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Thermal and non-thermal particle interaction with the LHCD launchers in Tore Supra

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Abstract

The interaction between the lower hybrid current drive (LHCD) launchers and the plasma has been studied during long pulse, high power operation in the Tore Supra tokamak. The main diagnostics used for characterising the plasma–launcher interaction are calorimetry of the energy extracted by the launchers and infrared (IR) imaging of the launchers and their side limiters. The calorimetry has allowed to identify three different heat sources on the LHCD launchers, namely the RF losses in the waveguides, a fraction (∼0.8%) of the total injected energy and, finally, fast ion losses during ion cyclotron resonance heating (ICRH), accounting for ∼1% of the injected ICRH energy. The interaction by fast ions is identified by infrared imaging of the LHCD launchers as a localised hotspot on the ion drift side, below or at the mid-plane.

Keywords: Tore Supra; LHCD; Calorimetry; Infrared imaging

1. Introduction

Radio frequency (RF) antennas operating in the Lower Hybrid (LH) range of frequencies or in the ion cyclotron (IC) range of frequencies are exposed to high heat flux from the plasma. The distance between the antennas and the last closed flux surface (LCFS) has to be as large as possible, while still ensuring good wave coupling. In ITER it is foreseen to have the antennas imbedded in the first wall. This should guarantee low enough heat flux from the radiated and conducted power from the plasma. However, interaction by suprathermal particles, as well as processes related to the local electric field in front of the antennas, have to be investigated in order to ensure safe and controlled operation in future fusion devices.

In the Tore Supra tokamak, the complete area of the two LHCD launchers and the three ICRH antennas are monitored via the new, powerful infrared (IR) diagnostic system [1]. This is included in the so-called CIMES project, which mainly involves an upgrade of the LHCD system in Tore Supra [2]. The

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infrared imaging allows identifying in detail specific phenomena of plasma–launcher interaction. Furthermore, a real-time control system has been implemented which monitors the temperature in real-time and reduces the power if excessive temperatures are obtained [3]. The IR data is complemented by calorimetric measurements of the energy extracted by the cooling loops on the launchers and their side limiters. The plasma facing components in Tore Supra are water-cooled, in order to evacuate the heat flux during long pulses. The long pulse capability of Tore Supra allows assessing different phenomena of plasma–launcher interaction in steady-state plasmas.

2. Calorimetric measurements

A database analysis of the calorimetric data for one of the LHCD launchers, called C3, has been made for 55 Tore Supra discharges. These discharges are either with pure LHCD power in the range between 1.3 MW and 4.5 MW, or with LHCD combined with ICRH, the ICRH power being in the range between 2.0 MW and 8.5 MW. The injected energy of the discharges included in this database ranges between 52 MJ and 1070 MJ and the duration of the heating powers range between 15 s and 370 s. A least square fit analysis gives a scaling law of the extracted energy in the launcher. This scaling contains three terms, i.e. three different sources of heat flux on the LHCD launcher, as indicated in Fig. 1. These three terms are proportional to the injected energy by the launcher (E_{C3}), the total injected energy (E_{Tot}) and the injected ICRH energy (E_{ICRH}). The main source is the RF losses in the waveguides, which accounts for ~4.5% of the energy injected by the launcher, i.e. $\sim 0.045 * E_{C3}$. The deduced RF losses are consistent with thermo-mechanical calculations, based on the temperature increase of the waveguides as measured with thermocouples. The second source of extracted energy is proportional to the total injected energy. This term accounts for ~0.8% of the total energy ($\sim 0.008 * E_{Tot}$), both in discharges with LHCD only as well as with LHCD + ICRH. Thirdly, one can distinguish a source of extracted energy related specifically to ICRH in the ion cyclotron minority heating scheme. This source accounts for ~1.1% of the injected ICRH energy, i.e. $\sim 0.011 * E_{ICRH}$. The most likely mechanism is the stochastic diffusion of fast ions orbits due to the strong magnetic ripple [4,5], resulting in loss of non-thermal ions (~500 keV) on the low field side, below or at the mid-plane, as also observed in JT-60 [6]. Most of the long discharges with LHCD + ICRH carried out in Tore Supra in 2004–2005 were at low plasma current ($I_P = 0.6$ MA) and at low electron density ($n_e \sim 2.5 \times 10^{19}$ m^{-3}), in order to have a large fraction of non-inductive current with LHCD. In these plasma conditions, the energy of the fast ions can be considerable.

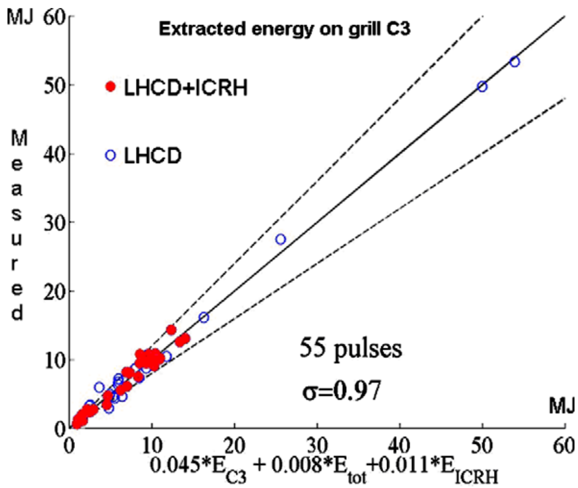

Fig. 1. Scaling of the energy extracted on the LHCD launcher C3. The three scaling parameters are proportional to: (i) the injected LHCD energy in the waveguides (E_{C3}), (ii) the total injected energy (E_{Tot}) and (iii) the injected ICRH energy (E_{ICRH}).

3. Fast ion interaction caused by ICRH

The hypothesis of fast ion interaction on the LHCD launchers has been confirmed by the IR images of the launchers. Localized heating of the waveguides below the mid-plane on the ion drift side (i.e. on the bottom left corner, as seen from inside the vessel) is seen in discharges with LHCD + ICRH (Fig. 2). Similar hot spot can also be distinguished on a non-powered ICRH antenna. The local temperature increase on the launcher C3, as deduced by the infrared measurements, as a function of the ICRH power is shown in Fig. 3. The temperature increase, ΔT, is taken as the maximum temperature in area B minus the maximum temperature in area A, as indicated in Fig. 2. In all the discharges in Fig. 3, the LHCD power is applied at 5 s and the ICRH power at 10 s. The temperature increase is measured at 30 s in the discharges, i.e. after 20 s duration of ICRH. Fig. 4 shows the same temperature data, but this time plotted against a

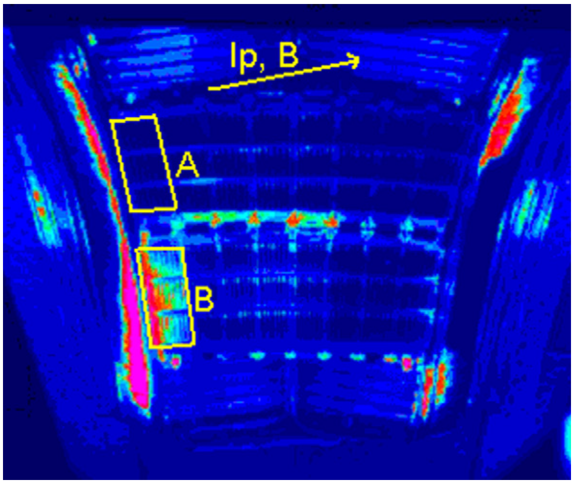

Fig. 2. IR image of the LHCD launcher C3 in 2004 (pulse 34182). The area B indicates the area of fast ion interaction. The area A indicates the background temperature.

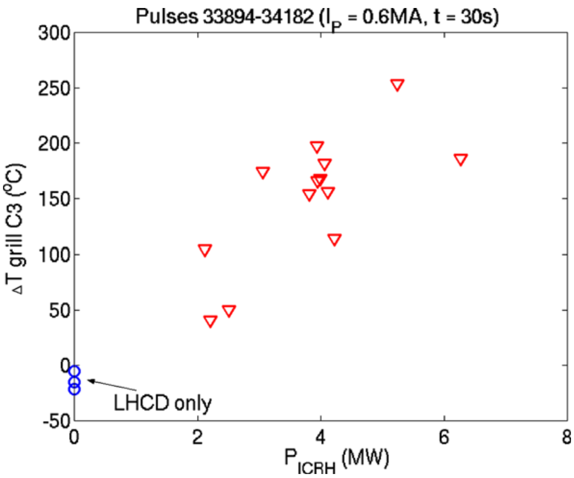

Fig. 3. Temperature increase of area B with respect to area A as a function of the injected ICRH power. The temperature increase is measured 20 s after the application of ICRH.

parameter representing the energy of the fast ions. This is proportional to the ICRH power times the slowing down time ($\propto T_e^{3/2}/n_e$) and divided by the number of minority hydrogen ions. The hydrogen minority concentration, η_H, is assumed to be constant (5%), since no hydrogen was injected in the discharges considered.

Modelling of the ion ripple losses with the FIDO code [4] for Tore Supra plasmas with low hydrogen minority concentration (5–10%) show that approximately 25% of the ICRH power is lost by ion ripple losses. Of these, approximately 10% are due to the

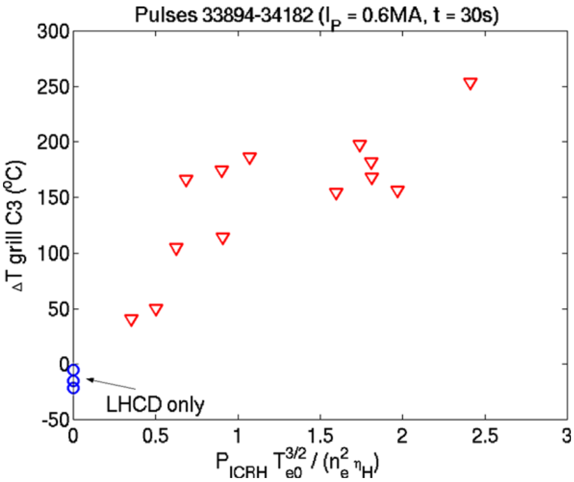

Fig. 4. Temperature increase of area B with respect to area A as a function of a parameter representing the fast ion energy, i.e. $\propto P_{ICRH} * T_e^{3/2}/(n_e^2 * \eta_H)$.

direct ripple losses, directed towards the bottom of the tokamak, whereas approximately 15% are due to the stochastic diffusion of wide orbits, localized towards the mid-plane on the low field side. The calorimetric measurements described above yield that approximately 1% of the injected ICRH energy was found on the LHCD launcher, located in a sector between two magnetic field coils. Tore Supra consists of 18 sectors (18 magnetic field coils). If one

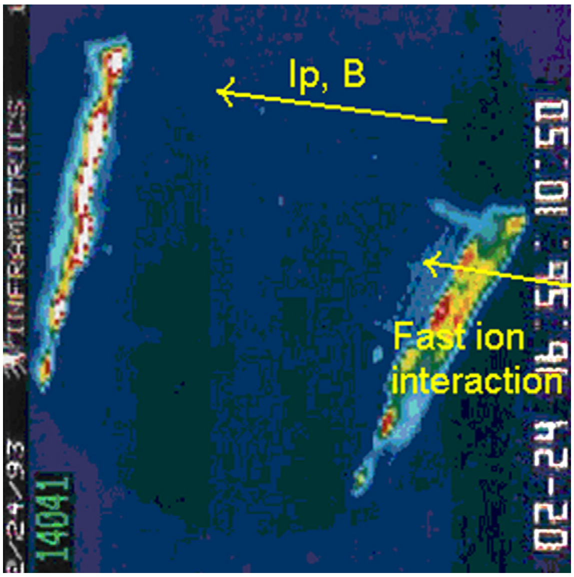

Fig. 5. IR image of one LHCD launcher during ICRH heating in 1994 (pulse 14041), with reversed direction of plasma current and toroidal magnetic field.

considers the losses to be symmetric around the torus, the total losses by stochastic diffusion becomes 18%, which is consistent with the modelling done by the FIDO code.

Another indication that the localized heating observed is due to fast ion interaction is obtained from old infrared images from discharges with reversed direction of plasma current and toroidal magnetic field. These show that the hot spot was located in the upper right corner, in agreement with the change in direction of the fast ion orbits (Fig. 5). Thermo-mechanical calculation of the temperature increase of the LHCD waveguides, based on the infrared measurements, has been carried out recently [7]. These yield a power flux due to the fast ions of approximately 1 MW/m^2.

4. Interaction caused by LHCD

In addition to the interaction of fast ions produced during ICRH, a different phenomenon possibly linked to the acceleration of electrons in the near-field of the LHCD launchers has been revealed. It manifests itself by a poloidally asymmetric heating in the waveguides, as seen in the photo in Fig. 6. Indication of a localised heating at the upper part of each waveguide row is observed. The asymmetric heating can possibly be associated with non-thermal electrons, created by acceleration in the near field of the LH wave. A possible explanation could be as follows: The electron acceleration gives rise to a positive charge in front of LHCD launchers [8], which in turn produces an ExB-drift, which for Tore Supra is directed upwards and towards the waveguides in the upper part of the waveguide rows. This phenomenon can be modelled by a 3D two-fluid numerical code [9]. Fig. 7 represents the result of the modelling of a toroidal row of waveguides. In the upper part of the waveguide row, the calculated flux is ~50 kW/m^2 and is directed towards the waveguides (indicated by negative numbers). In the bottom part of the waveguide the calculated flux is ~50 kW/m^2, but

Fig. 6. Photo of a waveguide row on one LHCD launcher. A poloidally asymmetric heat pattern is observed. Stronger heating is observed in the upper part of each waveguide row.

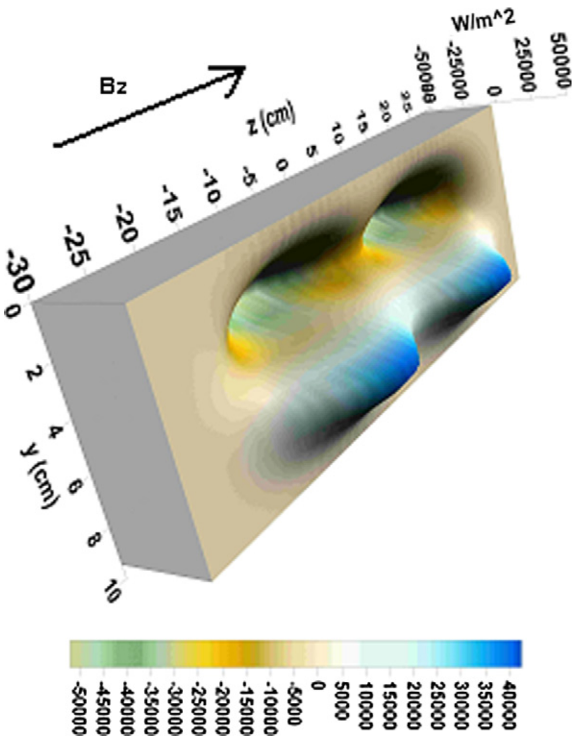

Fig. 7. Modelling of the power flux produced in the near-field of a toroidal waveguide row. The code predicts heat flux towards the waveguides in the upper part of each waveguide row (indicated by negative numbers) and heat flux away from the waveguides in the bottom part of the waveguide row (indicated by positive numbers).

directed away from the waveguides towards the plasma (indicated by positive numbers). The modelling predicts a flux towards the waveguides in the upper part of each waveguide row, which seems to be consistent which what is observed in the photo of the launcher. However, this effect is indeed small compared to the interaction by fast ions described above, but it has a different localisation and can be distinguished as an effect clearly related to LHCD, and most likely the acceleration of electrons in the near-field of the LH wave.

5. Summary and prospects

The plasma–launcher interaction during long pulse operation in Tore Supra has been investigated using two powerful diagnostic methods: calorimetry of the energy extracted by the cooling loops on the launchers and infrared imaging of the launchers and their side limiters. The identification of different heat flux sources on the LHCD launchers and ICRH antennas, using the infrared imaging, has been instrumental in the development of the real-time power control on Tore Supra. This has allowed optimizing the RF power output, while avoiding deleterious effects. The different parametric dependencies of the heat flux sources, obtained from IR imaging and calorimetric measurements, can be used for the design of RF antennas/launchers for ITER.

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