Charge Exchange Recombination Spectroscopy Measurement of Ion Temperature, Rotation and Impurity Density Profiles on the TCV Tokamak

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Introduction. The Charge eXchange Recombination Spectroscopy (CXRS) diagnostic [1] operated on the TCV tokamak with a modulated hydrogen diagnostic neutral beam (DNB) [2] and provides local measurements of ion temperature (*20 eV...1 keV*), impurity density, together with toroidal (up to *±50 km/s*) and poloidal rotation, through the analysis of spectral moments of impurity radiation, usually C^{VI} line (*529.1 nm, n=8→7*). The unique shaping capabilities (elongation *1-2.8*, positive and negative triangularity) of the TCV [3] (*R=0.88 m, a=0.25 m*), high (up to *4.5 MW*) available electron EC heating power, absence of auxiliary (NBI) ion heating permits to measure intrinsic plasma rotation and study the nature of momentum transport and generation in tokamaks [4] for limiter and diverted topology, in L- and H-mode. Performance of the CXRS diagnostic was enhanced by upgrades of the optical system and DNB, reducing temperature uncertainties to (*±5...30 eV*) and velocity uncertainties to (*±0.3...2.5 km/s*) for wide range of the TCV experimental scenarios.

1. CXRS principles. In the TCV, with near full graphite tiled first wall, the CX [5] is optimised for C^{6+} and *50 keV* H^0 neutrals, injected in 10-50 ms bursts by a low power DNB:

$$H^0+C^{6+} \Rightarrow H^{+}+C^{5+}(n,l); \qquad C^{5+}(n,l) \Rightarrow C^{5+}(n',l')+h\nu. \tag{1}$$

The diagnostic can also measure parameters of boron (B^V), helium (He^{II}) and other ions.

The ion rotation velocity (v_i), temperature (T_i) and concentration (n_i^Z) are deduced from Doppler shift (λ^D-λ_0^M), Doppler broadening ($\Delta\lambda_\sigma^D$) and intensity (Φ_{CCD}) of the line observed by CXRS diagnostic:

$$v_i = c\times\frac{\lambda^D-\lambda_0^M}{\lambda_0^M};T_i = m_i^Z c^2\left[\frac{\Delta\lambda_\sigma^D}{\lambda_0^M}\right]^2;n_i^Z = \Phi_{CCD}\Big/\int n_B^{E_0}dl\times\langle\sigma v\rangle_{CX}\times\Omega S\times\varepsilon_{tot}^{opt} \tag{2}$$

where λ^D is the measured line centroid wavelength, $\Delta\lambda_\sigma^D$ − line Doppler broadening width, Φ_{CCD} − photon flux on detector from diagnostic view line, $\int n_B^{Eo}dl$ − line integral of beam neutrals along view line, $<\sigma v>_{CX}(E_B,T_i,n_i,Z_{eff})$ − effective CX reaction rate; ΩS − geometrical factor for light collection from view cone, ε^{opt} − optical system transmission coefficient. A precise interpretation of the CX line features is required accounting for atomic physics and diagnostic instrumentation effects: λ_0^M (wavelength free from motional Doppler shift) depends on plasma parameters (n_e, T_i, Z_{eff}, B_T) due to the multiplet structure; the measured line width ($\Delta\lambda_\sigma$) is a combination of Doppler broadening, line width due to superposition of line fine structure ($\Delta\lambda_\sigma^M$) and

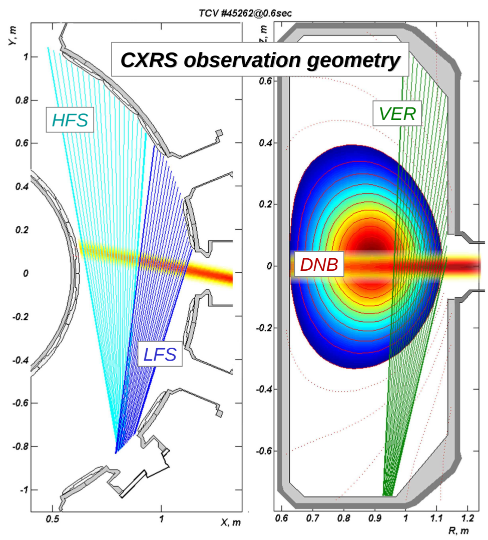

Fig.1: CXRS-TCV layout

diagnostic instrumental function ($\Delta\lambda_\sigma^{IF}$).

$$(\Delta\lambda_\sigma)^2 = (\Delta\lambda_\sigma^D)^2 + (\Delta\lambda_\sigma^{IF})^2 + (\Delta\lambda_\sigma^M)^2 \qquad (3)$$

The dependences of λ_0^M and $\Delta\lambda_\sigma^M$ on experimental conditions were evaluated using atomic and spectroscopic database ADAS for 37 allowed inter-multiplet (n=8, l=-7...7) to (n=7,l=-6...6) transitions of C^{VI} 5290.58 A^O line. For TCV's conditions (B_T=1.4 T, T_i=0.1...1.0 keV and n_e=0.2-12×$10^{19}m^{-3}$), λ_0^M varies by 0.07 A (±2 km/s), and $\Delta\lambda_\sigma^M$ is in the range of 0.2...0.6 A (up to 100 eV). Multiplet effects are relatively small for core plasma with high ion temperature (0.3-1.0 keV) and strong toroidal rotation (few 10 km/s), however, the effect is significant near the plasma edge (T_i:20...50 eV, v_i~0).

2. Diagnostic setup and instrumentation. The active CXRS diagnostic was installed on TCV in 2001 with 8 toroidal observation LFS chords, 2-3 cm spatial resolution. The current diagnostic setup comprises three observation systems (Fig.1): a full plasma minor diameter is covered by two toroidal Low Field Side (LFS) and High Field Side (HFS) systems with spatial resolution of ~15 mm; a Poloidal (VER) system intersects the DNB vertically on the LFS with a spatial resolution of ~7 mm. Each system uses collection optics, periscope mirrors and a focussing lens to collect light emitted by the plasma, a bundle of optical fibres to relay the light to Czerny-Turner spectrometer with multi-channel 2D CCD camera.

An increase of the active-to-passive CXRS signal ratio by ~5× was achieved during DNBI upgrades described in [2]. To improve the CXRS spatial resolution, the number of lines of sight were increased from 16 to 40. Two CXRS systems were equipped by CCD cameras featuring on-chip gain (Andor™ iXon^{EM+}) resulting in improved sensitivity (85→96%) and time resolution. Measurements (512x20 frame transfer format) with integration times down to 1.6 ms, instead of 12 ms (used in 2007-2010); the S/N ratio was improved by a factor of 8. These cameras provide flexibility in the acquisition parameters, with gain and integration time modifications, and the selection of EMCCD or conventional amplification between shots.

3. Alignment and calibration. The collection (sampling) CXRS volumes are determined from the observation view lines alignment in the tokamak vessel and the neutral density distribution of the diagnostic beam. For this procedure the position of each CXRS observation chord is first verified by back illuminating optical fibres through the observation mirrors of CXRS system onto an in-vessel target during a TCV vacuum opening (and/or on optical table, before installation on the tokamak). Since the observation chords of all CXRS systems (two toroidal and poloidal) consist of fibre pairs shifted either in the vertical or horizontal direction, the beam is aligned between paired chords to give equal CXRS signal intensities during Tokamak plasma discharges. This permits an alignment of CXRS diagnostic chords within the 8 cm beam to an accuracy of 2–3 mm. The beam profile in the tokamak is obtained from optical and calorimetric measurement of the beam divergence and focal length [2].

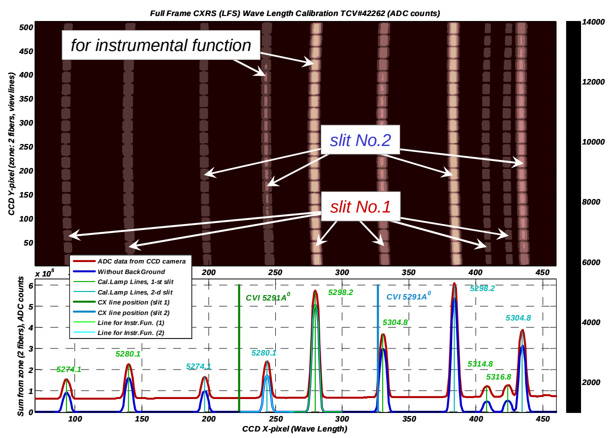

Fig.2: Post-shot calibration data in full frame mode with Ne pen-ray lamp.

The absolute calibration of the CXRS diagnostic ($\Omega S\times\varepsilon^{opt}$) was performed

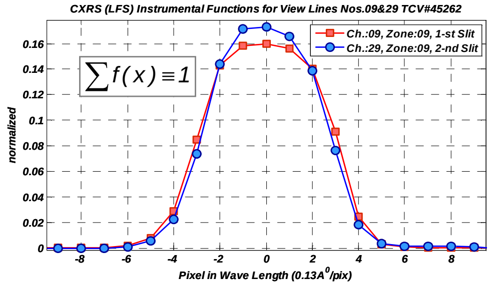

Fig.3: Instrumental function.

using homogeneous light source (Uniform Source Integrating Sphere by Labsphere Ltd., whose radiance is known as a function of wavelength) positioned in the vessel and filling the observation chord's numerical aperture. The complete optical path is thus calibrated, accounting for losses from mirrors, vacuum windows, lenses, fibres, spectrometer elements and characteristics of light collection cone. The total optical system transmission coefficients from the absolute calibrations are in a good agreement with estimations from multiplying optical efficiencies of individual optical elements from their specifications. The CCD camera performance optimisation and calibration (stability of instrumental function, EM gain vs photon flux, etc.) is performed by fibre illumination at the observation head side with a *He-Ne 5435*A^O gas laser or a low intensity Neon pen-ray lamp.

Plasma rotation measurements with an accuracy of *≤1 km/s* require precise wavelength calibration (relation between position on the CCD and the wavelength). This is achieved by acquiring spectral lines from retractable Ne calibration lamp, installed in the proximity of the fibre bundle head at the tokamak side, after each tokamak shot using full frame and with pixel binning for pairs of view lines. The 4-6 lamp lines covered the CCD (Fig.2) permits a wavelength calibration accuracy of *0.001...0.005 A* (*0.07...0.3 km/s*, negligible for V_i calculation) with a dispersion of *0.11-0.13* A^O*/pixel* at ~*5300* A^O and to track mechanical drifts. The diagnostic instrumental function ($\Delta\lambda_\sigma^{IF}$) is evaluated for well separated lines of the calibration spectra (Fig.3).

4. Data evaluation. Acquired CXRS raw data: experimental spectra and wave-length calibrations are analysed numerically in a sequence of steps:

- Normalised spectroscopic instrumental functions for each observation chord (Fig.3) are taken from well sampled calibration lines; the relation between CCD pixel and wavelength are obtained from least-squares fit with the convolution of multi-Gaussian calibration spectral profile;
- Active (with beam) and passive frames of spectra are evaluated referenced to the DNB current measurement during plasma discharge;
- The active spectra fit including convolution of bi-Gaussian spectra (two slits) and instrumental functions gives 7 parameters for observation chord pair: 2 FWHMs, 2 mean CX line positions, 2 active line integrals and a common offset; uncertainties in each parameter are evaluated based on photon statistics, time variation of passive signals, uncertainties in the calibration and camera noise;
- Sampling volumes coordinates (CX observation cones and DNB intersection) are mapped to flux coordinates from the plasma equilibrium reconstruction;

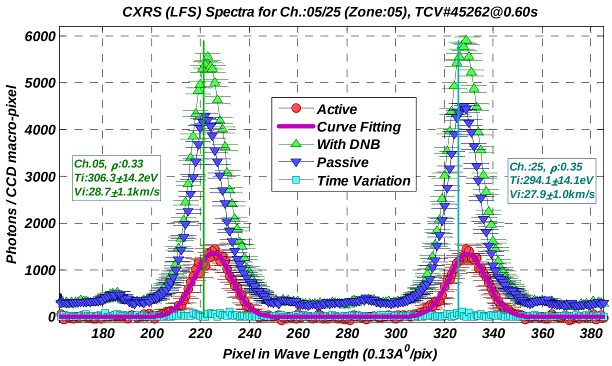

Fig.4: CX spectra: with DNB, active, interpolated passive and statistical variation for passive.

- Local ion parameters (v_i, T_i and n_i^Z) with uncertainties are calculated from active spectra fit (Fig.4), iterated for beam attenuation and plasma parameters;
- Local impurity parameters and uncertainties for each observation chord, each CXRS system and each time slide are stored in the TCV experimental data base for physics analysis, eg: ion temperature profile evaluation from all CXRS systems averaged during quasi-stationary phases of plasma discharges (Fig.5).

The measurement uncertainties in ion temperature and rotation are calculated from the uncertainties of active profiles least-squares fit to a non-linear function with local linearization. Photon statistics are essential for fitting uncertainties for quasi-stationary plasmas. The theoretical limits for uncertainties from photon statistics, evaluated from a simulation of the system based characteristics of the optical transmission lines, spectrometer and CCD camera give ΔT_i limited by ~5 eV & $\Delta v_i \geq 0.25$km/s. The accuracy of Gaussian fit is affected by "parasitic" spectral lines other than C^{VI}. The uncertainty from passive background subtraction are important for non-stationary conditions, especially when the characteristic variation timescale of plasma parameters is of the same order as the CXRS integration time. The noise introduced in the CCD camera is negligible (~10 photons/macro-pixel for Andor cameras). The uncertainties from instrumental function are non-negligible for low ion temperature ≤30 eV ($\Delta\lambda_\sigma^D \leq \Delta\lambda_\sigma^{IF}$) for LFS and VER systems and ≤70-100 eV for HFS. The uncertainty in the impurity density evaluation is dominated mostly by uncertainties in the absolute calibration (~10%) and uncertainties in the beam full energy neutral distribution in the observation region (5...10%).

Discussion. The performance of CXRS diagnostic fulfil the TCV requirement for ion temperature, toroidal rotation, and impurity (carbon C^{VI}) density measurement in quasi-stationary and slow evolving plasmas. The study of profiles evolution during transient cycles (ELMs, sawtooth, etc.) required to increase the DNB modulation frequency from 20-100 to 250-500 Hz (the CXRS acquisition already allows to operates at 1.6-2.0 ms integration time).

The poloidal rotation on the TCV is relatively small (~1 km/s), several options for upgrade of the vertical (poloidal) CXRS observation system, including differential Doppler spectroscopy scheme and direct imaging of plasma sampling volume to spectrometer, are recently under investigation.

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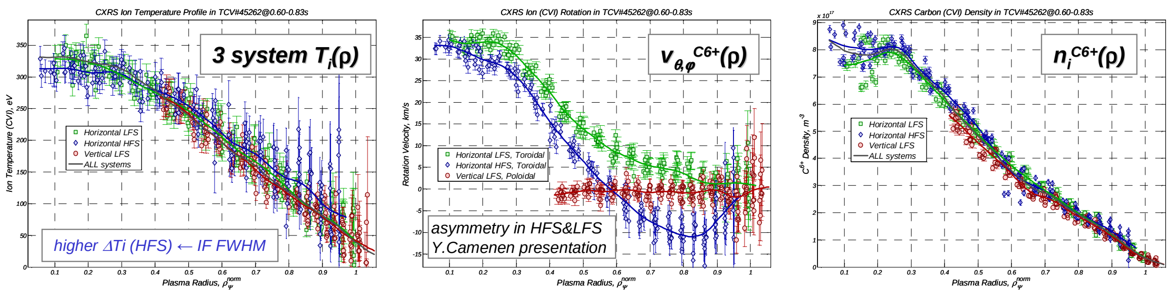

Fig.5: Ion temperature, rotation and impurity density profiles for quasi-stationary phase of the TCV discharge