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Development of high-density channel SXR FPGA-GEM-system for tokamak plasma diagnostics

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Abstract:
Soft X-ray (SXR) diagnostics are widely used in fusion research to investigate plasma behavior and provide data for detailed studies, particularly, in the context of magnetohydrodynamic (MHD) activities or impurities transport. The outputs can be used for monitoring the plasma stability, such as by tracking impurities during the discharges and their accumulation in the plasma core. Such measurements are especially relevant for next generation devices like ITER, where impurity control, such as tungsten, is critical for sustaining high performance plasma operation. Gas Electron Multiplier (GEM) detectors are considered promising candidates for diagnostic applications in advanced and future tokamaks due to their high tolerance to neutron radiation. The GEM detector consists of a gas filled amplification region and one or more perforated GEM foils, which are biased with high voltage to enable electron multiplication. When soft X-ray photons interact with the gas, they produce primary electrons that are subsequently amplified through successive stages in the GEM foils. The resulting electron charge is collected at the readout anode, typically implemented as a printed circuit board (PCB), which enables spatially resolved signal detection.

This work focuses on a new generation of SXR diagnostics based on GEM detectors integrated with a modern FPGA-based data acquisition infrastructure. The presented solution represents the third generation of SXR detection systems developed by our team. Earlier versions have been successfully deployed on the JET tokamak (UK, operated by CCFE) and the WEST tokamak (France, operated by CEA). These include a hardware histogramming system (1st generation) and a hybrid streaming system (2nd generation). The current design differs significantly form its predecessors, primarily due to the highly complex readout architecture of the GEM detector. It incorporates approximately 34,000 pixels, organized into around 3000 readout channels using an advanced XYUV coordinate mapping scheme. Due to foreseen particle flux at a level of ~2MHz/channel, the data acquisition requires high-performance electronics and dense signal connections in relation to a budget-optimized way of constructing the diagnostic. This work emphasizes a highly standardized system design, leveraging Customer-Off-The-Shelf (COTS) components, wherever feasible, and custom development of the most essential elements of the electronics. The architecture is based on multiple FPGA units, each capable of handling up to 256 signal processing channels. A key feature of the proposed system is its ability to acquire raw analogue signals directly from the GEM detector and process them though several stages, improving the quality of the output data. This processing is split between real-time FPGA-based preprocessing and post-acquisition analysis on an HPC cluster. The resulting data is high time resolution energy and topology spectra tailored user defined configurations.

The system is still under active development. In this work we present the most recent results, with a particular focus on the construction strategy and early performance validation.

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