

Measurements of Hard X-Ray Emission Profiles in the TCV Tokamak during Electron Cyclotron Heating and Current Drive

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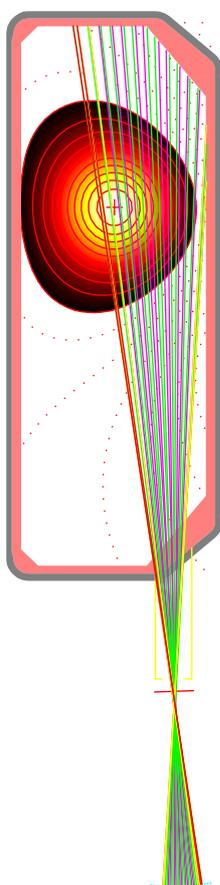


Fig. 1 Geometry of hard X-ray camera viewing chords for a typical EC-heated TCV plasma ($R = 88$ cm, $a = 23$ cm). The chords are partially overlapped.

1. Introduction

A multichannel hard X-ray (HXR) diagnostic system developed for the Tore Supra tokamak [1] has been employed on the TCV tokamak with the aim of characterising the spectral and spatial distribution of fast-electron bremsstrahlung emission during electron cyclotron heating (ECH) and current drive (ECCD). The system consists of a vertically viewing pinhole camera equipped with an array of CdTe detectors. CdTe technology was chosen for this system in order to satisfy the combined requirements of good temporal and spatial resolution, of efficient γ -ray rejection and of compactness. On TCV, 14 partially overlapped viewing chords span the entire outer minor radius of the plasma, with a radial resolution of ~ 2 cm on the midplane (Fig. 1). The intrinsic energy resolution is ~ 5 – 7 keV. After amplification, each signal is distributed to 8 discriminator-counter chains, generating spectra in the range 10–150 keV. Count rates up to 1.5×10^5 s⁻¹ can be detected before the onset of pileup. The time resolution, determined by the requirement of a relative statistical noise $< 10\%$, is in the order of 1–5 ms.

The ECH and ECCD experiments described in this paper have been carried out with up to three 0.5 MW gyrotrons, operating in X-mode at the second harmonic (82.7 GHz) [2]. The launching mirrors can be independently rotated in both the poloidal and the toroidal direction, providing great flexibility in the choice of heating locations and parallel wave numbers. The HXR camera constitutes a crucial tool for investigating the location of the power deposition and the distribution and dynamics of suprathermal electrons. Initial results are presented in this paper.

2. Suprathermal electron population during ECH and ECCD

The parallel wave number of the electron cyclotron (EC) wave was scanned in a set of similar discharges by varying the toroidal launching angle Φ from -35° to $+35^\circ$ (this angle is defined

at the launcher, the 0° case corresponding to pure ECH). In these discharges the plasma current was 170 kA, the toroidal field 1.4 T, the peak density $2\text{--}2.5 \times 10^{13} \text{ cm}^{-3}$, the plasma elongation 1.3 and the triangularity +0.3. A total power of 1.5 MW was injected near the plasma center.

The intensity of hard X-ray bremsstrahlung emission increases with $|\Phi|$, in both the co- and counter-ECCD directions (Fig. 2). In the co-ECCD case the current-drive efficiency has also been found to increase with Φ , and the largest non-inductive currents in TCV to date have been generated at the maximum toroidal angle explored in this scan (35°). This is somewhat in contrast with code predictions, which have generally placed the optimum angle between 25 and 30° [3]. This scan has proven fruitful also in allowing us to identify a range of angles ($5\text{--}15^\circ$) in the counter-ECCD direction in which very high central electron temperatures (up to ~ 10 keV) are obtained.

In the pure ECH case the shape of the measured spectrum is consistent with the emission from a Maxwellian plasma of temperature equal to that measured by the Thomson scattering

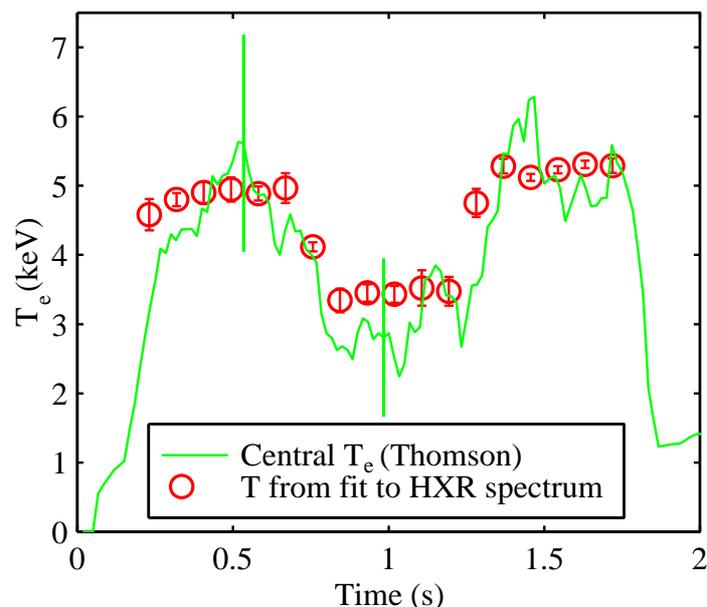


Fig. 3 Comparison between central electron temperature measured by Thomson scattering (solid line) and effective temperature obtained by a 3-point exponential fit to the hard X-ray spectrum from the plasma center (circles), with 1.5 MW of EC heating (off-axis in the middle part of the discharge, on-axis elsewhere).

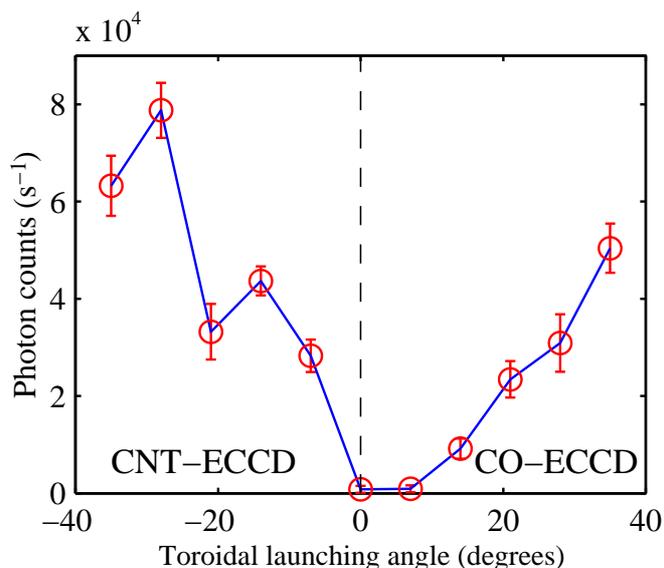


Fig. 2 Hard X-ray emission from the plasma center in the range 40–50 keV as a function of the toroidal launching angle, at constant current, density and plasma shape (central heating, 1.5 MW).

diagnostic; this comparison can be quantified by calculating an effective photon temperature through an exponential fit to the spectrum: an example is shown in Fig. 3. Rough analytical estimates of the expected absolute photon emission from a Maxwellian plasma are also in good agreement with the measurement.

In the ECCD cases, not only is the intensity considerably higher than in the ECH case at all energies, but the effective photon temperature is typically in the range from 20 to 60 keV (see Fig. 4), clearly revealing the presence of a suprathermal tail in the electron velocity distribution.

The dissimilarity between the ECH and ECCD cases, further seen in the integrated spatial profiles in Fig. 5, is in qualitative agreement

with numerical simulations carried out with the CQL3D Fokker–Planck code [4]. In the pure heating case the effect of the EC wave is to increase the temperature of the bulk plasma without appreciable modification of the shape of the distribution function, owing to rapid thermalisation of the heated electrons. By contrast, the preferential heating of suprathermal electrons on the low-field side of the resonance in the ECCD case permits the generation and sustainment of a non-Maxwellian tail, which carries the non-inductive current.

3. Investigation of fast electron dynamics

Studies of fast electron dynamics in large tokamaks have generally indicated [5,6] that collisional slowing-down (momentum destruction and pitch-angle scattering) is the dominant relaxation mechanism, whereas radial diffusion plays only a secondary role.

In the TCV tokamak the characteristic times for these phenomena are comparable with the temporal resolution of the HXR camera. In order to study the response and relaxation phenomena in detail, we have carried out an experiment with modulated EC power. Under stable plasma conditions, the excellent repeatability and localisation of EC-wave–plasma coupling have allowed a substantial enhancement of the effective time resolution (down to $\sim 300 \mu\text{s}$) through summation of the photon counts over multiple modulation periods. The modula-

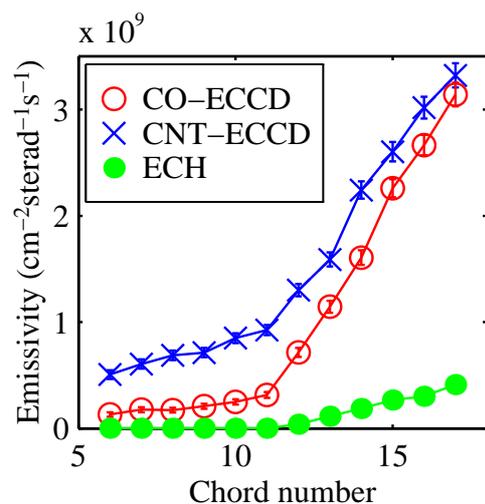


Fig. 5 Spatial profiles of line-integrated hard X-ray emissivity (24–32 keV), for the same conditions as in Fig. 4. The chords are numbered from the plasma edge to the center, with a radial separation of ~ 2 cm.

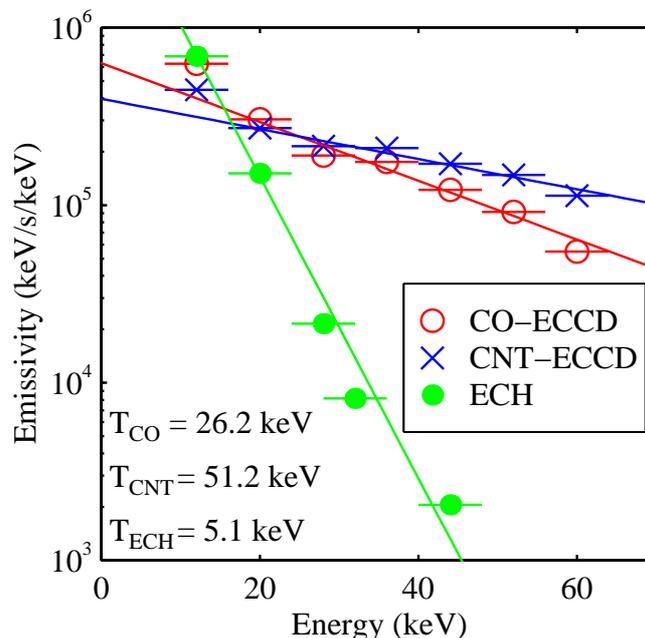


Fig. 4 Central hard X-ray emissivity for similar shots with co-ECCD ($\Phi = 21^\circ$), counter-ECCD ($\Phi = 21^\circ$), and pure ECH, respectively (central heating, 1.5 MW). In the exponential fits in the ECCD cases the lowest energy point was ignored, as it is influenced by the bulk Maxwellian distribution.

tion period must of course be a multiple of the sampling interval for the HXR diagnostic. In the example shown in Fig. 6, 1 MW of ECCD power was modulated at 100% with a period of 9.36 ms; the HXR sampling time was $585 \mu\text{s}$ and the counts were then summed over 10 periods. The resulting signal is shown in Fig. 6 for a central chord and four different energy levels. The relaxation dynamics at turn-on and turn-off are clearly adequately resolved.

To extract the essential physics of the suprathermal electron dynamics, we have employed a simple model consisting of a source (the localised

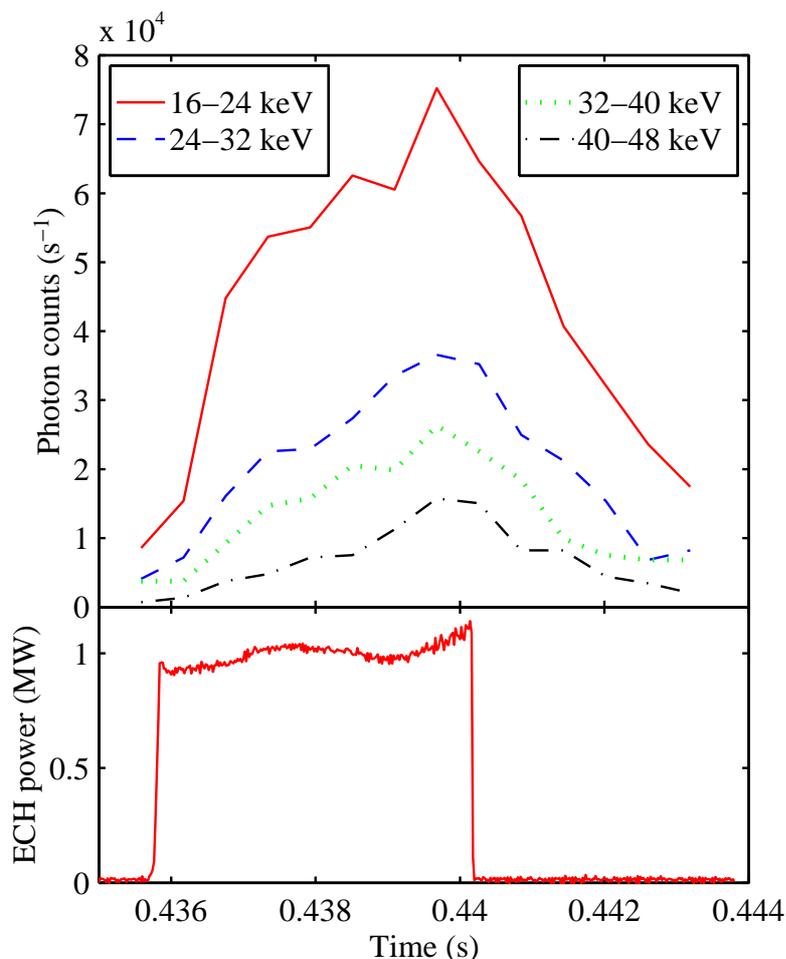


Fig. 6 Hard X-ray emission from the plasma center, for four different energies, and EC power vs. time (central co-ECCD, $\Phi = 21^\circ$). The photon counts are summed over 10 successive EC modulation periods.

EC power), a Krook collision operator, and a radial diffusivity. The characteristic times are varied to simulate the time history of the experimental HXR emissivity. In a preliminary comparison, we have found that satisfactory agreement is obtained only when the collisional term is dominant, with characteristic relaxation times of the order of 1–3 ms: these values are consistent with the collisional slowing-down time for the energy range under consideration.

Under these conditions, the spatial distribution of the HXR emissivity can be taken as a good measure of the EC power deposition profile. More detailed studies are currently in progress. Comparisons between the experimental local (Abel-inverted) emissivity profile and the power deposition profile calculated by ray tracing are also underway.

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