IMPROVED SCENARIO FOR COUPLING ICRF POWER TO ELECTRONS IN TORE SUPRA

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Abstract. Experiments on direct electron heating using the fast wave have been previously performed in several tokamaks (Tore Supra, DIII-D, JET) at low toroidal magnetic fields (B = 1 T / 2.8T), always in presence of competitive ion cyclotron absorption. Recently, for the first time, fast wave heating has been experimented at the frequency of 42 MHz in Tore Supra, without ion cyclotron absorption layers in the plasma center.

I. Introduction

The Fast Wave Electron Heating (FWEH) single pass absorption varies as $1/B^3$. First experiments were thus done on Tore Supra at a low magnetic field (B_0 = 1.4, 2.2, 2.8 T, f = 48, 48, 63 MHz). But, in such scenarios, FWEH can be in competition with ion cyclotron absorption due to the presence of the third harmonic Deuterium (3D) (Figure I-1 a).

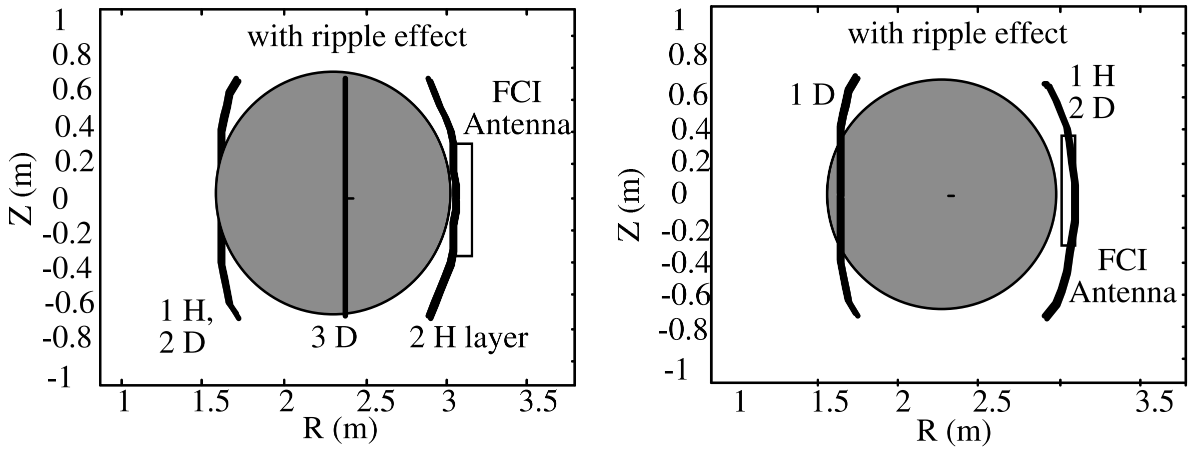

Figure I a) FWEH scheme at B_0 = *2.1 T*, R_0 = *2.28m, a = 0.71 m* (shot 18805). **b)** FWEH scheme at B_0 = *3.7 T*, R_0 = *2.27m, a = 0.72 m* (shot 23620)

In JET experiments[1], the absorption on 3D even dominated the FWEH scheme. By setting the frequency at 42 MHz, and the magnetic field at B_0 = 3.7 T, one can operate without any cyclotron resonance of Hydrogen or Deuterium (Figure I b)) in the plasma centre. This offers the opportunity to validate the FWEH mechanism (direct electron heating by the Fast Wave through Transit Time Magnetic Pumping and Electron Landau Damping).

II. Experimental results

II-1) FWEH scheme

The plasma aspect ratio (R=2.28m, a=0.72m) is carefully chosen to avoid the absorption of the wave on the first D and H harmonic layers, located at the very edge of the plasma (this is monitored by the charge exchange diagnostic[2]). Figure II-1 shows a comparison of the charge exchange energy spectra between a shot at 2.2 T, where FWEH is clearly seen (P_{FWEH} = 6 MW, βp = 1, #18805) and a shot at 3.7 T (#23620). In both cases, the level of fast ions is quite similar, and several orders of magnitude lower than in minority heating schemes. The difference for the hydrogen spectrum (Figure II-1a), low field side, between 42 MHz and 48 MHz cases, is probably due to the fact that the 42 MHz case involves a first harmonic (1H) damping, while the 48 MHz case involves a second harmonic (2H) effect. Despite the presence inside the plasma of the first harmonic deuterium layer (high field side), no ion tail is seen by the diagnostic(Figure II-1b).

At 42 MHz, the fraction of bootstrap current has been optimized by decreasing the plasma current (Ip<1.5MA). Unfortunately, a preliminary limitation was observed at Ip=1.1 MA. Either a disruption occurred a few hundred milliseconds after the power was applied, or the ICRF generators were not able to apply the power. In all the case, this limitation seems to be due to a poor damping of the wave to the plasma at low value of plasma current, and possible competitions with edge effects.

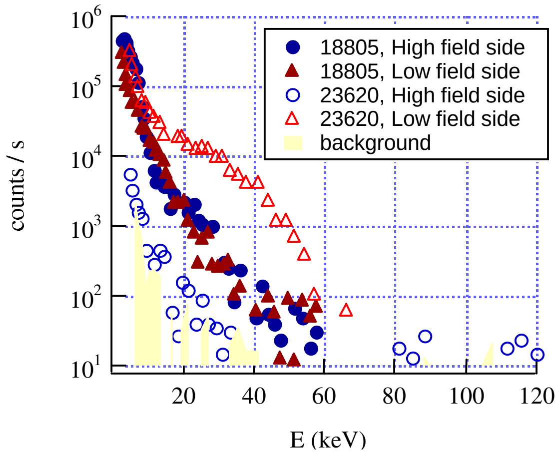

Figure II-1: a) Energy spectrum of neutral hydrogen. The background is the same for the two shots

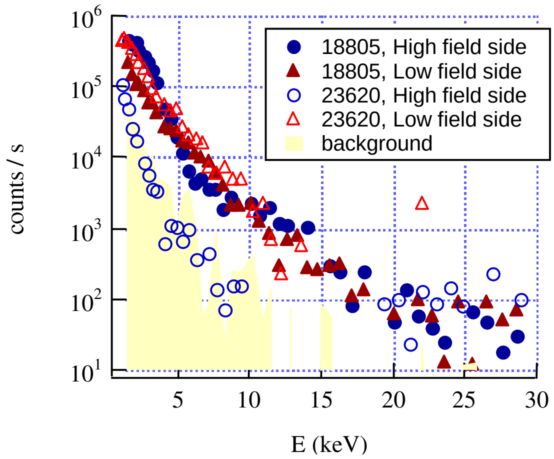

Figure II-1: b) Energy spectrum of neutral deuterium

Figure II-2 shows the bootstrap profiles, as computed by the NCLASS code[3], for two different magnetic fields, and the corresponding pressure profiles. The pressure profile being broader at 3.8T/42MHz, the corresponding bootstrap current is more off-axis. The characterization of the bootstrap profile can be made defining a so-called "barycentre" ρ_{bar} :

$$\int_0^{\rho_{bar}} I_{boot}\,\rho\,d\rho = \int_{\rho_{bar}}^1 I_{boot}\,\rho\,d\rho$$

One advantage of this characterization is to give a small contribution of the central bootstrap (inside ρ = 0.1), where the theory is quite inaccurate (50 % of uncertainty on the modeling for ρ < 0.1, 15 % of uncertainty for ρ > 0.1)

Bootstrap current profiles were calculated for a large database of shots[4], and Figure II-3 gives the evolution of ρ_{bar} with the plasma current for various magnetic fields, in ohmic and heating phase. The difference between 3.8 and 2.2 T can then be explained by:

i) The plasma current is higher for the shots at 42 MHz. The ohmic contribution to the bootstrap current is important and peaked around ρ = 0.7. In the 2.2 T series, the plasma current is reduced (0.6 MA), and the FWEH-driven bootstrap current is dominant.

ii) Moreover, due to a broader pressure profile, the FWEH power deposition profile is broader at higher plasma current. This profile is calculated by the codes ABSORB[5] and/or ALCYON (ABSORB is a fast fluid code whose results were validated by the full-wave ALCYON code). Deriving a barycenter for the deposition profile, ρ_{dep} :

$$\int_0^{\rho_{dep}} P_{FWEHt}\, \rho\, d\rho \;=\; \int_{\rho_{dep}}^{1} P_{FWEH}\, \rho\, d\rho,$$

one finds for 42 MHz, $\rho_{deb} \approx 0.28 \pm 0.02$, for 48 MHz, $\rho_{deb} \approx 0.18 \pm 0.02$

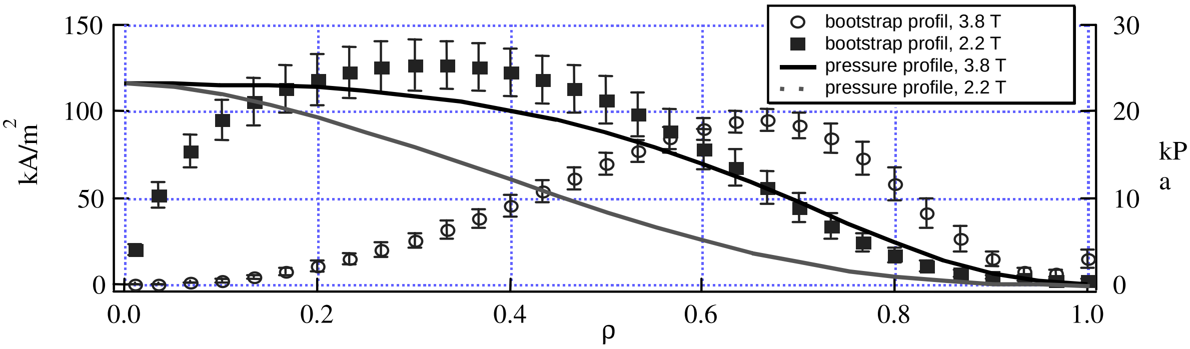

Figure II-2 : bootstrap profiles (markers) for two different magnetic fields (lines ⟶ pressure profile). The error bars are due to errors on experimental data (Temperature, density, *q* profile)

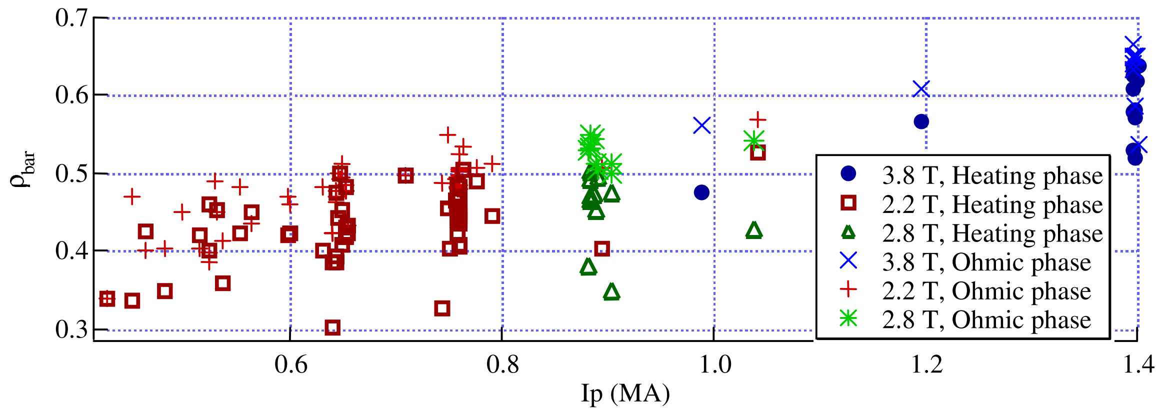

Figure II-3 : bootstrap barycenter versus plasma current for three different magnetic field

An enhancement of confinement through the electron channel (Figure II-4, We reached 1.4 x L-mode). It is the same that the one obtained at the same level of power per particle $P_n = P_{FWEH}/nl$ (P_{FWEH} is the injected power, nl is the linear density), with other frequencies, and is directly linked to the bootstrap current fraction which modifies the total current profile.

By taking into account the ohmic bootstrap current ($I_{\text{bootstrap ohmic phase}}$), we can derive an efficiency (η) of FWEH to create non-inductive current by means of bootstrap current, in the same way as any other current drive scheme :

$$\eta \;=\; \bar{n}\, R\, \frac{\left(I_{bootstrap\ \text{heating phase}} - I_{bootstrap\ \text{ohmic phas}}\right)}{P_{FWEH}}, \quad \bar{n} \;=\; \frac{n_l}{2\,a}, \quad n_l \;:\; \text{lined density } \left(m^{-2}\right),$$

R major radius (m), a minor radius (m), P_{FWEH} injected power (MW)

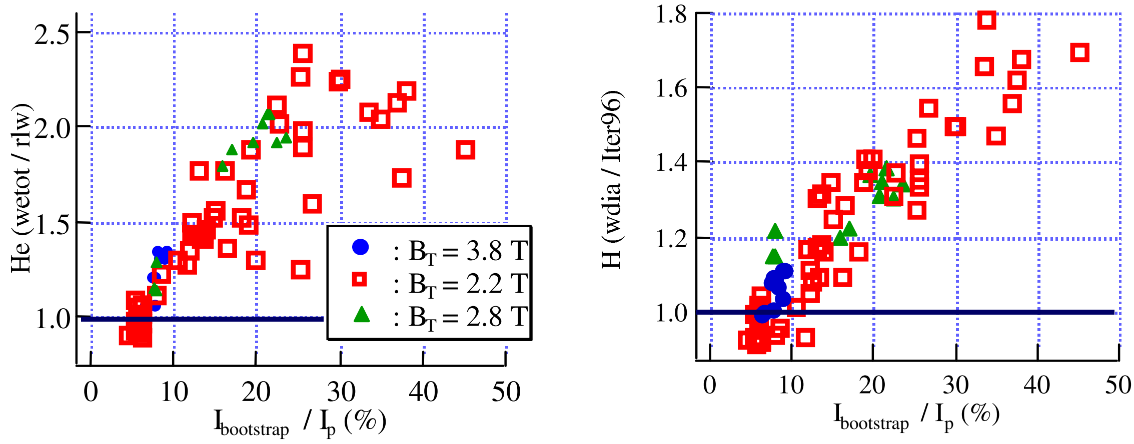

Figure II-4: a) electron confinement He versus bootstrap current (rlw : Rebut Lallia Watkins)

b) Global confinement (H) versus the bootstrap fraction

This efficiency is roughly constant over a large set of plasma parameters (plasma current, magnetic field, density, electron temperature) (Figure II-5) : $\eta \approx 0.2 \pm 0.05 \times 10^{19}$A/W/m^2 and is fairly comparable to other non-inductive current drive methods. Note that these points were derived in presence of a remaining ohmic electric field. But there is no effect of this electric field is expected on the result, since the bootstrap current is especially driven by the thermal electron pressure in our case.

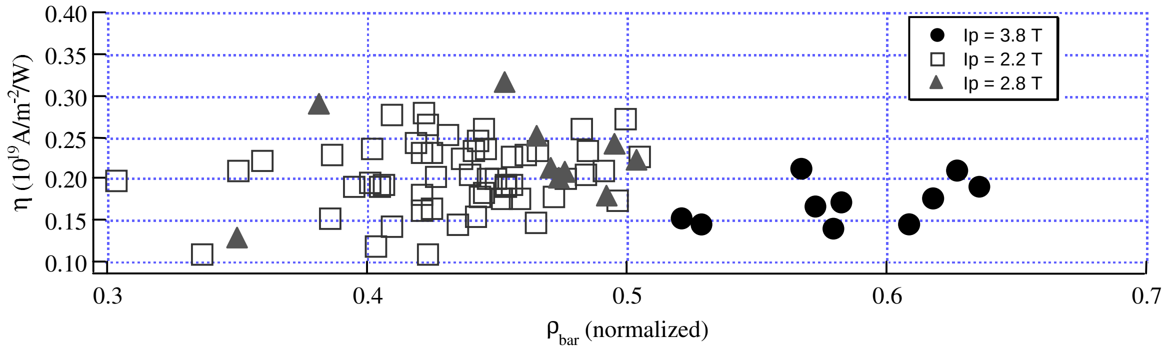

Figure II-5 : Current drive efficiency of FWEH for stationary shots in a large set of plasma parameters

III. Conclusion

For the first time, the concept of FWEH is validated on Tore Supra by the use of the 42 MHz/3.7 T scheme. The present study shows the same behavior as compared to the other frequencies/magnetic field schemes, and allows the use of the FWEH scheme over a large set of plasma parameters. Further experiments are planned during the 1998 campaign, at a higher power up to 12 MW to increase the bootstrap current at high density and plasma current, in a way to fully benefit of the effect of the bootstrap current on the energy confinement.

[1] F. Nguyen et al.: *22nd EPS*, Bournemouth, volume **19C**, part II, page 353
[2] B. Saoutic et al.: Plasma Phys. Control. Fusion **36** (1994) B123-132
[3] W.A. Houlberg et al.: Phys. Plasma **4** (9), September 1997
[4] V. Basiuk et al.: *12th Topical Conference*, Savannah, 1997, AIP Conference proceedings 403, page 239
[5] F. Nguyen et al.: *12th Topical Conference*, Savannah, 1997, AIP Conference proceedings 403, page 417