ECRH Experiments and Developments for Long Pulses in Tore Supra

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Abstract. The ECRH system presently under construction at CEA/Cadarache for the Tore Supra tokamak is described. The system will be equipped by 6 gyrotrons (118 GHz, 400 kW, cw), manufactured by Thomson Tubes Electroniques. The results of the tests of the prototype and of the first series gyrotron are reported and discussed. The best performance obtained was a pulse of 102 s at 310 kW average power on dummy load, which corresponds to the new record energy of 32 MJ. Results of first ECRH experiments on Tore Supra with the prototype gyrotron are also reported. 350 kW have been coupled in O-mode both to Ohmic and to LHCD plasmas in continuous or modulated pulses lasting up to 2 s. During non-inductive discharges, fully sustained by LHCD, a significant response of the hard X-ray signals to the ECRH power has been observed, despite the low power ratio between the two waves (0.35 MW EC / 4.5 MW LH waves).

1. Introduction

An ECRH system for the Tore Supra tokamak is presently under construction at CEA/Cadarache. The motivations for implementing a new RF heating system, in addition to Ion Cyclotron and Lower Hybrid waves, are related to the main goal of the next phase of the Tore Supra programme: the investigation of physics and technology issues associated with long (1000 s), stationary and controlled discharges. In this framework, Electron Cyclotron waves will provide an efficient tool for: i) current profile control; ii) MHD control (sawteeth and tearing modes); iii) localised heating for dynamic transport studies in steady-state regimes. This system will also offer a unique possibility of testing technical solutions of relevance for the next step, such as: cw high-frequency power sources, compact, actively cooled antenna, and, more generally, the global behaviour of the system and of its elements during long pulses. The system will be fully operational at the end of 2003 and will consist of 6 quasi-cw gyrotrons at 118 GHz, globally launching 2.4 MW for a pulse length of 210 s, or 3 MW for 5 s [1]. An overview of the Tore Supra ECRH system is presented in Sec. 2. Special attention is given to the long-pulse tests of the first series gyrotron. The results of the first experiments on Tore Supra plasma, performed with the prototype gyrotron, are presented and discussed in Sec. 3.

2. Overview of the Tore Supra ECRH system

The six gyrotrons will be grouped in two modules of 3 gyrotrons each, sharing the two thyristor-regulated 90 kV power supplies. These are followed by series tetrodes, both for voltage regulation (about 0.5 %), and for fast switching in case of arcing within the tube (deposited energy under 15 J). Each tube is connected to the tokamak via its own transmission line, consisting of about 25 meters of aluminium circular oversized corrugated waveguides (63.5 mm internal diameter). Each line is equipped with 5 miter bends, the second one containing the directional coupler for the measurement of the incident and reflected power, 1 DC break to isolate the gyrotron ground from the tokamak one and 2 pump sections. The vacuum level of the waveguides is of the order of 10^{-3} Pa, i.e., the same as the tokamak vacuum level, as there is no window on the torus side but only a RF valve. The efficiency of the transmission line is specified to be above 90%. The antenna is made of six fixed mirrors and three steerable ones, in both the toroidal and the poloidal directions; each mobile mirror groups the RF beams coming from two parallel transmission lines. The steering capability is of +/- 30 degrees around the perpendicular to the magnetic field in the toroidal direction; in the poloidal direction, it is defined for each steerable mirror in order to cover the entire plasma minor radius, which corresponds to a variation of 30 degrees approximately.

The gyrotron has been developed in the framework of a collaboration between Thomson Tubes Electroniques (France), Association Euratom-Confederation Suisse and Association Euratom-CEA (France), with technical support from Association Euratom - FZK (Germany). The tube is equipped with a triode electron gun, allowing the independent adjustment the various beam characteristics, a classical collector, and an output window made of sapphire and cooled by liquid nitrogen. The gyrotron is connected to the transmission line through a MOU (Matching Optics Unit) which converts the gaussian output beam into a HE11 mode, suitable for propagation in the circular corrugated waveguides. A 2-mirror polariser is also included in the MOU in particular to generate waves both in O-mode and X-mode. The overall efficiency of the gyrotron is around 30 % and each tube is specified to deliver 400 kW (500 kW) after the MOU for a pulse duration of 210 s (5 s).

So far, a prototype and a first series gyrotron have been delivered to CEA/Cadarache, after passing the factory acceptance test at 500 kW, 5 s. The final acceptance tests at 210 s are presently being performed at Cadarache, within the CEA facilities. The prototype was first tested on a dummy load: stable and repetitive oscillations have been obtained at the expected frequency of 117.6 GHz and the pulse length was subsequently extended up to 15.5 s, with 400 kW output, in August 1999. This progression was rather slow because of internal outgazing of the gyrotron and degassing in the transmission line. The cavity itself is already thermalized within a pulse length of 1s, as shown by the fact that the

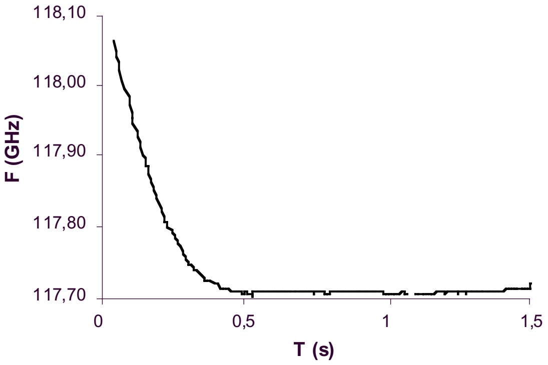

Figure 1: *Frequency shift during the beginning of the pulse.*

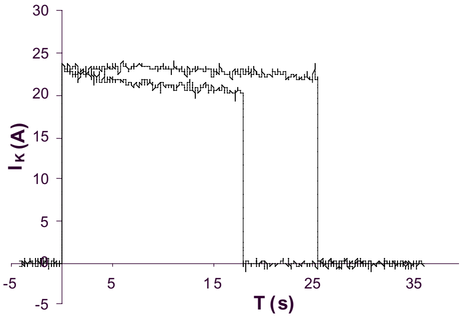

Figure 2: *Comparison between 2 beam currents, with and without the additional heating (upper and lower trace, respectively)*

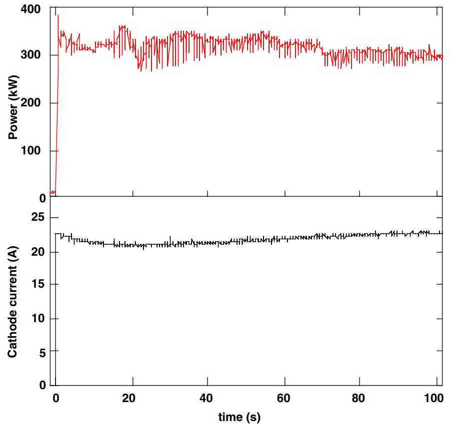

Figure 3: *The RF power and the cathode current for the 102 s length pulse.*

output frequency is stabilised at the value f = 117.6 GHz, after an initial frequency shift between 118.2 GHz and 117.6 GHz during the first 400 ms (see Fig.1).

The tests of the 1st series gyrotron began on a modified cw load in May 2000. Very quickly (less than 1 week), pulses of the order of 20 s were obtained, but a decrease of the cathode current was observed, up to several Amperes, due to the progressive cooling of the cathode itself. In order to prevent the corresponding decrease of the output RF power, the solution of overheating the cathode from the beginning was tested. The value of additional 50 W heating, suggested by simulations, was used in the tests, with satisfactory results, as shown in Fig. 2.

The best results obtained on the dummy load with the 1st series gyrotron and extra heating of the cathode is now 310 kW average output power on a pulse length of 102 s, which represents a total energy of the order of 32 MJ (Fig. 3). The cathode current has the same value at the beginning and at the end of the pulse, owing to the 50 W additional heating. The pulses are terminated due to the increase of the internal pressure of the tube, up to 100 A measured on the ionic pumps, which is the security limit (Fig. 4). Several pulses of duration of less than 102 s (55 s, 66 s, 72 s, 78 s, 82 s, 85 s) were obtained too, with similar or higher output power (around 320 kW), which were always stopped by the vacuum security. The degradation of the internal vacuum, which, for the pulse of 55 s of duration, becomes nearly exponential after 20 s of RF emission, seems to be due to the surrounding walls of the internal mirrors of the gyrotron (made by 3 cm thick stainless steel) which are not sufficiently cooled. After some conditioning, the RF pulse length could be extended up to 97 s within a month; a step around 70 s can be noticed for the longest pulses and the internal pressure of the tube still increases exponentially up to 100 µA. More conditioning seems necessary to further increase the pulse duration.

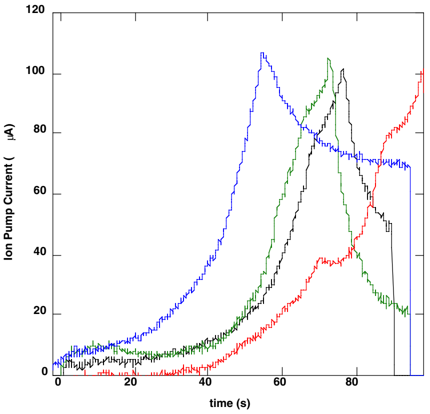

Figure 4: *Evolution of the internal pressure of the gyrotron with various pulses, before and after conditioning.*

3. First experimental results on Tore Supra

The first Electron Cyclotron Resonance Heating experiments have been performed in the Tore Supra tokamak at the end of 1999, using the prototype gyrotron [2]. 350 kW have been coupled both to Ohmic and to LHCD plasmas in pulses of duration up to 2 s. For these experiments, the first harmonic O-mode has been used. The power deposition width is estimated by numerical simulations to be about 2-3 cm for a normal incidence and thermal electrons. Significant electron heating has been observed (Fig. 5). The time response of a 16 channels heterodyne radiometer measuring ECE has been used for heat pulse propagation studies and to determine the power deposition in connection with various poloidal and toroidal injection angles. The radiometer is equipped with a lowpass filter (40 dB), rejecting frequencies higher than 110 GHz. This adds to the various built-in IF filters, giving an overall rejection of at least 120 dB. The plasma parameters of Tore Supra for ECRH experiments are: R = 2.31 m, a = 0.75 m, I_p = 0.5 - 1.3 MA, B = 3 - 4 T, $n_{e0} \approx 3\ 10^{19}\ m^{-3}$. Two types of experiments have been performed, in Ohmic plasmas and in plasmas sustained by up to 4 MW of LHCD.

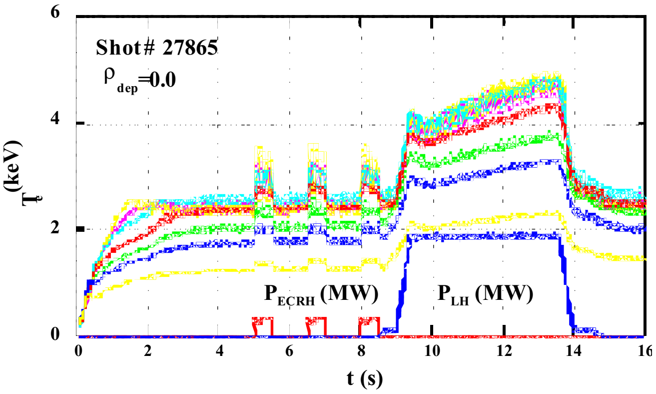

Figure 5: *Time traces of the ECE channels (upper curves) and of the EC and LH power*

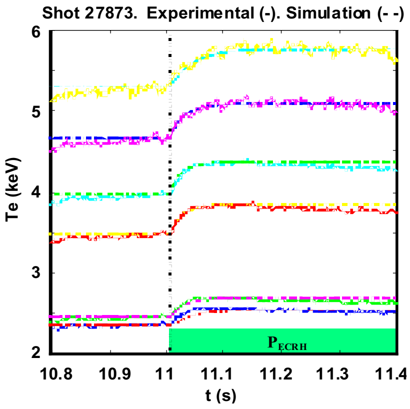

Figure 6 : *Time evolution of the ECE signals during ECRH. The dotted lines represent the analytical solution*

In Ohmic plasmas, transport analysis has been performed fitting the experimental temperature increase by an analytical solution of the simplified heat diffusion equation in slab geometry [3]. The heat source term is assumed to have a Gaussian form, of width estimated by ray-tracing/absorption calculations, and location estimated from the profile of dT_e/dt, measured during the first 5 ms of the ECRH pulse. The fit parameters are the local values of the electron heat diffusivity χ_e and a damping time τ_d associated to various electron losses, such as electron-ion equipartition, radiation, and Ohmic power decrease during the ECRH phase. The time evolution of the ECE signals for discharge 27873 and of the associated fits is shown in Fig.6. The heat diffusivity estimated by this method is shown, as a function of normalised radius, in Fig. 7. The estimated damping time is roughly constant

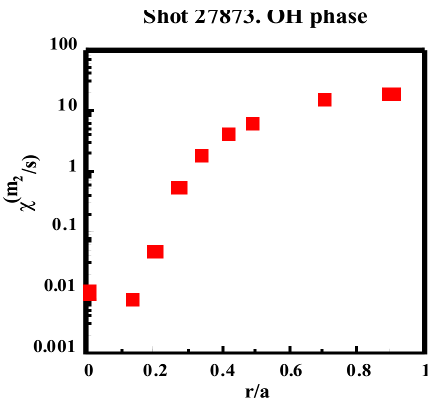

Figure 7: *Radial profile of χ_e determined by the analytical method*

and of the order of 40 ms.

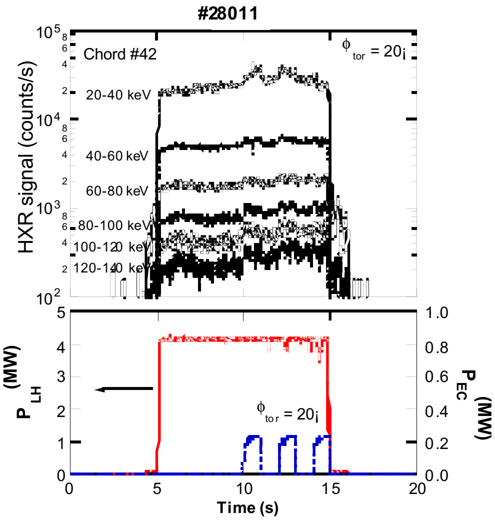

Figure 8 : *Time evolution of the HXR signals during the combined LH-ECCD experiment.*

ECCD experiments have also been performed during non-inductive discharges fully sustained by LHCD. In these experiments, $P_{LH} = 4.2\ MW$, $P_{EC} = 0.35\ MW$, and a toroidal injection angle of 20 degrees, which corresponds to counter-CD, were used. The suprathermal electrons created by LH and EC are measured by hard X-ray (HXR) spectroscopy [4]. A significant response of HXR signals to the ECCD power has been observed, as shown in Fig. 8, despite the low power ratio between the two waves. Moreover, an increase of the HXR signal level at all photon energies is measured, as well as a change of slope of the photon energy spectrum, which indicates an increase of suprathermal electrons proportionally higher at high energy than at low energy (Fig. 9). The maximum increase of the HXR signal is at r/a = 0.38, which is consistent with ray-tracing/absorption calculations (Fig. 10). Note that this additional effect on the HXR signal level is strongly reduced when the maxima of LH and EC power absorptions are not aligned. These observations suggest that fast electron generation by LHCD is enhanced by the EC waves, which has to be confirmed by experiments at higher EC power.

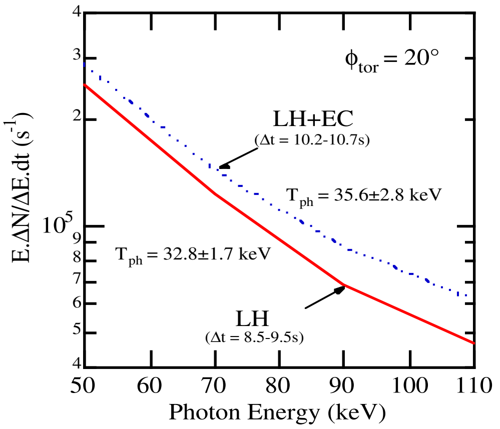

Figure 9 : *Comparison of the photon energy curves between a LH pulse and a combined LH+EC pulse.*

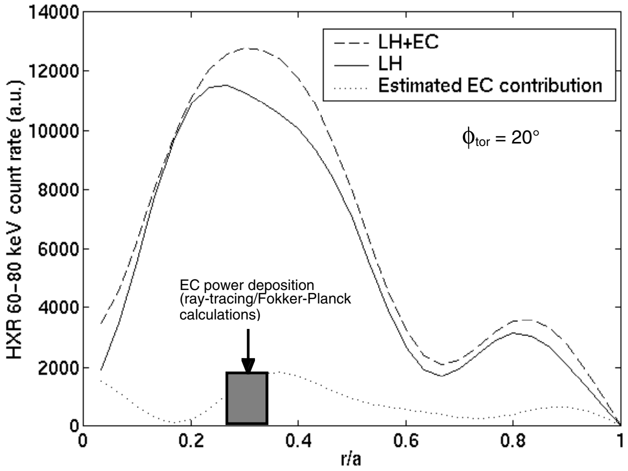

Figure 10: *Inverted Hard X-ray profile in the LH (solid) and in the LH+EC phase (dashed)*

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