A new hard x-ray spectrometer for suprathermal electron studies in TCV

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In the plasma of the Tokamak à configuration variable (TCV) electrons can be accelerated to suprathermal energies by its powerful (4.5MW) electron cyclotron resonance heating and current drive (ECRH/ECCD) system (fig. 1a). The dynamics of these electrons affect strongly the ECCD efficiency and location, which are crucial for its applications, in particular for MHD stability control and profile control. Another source of suprathermals is the electron acceleration during magnetic reconnection in internal MHD events and disruptions. In this case runaway electron creation is an important issue, especially at low densities.

To understand these effects and the underlying physics, it is important to gain more knowledge on the suprathermal electron population. The hard x-ray (HXR) bremsstrahlung emission (5keV – 1MeV) originating from their collisions with electrons and ions provides us with a significant amount of information on the emitting electrons, which can be aided by Fokker-Planck modeling. The approximation of a bi-Maxwellian electron distribution is also often used to simplify the analysis [1]. On TCV, a novel HXR tomographic spectrometer (HXRS) [2] has been designed to perform the first tomographic energy-resolved HXR reconstruction of a non-circular plasma, including a tangential observation capability.

Diagnostic hardware

A 29mm thick fan-type tungsten Soller collimator defines the 24 viewing chords of each of 4 HXR cameras (fig. 1c). Furthermore, at least 20mm of tungsten, in addition to stainless steel

![Figure 1: a) TCV EC heating system, b) HXRS lines of sight (first camera chords in green) in the poloidal plane, c) camera design with the detectors (red) behind the tungsten collimator (black), d) TCV top view with the chords of the camera turned to horizontal position.](image-url)
structures, shield every part of the diagnostic against uncollimated high energy (γ) photons from the tokamak. Two filter wheels with 6 filter positions each allow many choices of absorber thickness to cut off low energy photons. At the heart of this compact system are the CdTe detectors (24 plus one blind one to discriminate against uncollimated photons) with an energy resolution of 7keV in the range 13 – 300keV. They are connected via fast amplifiers to a digital acquisition system acquiring the full pulse history at 12 Msamples per second.

The first camera has proven the robustness of the diagnostic design by its problem-free operation during more than 1000 plasma discharges. It is located in a low field side midplane port and covers the poloidal cross section of the plasma or can be rotated by 90° to measure tangentially in the co- and counter-current directions in the horizontal plane (fig. 1d). Three additional cameras will complete the tomographic system by the end of 2012 (fig. 1b).

**Pulse detection**

The direct signal acquisition allows the use of digital pulse detection algorithms. These provide the arrival time and energy of each single photon detected, which in turn enables an optimal balance of time, space and energy resolution depending on the photon statistics by choosing the time and energy binning correspondingly. Additionally, more sophisticated data analysis such as conditional averaging becomes available compared to traditional analogue pulse detection.

A pulse detection framework including various detection and benchmarking algorithms has been implemented to optimize this key step in data analysis. Pulse shape discrimination (PSD) algorithms can only handle moderate count rates since they respond at least partially to the pulse decay shape specified by the instrumental integrator decay time $\tau_d = 4\mu s$. Contrary to these, filter algorithms observing only the rising part of the pulse can succeed even close to the detector charge collection time ($\sim 100ns$) and the pile-up limit. This results in detectable count rates in excess of 500kHz.

Figure 2 compares selected algorithms on simulated spectra. An algorithm detecting the change
in sign (CIS) of the differential of a zero-phase digitally filtered signal displays a good true positive detection rate but poor energy resolution. A PSD algorithm suffers from rather high false negative detection due to noise distorting the pulse shapes. A traditional analogue filter is reproduced by the \((\text{CR})^2(\text{RC})\) algorithm (IIR filter comprising two differentiators and one integrator) yielding a high true positive detection. The highest accuracy in energy at high true positive rates was achieved using trapezoidal FIR filters (abbr.: trap). The initial version was first improved by a linear weighting of the points taken into account (trap 1). Finally, our optimized trap 2 algorithm is obtained by applying the trap 1 filter twice to perform a double differentiation and following it by a numerical integrator. This combines the high true positive detection and maximal count rate of the \((\text{CR})^2(\text{RC})\) with the accuracy of the trapezoidal filters.

Results

During and after the commissioning phase of the diagnostic mainly limited L-mode plasma experiments with substantially high power ECRH/ECCD were carried out to study the suprathermal electron dynamics in this regime. Only a few examples can be provided here because of
Toroidal asymmetry With the HXRS camera rotated to lie in the horizontal plane the enhanced bremsstrahlung emission of suprathermal electrons in the forward cone due to relativistic effects was observed and quantified for the first time. Fig. 3a compares the spectra measured by the chords viewing in the co- and counter-current directions during 0.6s 2.4MW co- and cnt-ECCD phases. This is in good agreement with the emission modeled by the synthetic diagnostic LUKE/R5X2 [3], which reproduces the co- and counter-current asymmetry correctly (fig. 3b).

ECCD response One means of studying the suprathermal electron dynamics, and particularly the role of spatial transport, is to analyze the response of the electron distribution function to an ECCD step. To increase the time resolution, conditional averaging was applied over 12 ECCD duty cycles (30ms on - 30ms off). Figure 4 shows the resulting evolution of the hard x-ray emission and suprathermal electron temperature profiles. The suprathermal electron temperature profile rises quickly and remains spatially uniform and rather constant while the hard x-ray emission increases more slowly.

Suprathermal electrons and sawteeth The suprathermal electron dynamics associated with sawtooth crashes were analyzed using conditional averaging to obtain a time resolution better than 0.2ms. While in low density plasmas MeV-range HXR bursts due to runaway electrons appear right after the sawtooth crashes and dominate the signal, a time history closer to that of the soft x-ray emission behavior is observed at high density.

Between these two regimes there is a narrow density band in plasmas with strong ECCD in which a sharp peak is also observed immediately after the sawtooth crash, but at measurable, collimated photon energies of ≈ 100keV. While very preliminary, this analysis indicates that the HXRS diagnostic has a strong potential for elucidating the effect of MHD on the electron distribution function with high effective temporal resolution.

Summary A novel HXR tomographic spectrometer has been designed for the TCV tokamak and a first camera has already been installed and operated with extremely promising results. New, highly effective pulse detection algorithms have been developed for this diagnostic. The imminent installation of the three remaining cameras will result in the first HXR tomographic study of noncircular tokamak plasmas.

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References