EUROPEAN FUSION DEVELOPMENT AGREEMENT
JET

EFDA–JET–CP(03)03-03

A. Ekedahl, L. Colas, M.-L. Mayoral, B. Beaumont, Ph. Bibet, S. Brémond,
F. Kazarian, J. Mailloux, J.-M. Noterdaeme, A.A. Tuccillo
and JET EFDA Contributors

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A. Ekedahl[1], L. Colas[1], M.-L. Mayoral[2], B. Beaumont[1], Ph. Bibet[1], S. Brémond[1],
F. Kazarian[1], J. Mailloux[2], J.-M. Noterdaeme[3, 4], A.A. Tuccillo[5]
and JET EFDA Contributors*

[1]*Association Euratom-CEA, CEA/DSM/DRFC, CEA-Cadarache, 13108 St Paul-lez-Durance, France*
[2]*EURATOM/UKAEA Fusion Association, Culham Science Centre, Abingdon, OX14 3DB, UK*
[3]*Max-Planck-Institut für Plasmaphysik, Euratom Association, D-85748 Garching, Germany*
[4]*Gent University, EESA Department, B-9000 Gent, Belgium*
[5]*Associazione Euratom-ENEA sulla Fusione, CR Frascati, C.P. 65, 00044 Frascati, Rome, Italy*
** See annex of J. Pamela et al, "Overview of Recent JET Results and Future Perspectives",*
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Preprint of Paper to be submitted for publication in Proceedings of the
15th Topical Conference on Radio Frequency Power in Plasmas
(Moran, Wyoming, USA 19-21 May 2003)

ABSTRACT.
Combined operation of Lower Hybrid (LH) and Ion Cyclotron Resonance Frequency (ICRF) waves can result in a degradation of the LH wave coupling, as observed both in the Tore Supra and JET tokamaks. The reflection coefficient on the part of the LH launcher magnetically connected to the powered ICRF antenna increases, suggesting a local decrease in the electron density in the connecting flux tubes. This has been confirmed by Langmuir probe measurements on the LH launchers in the latest Tore Supra experiments. Moreover, recent experiments in JET indicate that the LH coupling degradation depends on the ICRF power and its launched $k_{||}$-spectrum. The 2D density distribution around the Tore Supra ICRF antennas has been modelled with the CELLS-code, balancing parallel losses with diffusive transport and sheath induced E×B convection, obtained from RF field mapping using the ICANT-code. The calculations are in qualitative agreement with the experimental observations, i.e. density depletion is obtained, localised mainly in the antenna shadow, and dependent on ICRF power and antenna spectrum.

1. INTRODUCTION

Lower Hybrid Current Drive (LHCD) is the main tool for achieving non-inductive current drive, as well as current profile control, with the aim to studying paths to achieve steady state operation in several tokamaks. In recent Tore Supra experiments, a plasma current of 0.5MA has been sustained for more than 4 minutes by the means of LHCD at a power level of 3MW [1]. In JET, LHCD plays an important role both for pre-forming the q-profile in the Internal Transport Barrier (ITB) experiments, as well as for providing an off-axis current during the main heating phase with Neutral Beam Injection (NBI) and ICRF waves [2]. Both scenarios and both tokamaks require application of LH waves simultaneously as ICRF. Effects on the LH coupling observed under these conditions are described in this paper.

2. COUPLING OF LH WAVES IN THE PRESENCE OF ICRF

2.1EXPERIMENTAL OBSERVATIONS IN TORE SUPRA.

Tore Supra has two LH launchers, located in adjacent ports, and three 2-strap ICRF antennas. In most experimental conditions the ICRF antenna Q1, which is located close to the LH launchers, is magnetically connected to at least one of the launchers. For efficient LH non-inductive current drive, the long pulse discharges in Tore Supra are carried out at low electron density (n_e<2.5×10^{19} m^{-3}), which generally lead to poor coupling conditions for ICRF [3]. If ICRF is applied simultaneously as LHCD, the coupling on the part of the LH launchers magnetically connected to the antennas decreases, indicating a decrease in the electron density in the connecting flux tubes. Figure 1 shows a discharge in which the ICRF antennas were powered, using dipole phasing, in sequence during LHCD. When antenna Q1 was powered, the reflection coefficient on the upper part on the nearby LH launcher increased, while when antenna Q4, which was not connected, was used there was no effect on the LH coupling. Figure 2 shows the recent results in the CIEL configuration, in which the

ICRF antennas are at different locations. However, antenna Q1 is still in the same location and still connected to the LH launchers. Figure 2 shows the reflection coefficients on the upper and lower waveguide rows on the LH launcher closest to the ICRF antennas. In agreement, the density deduced on the Langmuir probe on the upper part on this launcher decreases as ICRF is switched on, while the density on the lower part stays unaffected. The degradation in LH coupling is mainly seen when the LH launchers are retracted behind the ICRF antennas, indicating that the density decrease takes place in the shadow of the antennas, whici is also in agreement with observations in ASDEX-Upgrade [4].

2.2 EXPERIMENTAL OBSERVATIONS IN JET.

JET has four 4-strap ICRF antennas, located in pairs in opposite ports of the torus. The antenna pair A+B is located next to the LH launcher, separated by a poloidal limiter. A series of experiments was conducted in order to studying the effect of mainly antenna B, which is located immediately next to the LH launcher, on the LH coupling. The ICRF power, antenna spectrum, and the position of the LH launcher relative to the antenna were varied. Fig.3(a) and Fig.3(b) show a comparison of the effect of the ICRF antenna spectrum. When using dipole spectrum, the LH power remained constant as ICRF is switched on. The same result was obtained when using ICRF with $+90^{o}$ phasing. However, when applying ICRF with monopole spectrum, the LH coupled power dropped, indicating an increase in the reflected power levels. The drop in power is caused by a launcher protection system that switches off the power on a klystron if the difference in the reflected powers in the two multijunctions powered by the klystron is too large. Similar effect as monopole phasing was obtained with -90^{o} phasing. The effect of the launcher position relative to the ICRF antennas and the poloidal limiter is demonstrated in Fig.3(b) and Fig.3(c). At the position –15mm, <1MW from antenna B affects the LH coupling, while at –5mm, higher power on this antenna can be used. In order to increase the density to allow better coupling of the LH waves, injection of gas (CD_4 or D_2) near the LH launcher is used routinely in JET. The discharge shown in Fig.3(d) is identical to the one of Fig.3(c), except that local CD_4 injection was added. As a result, the electron density increased sufficiently to allow maintaining the LH power level. Using local gas injection, up to 3MW of LH power has been coupled in H-mode and ITB-plasmas with type I and type III ELMs, at a plasma-launcher distance of 10cm [5].

3. MODELLING OF ICRF DENSITY CONVECTION

The 3D electric field pattern of the Tore Supra antennas has been calculated with the ICANT-code, which uses the realistic geometry of the Tore Supra antenna Q1 [6]. The output of the ICANT-code is then coupled with the CELLS-code, which calculates the 2D density distribution around the antenna, by taking into account cross-field diffusion, parallel transport losses and the sheath induced E×B-convection from ICRF [7]. Figure 4 shows the radial dependence of the electron density profile, averaged over the poloidal extent of the Q1 antenna, for the experimental parameters of a discharge in the Tore Supra CIEL configuration (TS Pulse No: 30463, $n_e = 2.0\times10^{19}\ m^{-3}$, $I_P = 0.8MA$, $B_T = 3.8T$), having similar behaviour as the discharge in Fig.2. The resulting electron density profiles in front of the antenna, assuming 1.5MW with dipole and with monopole spectrum, are shown, as well as the initial ohmic electron density profile. In Fig.4, the radial positions of the side protections of the ICRF antennas and of the LH launchers are indicated. A stronger density decrease is obtained when using monopole spectrum compared to dipole, because the electric field is stronger with monopole phasing [7]. This is in qualitative agreement with the JET observations (Fig.3).

SUMMARY

Due to the formation of convective cells, application of ICRF waves can cause a decrease in the electron density near the antenna, which in turn can degrade the coupling of LH waves if the LH launcher is magnetically connected to the ICRF antenna. Avoiding placing an LH launcher next to an ICRF antenna is therefore recommended. The density depletion is stronger in the shadow of the ICRF antennas and, therefore, locating the LH launcher and the ICRF antenna at the same radial position reduces the effect. Being electric field dependent, the density depletion will depend on $P_{ICRF}^{1/2}$, as well as on the antenna spectrum, i.e. monopole spectrum has a stronger effect than dipole spectrum.

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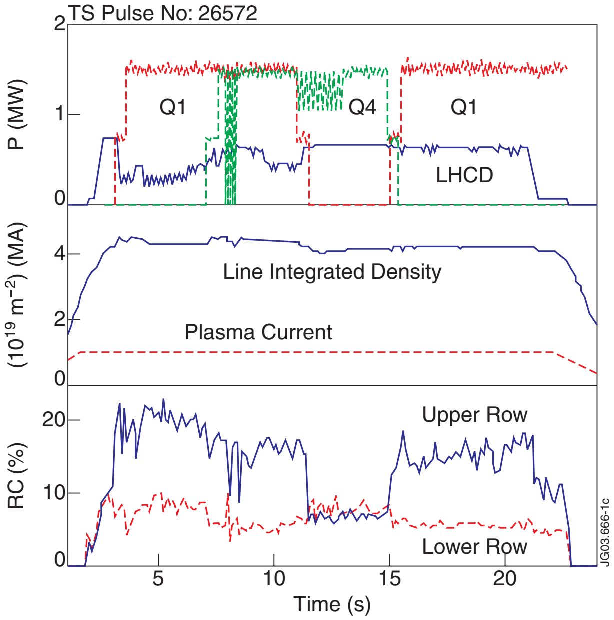

Figure 1: Behaviour of the LH reflection coefficients on the upper and lower parts of the launcher as antenna Q1 (connected) and antenna Q4 (not connected) are powered.

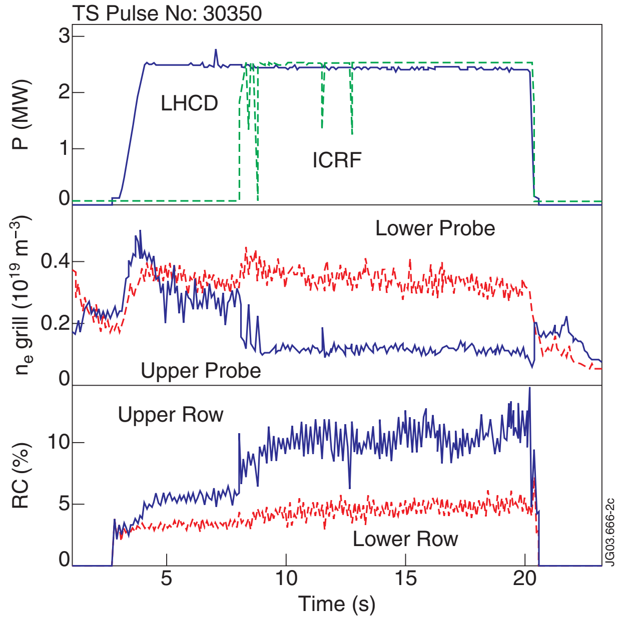

Figure 2: The LH reflection coefficient on the upper part of the launcher increases as ICRF is switched on. Accordingly, the electron density on the corresponding Langmuir probe decreases.

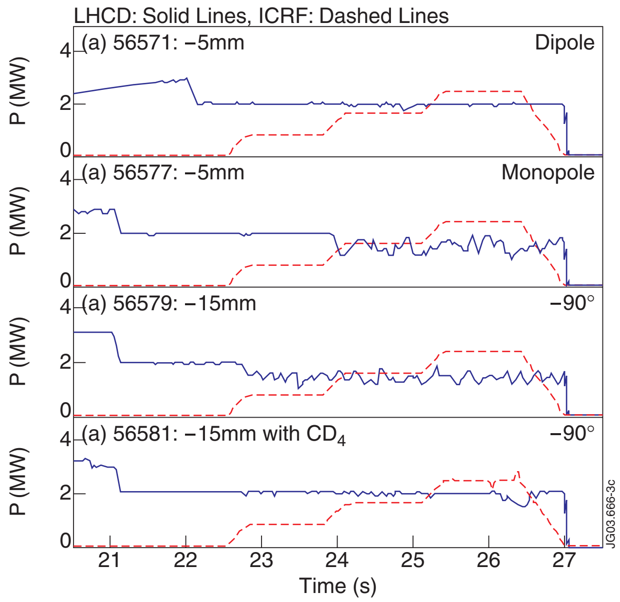

Figure 3: Results from JET: Effect of ICRF antenna B on the LH coupled power, with different antenna spectra and different positions of the LH launcher relative to the antenna.

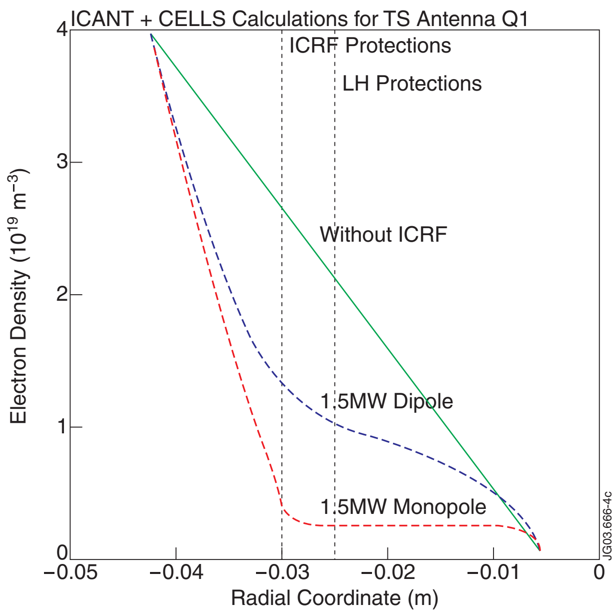

Figure 4: Radial electron density profiles averaged over the poloidal extent of the ICRF antenna Q1, for Tore Supra Pulse No. 30463. The separatrix is at –0.045m