma through identical filters providing a tomographic reconstruction of the natural x-ray emission. One of the main limitations of conventional x-ray tomographic diagnostic systems is the inference of basic plasma parameters (e.g. T_e, $n_{e,Z}$ and Z_{eff}) from MCF plasmas; this limitation stems from their inability to sample the local photon energy-distribution since these systems are fielded with standard filtered-diodes arrays measuring the space- and energy-integrated x-ray power. The novel multi-energy soft and hard x-ray pin-hole camera concepts (ME-SXR & ME-HXR) remove these limitations and is capable of measuring the time-history of the local x-ray emissivity in multiple energy ranges simultaneously, from which is possible to infer profiles of core measurements of 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. Intense line-emission from high-Z impurities from metal plasma facing components (PFCs) can be filtered-out from the continuum using appropriate energy thresholds. As such, traditional methods based on the slope of the continuum radiation can still be employed with adequate time- and space-resolution.

Versatile multi-energy soft and hard X-ray (SXR & HXR) pinhole cameras have been developed, calibrated, and deployed at MST, Alcator C-Mod, and WEST tokamaks with metal PFCs (see Fig. 1 below). These cutting-edge instruments, serving as enabling technologies, have facilitated investigations into a wide array of phenomena including particle, impurity, and thermal transport, heating and RF current-drive mechanisms, equilibria, MHD physics, and the diagnosis of non-Maxwellian effects such as runaway electrons (RE). This innovative imaging diagnostic leverages a pixelated x-ray detector capable of independently adjusting the lower energy threshold for photon detection on each pixel. The primary detector employed is a PILATUS3 100K, equipped with 0.45 mm Si and 1.0 mm CdTe sensors, enabling sensitivity to photon energies ranging from 1.6 to 30 keV and 20 to 200 keV, respectively. Through meticulous trimming and calibration of the lower energy thresholds, our team has successfully mitigated contributions from radiative recombination and line emissions from medium to high-Z impurities like Al, Mo, and W. Central electron temperature values are derived by modeling the slope of continuum radiation, extracted from ratios of inverted radial emissivity profiles across multiple energy ranges (see Fig. 1-c)), without relying on a-priori assumptions of plasma profiles, magnetic field reconstructions, high-density limitations, or shot-to-shot reproducibility. Recent breakthroughs include the temporal evolution measurement of central electron temperature during the C9 campaign at WEST, encompassing long-pulse L-modes lasting up to 364 seconds with 1.14 GJ of injected energy. Additionally, novel applications for diagnosing non-Maxwellian tails have been demonstrated, such as observing the birth, exponential growth, and saturation of runaway electrons (E_e~$100×T_{e,0}$) at MST as well as characterizing fast-electron losses near the W strike point and emission anisotropies at the edge and core in LHCD plasmas at WEST. Novel measurements of the Shafranov shift in steady-state plasmas and RE anisotropic signatures - which could be used as control "alarms" using the emission - in the HXR range will be discussed.

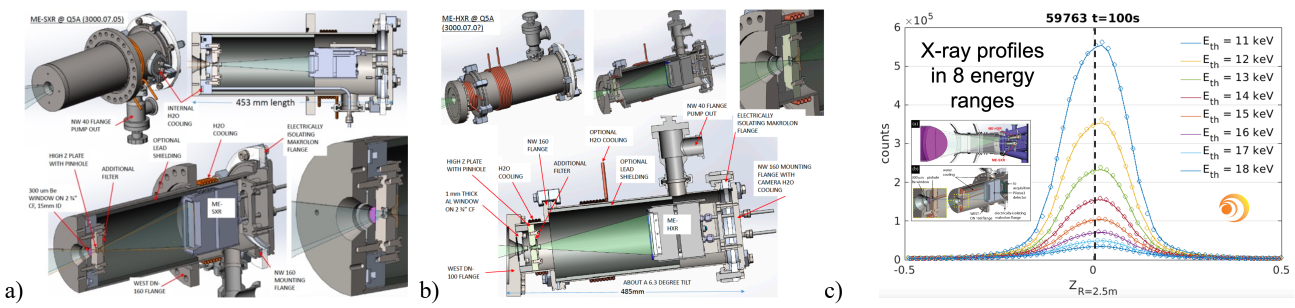

Fig. 1. a) ME-SXR and b) ME-HXR systems installed at WEST. c) Line-integrated brightnesses measured in a long-pulse shot