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D. Farina, L. Figini and JET EFDA contributors

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D. Farina, L. Figini and JET EFDA contributors*

JET-EFDA, Culham Science Centre, OX14 3DB, Abingdon, UK

[1]Istituto di Fisica del Plasma "P. Caldirola", Consiglio Nazionale delle Ricerche, EURATOM-ENEA-CNR
Association, via R. Cozzi 53, 20125 Milano, Italy
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ABSTRACT.
Investigation of electron cyclotron wave propagation, power absorption, and current drive has been performed for a set of JET scenarios, aiming to assess the optimal wave frequency, launching position, and injection angles to achieve the various physics goals of an EC system in JET. EC power absorption and current drive have been computed for three values of the EC frequency, namely, 113GHz, 150GHz, and 170GHz. On the basis of extensive beam tracing calculations performed in a wide range of magnetic fields (2.5 T–3.4T), the frequency of 170GHz has been chosen, since it covers the wider magnetic field range of operation in JET and corresponds to that foreseen in ITER.

1. INTRODUCTION

A feasibility study for an ECRH system at JET has been carried out in 2009 to explore the potential physics capabilities and the technical options [1,2]. An EC system working in JET before ITER operations would make the foreseen JET programme [3] more ITER relevant both from the viewpoint of the physics and of the related technology issues. The main physics tasks to be fulfilled by an EC system in JET have been identified as: i) electron heating in the plasma core, i.e., for $\rho < 0.3$ (ρ being the square root of the normalized toroidal flux); ii) well localized current drive for NTM control ($\rho \simeq 0.5-0.75$), for current density profile tailoring ($\rho \simeq 0.5-0.6$), and sawtooth control ($\rho \simeq 0.3-0.4$). The choice of the optimal wave frequency and the evaluation of the current drive performance in the main JET scenarios have been based on extensive and systematic EC beam-tracing calculations in a wide range of magnetic fields ranging from 2.5T to 3.4T. In addition, the inputs for NTM's stabilization studies [4], and for the antenna design [5] have been provided by the analysis.

In the feasibility study, three frequency values have been considered in detail, 113, 150, and 170GHz, each of these covering a different range of magnetic field operation. The first and last values of the frequency are those chosen in the previous JET project [6,7] and in ITER, respectively. The choice of the optimal EC frequency depends both on the range of magnetic field at which JET is expected to operate, and on the physics objectives of the project itself, which determine the radial region in which EC plasma interaction must take place. Being the EC interaction a resonance process that allows localized absorption and current drive depending on the magnetic field value, an EC system at a single frequency can not be designed to operate at all magnetic fields of interest in JET. A compromise between available sources and required physical objectives has to be found.

To lowest order, the features of the EC system can be identified investigating the occurrence of the EC resonance within the plasma volume varying the JET magnetic field. At 113GHz, first harmonic interaction occurs in the high field side for $B_0 > 2.8$T, while second harmonic resonance occurs in the low field side for $B_0 < 2.6$T. Interaction occurs at second harmonic both at 150 and 170GHz in the whole magnetic field range considered, and, at a given field, in inner regions at 170GHz. Third harmonic absorption may affect the EC efficiency for $B_0 < 2.8$T at 170GHz, if the electron temperature is large enough. For $B_0 > 3$T, interaction occurs in the low field side, thus reducing the current drive efficiency, due to trapped particle effects. In the following we shall focus on the analysis at 170GHz, while the results at 113 and 150GHz can be found in [1].

Two representative JET plasma discharges at $B_0 = 2.65T$ have been considered which correspond to a standard H-mode regime at high delta and high density (Pulse No: 73344), and to a non-inductive advanced regime (Pulse No: 77895). These two scenarios are among those developed at JET as being ITER relevant. Note that the advanced scenario has a higher temperature and lower density with respect to the standard H-mode scenario, with the ratio T_e/n_e 3÷4 times larger. Investigation of the ECCD performance has been performed in a wide range of magnetic field values rescaling the reference scenarios varying the magnetic field, the plasma current, and the plasma pressure keeping the edge safety factor q_{95} and the plasma constant, and the plasma density and temperature keeping n/n_{GRW} = const, being n_{GRW} the Greenwald density, so that I, n, T ~ B.

Two different launching positions have been considered, with the same radial and two different vertical positions, R = 4.3m, z = ±0.345m, roughly corresponding to the upper and the lower extreme of a JET equatorial port. A divergent beam with waist w_0 = 3cm at the mirror has been considered. The poloidal and toroidal injection angles α and β are varied in a wide range, $-40^o \leq \alpha \leq 40^o$, and $0^o \leq \beta \leq 26^o$, with β positive in order to drive a co-current.

Calculations are performed using the GRAY code [8], a quasi-optical beam tracing code for EC Gaussian beam propagation. Power absorption is computed solving the fully relativistic dispersion relation for EC waves [9], while the current drive is computed via the adjoint method. All the evaluations are done for a nominal EC injected power of 1MW, and for $Z_{eff} = 2$. While the values of the current and of the deposition radius are almost independent of the beam parameters, the current density profile may be strongly affected by the assumptions made for the beam width and divergence, except at large toroidal angles when Doppler broadening determines the Jcd profile shape. Optimization of the wave beam might lead to a better performance of the EC system.

2. ECCD PERFORMANCE AT 170GHZ

EC waves at 170 GHz are injected polarized as extraordinary mode, and are absorbed mainly at the second harmonic. Figure 1 shows the driven current obtained scanning the whole range of injection angles under consideration versus the radial position of the peak current density for three values of the magnetic field and the two scenarios. This kind of plots provides the following information: i) the envelope of the scattered points gives the maximum current that can be driven at a given radius, ii) the "density" of the points gives a qualitative estimate of the sensitivity with respect to variations of the injection angles. A much higher current is found in the case of the advanced scenario (by a factor up to 3, depending on the radius), since this scenario is more favourable to ECCD being a high temperature and relatively low density scenario. The driven current per unit power is inversely proportional to density and increases (almost linearly) with temperature for the JET parameters.

Third harmonic absorption may strongly reduce the driven current in scenarios at low magnetic field, this effect being more relevant at high temperature.

The third harmonic resonance is located within the plasma region for $B_0 \lesssim 2.6T$, so that, depending on the magnetic field value and on the plasma electron temperature, power available at the second harmonic resonance may be reduced due to downshifted third harmonic absorption in the low field side even for $2.6T \lesssim B_0 \lesssim 2.8T$.

The driven current and the maximum value of the EC current density as a function of the injection angles, together with the contours of the radial location of the driven current density peak are plotted in Fig.2. It is shown that it is possible to maximize either the driven current or the current density on a specific magnetic surface by means of a proper choice of the injection angles. For the considered launching conditions, the effective poloidal steering range required to cover all the plasma positions in the whole magnetic field range considered is about 40^o in the case of Pulse No: 77895, and somewhat lower, $\sim 30^o$, in the case of Pulse No: 73344.

In order to synthesize the large amount of ECCD results and to estimate the performance at different magnetic fields, the maximum value of the driven current attained in a given radial interval $\Delta\rho = 0.1$ is calculated and represented graphically as a density plot in the (ρ, B_0) space in Fig.3 for Pulse No's: 73344 and 77895. The ECCD efficiency is about 2.5 times larger in the case of the advanced scenario Pulse No: 77895 with respect to the H-mode Pulse No:73344, mainly due to the favourable high temperature and low density. The maximum ECCD is found at $B_0 = 2.8T$ for Pulse No's:73344 and at 3.0T for 77895, because of the larger outward shift of the plasma centre for Pulse No:77895. The inner region of the plasma ($\rho \leq 0.2$) at high and low B0 is not accessible in the H-mode scenario, since the EC resonance is located far from the center in the low and high field side respectively. Although Fig. 3 provides a simplified picture of the possible use of an EC system at 170GHz, we can conclude that a single frequency gyrotron at 170GHz would cover the range 2.7T−3.2T in both scenarios, and up to 3.3T in the case of the advanced scenario for which the ECCD efficiency is peaked at higher B_0. Further extension of the magnetic field range covered by the system can be obtained by using a double frequency gyrotron (e.g., 136GHz [1]).

CONCLUSIONS

As a result of the overall analysis, the frequency 170GHz has been taken as the reference value for the present ECRH project in JET. The choice has been made on the basis of the estimated performance, showing that the range $B_0 = 2.7-3.2T$ is well covered, with possible extensions to slightly higher fields. Lower magnetic fields suffer from parasitic third harmonic absorption that increases as the electron temperature increases. However, since also the current drive efficiency increases with temperature (at least in the range considered here), a large ECCD efficiency is still found in the high Te advanced scenario.

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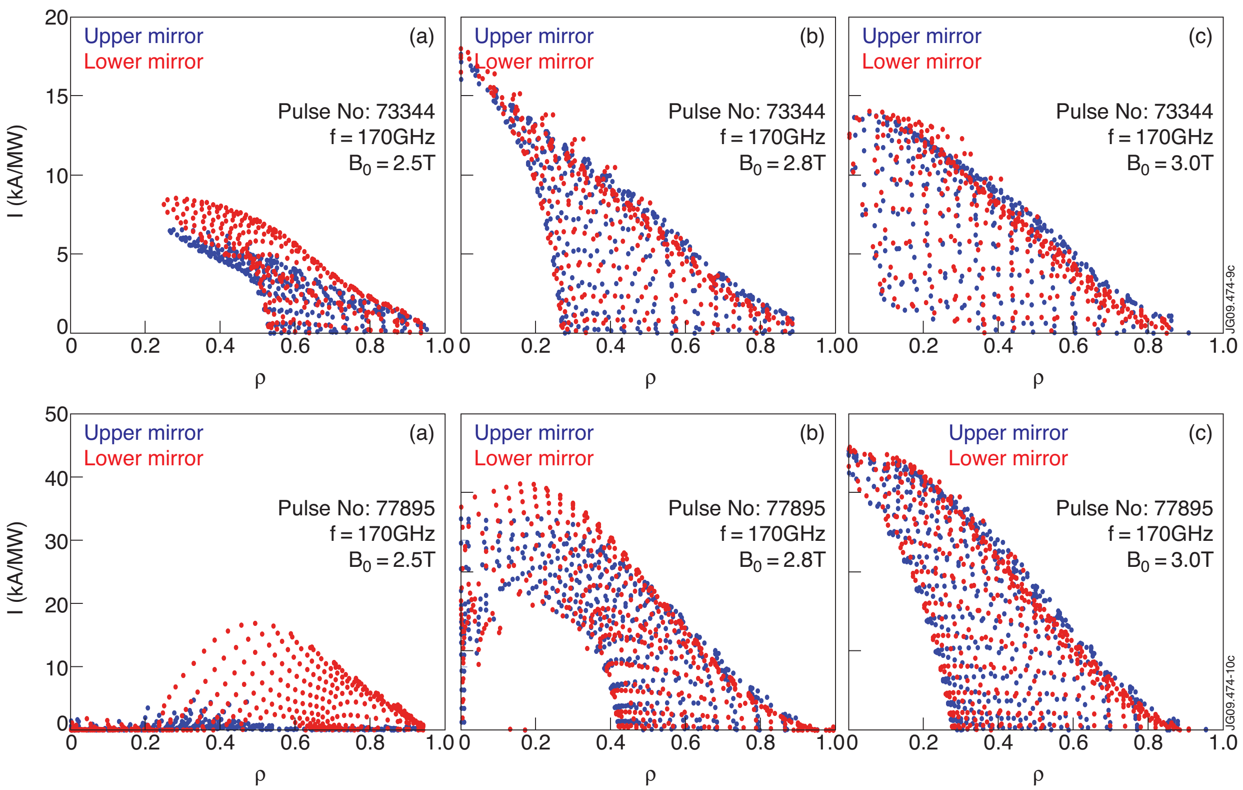

Figure 1: EC driven current versus normalized radius for f=170GHz in the H-mode scenario Pulse No: 73344 (top row) and in the advanced scenario Pulse No: 77895 (bottom row), obtained by means of a scan in poloidal and toroidal injection angles, for power absorption larger than 95%. Cases (a), (b), and (c) refer to B_0 = 2.5, 2.8, 3.0T,

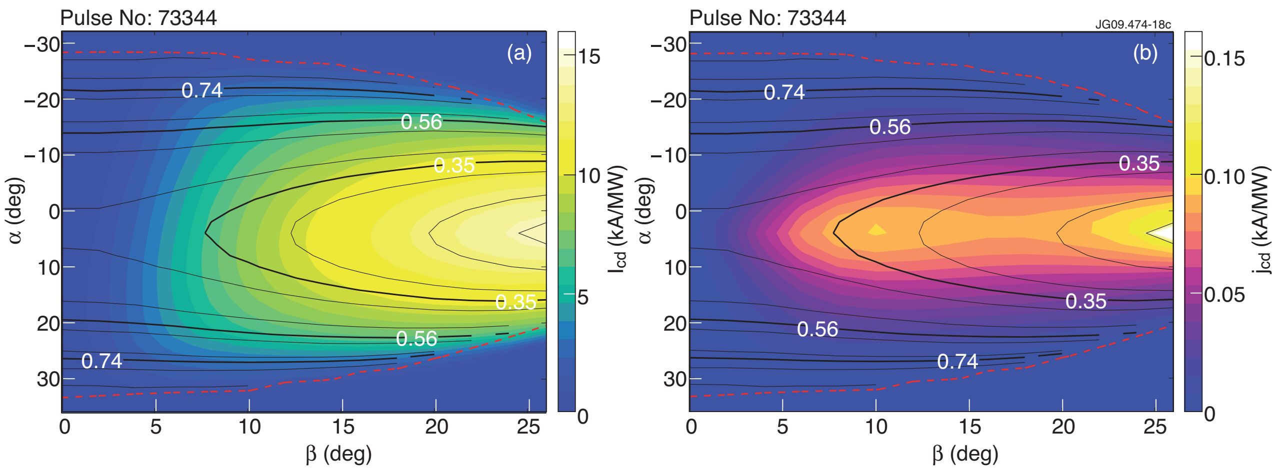

Figure 2. EC driven current (a) and peak current density (b) as a function of the launching angles from the upper mirror, for Pulse No: 73344 at $B_0 = 2.65T$. The contour lines give the radius at which J_{cd} is peaked.

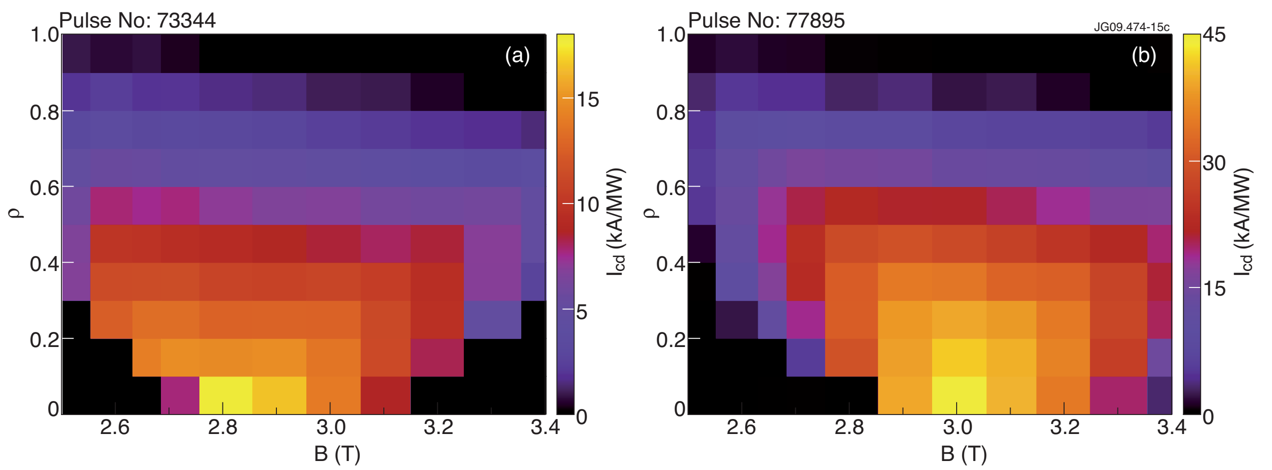

Figure 3: EC maximum driven current at 170GHz within the radial interval $\Delta\rho = 0.1$, for the H-mode scenario(a) and the advanced scenario (b). The plotted results are the average of the upper and lower mirror results, and are filtered with the following criteria: absorbed power larger than 95%, $\beta < 25\%æ$, and current profile width $\Delta\rho < 0.1$.