27th EPS Conference on Contr. Fusion and Plasma Phys. Budapest, 12-16 June 2000 ECA Vol. **24B** *(2000) 784 -787*

Ripple loss studies during ICRF Heating on Tore Supra

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Abstract: The high level of magnetic field ripple at the edge of the plasma (around 7 %) on Tore Supra induces fast ion losses during Ion Cyclotron Frequency (ICRF) heating. These losses could be as high as 30 % of the injected power in hydrogen minority scheme, depending on various plasma parameters, the main one being the location of the resonance layer R_{1H} inside the plasma. This paper reviews all the results obtained by the specific ripple diagnostics installed on Tore-Supra:

1. Introduction

Knowledge of the ripple induced losses and their location in Tore Supra is of major importance for long pulse scenarii (for the CIEL project[1] discharges as long as 1000 s are planned) using ICRF heating. In addition, ripple loss studies are needed for assessing the power balance[6]. Tore Supra is an actively cooled tokamak which allows to determine the power exhausted from the plasma by calorimetry[8]. Ripple losses can be a non-negligible part of this power and must be estimated.

Three sets of diagnostics were installed on Tore Supra and devoted to ripple loss studies during additional heating, and in particular ICRF heating:

- The first diagnostic[2] (DRIPPLE) was installed in 1992 and measures the fast ion current escaping from the plasma (radial resolution ~ 5cm, and time resolution ~1 ms)
- The second one[3] measures the thermal energy of these ions by means of calorimetric measurement (integrating over the whole shot). It was used during the experimental campaign of 1995 and again 1999, in an improved form.
- The third one was spatially resolved thermography of the calorimetric plate[7].

In deducing the lost power from these diagnostics, it is assumed that the losses are "periodically" symmetric (with a period $2\pi / N$, N=18 is the number of TF coils). The validity of this assumption is discussed in section 2.

2. Experimental results

A database comprising data from around a hundred shots from the last experimental campaign at TS has been assembled. The data cover a wide range of plasma parameters:

- P_{ICRF} : injected power (0.5 → 5 MW)
- E_{ICRF} : total energy injected, $E_{ICRF} = \int P_{ICRF}\,dt$ (5 → 40 MJ)
- n_l : central line-density (2 → 7.5 10^{19} m^{-2})
- R_{1H} : major radius of the hydrogen fundamental ion cyclotron resonance. $R_{1H} = \frac{qB_0R_0}{2\pi m_p \omega}$ (2.17 → 2.44 m). where B_0 is the magnetic field, R_0 the major radius, ω the antenna frequency, m_p the proton mass and q the electron charge.
- I_p : plasma current (0.5 → 1.5 MA)

All the shots in the database were carried out in a configuration relevant to the CIEL project[3] (major radius, R=2.4 m, minor radius, a=0.72 m). Thus, the scaling laws that can be obtained from the database are useful for extrapolation to CIEL scenarios.

2-a) Scaling laws. The following two scaling laws, one for the lost current (I_{lost}, figure I-b) and one for the thermal energy lost (E_{lost}, figure I-a) in 1/18 of the toroidal section, have been obtained:

$$I_{lost} = 5.72\,10^{-2}\, P_{ICRF}^{1.01\pm0.08}\, n_l^{-0.87\pm0.2}\, R_{1H}^{9.1\pm1.5}\, I_p^{0.2\pm0.1} \quad \{1\}$$

$$E_{lost} = 6.3\,10^{-6}\, E_{ICRF}^{1.3\pm0.06}\, n_l^{-1.17\pm0.2}\, R_{1H}^{9.5\pm1.0}\, I_p^{0.16\pm0.1} \quad \{2\}$$

These two scaling laws show that the ion flux is almost proportional the injected power, P_{ICRF}, while the lost power increases faster than linearly with the injected energy (E_{ICRF}).

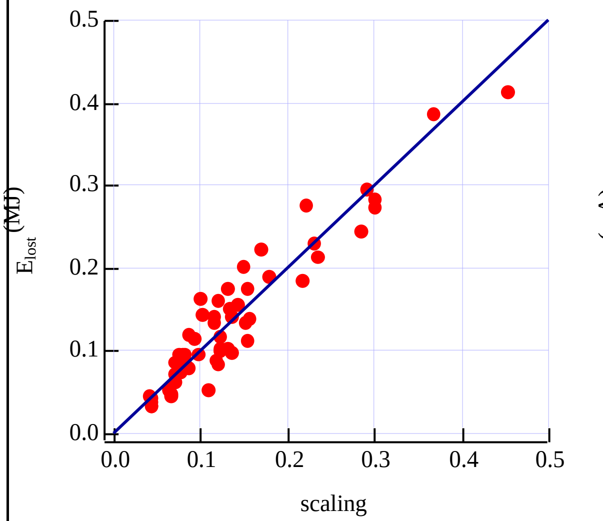

figure 1-a : Thermal energy lost deduced from temperature measurements

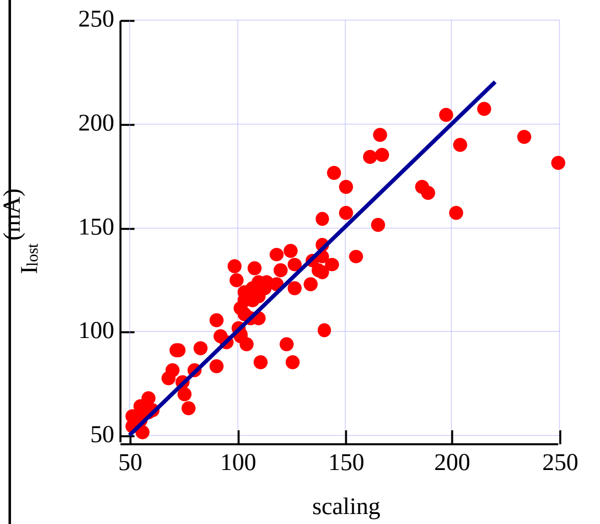

Figure 1-b : Current measurements of lost fast ions

The new improved calorimetric measurements show that there is no contribution from the thermal plasma to measured fast ion losses. This is in contrast to the data from the 1995 campaign which indicated a thermal contribution of around 0.04 MJ. It gives a better accuracy on the thermal energy. First estimations show a precision around 10 %.

2-b) Asymmetry In order to deduce the fraction of power lost in the ripple, “periodic” axi-symmetry of the losses is assumed. However, non symmetric losses might occur due to the toroidal distribution of the wave field accelerating the fast ions. To assess the axi-symmetric hypothesis, the fast ion current (I_{lost}) was studied during shots where power was applied consecutively to all three ICRF antennas of TS (i.e. only one antenna launched power at any given time). The plasma parameters (such as line-density, plasma current) were kept constant. Of the three antennas available (Q1, Q4 and Q5, figure 2-a), Q1 is the one with the greatest toroidal distance from DRIPPLE (160°). It is compared to the two others (20° for Q4 and 60° for Q5) .

A criterion for axi-symmetry (called deviation) has been devised, comparing the current measured when Q1 was operated to the current when the two other antennas were used. The result is plotted in figure 2-b. The main conclusion of this study is that the ripple losses are symmetric for an injected power above 1.5 MW (which is case for most of the shots in the database), i.e. the fraction of power lost in the ripple is just eighteen times (the number of coils) the value measured by the calorimetry in one port. This also means that data from the two diagnostics, which are located in different ports, can be combined with each other.

A significant deviation is, however, observed al low levels of injected power (below 1.5 MW) in deuterium plasmas. This deviation is not yet theoretically fully explained. However, preliminary experimental data suggest that the averaged energy of the lost ions decreases with the deviation. A possible explanation could therefore be that the asymmetry is due to trapped ions with relatively low energies and low toroidal drift velocity, but which are energetic enough not to collisionally de-trap too frequently. Such ions would absorb power in front of the antenna and be lost before they have had to time to drift too far toroidally. A theoretical study is under progress, coupling two codes: ALCYON, which calculates the ICRF electric field , and MOKA[4] which follows a fast ion using the output from ALCYON and a complete description of the magnetic field.

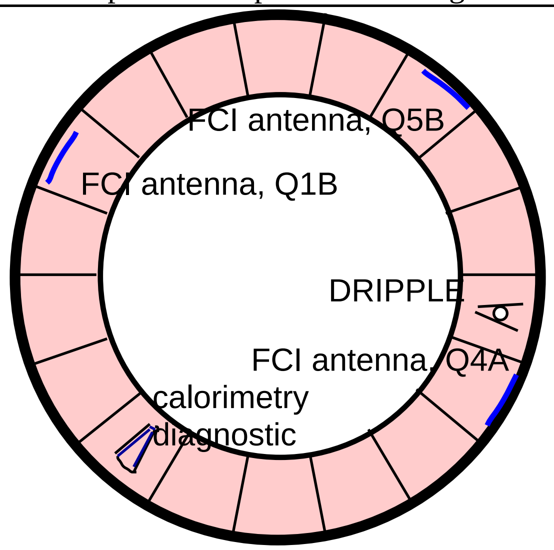

Figure 2-a: Top view of Tore Supra, with ICRF antenna and ripple diagnostic location

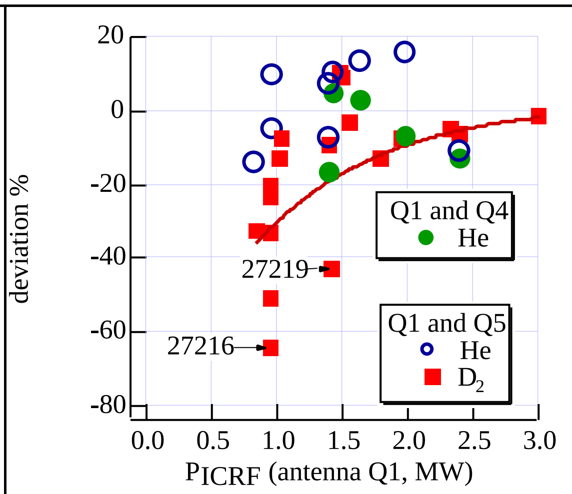

Figure 2-b: Deviation versus the injected power of the antenna Q1. Red curve is a polynomial fit with the square point.

3. Discussions

3-a) Lost fraction: Fig. 3 shows the fraction of lost power in the ripple and the effect of the location of the resonance layer on the level of ripple losses. Moving the resonance layer towards the high magnetic field side can reduce the losses. Fast ions are then generated far away from the loss domain. However, the off-axis heating scheme is less efficient in terms of central temperature increase than an on-axis heating scheme.

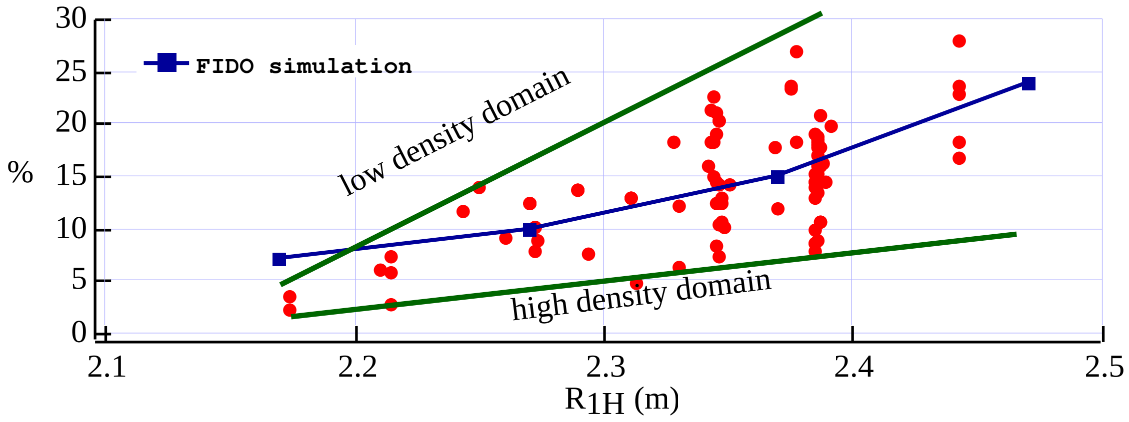

Figure 3: Fraction of power lost in the ripple versus the location of hydrogen fundamental resonance

For the most frequently used resonance positions (on axis-heating $2.34<R_{1H}<2.4$), the fraction of lost power is around 10-20%, depending on the density as shown by the scaling law 2. Owing to the increased collisional de-trapping frequency, the lost fraction decreases when the line-density increases. Thus, a good way to reduce ripple losses in the CIEL project is to utilize discharges with a high density.

Preliminary theoretical analysis using the code FIDO[5] shows a good agreement with the experimental data as shown in fig. 3, where for a given line-density and plasma current, FIDO simulations were made, varying the location of the resonance layer.

3-b) Mean energy: By combining the data from the two ripple diagnostics, it is possible to deduce the mean energy of the lost ions, $<E_{lost}>$:

$$\langle E_{lost} \rangle = \frac{E_{lost}}{\int I_{lost} dt}$$

Fig. 4 shows that $<E_{lost}>$ increases when the hydrogen concentration decreases, which is also well reproduced by simulations. The dispersion of the points could partly be explained by the fact that a small fraction of the fast ions make a charge exchange reaction on a neutral atom, and will not be seen by DRIPPLE[6]. On the contrary, calorimetry will largely account for these particles. The mean energy level (200-300 keV) is also confirmed by near infrared thermography measurements[7] for a few shots, looking at the main target area on the ripple protection plate.

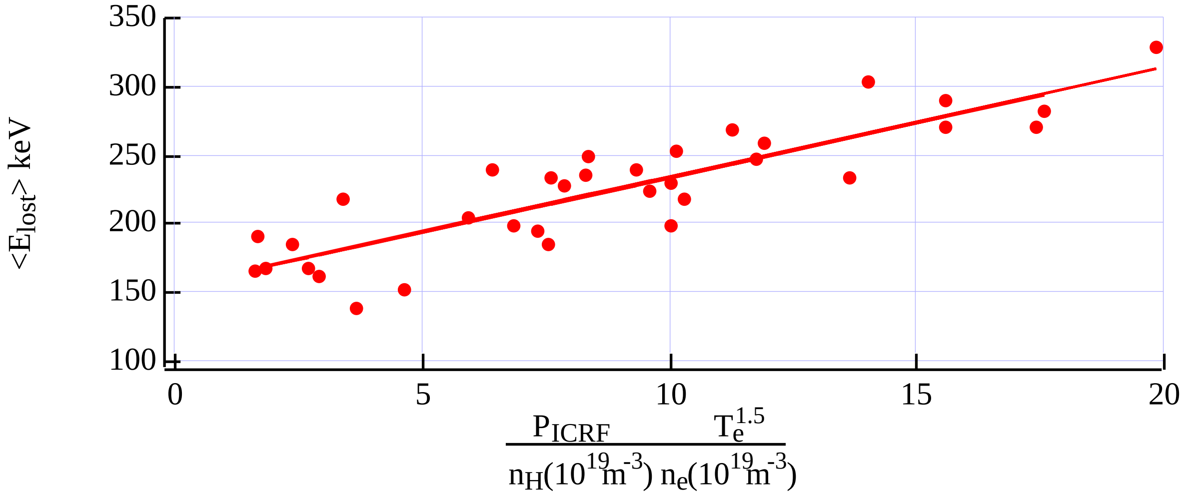

Figure 4 : mean energy of fast ions lost in the ripple versus the injected power per ion. $T_e^{1.5}/n_e$ is proportional to the electron-ion scattering time. Red curve is a linear fit.

3-b) conclusions: Ripple losses are well documented on Tore Supra both in terms of their localization and strength. Extrapolation from the scaling laws Eq. (1,2) for the CIEL project shows that the pumped limiter will in the worst case be subjected to a flux of 2.5 MW/m^2 for 12 MW injected power which is well within the design limits (10 MW/m^2). In addition, the assembled database is very useful for benchmarking codes such as FIDO. Finally, the fast ion lost fraction is now routinely taken into account in power balance analysis[8].

Acknowledgement

We like to thank E. Delchambre for the analysis of the thermographic data.

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