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ICRF Ion Heating with Mode Conversion on the Tokamak ASDEX Upgrade

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On the path to ignition in a fusion reactor, there is a great interest to avoid decoupling electron and ion temperatures. This requires both electron and ion heating. There are not so many scenarii for ion heating [1], and ICRH is a good candidate to fulfil this task. An interesting possibility is to use a non linear damping of an Ion Bernstein Wave (IBW) at the 3/2 cyclotron harmonic of an ion species: a self interaction of the wave occurs, making a beat wave that resonates with the bulk ions of the plasma [2]. Efficient ion heating has already been observed on ICRH experiments [3-4], with the direct excitation of IBW by toroidal loop antenna in a plasma with a single ion species. The originality of the heating scenario used for this experiment on the tokamak ASDEX Upgrade is that it relies on the fast magnetosonic wave launched from the low field side of the tokamak: an IBW is created at the centre in a two ions species (H and D) plasma by Mode Conversion (MC). This allows avoiding possible deleterious IBW non linear phenomena at the edge. The Fast Wave frequency was f_{ICRF}=30 MHz, and the magnetic toroidal field was B_0=2.7 T. In such a configuration (see Fig. 1), the ion cyclotron resonance layers (1D on the high field side at R=1.13 m, and 1H on the low field side at R=2.26 m) are excluded from the plasma, and one avoids the damping of the Fast Wave through these channels [5-6]: there is then a competition between, on one side, electron heating from Fast Wave (Electron Landau Damping (ELD) and Transit Time Magnetic Pumping effect) and IBW (ELD), and, on the other side, ion heating due to non linear damping of the IBW at 3/2 Deuterium cyclotron harmonic.

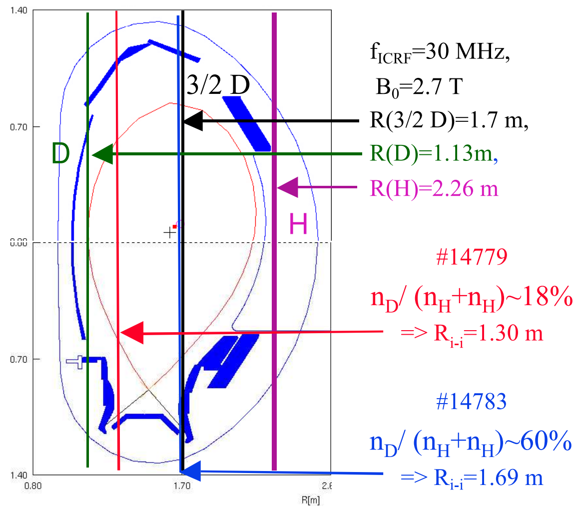

Fig. 1: positions of the different ion cyclotron resonance layers

The experiment was carried out on the tokamak ASDEX Upgrade during a transition from pure Hydrogen plasmas to Deuterium plasmas. The heating sequence was the following: pulses began by an NBI phase to make a robust target plasma for ICRH, followed by NBI + ICRH, and finally ICRH only. The (D)/(H+D) ratios, measured by Neutral Particle Analyser (NPA) [7] during ohmic and NBI phases, vary from 12 % to 64 % in nine discharges (see table 1). The position of the mode conversion layer changes with the isotopic ratio: the table 1 provides the distance between the mode conversion layer and the position of the 3/2 D cyclotron harmonic layer. The shots #14779 and 14783 provide a good comparison

AUG shots	14777	14778	**14779**	14780	14781	14782	**14783**	14784	14785
$n_D/(n_D+n_H)$ (%)	12	14	**18**	22	50	56	**60**	63	64
$R_{3/2D}$-R_{MC} (cm)	46.1	44.3	**40.5**	36.8	10.7	5.1	**1.4**	-1.4	-2.3

Table 1: isotopic ratio in % and distance between Mode Conversion layer and 3/2 D cyclotron harmonic layer.

in the sense that they have comparable ICRH power (2.3 MW and 1.9 MW resp.) with a very different isotopic ratio (18 % and 60% resp.). This means that the mode conversion should take place largely off axis for #14779, and almost on axis for #14783 (see table 1 and Fig. 1).

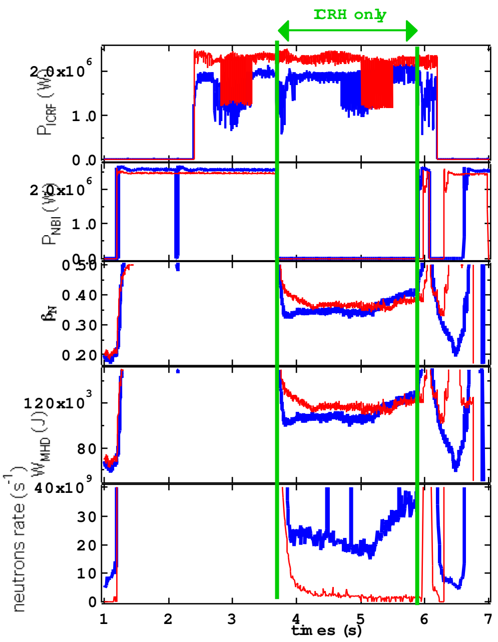

Fig. 2: times traces of shots # 14779 (red) and # 14783 (blue); a/ ICRH power, b/ NBI power, c/ poloidal beta, d/ MHD energy content, e/ neutron flux

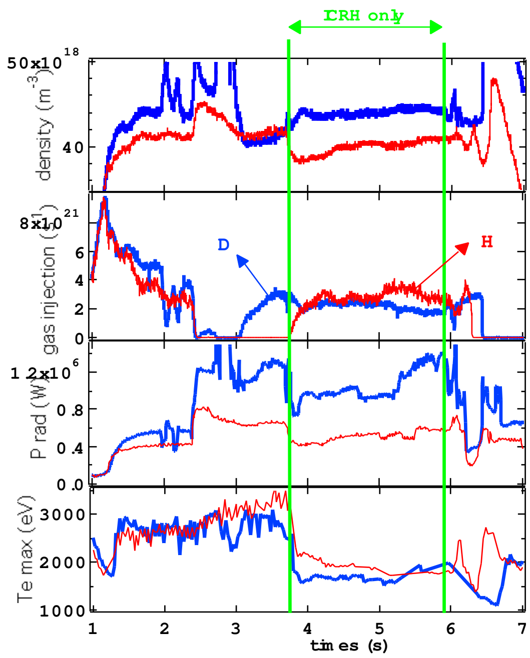

Fig. 3: times traces of shots # 14779 (red) and # 14783 (blue); a/ line averaged density, b/ gas injection (H for #14779, and D for #14783), c/ radiated power, d/ maximum electron temperature from ECE Michelson interferometer

The radial profiles of the direct damping of the ICRF power on electrons are deduced from power modulation performed during the ICRH only phase (e.g. between 5 and 5.5 s on #14779, see Fig. 2a) for these two shots (Cf. Fig. 4). One finds effectively that the location of the maximum of the power deposition on electrons (reflecting the damping of the IBW on electrons) varies with the plasma mixture, in agreement with the position of the MC layer, i.e. off axis for low D concentration and much more on axis for large (60%) D concentration. The different times traces of these two shots are fairly comparable (β_N, W_{MHD}, Te max), except the radiated power that is larger for #14783 although there are very low level of high

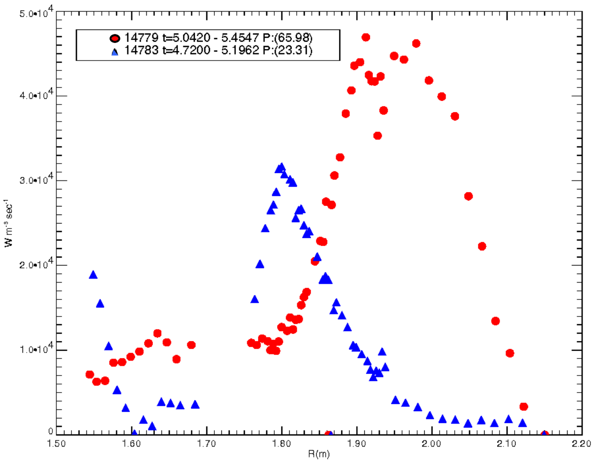

Fig. 4: direct damping on electrons deduced from ICRH power modulation for shots # 14779 (red circles) between 5 and 5.5 s and # 14783 (blue triangles) between 4.7 and 5.2s

Z impurity in both cases. The light impurity concentration are also low during ICRH only : (C)~0.5 %, (O)~0.45% at t=4.5 s for #14779, and (C)~0.3 %, (O)~0.13% at t=4.5 s for #14783. Checking whether the power goes to electrons or ions experimentally is not straightforward: if part of the ICRF power is damped through the ion channel, the low electron temperature and the high density would ensure a fast equipartition, so the D temperature profile might not differ too much from the profile due to a pure electron heating. However, there are several indications that the ICRF power couples to ions through IBW where expected by the theory. Firstly, the spectrum of D fluxes measured by the NPA in the ICRH only phase for the shot #14779 differs barely from thermal spectra of plasmas with maxwellian distribution and ion temperatures of 2 to 3 keV (see Fig. 5). It falls below the detection limit at less than 25 keV. On the contrary, in the case of shot #14783, the spectrum of the D flux is much flatter and extends to energies higher than 50 keV. If the spectrum were interpreted as thermal spectrum, the slope would indicate an apparent ion temperature of approximately 8 keV (see Fig. 5) to be compared to Ti ~ 1 keV in the ohmic phase. This could be attributed to D heating through non linear damping, which could occur, when the MC process takes place close to the 3/2 D cyclotron harmonic and the IBW wave is not totally damped on electrons. One should note that the D spectra of # 14783 are clearly higher and flatter than all other shots of this series (it is the only one presenting a significant D flux in the 40 keV channel). The D fluxes fall off within the short time of 10 ms after ICRH switch off: the critical energy (below which an ion collides more on ions than on electrons) is about 30 keV, the ion-electron collision time is about 100 ms and the ion-ion collision time is about 3 ms: it means that an ion of 30-40 keV at plasma centre could disappear on a timescale of 10 ms. In addition, other phenomena could contribute to reduce this time, namely a redistribution of ions due to sawteeth [8], and the energy diffusion. A fast decrease of the neutral density at the edge at the ICRH switch off would also influence the D fluxes fall off measured by NPA. On the other hand, one could not completely rule out some effect from ion cyclotron damping at D second harmonic on the low field side, although the available energy per particle is low on the LFS due to a volume effect, and that make difficult to accelerate a D ion up to 50 keV. The neutron rate though provides confirming evidence that the fast D seen by the NPA come from the centre. Indeed, the neutron rate is a factor 20 higher for #14783 (e.g. $3.5*10^{10}$ s^{-1} at 5.7s) compared to #14779 (e.g. $1.8*10^{9}$ s^{-1} at 5.7s). Keeping in mind that the D concentration varies by a factor of 3, the D-D reaction rate would be expected to differ only by a factor of 9. Even renormalized in this way, the neutron rate presents a peak for shot #14783, in agreement with the highest and flattest D spectrum for #14783. Finally, the fraction of the coupled ICRF power directly damped on electrons as could be deduced from the modulation of power (see Fig. 4) is very different between # 14779 (59%) and #14783 (23%): as already mentioned above (see Fig. 2 and 3), the two shots present similar performances which means that some ICRF power is coupled through ions on #14783. In addition, one should note that there is a clear evolution after 5.3 s on shot #14783 (see fig. 2 and 3) towards higher performances (Te, neutron rate, W_{MHD}, β_N). There is probably an evolution of the isotopic ratio with time, and, consequently, a modification of the localisation of the MC layer: one could think about an effect of this MC layer on the turbulence that might in turn affect the confinement. There is no tail of very fast D (100 keV to 1 MeV range), even in combined heating (ICRH + NBI of D), as was seen for instance on TFTR in MC experiment in presence of D NBI [9]. Simulation of the power partitioning between FWEH and mode conversion is under progress with the TORIC code [10].

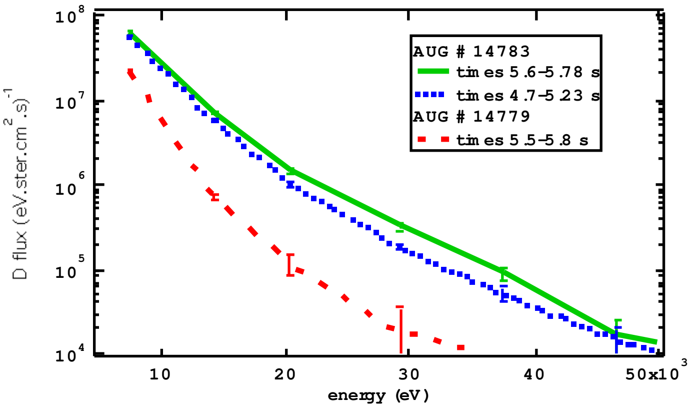

Fig. 5: D fluxes measured by Neutral Particle Analysers at different times intervals for shots #14779 (red dashed line) and #14783 (green line and blue dots)

Mode Conversion experiment with ICRH have been carried out in D-H plasmas in ASDEX Upgrade. Power deposition on electrons has been measured by power modulation, and the location of the maximum of the damping varies accordingly with the position of the MC layer. Neutral Particles Analyser measurements, neutron rates, and the modification of the fraction of ICRF power directly damped on electrons provide a clear indication that some ion heating takes place when the MC layer lies close to the 3/2 D cyclotron harmonic layer, meaning that a non linear damping mechanism is effective. As a further experiment on JET, one could imagine a T trace experiment in D-H plasma: the position of the 5/2 T cyclotron harmonic is exactly 5/3 of the radius of the fundamental cyclotron harmonic of D. One could then locate the two layers R(5/2T)=1.67*R(1D) and R(3/2D)=1.5*R(1D) at plasma centre, adjust the plasma isotopic ratio H/(H+D) such that the Mode Conversion occurs in this region, and thus heat both T and D.

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