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^{3}He in H, Ion Cyclotron Resonance Frequency Mode Conversion and Minority Heating Experiments in ASDEX Upgrade

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Abstract When power is deposited inside the q=1 surface into the electrons, the central electron temperature profiles become very peaked, and the sawtooth frequency increases with increasing electron temperature. This is in contrast to the $T_e^{-3/2}$ dependence of the sawtooth frequency, observed with NI and minority heating. Fast particles in the edge are inversely correlated with central absorption. To locate the power deposition correctly in the mode conversion scenario using ^{3}He in H, it is important to take into account the presence of residual D.

1. Introduction

Experiments using ^{3}He in H, heated with ion cyclotron resonance frequency power, provide the possibility to vary, by changing the ^{3}He concentration, the location of the power deposition within the plasma and the distribution of the power between species (electron/ions) [1,2]. At concentrations above 5 % the power goes directly to the electrons by mode conversion, below that concentration minority heating dominates.

Since the location can also be independently varied by changing the magnetic field or the ion cyclotron frequency, we can separate the effect of location and repartition of power.

^{3}He in H scenarios are equivalent in terms of charge to mass ratio (Z/A) to scenarios with T in D for ignition experiments, and thus particularly relevant for ignition scenarios.

2. Observations

The experiments were performed on ASDEX Upgrade (D-shaped divertor tokamak, R = 1.65 m, a = 0.5 m, b = 0.8 m) with B_t in the range 2.69 T to 3.01 T, I_p = 800 kA (Fig.1). The plasma was heated with up to 2 MW ICRF (2 double strap antennas at 30 MHz, 2 double strap antennas at 31.6 MHz) and 1.8 MW NI (H, 60 kV). The line averaged density was 5 10^{19} m^{-3}, the majority species H. He_3 was injected as one or two pulses, typically 1.5 s apart (Fig. 2). The pulses had flow rates between 2 and 10 10^{21} ^{3}He atoms/s (absolutely calibrated) and pulse lengths of 40 to 170 ms. The total injected atoms/pulse varied between 80 and 500 10^{18} atoms.

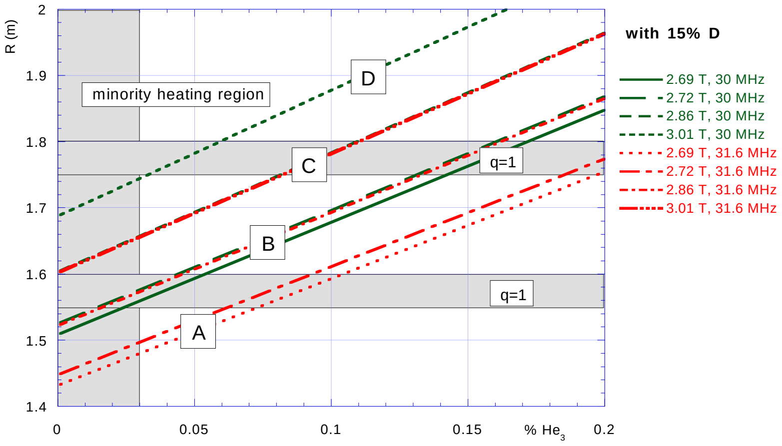

Figure 1. Position of the ^{3}He mode conversion layer for 15 % of D in H. Shown are typical regions of the q=1 surface for the discharges. At low ^{3}He concentration minority heating dominates.

2.1. Estimate of the ^{3}He concentration

Central to the analysis is the determination of the ^{3}He concentration. It cannot be deduced directly from spectroscopic measurements with sufficient absolute precision for our purposes. Using the method outlined hereafter we can estimate the concentration (though somewhat indirectly) with sufficient accuracy. The ^{3}He concentration immediately after the pulse can be calculated from the total injected amount of ^{3}He and a fuelling efficiency (^{3}He atoms in the plasma/total injected atoms) assuming an equal distribution throughout the plasma. The fuelling efficiency has a lower bound obtained from the plasma density increase following the ^{3}He pulse. This lower bound is 0.12±0.03 for the old divertor (Div I), and 0.08±0.03 for the new divertor (Div II). The value of the fuelling efficiency was obtained for Div I from modulation experiments [3] : the calculated and measured (based on Fourier analysis of T_e) position of the power deposition are matched by varying in the code the ^{3}He concentration (it is thereby important [4,5] to take into account the presence of residual D). This gives a fuelling efficiency of 0.3 for Div I. Consequently we used a fuelling efficiency of 0.3±0.05 for Div I and 0.2±0.05 for Div II (the value for Div II is reduced in proportion to the lower density increase following the ^{3}He pulse in this divertor configuration). The time dependence of the ^{3}He concentration was then calculated from the initial value and an (exponential) decay time. This decay time was obtained from the decay of a central He II line or from the decay of a He I line in the divertor.

The decay of the ^{3}He concentration, following the pulse, scans the location of the power deposition along the lines shown in Figure 1, depending on magnetic field and ICRF frequency. Typical values of the concentration (^{3}He ions / electrons) were in the range from 20% down to 2 %.

2.2. Variation of the sawtooth frequency and electron temperature profile

Fig. 2 shows time traces. During ICRF at 30 MHz, the ^{3}He pulse corresponds to a variation of the location of the power deposition along line C of Fig. 1, between 15 % (low field side electron heating) down to 5 % (central minority heating). With 31.6 MHz, it corresponds to a scan of the concentration along line B. Starting with high field side off-axis minority heating

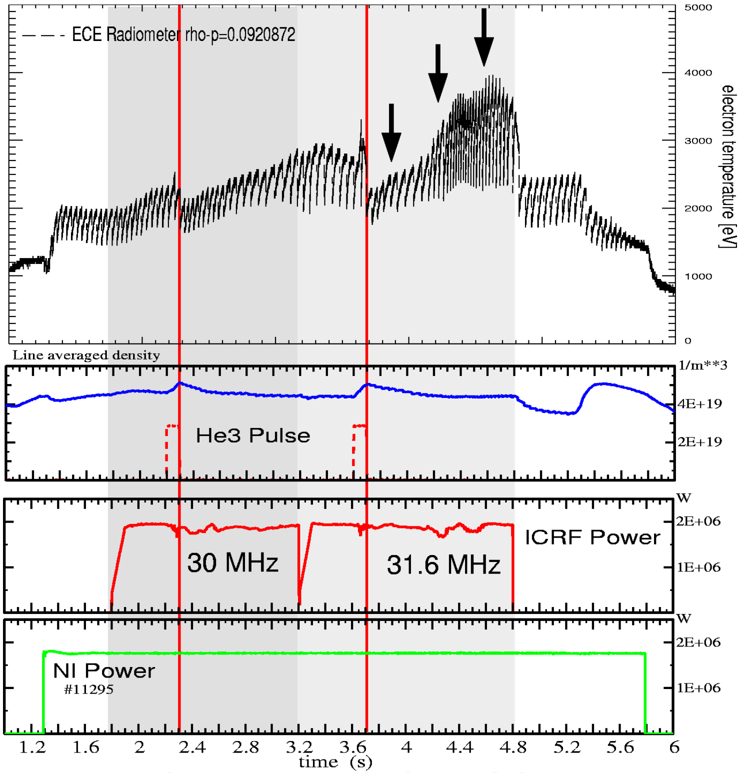

Figure 2. (above) Time traces with central electron temperature, line averaged density, ^{3}He pulses, ICRF power and NI power.

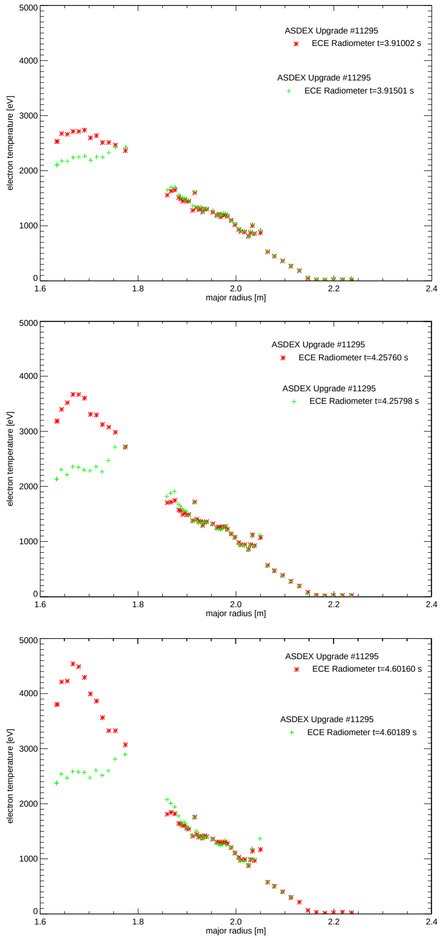

Figure 3. (right) Electron temperature profiles at 3.91s, 4.35s and 4.6s, at the top and bottom of the sawteeth. Vertical scale : electron temperature from 0 to 5000 eV; horizontal scale : major radius from 1.6 to 2.4 m (plasma center 1.67 m).

(5 %), the concentration increases after the second ^{3}He pulse to 20 % (electron heating LFS, near 1.85 m, first profile) to become at 10 % central electron heating (third profile). The largest variations in the electron temperature are observed when power is deposited directly to the electrons inside the q=1 surface. The profile peaks strongly and the sawtooth frequency increases with electron temperature [5]. This is in contrast to the usually observed $T_e^{-3/2}$ dependence of the sawtooth frequency observed with NI and central minority heating [6]. An increasing frequency with increasing temperature was also observed under the same conditions of central electron heating when the temperature was varied by changing the ICRF power.

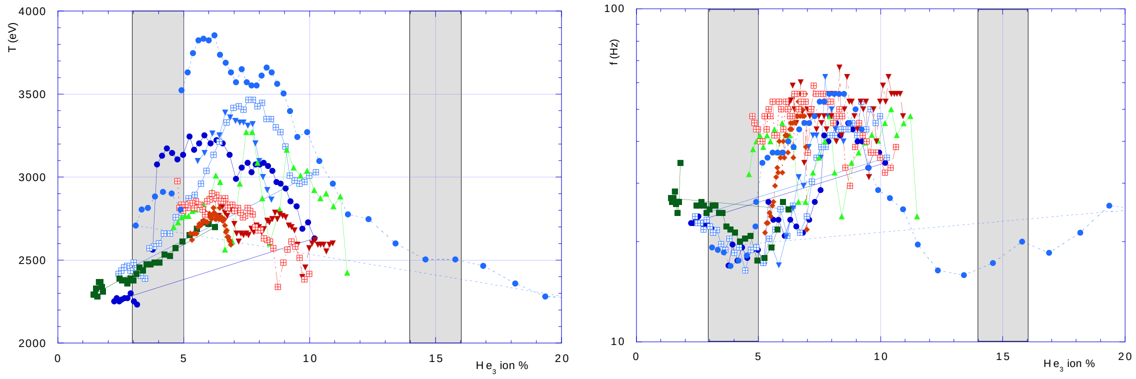

Figure 4. (left) Variation of the central electron temperature for a series of discharges along the line B of Fig.1. Indicated are the ^{3}He concentrations corresponding to power deposition at the location of the q=1 surface on the low field side and the high field side, the plasma center corresponds to a concentration of 10%. (right) The variation of the sawtooth frequency.

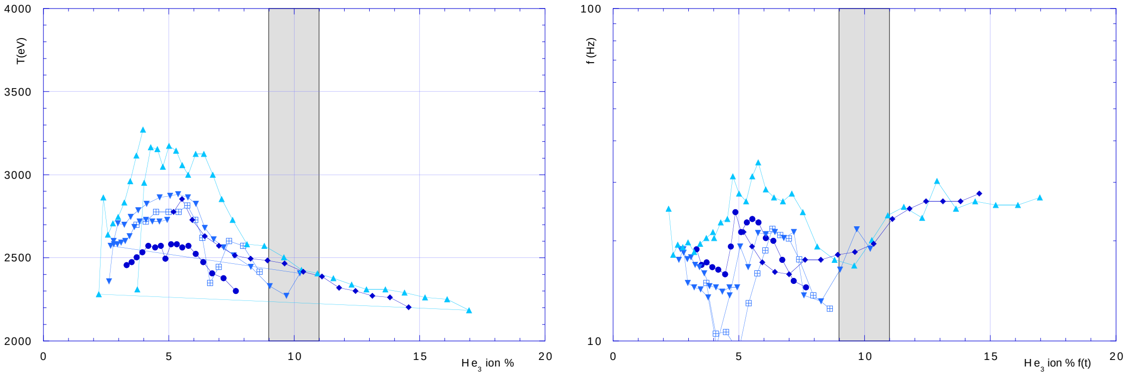

Figure 5. (left) Variation of the central electron temperature for a series of discharges along the line C of Fig.1. Indicated is the concentration corresponding to the location of the q=1 surface on the low field side, the plasma center corresponds to a ^{3}He concentration of 5 %. (right) Variation of the sawtooth frequency.

Fig. 4 and 5 summarize the behaviour of central electron temperature and sawtooth frequency for a series of discharges. Because of the choice of ICRF frequency and magnetic field, the conditions are different between the two figures. For power deposition inside the q=1 surface, in Fig. 4, the ^{3}He concentration is such that mode conversion dominates; the power goes directly to the electrons. In Fig. 5, for central power deposition, the ^{3}He concentration is 5% and minority heating dominates. Note the different behaviour of the sawtooth frequency with temperature : for power directly to electrons in the center, the sawtooth frequency increases as the temperature increases (Fig. 4); when the power goes centrally to the minority (^{3}He< 5%), the sawtooth frequency strongly decreases, and for scans under similar conditions, decreases with increasing temperature.

2.3. Observation of fast H and D particle fluxes

For some combination of magnetic field and ICRF frequency (2.73 T, 30 MHz and 2.87T, 31.6 MHz) corresponding to a H resonance 14 cm outside the plasma on the LFS), fast H and

D particles in the perpendicular charge exchange analyser were observed. Their temporal behaviour (sudden appearance and disappearance at turn on and turn-off of the ICRF) indicate that they are produced near the edge and unconfined. The addition of ^{3}He in the 5 % range (minority heating, good absorption) decrease their fluxes drastically, and as the concentration decreases further the fluxes are modulated with the sawtooth frequency. The addition of ^{3}He at higher concentration (resulting in the appearance of cut-off and mode conversion layer), increases the fluxes. As the ^{3}He concentration decreases they are slowly modulated. This could be an indication of a standing wave up to the H/^{3}He cut-off, whose maxima and minima are modulated as the location of the cut-off moves with the changing concentration. Simulations with the TORIC code [7] (full wave, toroidal) indicate that the number of maxima and minima in the modulation is not in disagreement with this explanation.

3. Discussion and conclusions

The analysis is sensitive to the estimate of the ^{3}He concentration. When modulation experiments are used to calculate the ^{3}He concentration (from the location of the power deposition), the presence of residual D has to be taken into account. It introduces an additional cut-off/resonance layer and appreciably shifts the position of the H/^{3}He ion-ion hybrid cut-off and resonance. Modulation experiments could not be used as they would influence the sawtooth behaviour. The consistency of the data provides some confidence in our estimates of the ^{3}He concentration.

Using ^{3}He in H with ICRF heating, we could vary the localization of the power deposition within the plasma as well as the distribution of the power between species. Central electron heating results in very peaked electron temperature profiles inside the q=1 surface and an unusual dependence of the sawtooth frequency with temperature (the frequency increases with central electron temperature). Ignition experiments will have very localized electron heating (though also a stabilizing effect of fast alpha particles in the center). The behaviour of the central temperature and the sawtooth frequency may well be quite different from what is seen on present machines [8,9,10].

Fast H and D particles were observed near the edge. Their behaviour depends on the ^{3}He concentration, its temporal evolution and the plasma conditions indicating that edge parasitic absorption of the power not absorbed in the central plasma plays a role in their generation.

References

[1] Majeski R., Rogers J.H., Batha S.H., Budny R., Fredrikson E., et al., "Mode conversion heating and current drive experiments in TFTR", Phys. Rev. Letters **76** (1996) 764.

[2] Brambilla M., Noterdaeme J.-M., "He minority heating scenarios in ASDEX Upgrade", *in Radio Frequency Heating and Current Drive of Fusions Devices,* (Top. Conf., Brussels, 1992) Europ.Phys.Soc., 16E, 125.

[3] Noterdaeme J.-M., Wukitch S., Hartmann D.A., Brambilla M., Braun F., Cattanei G., Gafert J., Lyon J.F., Neu R., Plyushnin V. et al., "ICRF heating results in ASDEX UPgrade and W7-AS", *in Fusion Energy,* (16 th. IAEA Conf., Montreal, 1996), Vol. 3, IAEA (1997) 335.

[4] Noterdaeme J.-M., Brambilla M., Gafert J., Gude A., Suttrop W., and Zehrfeld H.-P., "Variation of the sawtooth activity with ICRF in ASDEX", *in Radio Frequency Heating and Current Drive of Fusions Devices,* (2 nd. Top. Conf., Brussels, 1998), Europ.Phys.Soc., 22A, (1998) 9.

[5] Noterdaeme J.-M., M. Brambilla, B. Brüsehaber, R. Dux, H.-U. Fahrbach, et al., "ELMs and sawteeth with ICRF heating on ASDEX Upgrade", *in RF Power to Plasmas* (13 th. Top. Conf, Annapolis, 1999), AIP Press (1999) to appear.

[6] Noterdaeme J.-M., Hartmann D.A., Stäbler A. et al., "Comparing high power ion cyclotron resonance frequency heating with neutral injection in ASDEX Upgrade: differences, similiarities and synergies", *in Fusion Energy,* (17 th. IAEA Conf., Yokohama, 1998), IAEA, to appear, IAEA-F1-CN-69/CDP/11.

[7] Brambilla, M., Plasma. Phys. Contr. Fus. **41** (1999) 1.

[8] Campbell D.J., Start D.H.F., and Wesson J.A., Phys. Rev. Lett. **60** (1988) 2148.

[9] Bhatnagar V.P., Start D.H.F., et al., "Local Magnetic Shear Control in a Tokamak via fast wave minority current drive: theory and experiments in JET", Nucl. Fus. **34** (1994) 1579.

[10] Pochelon A., Goodmann T.P., Henderson M., Angioni C., Behn R. et al., "Energy confinement and MHD activity in shaped TCV plasmas with localised electron cyclotron heating", *in Fusion Energy,* (Yokohama, 1998), IAEA, to appear, IAEA-F1-CN-69/EX8/3.