Suprathermal Electron Studies in the TCV Tokamak: Design of a Tomographic Hard-X-Ray Spectrometer

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Introduction and motivations

Electron cyclotron resonance heating (ECRH) and current drive (ECCD)⁴, disruptive events, and sawtooth activity⁵ are all known to produce suprathermal electrons in fusion devices, motivating increasingly detailed studies of the generation and dynamics of this suprathermal population. Measurements have been performed in past years in the TCV tokamak⁶ using a single pinhole hard-X-ray (HXR)⁷ camera and electron-cyclotron-emission (ECE)⁸ radiometers, leading in particular to the identification of the crucial role of spatial transport in the physics of ECCD⁹. The observation of a poloidal asymmetry in the emitted bremsstrahlung radiation motivates the design of a proposed new tomographic HXR spectrometer, reported in this poster. The design, which is based on a compact, modified Soller collimator concept, is being aided by simulations of tomographic reconstruction. Quantitative criteria have been developed to optimize the design for the greatly variable shapes and positions of TCV plasmas.

Electron cyclotron resonance heating (ECRH) and current drive (ECCD)

2nd harmonic (X-mode): 6 steerable launchers
Power: 0.5 MW each
Frequency: 82.7 GHz
Density limit: 4X10¹⁹ m⁻³
Pulse length: 2s

3rd harmonic (X-mode): 1 upper steerable launcher
Power: 1.5 MW
Frequency: 118 GHz
Density limit: 1.1X10²⁰ m⁻³
Pulse length: 2s

Suprathermal electron generation in TCV

Suprathermal electron population

Disruptive instability events and magnetic reconnection:

Neoclassical Tearing Modes (NTM)
Sawtooth activity

Review of TCV Results

RF field-particle resonance interaction (ECRH, ECCD)

Bremsstrahlung emission (hard X-rays) due to electron-ion collisions.

ECE emission due to the Larmor motion predominantly from suprathermals on HFS or obliquely on LFS.

The HXR camera on loan from TORE SUPRA⁴ clearly evidenced the LFS-HFS asymmetry of the poloidal bremsstrahlung distribution (properly related to trapped particles).

Other diagnostics used:
- High-field-side electron cyclotron emission (ECE) radiometer
- Oblique ECE
- Multiwire proportional chamber
- Diamagnetic loop coil

New diagnostics being installed:
- tangential HXR camera
- Vertical ECE

Suprathermal electron population is generated

X2 generates suprathermal electrons and contributes to enhance the X3 power absorption⁹

Fast electron broadening from transport observed in many ECCD discharges (resulting in ECCD profiles)

Design for up to nine spectroscopic HXR cameras (C1,…,C9) on the right figure.

Novel collimator system design adapted from the Soller collimator concept; radially-disposed Soller plates

Two limiting concepts can be envisioned:
- a) Uniform angular detector spacing: provides finer spatial resolution near the instrument axis than at its edges, suitable for cameras with a small fan aperture as in the case of mainly vertically viewing cameras (C1, C2, C3, C7, C8, C9) but also C4 and C6.
- b) Uniform chord separation on any plane perpendicular to the camera axis: advantageous in the case of camera C5, which has a wider angular fan view.

Spatial sampling: ~ 2 cm
Energy range: 20-200 keV
Pile up limit: ~1MHz
Energy resolution: ~ 5 keV at 60 keV of photon energy
Time resolution: down to 1 ms

Proposed tomographic spectroscopic system for TCV

Spatial sampling: ~ 2 cm
Radial detector array (~30 CdTe detectors)
Energy range: 20-200 keV
Pile up limit: ~1MHz
Energy resolution: ~ 5 keV at 60 keV of photon energy
Time resolution: down to 1 ms

Adaptable to other fusion devices
Wide poloidal coverage
Filters (Al, S.S.) and vacuum windows (Be)
Neodymium YAG crystals for amplification

Cameras (C1,…,C9 but also C4 and C6).
Uniform angular detector spacing: provides finer spatial resolution near the instrument axis than at its edges, suitable for cameras with a small fan aperture as in the case of mainly vertically viewing cameras (C1, C2, C3, C7, C8, C9) but also C4 and C6.
Uniform chord separation on any plane perpendicular to the camera axis: advantageous in the case of camera C5, which has a wider angular fan view.
Radial detector array (~30 CdTe detectors)
Modified Soller Collimator design: tungsten metal foil with adjustable collimator aperture:
- Protect the photon statistics
- Guarantee oblique photon shielding
- Filters (Al, S.S.) and vacuum windows (Be)
- Wide poloidal coverage
- Adaptable to other fusion devices
- Time resolution: down to 1 ms
- Energy resolution: ~5MeV@500keV of photon energy
- Time resolution: down to 1 ms
- Energy resolution: ~5MeV@500keV of photon energy
- Energy range: 20-200 keV
- Spatial sampling: ~ 2 cm

Graphs and figures showing the proposed tomographic spectroscopic system for TCV.
Tomographic reconstruction procedure

Tomographic reconstruction of a 2D emission pattern on the TCV poloidal plane

Minimum Fisher information regularization [14,15]

The number and distribution of the cameras is determined by a compromise between the quality of tomographic reconstruction and the cost, within the constraints set by the TCV port geometry.

A quantitative estimation of the quality of the reconstructed emissivity by assuming a given set of cameras (CS) used in the tomographic process is given by defining a reconstruction variance (RV):

$$RV_{CS}(O,R) = \frac{\sum_{i=1}^{N_\text{LOS}} (\frac{R_i}{O_i} - \frac{O_i}{R_i})^2}{\sqrt{\sum_{i=1}^{N_\text{LOS}} (R_i/O_i)^2 \sum_{i=1}^{N_\text{LOS}} (O_i/R_i)^2}}$$

where $F = \left( \sum_{i=1}^{N_\text{LOS}} F_{i}\right)/N_p$

which compares the original simulated emission (O) with the reconstructed one (R).

The gain in the quality of the reconstruction obtained by adding an additional camera is not a constant, the benefits being more significant when going from a 2 to a 3 camera setup and from 3 to 4 and becoming modest with each additional one. On the right-hand graph, the typical RV behavior for a particular $m=2$ emission pattern is shown (see also the section below).

Tomographic validation

Best camera setup for $N=2,3,4$ tomographic camera system

Conclusions:
The physics of heating and current drive and of MHD instabilities and their mitigation are all crucial to tokamak reactor operation and are tightly linked to the understanding of suprathermal electron generation and dynamics. To address these physics questions a novel design of a tomographic hard-X-ray spectrometer is being developed for the TCV tokamak. The design for different camera setups has been assisted by tomographic validation. The flexibility and compactness of the present design is expected to be readily adaptable to other fusion devices.