

Progress in Charge Exchange Recombination Spectroscopy (CXRS) and Beam Emission Spectroscopy (BES) for ITER

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Introduction and overview A CXRS diagnostic for ITER based on a 100 keV/amu diagnostic neutral beam has been accepted as a vital and viable path towards key core plasma parameters such as ion temperature, plasma rotation and the main low-Z ion densities including helium ash^{1,2,3)}. The high density of an ITER plasma leading potentially to a substantial beam attenuation has been a particular concern for the feasibility of an active beam diagnostic. In the current paper we demonstrate that the use of Beam Emission Spectroscopy (BES) in combination with Charge Exchange Recombination Spectroscopy (CXRS) extends the scope for the core diagnosis of high-density fusion plasmas considerably. Substantial progress has been made in recent years in the use of BES for the diagnosis of hot fusion plasmas mostly in terms of magnetic field measurements – via the motional Stark features (MSE) – but also in terms of local beam densities deduced from absolute beam emission intensities⁴⁾. Making use of beam densities derived from BES intensities avoids intrinsic error propagation linked to standard beam attenuation calculations and serves also as a tool for spectroscopic self-calibration, which is an important asset in view of anticipated ‘first-mirror’ deterioration.

CXRS diagnostics and global data consistency. The ultimate aim of a functional CXRS diagnostic is to provide a comprehensive

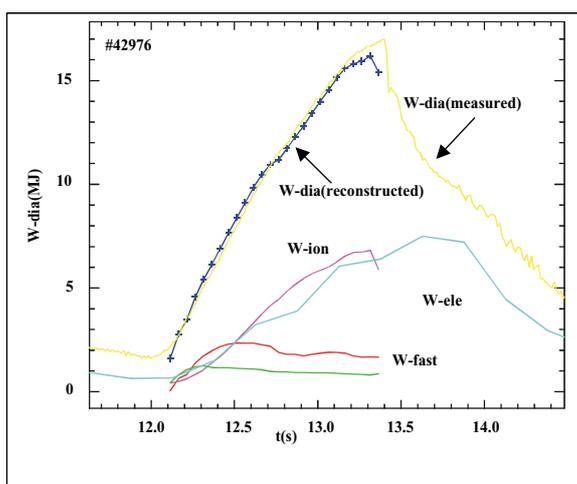


Figure 1 Example of reconstruction of W_{dia} from CXRS (W_{ion} , W_{fast}) and LIDAR (W_{ele}) and comparison with measured diamagnetic energy, see reference [1].

experimental data base required for plasma control and for consistency checks of key plasma data such as plasma energy (cf. Fig.1), Z_{eff} and beam-target and thermal-thermal neutron production. To achieve this goal a comprehensive data base on densities, temperatures and toroidal speed of the main ions (intrinsic and seeded impurities, helium ash and also bulk plasma ions) have to be provided with sufficient accuracy by CXRS. In fact, the challenge of providing

accurate helium ash density data is inseparable from the task of assessing the entity of all ions present in the plasma. Moreover, the sensitivity of helium ash measurements is considerably increased making use of ion temperature and plasma rotation as deduced from the CXRS analysis of CVI or NeX spectra due to their much higher emission rates.

Combination of CXRS and BES Combining the measurement of beam emission and CXRS with:

$$I_{\text{bes}}(E) = \frac{1}{4\pi} n_e \cdot Q_{\text{BES}} \cdot \int n_b(E) ds \qquad I_{\text{cx}} = \frac{1}{4\pi} n_z \cdot Q_{\text{cx}}^z \cdot \int_{\text{l.o.s}} n_b ds$$

respectively, leads to

$$\frac{n_z}{n_e} = \frac{I_{\text{CX}} \cdot Q_{\text{BES}}}{I_{\text{BES}} \cdot Q_{\text{CX}}}$$

In this way the absolute intensity measurement of CX photon fluxes is replaced by an intensity ratio ($I_{\text{CX}}/I_{\text{BES}}$), which can be cross-referenced by the underlying continuum background. Any changes of periscope mirror reflectivity in course of an ITER pulse or during extended operations are thus taken care of. Moreover, the exponential error propagation characteristic for beam stopping calculations emphasised by the high dimensions and density of ITER is avoided.

Signal-to-Noise predictions for ITER The spectral signal-to-noise ratio is calculated for the case of continuum radiation fluctuations as the main noise source, that is, we assume that beam modulation leads to a perfect suppression of background line-emissions. In fact, the occurrence of ELM related spurious spectral emissions would require optimisation of data acquisition schemes, avoiding thus asymmetries in beam-on and beam-off phases.

The exponential beam attenuation factor in the S/N-ratio leads to a substantial reduction,

$$\frac{S}{N}(\lambda_{1/2}) = \frac{I_n c_\alpha \sigma_{\text{CX}} \exp\left\{-\int_z dr n_e \sum c_z \sigma_{z,\text{stop}}\right\}}{8\pi^2 w_\perp \cdot \sin \alpha \cdot e \sqrt{\pi Z_{\text{eff}} g_{\text{ff}} L_p B}} \sqrt{\Delta t \frac{\Delta \lambda \cdot \lambda_{\text{de}}}{\lambda_\alpha^2} \mathfrak{R}}$$

which has to be compensated by a boost in detector sensitivity $\mathfrak{R} = T \cdot \eta \cdot \Delta \Omega \cdot A_{\text{spec}}$. We propose to use high-étendue (f/3), high resolution spectrometer (2.5Å/mm) with one instrument dedicated to one radial channel each.

	$7.25 \cdot 10^{19} \text{m}^{-2}$	$1.08 \cdot 10^{20} \text{m}^{-2}$	$1.27 \cdot 10^{20} \text{m}^{-2}$	$1.45 \cdot 10^{20} \text{m}^{-2}$
CVI (1.2%)	353	115	65	37
HeII(4%)	73	26	15	9
Be(2%)	272	91	52	30
D,T(38.4%)	125	45	26	16

Figure 2 S/N table summarising the expected spectral signal-to-noise for the main light impurity ions including deuterons and tritons at $r/a=0.3$.

BES and MSE on ITER using DNB Calculations using relevant ITER equilibrium plasma parameters and ADAS excitation rates for beam emission show that the MSE H_α spectral features are clearly separated with intensities well above the continuum background and the broad-band CX D_α and T_α features representing thermal deuterons and tritons (cf.Fig.3).

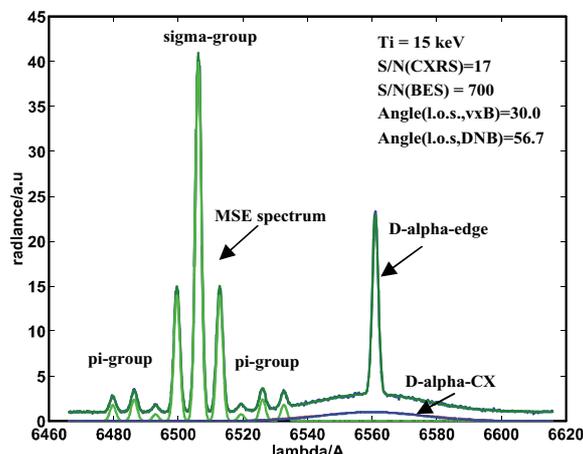


Figure 3 Simulated D-alpha/T-alpha CX spectrum including MSE features for intensity cross-calibration and magnetic field measurements. The ratio I_π/I_σ experiences maximal variations for the expected ITER q-profile.

CXRS periscopes for ITER The selected top port periscope viewing the diagnostic beam at an angle of about 70° (cf.Figs.4,5) with respect to the toroidal direction and of 30° with respect to the Lorentz field vector ($\mathbf{E}_L = \mathbf{v} \times \mathbf{B}$) enables the measurement of toroidal and poloidal plasma rotation as well as a deduction of the total magnetic field (Stark splitting) and its pitch angle(intensity ratio of σ - and π -components).

A central issue for the ITER CXRS diagnostic is the capability for helium ash measurements in the plasma core. Competing active excitation processes, e.g. the ‘plume effect’, are minimised by the observation port with a view approximately perpendicular to the magnetic field lines. For this reason an

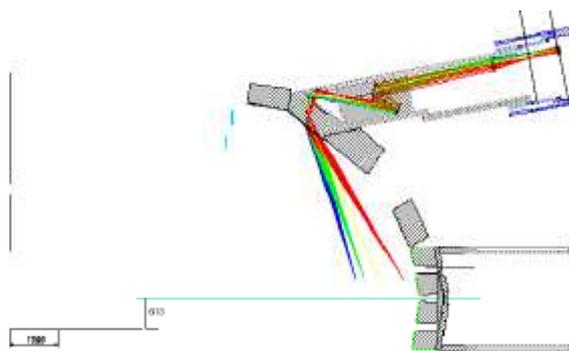


Figure 4 Schematic layout of CXRS top view ‘edge’ periscope

assembly of top view periscopes was chosen. One ‘edge periscope’ (cf. Fig.4), one ‘core periscope’ in the section next to DNB section, and finally, a reference edge periscope for poloidal rotation measurements in the DNB section.

CXRS diagnostic for bulk plasma ions

The ITER simulation including MSE and CX features demonstrates also the potential deduction of the local fuelling ratio $n_D:n_T$ along the beam-path. Recent tests at JET and TEXTOR have shown that the local deuteron density can be extracted from the analysis of a CX D-alpha spectrum (cf. [5]) and radial profiles of H/D can be deduced. A key issue for this technique is the use of independently measured ion temperatures and rotations (e.g. $T_i(C^{6+})$) thus reducing the number of free parameters in the

D-alpha spectral analysis. The projected error margins for the ITER case are of the order 20% for local D and T densities. Further atomic modelling of competing excitation features (beam-halo, passive CX features, CX cross-section effects) and optimisation studies of suitable extraction algorithms together with more experimental evidence from TEXTOR or JET are scheduled for the near future. The spatial resolution of the ITER CXRS periscope varies between 8 cm (plasma centre) and 15 cm (plasma edge).

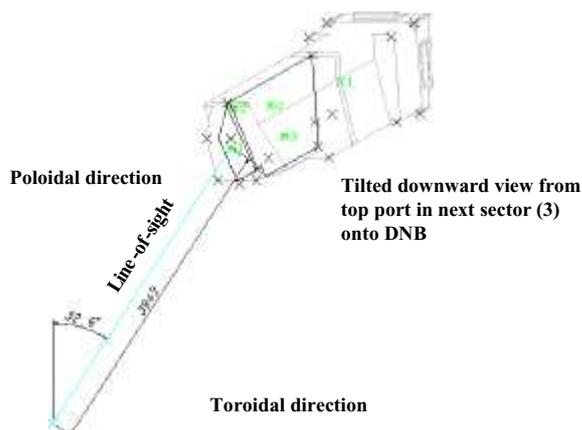


Figure 5 A tilted downward view enables the measurement of a toroidal velocity component and provides also an average angle of about 45° for the $\mathbf{v} \times \mathbf{B}$ Lorentz field vector.

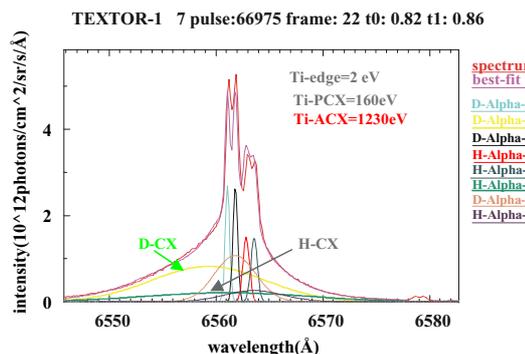


Figure 6. Extraction of radially resolved H/D ratios from a CX analysis of an active D-alpha/H-alpha spectrum at TEXTOR. The H/D ratio is scanned by fuelling a D-plasma with H neutral beams.

Summary and Conclusions: A

combined CXRS and BES/MSE diagnostic based on the ITER DNB promises to be a powerful diagnostic tool for impurity and bulk ions as well as local magnetic fields.

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