The CXRS diagnostic for ITER and the CXRS-Pilot Experiment on TEXTOR

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Abstract. Charge eXchange Recombination Spectroscopy (CXRS) will play a crucial role in the diagnosing of burning plasmas: items like helium ash, transport barriers, impurity content or fuel ratio can all be assessed with CXRS. In fact this is the only direct method to obtain information about the light impurity ions, such as temperature, concentrations and rotation, in the core of the plasma. Two of such systems are foreseen at ITER, one in the upper port plug and one on the equatorial level, both viewing the 100 keV diagnostic H-beam.

Challenges for this diagnostic development project are: constructing a mirror close to the plasma able to keep its reflectivity under the extreme bombardment by neutrons, erosion by fast neutrals and deposition of sputtered material, design of an optical labyrinth with well enough neutron shielding, developing spectrometers with a throughput about a factor 100 larger than on present day devices, with a similar or better dispersion, calibration and alignment techniques and last but not least, finding ways to obtain the physics relevant information from the measured complicated spectra in real time.

With all these issues in mind, an ITER-CXRS pilot experiment has been developed and became operational on the TEXTOR tokamak, to address some of the above aspects. The results of this show the feasibility and the sensitivity of the ITER system: the simulation code for ITER signal levels could be verified, the sensitivity to the current profile has been tested, the beam emission has been compared to beam attenuation calculations and used to obtain absolute impurity concentrations and a high throughput spectrometer became operational.

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THE ITER CXRS SYSTEM

The motivation for the CXRS diagnostic on ITER is the unique measurement of the core helium ash concentration, as well as the ability to provide profiles of the ion temperature, plasma rotation and low-Z impurity content. The measurement requirements of this system are summarized in table I. To achieve these, a 3.6 MW, 100 keV hydrogen diagnostic neutral beam (DNB) is foreseen. Two optical systems are planned: one periscope in the upper port 3 for the core observation (from $\rho=0$ to $\rho=0.8$) and one in the equatorial port for the edge (from $\rho=0.5$ to $\rho=1.0$).

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TABLE I: Measurement specification of the CXRS system for ITER, according to [1].

Parameter	Range	Time resolution	Space resolution	Accuracy
Helium density	1-20 %	100 ms	a/10	10%
Ion temperature	0.5-40 keV	100 ms	a/10	10%
Poloidal plasma rotation	1-50 km/s	10 ms	a/30	5 km/s – 30 %
Toroidal plasma rotation	1-200 km/s	10 ms	a/30	5 km/s - 30 %
Impurity conc. ¹ : $Z \le 10$	0.5-20 %	100 ms	a/10	20 %
Z > 10	0.01-0.3 %	100 ms	a/10	20 %

¹ presently foreseen is the diagnosis of the elements: H,D,He,Be,C, N, Ne, Ar

The analysis of the core (upper port) CXRS system starts with a simulation of the CXRS measurement process, aiming to determine the minimum sensitivity *S* required to achieve at the statistical error for the parameters as listed in table I:

$$S = E \times T \times Q.E. \times t_{int} \tag{1}$$

where *E* is the etendue *E*, *T* denotes the total optical transmission (mirror labyrinth, fibres and spectrometer), *Q.E.* the quantum efficiency of the detector and t_{int} the required integration time. The most critical parameter is the core helium density. It is found that $E=1 \text{ mm}^2 \text{sr}$ is necessary to arrive at the requirements (for T=0.05 and *Q.E.* =80 %). This provides the basic number for the spectrometer development [2].

The main components of the conceptual design of the core system are: (see Fig. 1):

- The first mirror, this 100 mm diameter mirror will be subject to high radiation levels, erosion by fast particles and deposition of sputtered material. Mirrors of mono crystalline Mo or with a Rh coating are presently under discussion.
- The retractable tube for 'easy' maintenance and replacement of the first mirror, mounted on the tube. The tube will also hold the shutter.
- The optical labyrinth to transport the light of the CXRS process with the required etendue and spatial resolution to the fibres at the end of the port plug.



FIGURE 1. Overview of the conceptual design of the core CXRS system on ITER, located in the upper port plug number 3. The central tube and the optical labyrinth are shown.

- The fibre bundle to transport the light over tens of meters to the spectrometer room. Goal is to reduce the radiation level inside the port plug to such values that there is no need to use radiation-hard fibers
- The spectrometer and detection system; Several options are yet under study to arrive at a system measuring simultaneously four wavelength bands (1: around 465 nm for He/Be; 2: 525 nm for C/Ar/Ne; 3 656nm for H/D/T; 4: 567 nm for N) with E=1 mm²sr, spectral resolution < 0.2 nm, time resolution = 10 ms, Q.E. > 80 %, spectrometer efficiency > 60 %.

THE TEXTOR PILOT CXRS SYSTEM

Several aspects in the design of the ITER CXRS system lack a firm scientific basis and additional experimental validation is desirable. For this specific purpose a CXRS system has been implemented on TEXTOR. This system has approximately the same geometry as on ITER, comprises of a spectrometer with characteristics close to the ITER requirements and ample experimental time on TEXTOR is available for specific diagnostics tests.

Potentially, the emission of the excited neutral beam particles can be used as a cross-calibration tool for absolute local impurity densities. Combining the measurement with the active CXRS signal, allows deducing the impurity concentration from the ratio of both intensities, without the need for a cumbersome absolute calibration [3,4]. This method will also avoid the accumulation of errors in the beam attenuation calculation. A test has been made on TEXTOR to compare three ways of deducing the helium density: from the electron density increase after a helium puff, from the calibrated CXRS signal in combination with a beam attenuation code, or from the ratio of CXRS to beam emission light. The result is shown in Figure 2.



FIGURE 2. The helium concentration f_{He} determined in three ways: a) by the increase of the electron density: $f_{He}=0.18\pm0.03$ (blue data point), b) from the I(CXRS) and a beam attenuation code (CHEAP, red) and c) from the I(CXRS) and beam emission intensity (black).

The three methods give similar values, but an extensive assessment of the accuracy of the latter method has not been done yet, and some discrepancies are still observed.

The beam emission spectral feature is also used for the determination of the direction of the magnetic field. On the TEXTOR setup it is tested if this diagnostic information, usually denoted as MSE (Motional Stark Effect), can be obtained from a purely spectral measurement such as shown in the left graph of Figure 3. On the right hand side the intensity ratio derived from this spectrum is compared to the theoretical prediction. Whereas in the centre these values correspond reasonably well, more to the edge large discrepancies appear which are attributed to the polarization characteristics of the metallic mirror used in the periscope. An assessment of the value of this technique is still ongoing.

A third item to be tested on TEXTOR is the validation of the CXRS simulation code, used to predict the ITER performance [4]. In general sufficient agreement between the signal to noise from the code prediction and the TEXTOR data is obtained, as shown in Figure 4. However, an accurate model for the passive emission in the code is still lacking, but absolutely necessary for predicting the ITER performance. An effort in this direction has now been initiated.



FIGURE 3. Typical beam emission of a TEXTOR discharge. The three multiplets are the D_{α} lines of the beam emission. From this the intensity ratio is deduced. The result is shown on the right hand side: In the plasma centre (1.88 m) good agreement with the expected value is obtained. More to the edge large deviations appear, attributed to polarization characteristics of the metallic mirror in the periscope.

Finally, a spectrometer has been tested on TEXTOR, with an etendue of 0.75 mm^2 sr and resolution of 0.25 nm. This device [5] is used to record the spectrum of Figure 4. An assessment on the overall efficiency of the periscope optics, fiber transmission and spectrometer efficiency has been made, leading to a total transmission of 2% (with a spectrometer efficiency of 15%). This shows that there is still room for improvement.



FIGURE 4. Left: measurement, Right: Simulation. Shown here is a typical example of a Helium spectrum of TEXTOR, compared with the results of the simulation code. In both cases the signal-to noise is comparable (S/N=35 at half width), but the passive emission is apparently not well modeled.

Future work on the TEXTOR CXRS system with respect to the ITER application includes: the investigation of the possibility to measure fast alpha particles with this setup, quantitative assessment of accuracies of the Beam emission and Motional Stark effect, simulation code validation and passive emission modeling and verification.

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