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Neutral beam energy scan experiments in ASDEX Upgrade for impurity ion density evaluation wih CXRS

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1. Introduction

For accurate evaluation of impurity ion densities by means of charge exchange recombination spectroscopy (CXRS), the contribution of excited state populations in the neutral beam (NB) needs to be considered. For visible wavelength transitions of low Z impurity ions, the cross sections typically peak around 50 keV/amu for charge transfer from D^0 beam donors in the ground state. In the case of an excited neutral beam population (n = 2) the cross sections peak at much lower collision energies. For this reason, CXRS systems that rely on neutral beams with energies below 40 - 50 keV/amu need to include this effect in the deduction of impurity ion densities. This indeed is the case in ASDEX Upgrade (AUG), which is equipped with two NB boxes, operating at maximum extraction voltages of 60 and 93 kV in D, respectively.

2. CXRS diagnostics on ASDEX Upgrade

The AUG CXRS system [1] has been recently upgraded, with the addition of a new diagnostic focussed on one source of NB box 2, thus complementing the standard diagnostic, which is aligned to view a source of NB box 1 (Fig. 1). The new diagnostic consists of a 2D frame transfer CCD camera coupled to a 0.5 m Czerny-Turner spectrometer and is equipped with both toroidal and poloidal lines of sight. In this paper only measurements from the toroidal system are reported. The light from the plasma is carried through an array of quartz optical fibers (diameter of 400 μm) and imaged onto the CCD with sampling rates ≥ 10 ms. Since at present the diagnostic is focussed on one of the two current drive sources (source 7), radial profiles of ion temperature, ion flow velocity and impurity density can only be obtained for intervals of ρ_{pol} of order 0.3 – 0.8 (the exact value depending on the equilibrium of the discharge). Work is in progress to realign the diagnostic to a nearby radial source, so that the measured profiles will extend to the plasma center.

3. Beam energy scan experiments

A controlled NB energy scan was performed over a series of discharges, in which the extraction voltage of one of the two NB injectors was varied from pulse to pulse, so as to obtain a variation in beam energy from 46.5 to 15 keV/amu in D, as shown in Table 1. The experiments were performed in steady state ELMy H-modes (Bt = 2T, Ip = 1 MA) with combined NB and ICRH central heating, in order to ensure constant total input power and similar power deposition profiles in subsequent discharges. This, in turn, should lead to the same impurity density profile throughout the scan, a necessary requirement for this study. Note also that the addition of RF prevents density peaking in the discharges [2]. CX spectra from C VI (C series) and Ne X (Ne series), following Ne gas puffing, were collected using both diagnostic systems. The time evolution of the main plasma parameters of the discharges is shown in Fig. 2 for the C series. These discharges were then repeated adding Ne gas puffing from the midplane of the machine, at two intervals in the pulse (2.0 s and 3.5 s) and in fluxes large enough for the CX spectra to be measured, but small enough to keep the perturbation to the total radiated power to a minimum.

Table 1. *Summary of the discharges of the NB energy scans. Pulse type 2 provides a cross calibration between the two CXRS diagnostic systems.*

Pulse type	NB 1 config.	NB 2 config.	RF power	Shot # C	Shot # Ne
1	49 kV (1.64 MW)	93 kV (2.52 MW)	2.00 MW	16783	17044
2	60 kV (2.52 MW)	60 kV (1.07 MW)	2.40 MW	16705	17046
3	40 kV (1.05 MW)	93 kV (2.52 MW)	2.60 MW	16707	17049
4	30 kV (0.49 MW)	93 kV (2.52 MW)	3.15 MW	16708	17051

4. Calculation of the impurity density

The impurity densities are evaluated with a new CXRS analysis package, presently being developed at AUG, which is based on IDL shared data structures and which allows generic analysis with a machine-independent code. The package is based on the JET CHEAP analysis code [3] and is linked with ADAS [4] for the extraction of beam population fractions, CX and beam stopping rate coefficients. For this purpose, the suite of codes in ADAS has been modified to increase the speed at which these rates are provided. In addition, the ADAS atomic database has been extended to include data for excited state beam CX donor populations, the main subject of this paper. The goal of the development is to provide, in the framework of ADAS, an analysis package which can be applied to different present and next generation fusion devices. For each new application, only input and, optionally, output routines need to be supplied.

In order to produce the best estimate of the CX rates, it is necessary to refine the intensity calibration of the detection system *in situ*. For the established detection system which views the first NB box, relative calibrations from channel-to-channel have been adjusted using dedicated sweeps of the plasma across the viewing locations [5]. The absolute calibration is then fixed in a high density discharge in which the impurity content of the plasma is low (Zeff~1.5) by comparing the continuum bremsstrahlung emission with the active CX signals of the dominant light impurities (He, C). The resulting correction factors, up to a factor of 1.6, are consistent with a degradation of the in-vessel viewing optics during tokamak operation and will be checked by a post-campaign calibration. The calibration of this standard system is then transferred to that of the new system using the reference discharge in each sequence with equal beam energies (pulse type 2). During the analysis it became clear that there is a problem with the calibration of the new system. In particular, the cross check between active CX signal and continuum emission is not satisfied. The results quoted in this paper therefore only use relative measurements from the new system as a means of correcting for shot-to-shot variations in the impurity density. This correction is necessary for the one shot in the carbon series (#16783) which was executed on a different day and for the Ne series during which the puff size was adjusted to optimise the CX signal at low beam energy. In cases where the same operational parameters were used on the same day, the impurity level is found to be reproducible to a level of ~10%.

5. Discussion

The results of the beam energy scan analysis are summarized in Figs. 3 and 4. Plotted are the deduced impurity densities for the case where only the n=1 beam donor is considered and for the case where both the n=1 and the n=2 donors are included. It can be seen that the n=2 donor contribution dominates the calculation at low beam energies. When the excited state donor is included, however, the calculated densities are constant as a function of beam energy to within 20%. We thus conclude that the ADAS rates are verified to within this 20% uncertainty. Since in AUG the full and half energy beam components contribute roughly equally to the CX emission at the plasma edge, this verification of the ADAS rates applies to the energy range ~7.5 – 30 keV/amu. Note that what is being tested in reality is the product of the n=2 donor effective CX rate coefficient and the n=2 population fraction in the beam. The close agreement with experiment gives confidence that the rates can be applied to impurity analysis in fusion devices.

As an alternate way of describing the data, Fig.5 gives the error which would result if the impurity densities were calculated using the n=1 donor alone. Even at the normal AUG beam energy (30 keV/amu in D) the omission of the excited state donor results in an overestimate of the impurity densities by a factor of two or more.

References:

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[4] Atomic Data and Analysis Structure, http://adas.phys.strath.ac.uk
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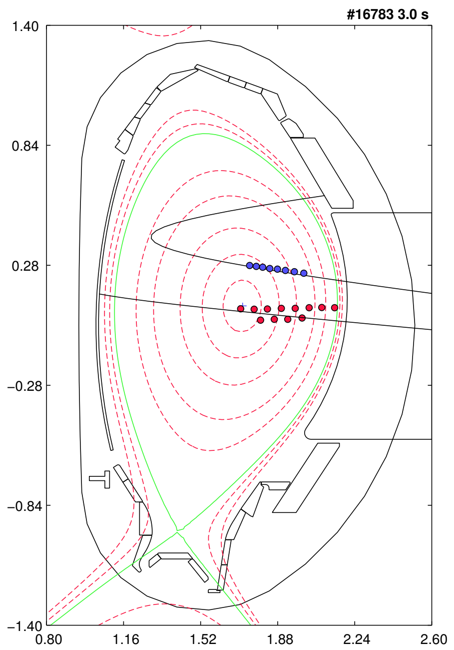

Figure 1. *Poloidal cross section of the plasma equilibrium for #16783 at 2.3 s, with superimposed the toroidal lines of sight of the two CXRS diagnostics, focussed on NB 1 (source 3) and NB 2 (source 7, current drive) respectively.*

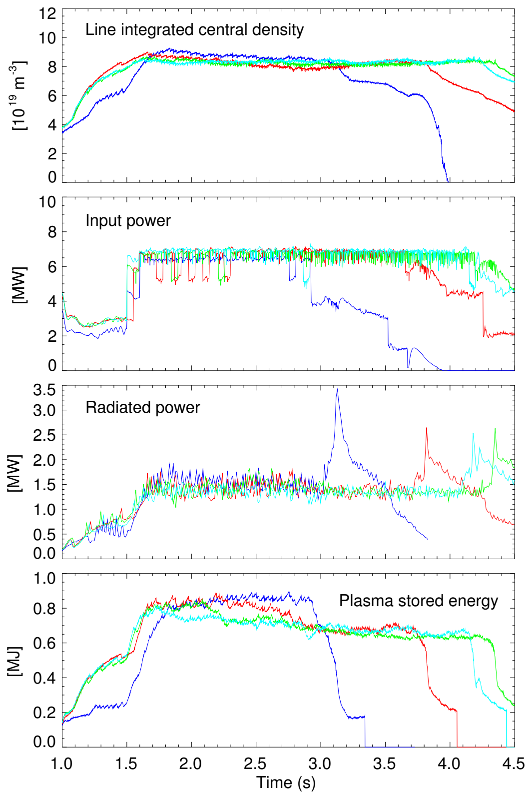

Figure 2. *Overview of the main plasma parameters for the NB energy scan experiments (C series). From top to bottom: central line averaged density, total input power, core radiated power and total plasma stored energy.*

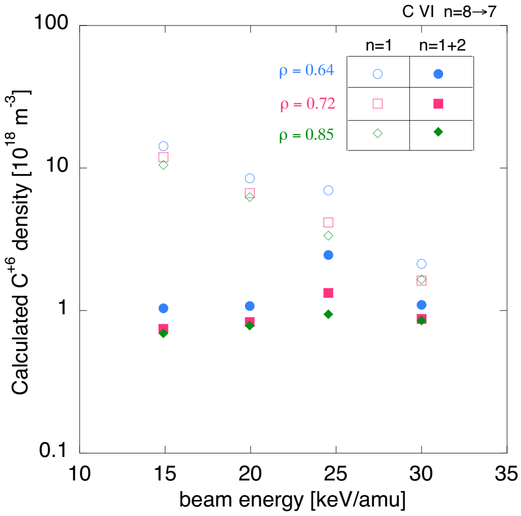

Figure 3. *Calculated C impurity densities for the beam energy scan experiment. Solid points are for calculations including the n=1 and n=2 beam donors and the open points are for the n=1 (ground state) donor only.*

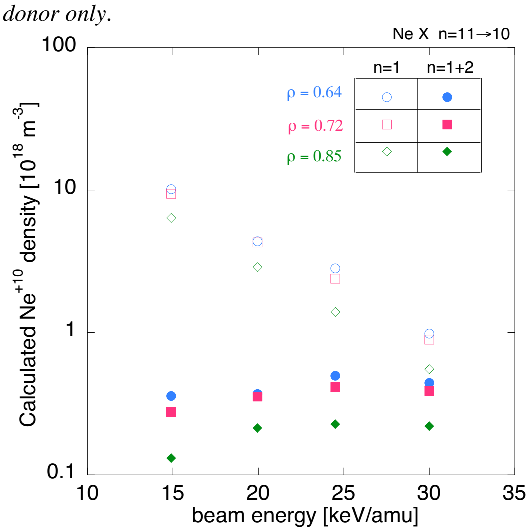

Figure 4. *Calculated Ne impurity densities for the beam energy scan experiment. Solid points are for calculations including the n=1 and n=2 beam donors and the open points are for the n=1 (ground state) donor only.*

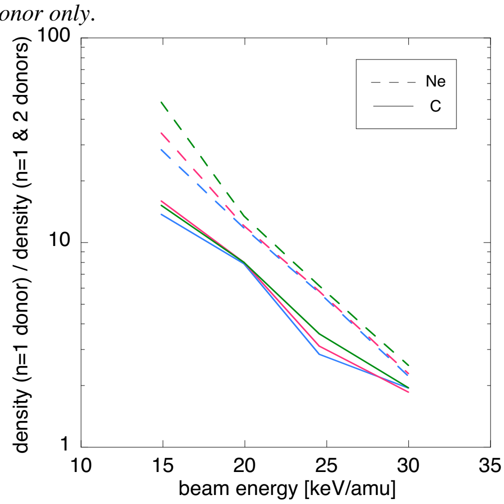

Figure 5. *Error introduced into the CX density calculation by not including the n=2 donor.*