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FIRST ECRH EXPERIMENTS IN TORE SUPRA

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1) Introduction

An Electron Cyclotron Resonance Heating (ECRH) system is being installed on Tore Supra with the main goal of helping in current profile control during long pulse (≤ 1000 s), fully non-inductive discharges. The system will be fully operational in 2003 with total injected power of 2 MW. A prototype gyrotron of this type has been operated on a dummy load at the 400 kW power level and up to 15.5 s long pulses. This prototype has been then used for ECRH experiments in Tore Supra. The first gyrotron of the series is also operational now at Cadarache and is being tested at high power, with the aim of attaining its nominal pulse length of 210 s. In this paper, results concerning both the gyrotron tests and the first ECRH experiments on Tore Supra are reported.

2) ECRH System

The ECRH system now being installed on Tore Supra will consist of 6 cw gyrotrons, manufactured by Thomson Tubes Electronique (development supported by CEA – France, EPFL – Switzerland and FZK – Germany), with frequency 118 GHz, unit power 400 kW, globally launching 2 MW in the plasma. The first series tube is presently undergoing long pulse tests on site, and a long pulse of 330kW×37s has been obtained (Fig.1), which constitutes a new record of the energy delivered in this frequency range (Fig.2). The final goal is to reach 400kW×210s. The ECRH antenna consists of six fixed mirrors and three independently steerable mirrors (both in the poloidal and in the toroidal direction). The aim is to scan the power deposition from the plasma center to the plasma edge, for various current drive scenarios with co- or counter-injection with respect to the plasma current. The

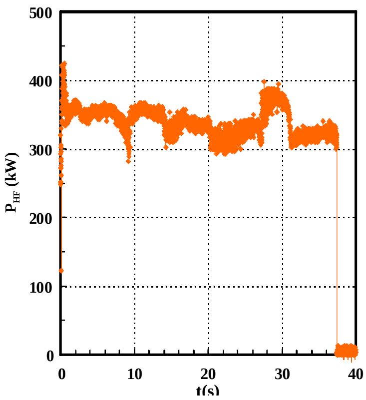

Figure 1. Record long pulse of the gyrotron. The mean total output energy is 12.2 MJ.

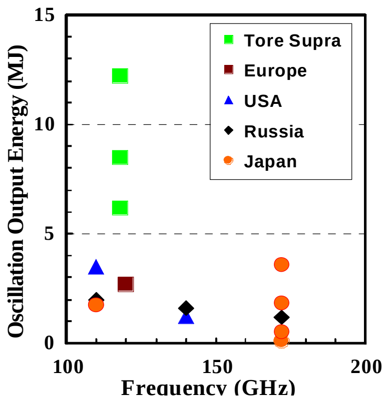

Figure 2. Diagram showing the current status of development of gyrotron for nuclear fusion.

transmission line is made of HE11 mode corrugated waveguides. The efficiency of this transmission line is 90 %, with an extremely weak attenuation: 0.25 % for 30 m. The emitted wave beam is a gaussian beam with polarisation controlled by corrugated mirrors. Note that the maximum axis deviation is estimated to be 0.5 mm, which corresponds to 1 % max mode conversion loss for 30 m.

3) First Results of ECRH/ECCD Experiments

The first Electron Cyclotron Resonance Heating experiments have been performed in the Tore Supra tokamak at the end of 1999, using the prototype gyrotron. 350 kW have been coupled both to Ohmic and to LHCD plasmas in continuous or modulated pulses of duration up to 2 s. For these experiments, the first harmonic O-mode has been used with the resonance condition: $\omega_0 = \omega_{ce}/\gamma + k_{\|}v_{\|}$, where $\omega_{ce} = (q_e/m_e)B$ is the electron cyclotron frequency, γ is the relativistic coefficient, and $k_{\|}v_{\|}$ representing the Doppler shift effect in the direction parallel to the magnetic field. The power deposition width is estimated by numerical simulations to be about 2-3 cm for a normal incidence and thermal electrons. Because of its narrow power deposition, the ECRH is often considered to be an interesting tool for current profile control, MHD mode stabilisation and transport investigation. 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 plasma parameters of Tore Supra for ECRH experiments are $R = 2.31m,\quad a = 0.75m,\quad Ip = 0.5 - 1.3MA,\quad B = 3 - 4T$.

3.1) Transport Analysis

The best way for transport analysis is to use the ECRH modulation. In this paper our method to investigate the transport is fitting the experimental temperature increase $\tilde{T}_e$ by an analytical solution of the simplified heat diffusion equation:

$$\partial\tilde{T}_e \big/ \partial t = (2\chi/3)\partial^2\tilde{T}_e \big/ \partial x^2 - \tilde{T}_e \big/ \tau_d + S(x,t) \qquad (1)$$

where χ is the electron heat diffusivity, τ_d is the damping time characterising the electron energy losses including the ion-electron equipartition, radiation and the ohmic current decrease during the ECRH phase. The heat source term is assumed to have a gaussian form: $S(x,t) = S_0\,(1/\sqrt{\pi}\,w)\exp\left(-(x-x_0)^2 \big/ w^2\right)H(t)$, where x_0 is the deposition centre, w is the deposition width, S_0 is the deposition amplitude, $H(t)$ is the Heaviside function. With the above assumptions, equation (1) can be analytically solved as shown in reference [2]. The solution depends on five parameters: $\tilde{T}_e(r,t) = g(r,t,\chi,\tau_d,x_0,w,S_0)$. As shown in figure 3 this solution, represented by dotted lines, reproduces the ECE temperature signals well. Fig.4 shows the derivative of temperature $d\tilde{T}_e/dt$ at beginning of the HF pulse measured over a duration of 2 ms. The maximum of $d\tilde{T}_e/dt$ being around *r/a*=0.2 indicates the deposition centre. From the value of the electron temperature rise at deposition centre $dT_e/dt\big|_{\max}$, we can estimate the deposition width w by using the following approximate equation:

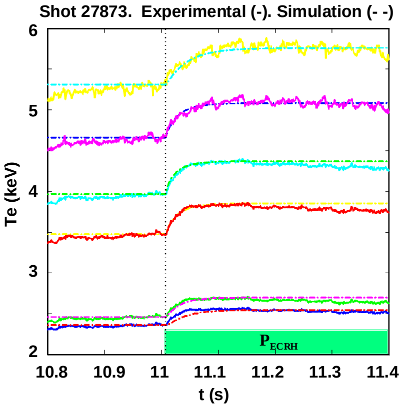

Figure 3. Time evolution of the ECE temperature signals during the ECRH phase. The dotted lines represent the analytical solution.

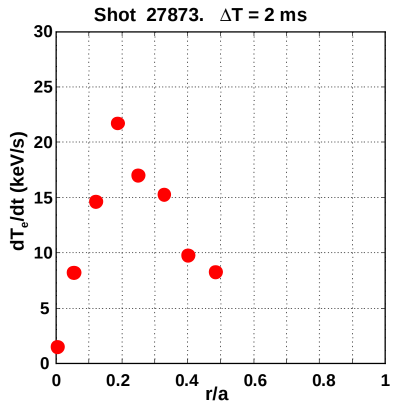

Figure 4. Radial profile of dT_e/dt measured duringt the first 2 ms of ECRH.

$$P_{abs} \approx (3/2) n_e \left(d\tilde{T}_e / dt \big|_{\max} \right) 2\pi R \; 2\pi r_{dep} \; w \qquad (2)$$

With $P_{abs} \approx 350kW$, $d\tilde{T}_e / dt\big|_{\max} \approx 22keV/s$, $n_e \approx 4\times10^{19} m^{-3}$, $r_{dep} \approx 0.2a \approx 0.15m$, $R = 2.31m$, the deposition width is estimated to be $w \approx 11cm$. This value is much larger than expected ($w \approx 3cm$). If we want to determine the deposition width with this method, we have to measure the temperature rise over a duration less than $\Delta t = (3/8) w^2 / \chi \approx 0.2ms$, which is too short to observe any temperature rise. Figures 5 and 6 show the radial profile of χ and τ_d, respectively, obtained by the analytical method. From Fig.5, we observe that the value of χ representing a transient transport is much larger than that obtained by power balance in stationary phase. Note that the e-i energy exchange time is $\tau_{e-i} \approx 20ms$ for $T_e \approx 1keV$, $n_e \approx 4\times10^{19} m^{-3}$, which is of same order as τ_d. It should be noted that in our appproach, the following effects are neglected: cylindric geometry, ∇n, ∇χ.

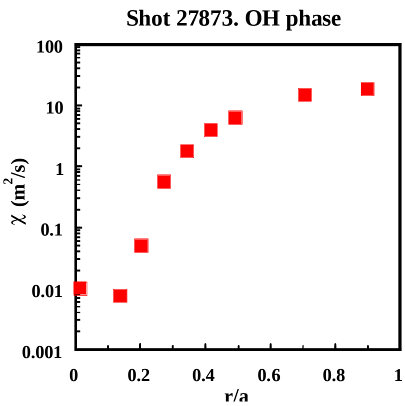

Figure 5. Radial profile of χ determined by analytical method.

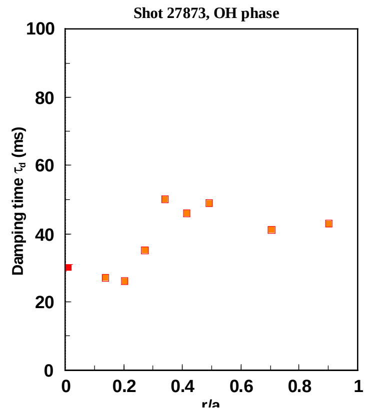

Figure 6. Radial profile of the damping time determined by analytical method.

3.2) LH-ECCD Experiments

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*, Φ_{lh} = 0°, ϕ_{ec}(tor) =

20°. The suprathermal electrons created by LH and EC are measured by hard X-ray (HXR) spectroscopy [3]. A significant response of HXR signals to the ECCD power has been observed as shown in figure 7, despite the low power ratio between the two waves. Moreover, an increase of the HXR signal level at all photon energies is observed, 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. The maximum increase of the HXR signal is at *r/a* = 0.38, which is consistent with the EC power deposition obtained by the previously described method. Note that the EC Ray-tracing yields a deposition centered at r/a = 0.3. Note also that this additional effect on the HXR signal level is strongly reduced when the maxima of LH and EC power absorptions were not aligned. These observation suggest that a possible synergy exist between the two waves. This has to be confirmed by experiments at higher EC power.

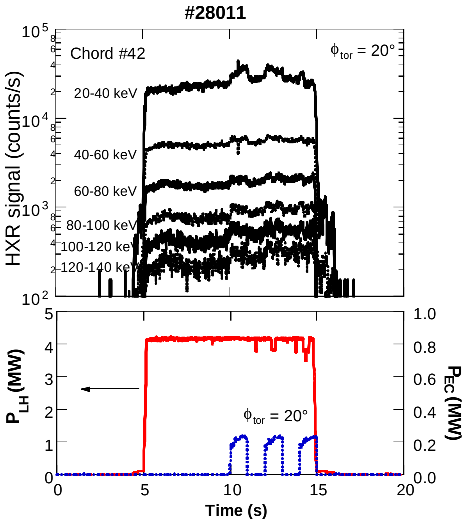

Figure 7. Time evolution of the HXR signals during the combined LH-ECCD experiment.

4) Conclusions and Future Prospects

The antenna transmission line and ancillary equipments of the ECRH system have been tested and installed on Tore Supra. A prototype gyrotron has been tested up to 400kW×15.5s. First experiments on plasma with this ECRH system were performed at the end of 1999. A first series tube has passed the factory acceptance tests at 500kW×5s and is presently undergoing long pulse tests on site: a pulse of 330kW×37s has obtained. The final goal is to reach 400kW×210s. The first module including 3 tubes is expected to be operational for ECRH experiments at the end of 2001, and the second module at the end of 2003.

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/4.2 MW LH waves). Relevant parameters (χ, τ_d, x_0) have been deduced by transport analysis during the temperature rise phase. In the future, the ECRH experiments will be devoted for the following topics: the possible synergy between LH and ECCD, current profile control and MHD modes stabilisation by ECRH/ECCD, transport analysis by ECRH modulation experiments (profile resilience, critical temperature gradient).

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