Fast Wave Current Drive experiments in JET divertor plasmas

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Abstract:

As part of the JET experimental campaign in the pumped divertor configuration with the new ICRF A2 antennae [1], studies of Fast Wave Heating and Current Drive scenarii have been carried out [2]. For the experiments described in this paper, the scenario with 3rd harmonic D cyclotron layer at centre and both fundamental and 2nd harmonic H cyclotron layers at the edge has been chosen. The experiments have been carried out in 2 MA D plasmas and 2.2 T on axis with f_{ICRF}=51.4 MHz and a target temperature of T_e (0)~1.5-2 keV. Significant Fast Wave Heating has been observed and studied for varying plasma parameters (B_T, ICRF power, antenna phasing, density). There is evidence of both Fast Wave Direct Electron Heating and heating through 3rd harmonic D cyclotron absorption. These two effects disappear when the 2nd harmonic H cyclotron layer enters in the plasma on the high field side. The power partition between these two heating channels is difficult to assess experimentally. The results are compared with numerical simulations of the power deposition (PION, SINGLE). Furthermore, a prediction of the current drive efficiency is given (ALCYON). This scenario provides efficient heating, since elmy H-mode is triggered when the electron density and the ICRF power in 0ππ0 phasing are increased and a RF only record DD reaction rate of 1.8 10^{16} s^{-1} has been achieved. 0π0π phasing gives similar results.

Fast Wave Electron Heating and Current Drive scenario:

The target plasma parameters are B_T=2.2 T, I=2 MA and T_e(0)~1.5-2 keV in Deuterium. At ICRF frequency of 51.4 MHz, 3rd harmonic D cyclotron layer is at centre while both fundamental H cyclotron resonance (also 2D and 2 ^{4}He) and 2nd harmonic H (also 4D and 4 ^{4}He) cyclotron layers are marginally present at the edge (e.g. # 35320, fig. 1). Unless otherwise specified, the phasing is 0ππ0. A similar scenario has been experimented on Tore Supra [3].

Experiment:

A heating with sawteeth is observed but is sensitive to H resonance layer position. A scan of the magnetic toroidal field has been done (# 35520). When the H cyclotron 2nd harmonic layer enters plasma on the low field side (fig. 1), the density, the radiated power and neutral H flux (Neutral Particle Analyser horizontal line) increase while the DD reaction rate, high energy neutral D flux (NPA horizontal line) and T_e drop. There is evidence of Fast Wave Electron Heating. The analysis of the fast switch off of P_{ICRF} and of the sawteeth slope [4] yields peaked deposition profiles (# 35319, fig. 2a, b). One finds P_{FWEH}=0.9 MW for an ICRF launched power of 6.5 MW which means 14% of damping on electrons in 0ππ0 phasing (fig. 2b). The power directly coupled to electrons in + 90° and - 90° phasing is estimated to be less than 50% of 0ππ0 heating [5]. The pre-heating with LH power produces no visible difference. Two pulses in ^{4}He have been performed. The second one (# 35328) is approximately 50% ^{4}He and 50% D and the results are similar to D plasma (# 35325). In particular, the T_e profiles are identical. Part of the ICRF power is clearly absorbed at the 3rd harmonic D cyclotron resonance as indicated by a high DD rate and γ emission from the plasma centre (3.1 MeV from ^{12}C(d, p)^{13}C with E_d>1.8 MeV). Fast D is detected with the vertical high energy NPA up to the highest energy channel available (E=1.1 MeV) (fig. 3). This contrasts with Tore Supra results that show dominant electron heating and no fast ions in ^{4}He plasma [3]. This is likely to be due to the better ion confinement in JET that allows the build up of a hot ion tail but models have to be developed. A power and density scans have been done. When the density and ICRF power increase, the plasma evolves towards better performance (fig. 4): the diamagnetic energy content and the DD reaction rate increase and one finally obtains an elmy H-mode. The H factor was 1.6 (ITER89-P) and 0.8 for H93 (H-mode scaling with subtraction of the energy of fast particles) for pulse # 35525 with 0ππ0 phasing (fig. 3) (similar results were obtained for # 35526 with 0π0π phasing). For this pulse, the record DD reaction rate for ICRF only (1.8 10^{16} s^{-1}) was achieved with P_{ICRF}=12.9 MW. The other parameters are W_{DIA}=3.2 MJ (with $W_{fast\ particles}$=0.6 MJ), $<n_e>=3.9.10^{19}$ m^3, $T_e(0)$=5.7 keV, P_{total}=13.5 MW. This performance is comparable to hot ion mode (DD reaction rate of 2.10^{16} s^{-1} for P_{NBI}~14.6 MW at 1.75 MA, # 34489).

Numerical simulations (based on the ICRF and plasma parameters of pulse # 35320):

The power partition between Fast Wave Direct Electrons Heating and heating through D cyclotron absorption at the 3rd harmonic is difficult to estimate. Single Pass Absorption (SPA) estimate (SINGLE code [6], (fig. 5)) is larger for electron (4.5 keV) compared to D absorption of the bulk (2.7 keV) but the SPA for a population of fast D (1% of the D bulk) becomes predominant above 300 keV at the most favourable $k_{//}$ for electron damping (N=33, $k_{//}$=11 m^{-1} on axis). The PION code simulation (self consistent treatment of the D tail formation and the Fast Wave absorption [7]) with hot D confined up to an energy of 2.5 MeV indicates equipartition of the coupled ICRF power between electron and deuterium. The ALCYON (2D full wave code [8]) simulation provides almost identical power deposition profile on electrons for 90°, 0ππ0 and 0π0π phasing and predicts a current drive efficiency of 0.018 10^{20} A/W/m^2 in 90° phasing.

Conclusion:

Significant Fast Wave Direct Electron heating (~14%) and heating through D absorption at cyclotron 3rd harmonic have been observed. This contrasts with the Tore Supra results that show dominant electron heating and no fast ions with the same scenario [3]. The power partition is difficult to assess. The competition with lower cyclotron harmonic (H or D) should be avoided (edge absorption). The Fast Wave Current Drive efficiency is estimated to be 0.018 10^{20} A/W/m^2 for 90° phasing with the plasma parameters of pulse # 35320 which is comparable to the Tore Supra results [3]. Elmy H-mode is triggered when density and ICRF power in 0ππ0 phasing are increased and a RF only record DD rate of 1.8 10^{16} s^{-1} has been achieved. Similar effect is observed in 0π0π phasing. An efficient heating scenario at 2 MA, 2.2 T with no minority ion population has been found, which can start on low T_e (1-2 keV) target plasma and might provide suitable conditions for very long pulse (60 s) operation for advanced tokamak scenarii on JET.

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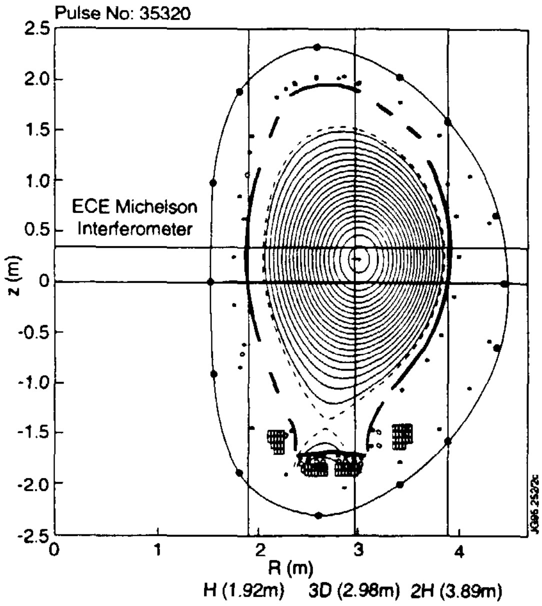

fig. 1: location of the different ion cyclotron layers on a poloidal view of the plasma.

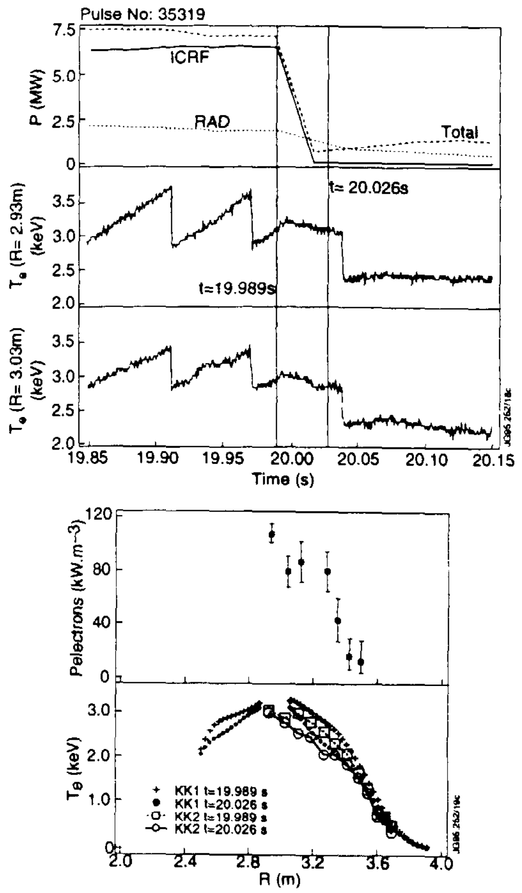

Fig. 2: pulse n° 35319, 0ππ0 phasing, 51.4 MHz, 2.18 T, Deuterium, 1.8 MA, a: P_{ICRF} sharp switch off, effect on the sawteeth, ECE Grating Polychromator (z=25cm), b: direct electron heating profile c: ECE T_e, profiles in the plane z=z(axe).

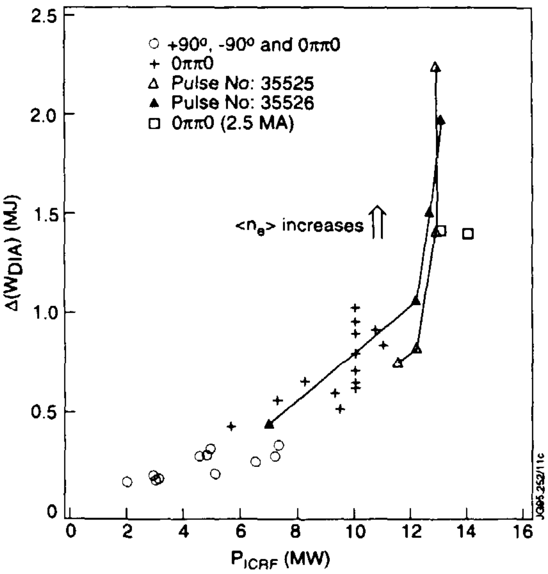

Fig. 4 diamagnetic energy increase in function of the ICRF power, 51.4 MHz, 2 MA, 2.18 T.

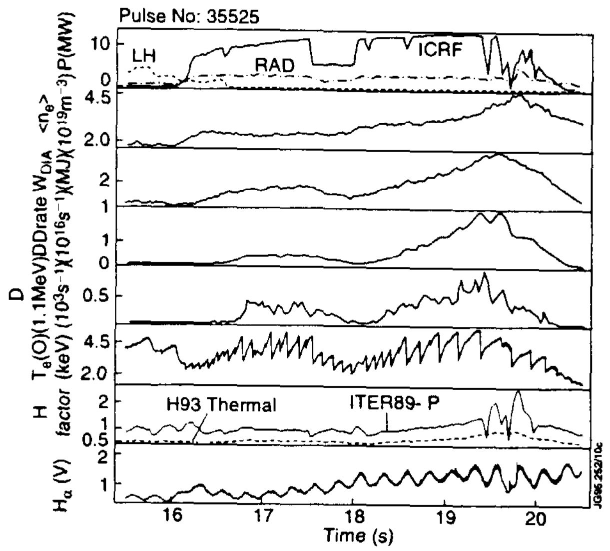

Fig. 3: pulse n° 35525 0 π π 0 phasing, 51.4 MHz, 2 MA, 2.18 T, Deuterium.

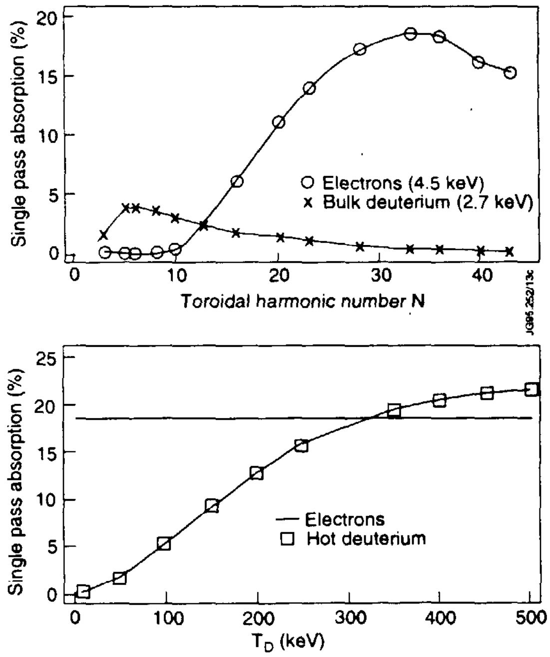

Fig. 5: SINGLE simulation of the pulse n° 35320 at t=16.2 s, a: SPA on electrons (TTMP and ELD) and on bulk D (3rd harmonic) in function of the toroidal harmonic number N, b: SPA for the toroidal harmonic number N=33 ($k_{//}=11\ m^{-1}$ on axis)on electrons and hot D (1% of the bulk in density) in function of T_D.