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A high etendue spectrometer suitable for core charge eXchange recombination spectroscopy on ITER[a)]

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A feasibility study for the use of core charge exchange recombination spectroscopy on ITER has shown that accurate measurements on the helium ash require a spectrometer with a high etendue of 1mm^{2}sr to comply with the measurement requirements [S. Tugarinov *et al.*, Rev. Sci. Instrum. **74**, 2075 (2003)]. To this purpose such an instrument has been developed consisting of three separate wavelength channels (to measure simultaneously He/Be, C/Ne, and H/D/T together with the Doppler shifted direct emission of the diagnostic neutral beam, the beam emission (BES) signal), combining high dispersion (0.02 nm/pixel), sufficient resolution (0.2 nm), high efficiency (55%), and extended wavelength range (14 nm) at high etendue. The combined measurement of the BES along the same sightline within a third wavelength range provides the possibility for *in situ* calibration of the charge eXchange recombination spectroscopy signals. In addition, the option is included to use the same instrument for measurements of the fast fluctuations of the beam emission intensity up to 2 MHz, with the aim to study MHD activity. © *2012 American Institute of Physics*. [http://dx.doi.org/10.1063/1.4732058]

I. CHARGE EXCHANGE RECOMBINATION SPECTROSCOPY (CXRS) ON ITER

CXRS is the standard technique in magnetic confinement experiments to determine profiles of ion temperature, plasma rotation, and impurity densities. Fully ionized light elements will emit light upon a charge exchange reaction with the externally injected neutral beam. The accuracy of this local measurement depends on the photon statistics of the resulting spectrum: as a qualifier the signal-to-noise ration, *S*/*N* has been introduced:[2] the signal *S* is governed by the CX emission, i.e., related to the product of impurity density, beam density, and the effective emission rate; and the noise *N* being the square root of the overall emission, dominated by the bremsstrahlung and passive emission. The detection efficiency is given by $\Re = T \cdot \eta \cdot \Delta\Omega \cdot A_{spec}$, with *T* the overall transmission of the optical system, η the detector efficiency, and $G = \Delta\Omega A_{spec}$, the product of acceptance angle and area is the etendue of the system. Clearly $S/N \sim \sqrt{\Re}$. The situation at the core of a fusion reactor is quite dramatic: the signal is low due to the large beam attenuation (for an ITER high performance discharge only about 1% of the injected neutral beam particles reach the plasma centre), whereas the noise (from bremsstrahlung), is much higher than in present fusion devices, due to the longer integration length in combination with the high density. Therefore, in order to comply with the measurement requirements and compensate for those two effects, a high efficient optical system is required. A feasibility study for the ITER core CXRS system[1,3] pointed out that the spectrometer etendue should be at least 1mm^{2}sr, to have a *S*/*N* of the order of 10. This value, in combination with the boundary conditions on the spectral wavelengths bands, resolutions, and transmission efficiencies, motivated a new dedicated design of such instrument.

II. REQUIREMENTS FOR THE CXRS SPECTROMETER ON ITER

The core CXRS diagnostic for ITER is meant to provide the profiles of the ion temperature, plasma rotation, helium and carbon content subject to the requirements listed in Table I.

For the detection channel, this led to the following considerations: (i) The detection channel should include a measurement of the beam density to be able to determine the impurity density, preferably at exactly the same location as the

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TABLE I. Main requirements on the core CXRS diagnostic for ITER.

Parameter	Accuracy (%)	Time resolution (ms)	Radial resolution
Ion temperature T_i	10	100	a/30
Impurity density: He, Be, C	20	100	a/10
Plasma rotation v_{tor}	30	10	a/30
Z_{eff} (line averaged)	20	10	...

CXRS emission. Note that for large beam attenuation the error propagation in the calculation of the beam density from the stopping cross sections is exponentially increasing, leading to intolerable inaccuracies. Therefore, a measurement of the beam density (instead of a calculation) is required; (ii) At least three wavelengths bands should read out simultaneously: one for carbon, one for helium and berylium and one for hydrogen to be able to monitor the beam density; (iii) to be compatible with the time resolution requirement on v_{tor} and Z_{eff} the readout time of the system was set at 10 ms; (iv) the radial resolution is determined by the front optics and beam width and independent of the detection channel. Since the lowest intensity originate from the plasma core, the etendue of the spectrometer will be chosen such to arrive at the required accuracy for one radial channel per spectrometer. Further to the plasma edge, where the beam density is much higher, more radial positions can be imaged onto one instrument.

The above considerations, in combination with the known CX lines used in present experiments, resulted in the spectral specifications of the three detected wavelength band of the spectrometer as listed in Table II.

Concerning the spectral resolution it was derived[4] that making the spectral resolution better than 0.2 nm for the He II band would hardly improve the performance of the system.

III. SPECTROMETER DESIGN

A number of high-level decisions have been made to design a spectrometer that provides the required large etendue within the other constraints. The first high-level design decision was to use a single grating for all three channels. The alternative would have been to build separate spectrometers for each channel, which would have resulted in a larger cost, since the grating is a major cost driver. Second, the grating size has been limited to a length of 200 mm. Although this complicates the optical design, it makes commercial procurement of the grating possible.Third, it was decided to base the design on commercially available sensors and not to anticipate sensors with larger image areas that might become available in the future, although this seriously complicated the optical design.

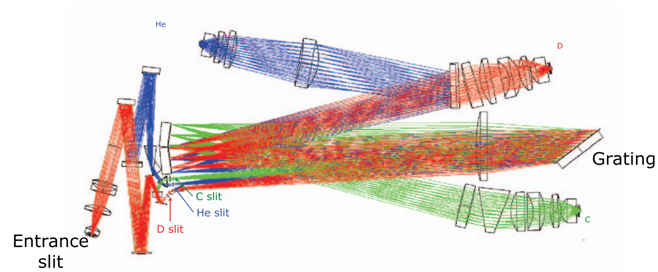

FIG. 1. Design of the high etendue, 3 channel spectrometer. The blue lines represent the helium channel, the green lines the carbon and the red lines the hydrogen channel.

Finally, CCD sensors have been selected, because they allow for binning on chip, which significantly reduces the readout noise.

Figure 1 shows an overview of the design. The light enters the spectrometer via a fiber bundle. This bundle consists of a row of 68 fibers with a core diameter of 300 μm. The first part, the entrance optics, have the function to split the three wavelength ranges and to image each range onto a separate slit with a demagnification factor. This factor is needed to adapt the *f*-number from the fibers to the *f*-number required by the subsequent optics. In principle the design is suited to adapt a fourth wavelength band.

The entrance optics are followed by the actual spectrometer. In the spectrometer, the light from the three slits is combined by a large collimator lens on a single grating. This grating has an active area of 100 × 200 mm^2 and 500 lines/mm. The light coming from the grating travels back through the collimator to two field mirrors. The two mirrors provide a spatial separation between the carbon channel, which is reflected downwards in Fig. 1, and the helium and BES channels, which are reflected upwards. The separation between the helium channel and BES channel is performed by a dichroic. For each channel, an *F*/1 objective is used to demagnify the image so that the spectral image fits onto the sensor (size: 13 × 13 mm^2, 1024 × 1024 pixels).

The dispersion of the instruments amounts to about 1.5 nm/mm (∼0.2 Å/pixel), with some variation between the 3 channels. The spectra are recorded in the 5th, 6th, and 7th order for the different channels.

IV. PERFORMANCE CHARACTERISTICS

A prototype has been built and put into operation at the TEXTOR tokamak for testing and has now been mounted on ASDEX upgrade. It has a modular design consisting of assemblies that can be replaced very accurately on the base

TABLE II. Main requirements on the spectrometer.

Wavelength band (nm)	Spectral resolution (nm)	Spectral lines	Efficiency × etendue (incl. QE) (mm^2 sr)
460.8–473.6	0.2	He II, Be IV	0.24
518.9–533.1	0.2	C VI, Ne X, Ar XVII	0.13
649.0–663.0	0.1	H_α D_α (BES)	0.06

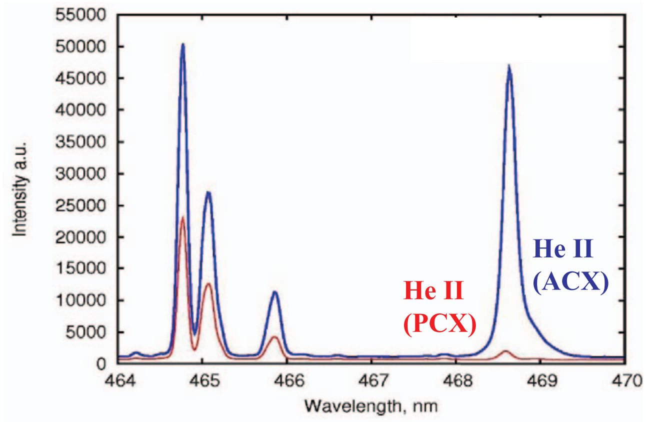

FIG. 2. Example of a helium spectrum as measured on TEXTOR, with passive emission only (PCX) and with the neutral beam switched on, yielding the CXRS component (Active Charge eXchange, ACX).

plate. A minimum set of compensators is chosen and the result is a stable spectrometer design that can be transported easily, aligned, and re assembled with minor effort. Performance of the system is close to expectation. Typical examples (for only one out of the 68 fibers, 40 ms integration time) of the helium (He II at 468 nm, $n = 4 \rightarrow 3$) and hydrogen (H_{alpha} at 656 nm) spectra are shown in Figs. 2 and 3, respectively.

One of the goals of this spectrometer prototype was to determine the severity and impact of any ghost lines. Ghost lines are measured lines that originate from light with a wavelength outside of the intended wavelength range or originating from one of the other two entrance slits. Ghost lines can, for instance, be caused by unwanted reflections on lens surfaces or by unwanted orders of the grating. Some ghost lines where observed initially on all three wavelengths bands, but could be eliminated by a suitable filter after the entrance slit. At the H_α band however, still two lines can be recognized as seen in Fig. 3, which have been identified to be H_α light at a $<1\%$ level of the other two slits. Measures are being taken to eliminated those as well.

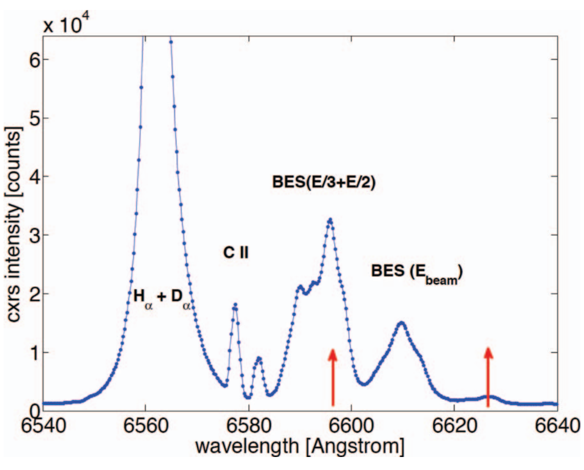

FIG. 3. Typical example of the hydrogen spectrum on TEXTOR. The CII emission from the plasma edge is visible as well as Doppler shifted beam emission of the three energy components. The red arrows indicate the positions of the ghost lines (the H_α emission entering from the other slits.

V. OUTLOOK

The results of this prototype spectrometer have shown that it is feasible to measure the CXRS emission at the required accuracy for ITER. For the final design a dedicated coating for each wavelength band will marginalize the effect of the ghost lines. The present detectors are well suited for a single channel readout, but will be replaced to be able to measure more ($\geq$30) radial positions simultaneously at a rate of 100 Hz or faster. The focus now will be to use the instrument at AUG for physics investigations such as:

(i) impurity investigations: combination of CX emission with beam emission allows absolute impurity profiles;[5]

(ii) fast ion investigations: the high etendue allows to focus on the wings of the spectra incorporating information on the energetic ions;[6]

(iii) transport investigations: many radial channels should provide accurate profiles of ion temperature, plasma rotation, and ion densities;

(iv) MHD fluctuations: The main aim of the H_α band in the spectrometer is to determine the beam density. Alternatively the possibility to measure the fluctuations in the beam emission system (by flipping a mirror) has been integrated into the design. This allows to measure core MHD activity at 8 spatial channels sampled at 2 MHz. Pilot results on TEXTOR showed that the measurement fully confirmed the simulation results on achievable photon current at the detector and on the signal to noise ratio. Both fluctuation spectra as well as correlation spectra between the channels could be obtained.[7]

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