NOVEL SOFT X-RAY MULTI-ENERGY CAMERA TO STUDY THERMAL PLASMAS AT WEST

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The WEST, or tungsten (chemical symbol "W") Environment in Steady-state Tokamak, is a French experiment at CEA equipped with a challenging all-metal tungsten cladding mainly for unique long-pulse experiments, and an ITER-grade actively cooled tungsten divertor capable of withstanding power fluxes above 10 MW/m^2. Long pulse operation is uniquely available at a nominal magnetic field of 3.7 T with dominant electron heating and no external momentum source with up to 16 MW of RF power (7 MW of LHCD and 9 MW ICRH) for 1000 s [1]. An additional 3 MW of electron cyclotron heating will be installed in the next 2025 campaigns. To access new physics and operational expertise, a versatile multi-energy soft x-ray camera has been developed, calibrated, and deployed at WEST, providing measurements of the local x-ray emissivity in multiple energy ranges simultaneously [2]. This innovative diagnostic leverages a pixelated detector capable of independently adjusting the lower energy threshold for photon detection on each pixel providing unprecedented flexibility in the configuration of an imaging x-ray detection system. Through meticulous trimming and calibration of the lower energy thresholds it is possible to separate signal from W line emission from the continuum, in order to simultaneously investigate multiple plasma properties [3].

From these measurements it is possible to infer the time-history of the plasma centroid (R_0,Z_0) and profiles measurements of electron temperature (T_e) impurity density (n_Z), radiated power densities (P_{rad}) and the effective plasma charge (Z_{eff}) with no a-priori assumptions of plasma profiles, high-density limitations, or need of shot-to-shot reproducibility.

Central electron temperature values are derived by modeling the slope of continuum radiation ($\propto\exp(-E/T_e)$), extracted from ratios of inverted radial emissivity profiles across multiple energy ranges (see top figures). Recent breakthroughs at WEST include the temporal evolution measurement of central electron temperature during plasma experiments lasting more than 800 s, encompassing truly non-inductive ($V_{loop}\rightarrow0$) long-pulse discharges with no external input torque, resilience to tungsten UFOs [4], and an improved L-mode confinement ($H_{98y,2}$~1) with injected energy approaching 2 GJ [5].

Impurity transport analysis in steady-state without perturbing the plasma is carried out by measuring the SXR emission at few keV photon energy where the radiation is dominated by tungsten line emission. Tungsten density is estimated by modeling the inverted radial emissivity profiles with an analytic SXR tomography code based on plasma emissivity calculated with the FLYCHK spectral tool [6] [7].

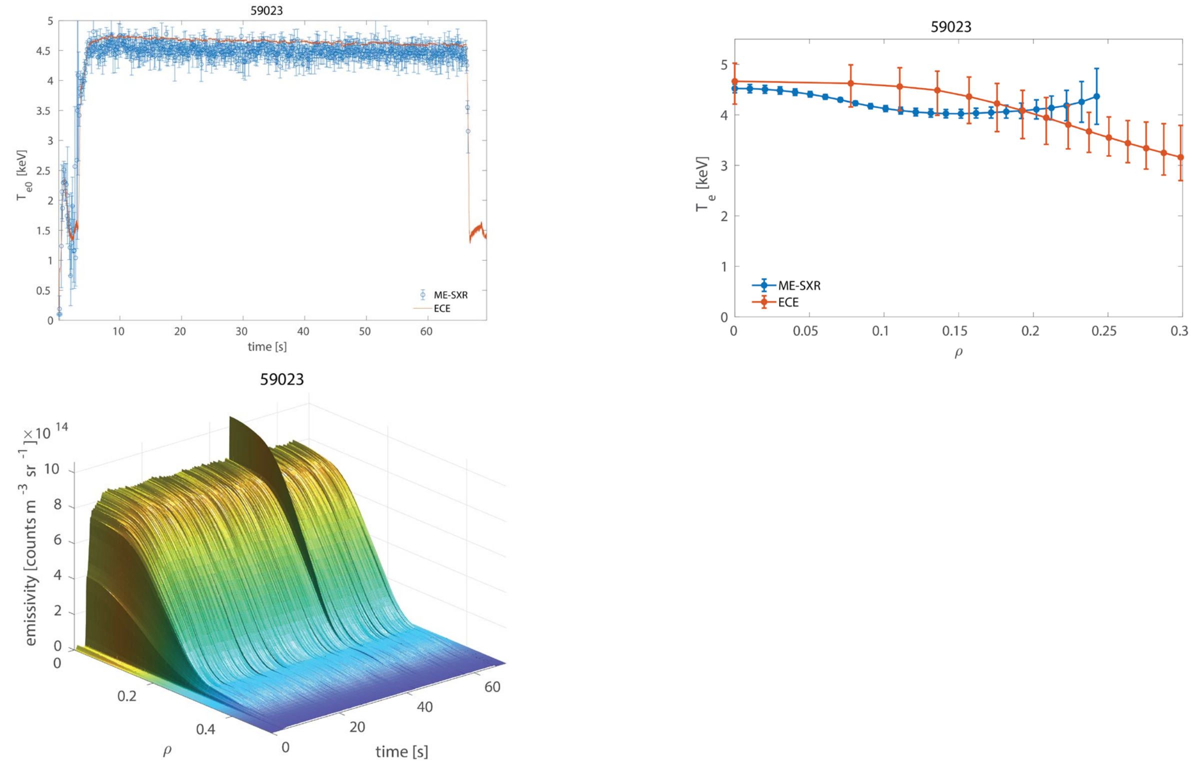
The diagnostic is also used to identify transient event such as tungsten UFOs, through enhancement of the reconstructed emissivity profile (see bottom figure).

Additional applications of this powerful diagnostic include observation of runaway electron beams.

Future developments foresee real-time applications of such technique to detect UFOs, runaway electrons and electron temperature through line-integrated measurements.

Neoclassical and turbulence W transport simulations using the XGC code with W ions modeled with a few W bundles are under preparation [8]. The implementation of a synthetic SXR diagnostic in such modeling tool is foreseen and will allow direct comparison between measurements and simulations.

This versatile measurement technique is now being considered by ITER to be explored also as a burning plasma diagnostic in-view of its simplicity and robustness.



Top left: time evolution of the central electron temperature (T_{e0}) inferred from SXR measurements compared with ECE measurements. Top right: T_e profiles in the core from the two diagnostics. Bottom: time evolution of the reconstructed SXR emissivity profiles showing the sudden enhancement due to a transient W UFO.

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