

Edge ion temperature measurements at ASDEX Upgrade

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Introduction The strong influence of edge parameters on the core of magnetically confined tokamak plasmas motivates local edge measurements of all relevant plasma properties. At ASDEX Upgrade electron density and temperature are routinely measured with high temporal and spatial resolution, but temperature measurements of plasma ions at the edge are still demanding. The widely used diagnostic of charge exchange spectroscopy on neutral heating beams doesn't provide the necessary spatial resolution to resolve temperature gradients at the edge. Passive spectroscopy and neutral particle analysis only provide local measurements after inversion of multiple line-integrated measurements, the radial position of which may be ambiguous due to equilibrium issues. At ASDEX Upgrade, a diagnostic based on the neutral lithium beam, which routinely provides measurements of electron density at the plasma edge, has been extended to simultaneously measure ion temperatures via charge exchange on fully stripped helium and carbon impurity ions [1]. Assumption of a Maxwellian velocity distribution allows an easy interpretation of the linewidth as thermal ion temperature. ADAS [2] is used to calculate the effects of non-thermal Zeeman broadening and collisional l-mixing on the line-shape, yielding a derating factor, which is a multiplicative correction to the apparent temperature. This is especially important for the temperatures at the plasma edge, where derating factors as low as 0.7 are found.

Experimental Setup

The ASDEX Upgrade lithium beam is operated at 35-60 keV acceleration voltage, producing an ion current of up to 4 mA. Neutralization efficiencies of up to 95% depending on the chosen particle velocity are possible. Deflection plates are the basis for beam modulation, which then allows an accurate determination of the background radiation (passive signal) on all spatial channels. The array of optical fibres looking from below onto the beam axis provides a spatial resolution of about 6 mm. The two frame-transfer CCD cameras of the detection system, attached to Czerny-Turner spectrographs, limit the theoretical time resolution since the CCDs' multi-region setup requires a minimum read-

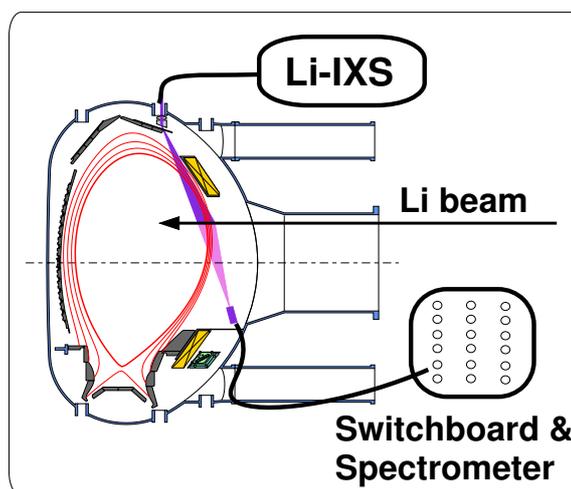


Figure 1: Injection geometry of ASDEX Upgrade lithium beam

out time of 4 ms. Unless recording time is specifically sacrificed for the readout, this is also the minimum exposure time. The modulation cycle was chosen to be 80 ms, since the signal-to-noise ratio of the background corrected net spectra is poor and requires an integration of at least 200 ms even under good conditions and up to 2 s in below average conditions. During this time interval the plasma must be sufficiently stationary for a meaningful measurement.

Data evaluation and corrections Data is recorded as a series of consecutive camera frames. Frames are either passive (lithium beam deflected, i.e. off) or active (lithium beam on and thus charge exchange visible). The passive radiation is much more intense than the charge exchange component induced by the neutral beam. One beam modulation cycle of 80 ms usually consists of 30% passive and 70% active frames, which are combined to get a net signal for each cycle before averaging those over the full stationary plasma phase. The use of contemporary background measurements for net signal determination ensures that correct statistical errors of the net signal can be determined. The errors could become too large, if the active and passive frames were averaged separately for all beam modulation cycles in a long interval due to possible background signal drifts (e.g. by changing impurity density), because of the error progression of a difference of large numbers.

Once a net spectrum for each channel is determined this way, a Gaussian fit following

$$I(\lambda) \propto \exp\left(-\frac{(\lambda - \lambda_0)^2}{2\sigma^2}\right) \quad (1)$$

is used to determine the apparent temperature for the impurity species in question by calculating

$$kT_{imp} = \left(\frac{\sigma}{\lambda_0}\right)^2 m_{imp} c^2 \quad (2)$$

where σ and λ_0 are replaced by the fitted parameters (see figure 2).

After an apparent temperature is calculated this way, the actual temperature is determined by constructing a Gaussian peak with help from ADAS routines. Firstly, ADAS306 is fed with beam and plasma parameters and calculates an LJ-resolved electron population of the relevant upper level of the observed transition ($N=8 \rightarrow N=7$ for carbon, $N=4 \rightarrow N=3$ for helium) which may differ from the statistical distribution. The ADAS routine is also treating cascade processes up to typically $N=20$. Regarding electron capture from different excited states of lithium, test runs indicate no different behaviour between Li(2s) and Li(2p). Contribution of higher excited states is not relevant. Secondly, all Zeeman components are calculated with a subroutine of ADAS603, performing a complete treatment of the line splitting due to a magnetic field. Each of these components is then assigned an estimated physical temperature and a line intensity taken from the output of ADAS603 with additional weighting according to the CX-induced electron population from ADAS306. All these Gaussian shaped components are folded with an empirically determined instrumental line profile for the relevant impurity and summed up to form the apparent line-shape. This is fitted with the same fitting routine used to determine the apparent temperature from the experimental spectra and the results are compared. An iterative process continues to change the estimated temperature until sufficient agreement is reached.

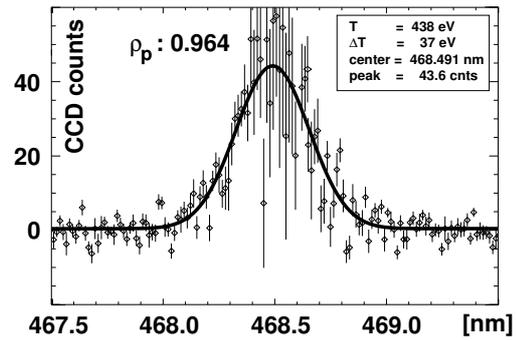


Figure 2: Typical Gaussian fit of net spectrum

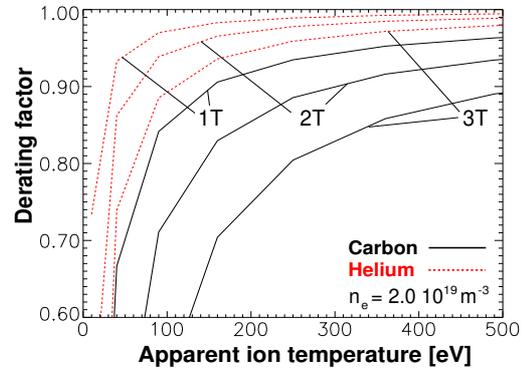


Figure 3: Dependence of derating factors of He and C on magnetic field strength

A brief survey of applicable derating factors of the apparent temperature due to this calculation shows that the instrument function is the dominant source of all non-thermal broadening effects. Zeeman and collisional broadening only appreciably influence the results for low temperatures (<300 eV) and high magnetic fields (>2 T) in the case of carbon. The maximum effect seen for helium at 3 T is below 10 eV. For carbon, a magnetic field of 2 T is already high enough to require more than 20 eV correction (see figure 3).

Moreover, the dependence on local electron density, influencing mainly the degree of collisional broadening, is higher for carbon (see figure 4) than for helium. Since the carbon concentration in ASDEX Upgrade plasmas has been reduced due to the tungsten program, measurements utilising this impurity become more and more difficult. Helium, initially chosen as a potential replacement, has shown many advantages over carbon at determining ion temperatures by lithium beam charge exchange. All data shown have been acquired using the He II line, but temperatures derived from the C VI line in similar discharges are consistent while exhibiting larger uncertainties.

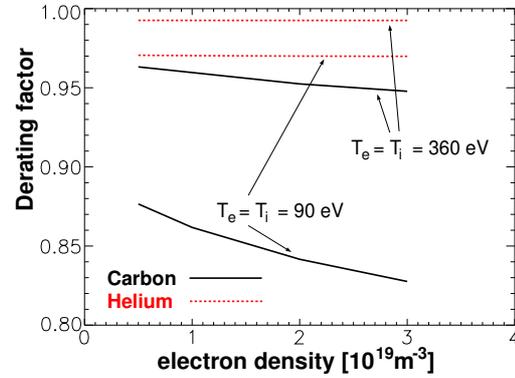


Figure 4: Electron density dependence of derating factor

Results from low density plasmas Since at densities below $10^{19} m^{-3}$ heat exchange times between electrons and ions become comparable to the energy confinement time, a comparison of ion and electron temperatures provides data for theoretical simulations. Low plasma densities are easily achieved in ohmic or ECRH heated plasmas, since these heating methods do not cause any particle fuelling. A series of such discharges has been performed in order to compare the temperatures of ions and electrons at the plasma edge. A general observation is the expected higher electron temperature compared to ions in the core plasma (not explicitly shown) while close to the edge this is reversed and ion temperatures are seen to exceed the electron temperatures, at the separatrix by up to a factor of 3 (see figures 5(a), 5(b) and 5(c)).

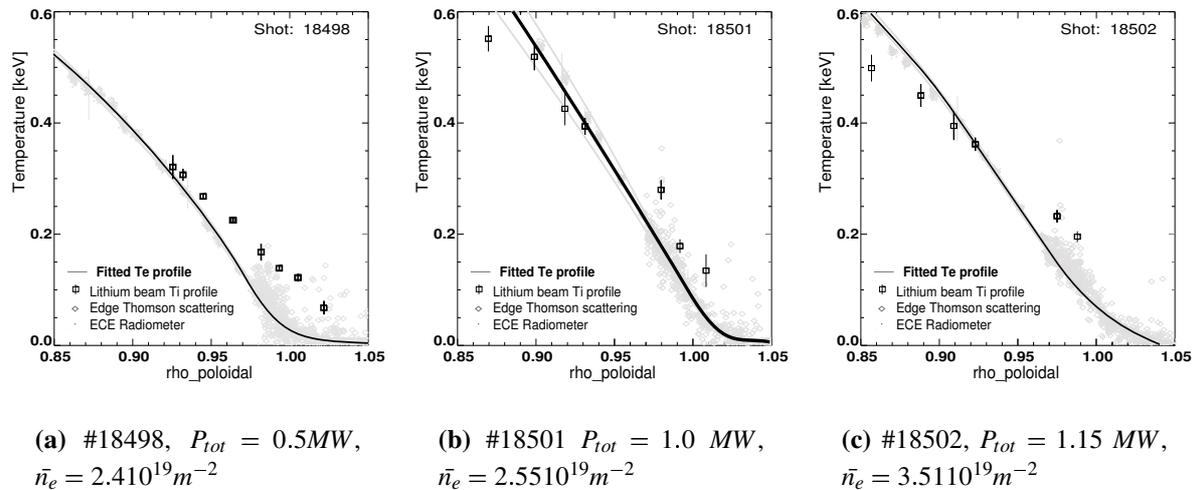


Figure 5: Electron temperature (ECE and Thomson scattering) fit and ion temperature measurements (Lithium beam) for different total heating power and electron densities

The performed discharges have the following properties:

Shot	Plasma current	Magn. field	Heating (Ω +ECRH)	Line avg. density ctr/edge
18498	794 kA	2.4 T	485 kW	– / $1.3 \cdot 10^{19} m^{-2}$
18501	793 kA	2.4 T	335 kW + 672 kW	$2.6 \cdot 10^{19}$ / $1.5 \cdot 10^{19} m^{-2}$
18502	794 kA	2.4 T	409 kW + 742 kW	$3.5 \cdot 10^{19}$ / $2.0 \cdot 10^{19} m^{-2}$

As can be seen in the figures, the electron temperature profiles are influenced by the total input power and electron density variation, but the ion temperature gradient hardly changes in the different cases. In all scenarios the crossover of the respective profiles is clearly within the separatrix with the exact position varying with density and heating power. Theoretical modelling of these results is currently in progress.

Measurements in QH-mode

The quiescent edge mode is an ELM-free high confinement regime accessible in plasma configurations with high wall clearance and counter NBI-injection [3]. One of this regime's features is a high pedestal pressure with ion temperatures well in excess of 1 keV [4]. Since the charge exchange measurements of the core system do not have the necessary spatial resolution to accurately determine the position and width of the pedestal, the lithium beam is needed to provide information about the actual gradient length for the ion temperatures and thus the width of the H-mode barrier. Recent measurements in this regime show excellent agreement of the ion temperatures in the overlapping region of core CXRS and edge lithium beam charge exchange and the expected steep gradient zone is seen with high spatial resolution. The data shown is taken from a QH-mode discharge with a stationary quiescent phase of about 1 second length (figure 6).

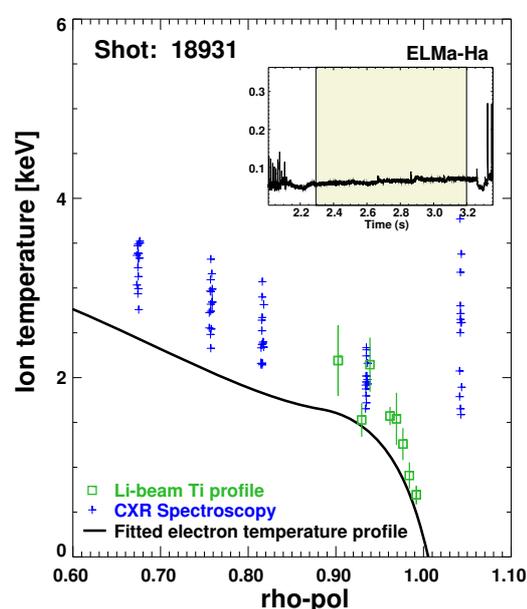


Figure 6: High pedestal ion temperatures in QH-mode confirmed by Li-beam CX measurements

Conclusions The lithium beam at ASDEX Upgrade is successfully measuring edge ion temperatures. Results from ohmic, L-mode and QH-mode discharges are presented. Necessary corrections include the instrument function as well as other non-thermal effects (Zeeman, l-level mixing), which are accurately calculated using ADAS routines. Helium has de facto replaced carbon for current and future ASDEX Upgrade edge ion temperature measurements.

References

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