Capabilities of the ITER Upper Launcher for ELMy-H mode plasmas at low magnetic fields

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Abstract. The capabilities of the ITER ECRH upper port launcher to drive a well localized current (co-ECCD) either at the q=1.5 or at the q=2 surface by injecting EC waves as first harmonic O-mode at the nominal frequency \( f = 170 \text{ GHz} \) have been already explored for a number of ITER scenarios relevant for neoclassical tearing modes (NTM) stabilization. The analysis, made by including the hybrid scenario 3 and a low q scenario (scenario 5) as well as equilibrium and poloidal beta variations in addition to the Q=10 reference scenario 2, explored a wide range of relevant surfaces with different kinetic data for each scenario. ‘Optimal’ toroidal and poloidal injection angles for application of co-ECCD on the relevant flux surfaces have been identified for the two rows of mirrors, and performance evaluations by taking into account several beam parameters have been carried out. However, the analysis so far has been done only for one specific value of the vacuum toroidal magnetic field (\( B_0 \approx 5.3 \text{ T at } R_0=6.2 \text{ m} \)). In this work the capabilities to drive efficient and well localized co-current for a range of relevant surfaces in ELMy-H mode ITER plasmas at lower magnetic fields are explored by an updated version of the Milano beam tracing code. On the beam trajectories fully relativistic EC absorption and CD are calculated at both first and second harmonic. The changes of the ‘optimal’ launch angles as a consequence of the shift of the resonance to lower values of major radius are shown. The range of magnetic fields for which power deposition and current drive at relevant surfaces becomes impossible for EC waves injected from upper launcher as first harmonic O-mode is pointed out. Further, the effectiveness of the upper launcher for stabilization of (3,2) and (2,1) NTM is investigated in the range of magnetic fields where EC waves at \( f = 170 \text{ GHz} \) should be injected as second harmonic X-mode.

1. Introduction
The main purpose of the ITER electron cyclotron resonance heating (ECRH) upper port launcher will be to stabilize the neoclassical tearing mode (NTM) by driving currents (co-ECCD) locally inside either the q=3/2 or q=2 island. In order to stabilize the NTM, co-ECCD should be able to replace the “missing” bootstrap current. Since the islands rotate, the most efficient injection of current is near the magnetic island O-point, i.e. in phase with the rotating island, and the amount of positive EC current density required to appreciably reduce the island size is comparable to the ‘lost’ bootstrap current density. As a result, the important quantities for an efficient NTM stabilization by means of ECCD are the localizability at the relevant rational surfaces and a narrow, high peak current density profile in order to maximize the helical component of the driven current, besides the possibility to have a temporal modulation of the EC power.
The present reference design of the upper launcher uses three ports, through each port eight beams are injected as O-mode at 170 GHz in an arrangement of two horizontal rows (upper and lower row) with four beams in each row. A total power of 20 MW at the plasma is foreseen. An analysis and optimization study of the upper launcher with respect to its capabilities of stabilizing (3,2) and (2,1) NTMs has been already performed under the EFDA technology research program activities of 2003-2004, for different design options. In addition to the reference scenario 2, scenario 3a (hybrid operation at reduced \( I_p = 12 \text{ MA} \)) and scenario 5 (low q, higher \( I_p = 17 \text{ MA} \)) have been studied, as well as equilibrium variations for each reference scenario related to variations of the internal inductance and of the poloidal beta \([1],[2],[3]\). A wide range of location of relevant surfaces for (3,2) and (2,1) NTMs has been identified, \(0.65 \leq \rho \leq 0.93\), (\( \rho \) being the square root of the normalized poloidal flux function), and ‘optimal’ toroidal injection angles have been found to be \(\sim 20^0\) for injection from the lower row and \(\sim 18^0\) from the upper row.

All the ‘official’ ITER scenarios taken into account in the analysis so far have different equilibria and kinetic profiles, but the same ‘vacuum’ magnetic field \( B=5.3 \text{ T} \) at \( R=6.2 \text{ m} \). On the other hand, the ITER operation plan foresees to reach full field and full current after three years from the first plasma \([4]\). The main purpose of this work is to study the capabilities of the upper launcher with respect to the stabilization of (2,1) and (3,2) NTMs in first ELMy-H mode ITER plasmas at reduced performances.

### 2. Low magnetic field ELMy-H mode scenarios

In order to simulate low magnetic field ELMy-H mode ITER plasmas, we consider the equilibrium and kinetic profiles of the reference scenario 2 EOB2_076_062, with \( B_{\text{Tax}}=5.37 \text{ T} \), \( R_a=6.4 \text{ m} \), \( I_p=15 \text{ MA} \), \( \ell_i=0.76 \), \( q_{95}=3 \), \( \beta_{\text{pol}}=0.62 \) \([5]\), and rescale the toroidal magnetic field \( B_T \) by a factor \( g \), with \( 0.5 \leq g <1 \). The main plasma parameters of the low field, low current plasmas are obtained by means of the following constrains: i) \( q_{95}=\text{const.} \) ii) \( \beta_{\text{pol}}=\text{const.} \) iii) \( \nu^*=\text{const.} \). From these conditions, it is found that both the (total) magnetic field and the (total) plasma current scale as \( g \), the plasma pressure \(<p>\) (\(\sim <n_e T_e>\)) as \( g^2 \), while the plasma density and temperature as \( g^{2/3} \), and \( g^{1/3} \), respectively.

It should be noticed that with the above choice in the scaled scenarios the local ratio \( T_e/n \) increases for decreasing \( B_{\text{Tax}} \) as \( g^{-2/3} \), while the ratio \( n/n_G \) (being \( n_G \) the Greenwald density) decreases as \( g^{1/3} \).

In the present analysis, six scenarios have been investigated, varying the factor \( g \) in the range \( 0.5 \leq g \leq 1 \). Table 1 shows the main parameters of the plasmas considered, the typical parameters for wave propagation and accessibility, and the location of the cold resonance for waves at \( f=170 \text{ GHz} \) near the plasma equatorial plane.

| \( g \) | \( B_{\text{Tax}} \) (T) | \( I_p \) (MA) | \( n/n_G \) | \( (\omega_{p0}/\omega)^2 \) | \( (\omega_{\phi0}/\omega)^2 \) | Mode | \( R_{\text{sw}} = n_G e_0 \) (at \( Z\sim Z_{\text{sw}} \)) (m) |
|---|---|---|---|---|---|---|---|
| 1 | 5.37 | 15.00 | 0.85 | 0.28 | 0.78 | O1 | 5.62 |
| 0.90 | 4.83 | 13.50 | 0.82 | 0.24 | 0.63 | O1 | 5.02 |
| 0.85 | 4.56 | 12.75 | 0.80 | 0.22 | 0.56 | O1 | 4.73 |
| 0.80 | 4.29 | 12.00 | 0.79 | 0.21 | 0.50 | O1 | 4.43 |
| 0.55 | 2.95 | 8.25 | 0.70 | 0.12 | 0.24 | X2 | 6.16 |
| 0.50 | 2.68 | 7.50 | 0.67 | 0.11 | 0.19 | X2 | 5.60 |

When \( g \) decreases, the EC resonance layer shifts toward lower values of the major radius, and for \( 4 T > B_{\text{Tax}} > 3.1 \text{ T} \) the EC resonance condition as first harmonic cannot be met in the plasma, while the
second harmonic is still on the low field side. Therefore, by varying the factor \( g \) in the range \( 0.8 \leq g < 1 \), three scenarios have been obtained where the EC waves at \( f=170 \text{ GHz} \) are launched as first harmonic O-mode (O1). At lower fields, we shall consider only two cases \( (g=0.55 \text{ and } g=0.5) \) for which the second harmonic resonance layer is on the high field side, and X-mode (X2) second harmonic absorption and current drive (CD) from upper launcher is allowed, since current drive on the low field side is not allowed for present location of the upper launcher. It is worth noticing that in the case \( g=0.5 \) the second harmonic cold resonance occurs almost in the same as for the first harmonic in the reference case \( (g=1) \).

3. Description of calculations

The EC power deposition and current drive are computed with the GRAY beam tracing code [6]. A fully relativistic dispersion relation is used for the wave damping and the ECCD efficiency is calculated with a model based on the linear, relativistic, bounce averaged calculation of Cohen, by including the proper polarization terms [7]. We notice that the EC power density for \( P_{\text{EC}}=20 \text{ MW} \) is below the threshold power density for quasi-linear effects [8], \( dP_{\text{EC}}/dV < 0.5 \left(n_e/10^{14} \text{ cm}^{-3}\right)^2 \left(W/\text{cm}^3\right) \), in all the considered rescaled scenarios, even for \( g=0.5 \), i.e., in the lowest electron density case.

The beams used in present calculation are realistic beams, presently taken into account for the front steering option of the upper launcher [9]. The lower beam is characterized by a waist \( w_0=1.9 \) cm at a distance \( d_L=154.14 \) cm from the launching point, located at \( R=683.0 \) cm, \( Z=415.3 \) cm. The upper beam is characterized by a waist \( w_0=1.9 \) cm at a distance \( d_u=165.14 \) cm from the corresponding launching point located at \( R=675.4 \) cm, \( Z=436.3 \) cm. These beams are focused within the plasma and their radius is quite small in the absorption region (about 5 cm at a distance \( s \approx 3 \) m from the launching point, and about 10 cm at \( s \approx 5 \) m). As a consequence, the width of the EC driven current density profile is mainly determined by the Doppler effect and/or by geometric effects.

The toroidal and poloidal launching angles, \( \beta \) and \( \alpha \), are defined with the aid of a cylindrical co-ordinate system \( (R, \Phi, Z) \) with the \( Z \) co-ordinate line along the axis of symmetry of the torus, in such a way that the component of the refractive index at the launching point \( (\Phi=0) \) read: \( n_\Phi = \sin \beta, \quad n_R = -\cos \beta \cos \alpha, \quad n_Z = -\cos \beta \sin \alpha \), so that the parallel component of the refractive index is \( n_\parallel = \sin \beta b_\parallel - \cos \beta \cos \alpha b_R - \cos \beta \sin \alpha b_Z \), being \( (b_R, b_\theta, b_Z) \) the cylindrical components of the magnetic field versor. In our reference system both the plasma current and the toroidal field are negative, so that a negative \( n_\parallel \) is necessary to have a co-current, i.e. the toroidal angle \( \beta \) must be positive.

4. Results for O1 mode

We first consider the power of 1 MW launched as O-mode from the lower mirror at \( \beta = 20^\circ \). Besides the reference scenario \( (g=1) \), three scenarios at lower magnetic field \( (g=0.9, 0.85, 0.80) \) are taken into account. Fig.1 shows the behavior of the peak current density, of the total driven current, of the profile width at \( 1/e \) of the peak current density as well as the values of the poloidal launching angles necessary to drive the current in the region of interest for NTMs stabilization.

As expected, when the magnetic field decreases the ‘minimum reachable’ \( \rho \) is shifted towards larger values as a consequence of the displacement of the cold resonance towards lower values of the major radius. It may be noticed from Fig.1 that, by lowering the magnetic field, ECCD occurs only at \( \rho > \rho_{\text{min}} \), with \( \rho_{\text{min}} \) increasing as \( g \) decreases.
Curves in Fig.1c) also show that the current at $\rho > \rho_{\text{min}}$ may be driven for two $\alpha$ values, either lower or larger than the $\alpha$ value corresponding to $\rho_{\text{min}}$. It is worthwhile noticing that the range of $\alpha$ shown in the figure is that necessary for driving current in the region of interest for NTM stabilization, and that for the reference case ($g=1$) the EC current may be driven even inside the $q=1$ surface. For the reduced magnetic field cases, the largest driven current densities of Fig.1b) correspond to the lowest values of $\alpha$ of Fig.1c) since in this case the EC power absorption occurs in the upper region of the plasma. Moreover, $J_{\text{cd}}$ first increases, for $g=0.9$, due to geometric effects related to tangencies of the beam to the relevant surfaces in the absorption region, then decreases.

Beam trajectories for the three cases at lower field are shown in Fig.2. The poloidal launching angles have been chosen in order to drive current at the outermost chosen surface and at the innermost 'reachable' surface. Note that CD at $\rho_{\text{min}}$ is driven for $\alpha$ values such that absorption of the power occurs very close to the (plasma) equatorial plane, where the magnetic field has its maximum value.
Fig. 2. Beam trajectories are shown, for three scenarios corresponding to \( g = 0.9 \) (left), \( g = 0.85 \) (center) and \( g = 0.8 \) (right). Two beams are injected, in each case, from lower row, with toroidal launching angle \( \beta = 20^\circ \) and \( \alpha \) values necessary to drive co-current at the outermost chosen surface (\( p = 0.93 \)) and at the innermost ‘reachable’ surface. The EC absorption region along the ray trajectory is shown in red.

Fig. 3 shows the current density profiles that are obtained injecting 20 MW of EC power at \( \beta = 20^\circ \) from lower row, and the corresponding bootstrap current density. It may be noticed that in all cases the peak current densities are well above the local values of the bootstrap current. However, for a reduction of the magnetic field of 20\% (\( g = 0.8 \)), ECCD cannot be driven at the \( q = 3/2 \) surface of the present scenario (\( p_{\text{min}} \geq 0.8 \)).

Fig. 3. Profiles of the driven current are shown, for 20 MW of EC power injected with \( \beta = 20^\circ \) from lower row, for a): reference case, b): \( g = 0.9 \) c): \( g = 0.85 \) d): \( g = 0.8 \). The dashed blue lines indicate the bootstrap current density in each scenario, coloured figures indicate the poloidal launching angles.
We note that for ITER parameters, the EC power is absorbed very close to the ‘maximum’ up-shift, i.e. where the following condition \((\omega_c/\omega)^2 \approx 1 - n_{ji}^2\) is satisfied. To drive current at the innermost relevant radial locations, larger \(n_{ji}\) values, i.e. larger \(\beta\), would be necessary with respect to the reference values 20 and 18 degrees.

Results obtained by varying the toroidal injection angle \(\beta\) in the range (20° – 26°) are shown in Fig. 4 for the case \(g=0.85\), corresponding to the magnetic field \(B_{TAX}=4.56\) T.

It is found that, \(\rho_{\text{min}}\) decreases as \(\beta\) increases, so that ECCD may be driven at the innermost surfaces. Moreover, for larger \(n_{ji}\), the driven current \(I_{\text{cd}}\) also increases while the profile widths are almost unchanged, so that larger values of the peak current density are obtained.

Similar behaviour is found for the upper row.

Fig. 4. The behaviour of the peak current density (a), of the profile width (b), of the poloidal launching angle (c) and of the total driven current (d) is shown as a function of the radial location of the driven current, for \(g=0.85\) and 1 MW of power injected as O1 mode from the lower row, by varying the toroidal launching angle \(\beta\) in the range (20° – 26°).

5. Results for X2-mode
We consider here the two plasmas of Table I for which the EC power at 170 Ghz is injected as X-mode resonating as second harmonic. It is worth noticing that in the case of \(B_{TAX}=2.95\) T (\(g=0.55\)) the cold resonance is at a radial location quite close that of the launching mirrors. This means that this should be considered an ‘extreme’ case for driving current by launching the EC power from the upper launcher, and that for a somewhat larger magnetic field the EC power should be launched from the
mid-plane launcher. For $B_{\text{Tax}}=2.68$ T ($g=0.5$) the cold resonance location is nearly the same as for the reference case and similar beam trajectories may be expected.

Fig.5 shows, for the two plasma cases, the behaviour of the peak current density, of its width, of the poloidal launching angles and of the total driven current $a$ as a function of $\rho$, by considering the EC power of 1 MW launched as X-mode from the lower mirror at $\beta = 20^\circ$.

![Fig.5](image_url)

**Fig.5.** The behaviour of the peak current density (a), of the profile width (b), of the poloidal launching angle (c) and of the total driven current (d) is shown as a function of the radial location, for 1 MW of power injected as X2 mode with $\beta = 20^\circ$ from lower row, for the two plasmas corresponding to $g=0.55$ (blue lines) and $g=0.5$ (red lines).

In Fig.6 the current density profiles obtained by injecting from the lower row a total power $P_{\text{EC}}=20$ MW are shown, compared with the corresponding bootstrap current density.

It is worth noticing that, in the case $g=0.5$, greater ECCD efficiencies are found than in the reference scenario 2 case. This is mainly related to the fact that, with our choice of scaling the electron density and temperature under the constraint $v^*=\text{const}$, the ratio $T_e/n_e$ increases as $g$ decreases.

While for the case $g=0.5$ the required $\alpha$ angles are very similar to those of the reference case O1-mode, as expected being the cold resonance locations very similar in the two cases, it is clear from Fig.5 that, for $B_{\text{Tax}}=2.95$ T ($g=0.55$) and $\beta=20^\circ$, quite large $\alpha$ values are required to drive current at the relevant locations, leading to broad current density profiles. In this case a lower $n_e$ value, i.e. lower $\beta$, would give narrower profiles and higher peak current densities, as shown in Fig.7, where the relevant quantities are shown by varying the toroidal angle in the range $16^\circ \leq \beta \leq 22^\circ$. 

![Diagram](image_url)
Fig. 6. Profiles of the driven current are shown, for 20 MW of EC power injected as X2-mode with \( \beta = 20^{\circ} \) from lower row, for a) \( g=0.55 \), b) \( g=0.5 \). The dashed blue lines indicate the bootstrap current density, coloured figures indicate the poloidal launching angles.

Fig. 7. The behaviour of the peak current density (a), of the profile width (b), of the poloidal launching angle (c) and of the total driven current (d) is shown as a function of the radial location of the driven current, for 1 MW of power injected as X2 mode from the lower row in the case of \( B_{TaN}=2.95T \) (\( g=0.55 \)), by varying the toroidal launching angle \( \beta \) in the range \( 16^{\circ} - 22^{\circ} \).

6. Conclusions
An analysis of the capabilities of the Upper launcher on low magnetic field, low performance ELMy-H mode ITER plasmas has been made by considering 5 plasmas at reduced field, with a large variation of plasma parameters.
It has been shown that, for $5.3 \, T > B \geq 4.3 \, T$, the EC power as O1-mode should be injected at toroidal angles larger than the ‘optimal’ for the reference case, in order to drive the current at the innermost relevant surfaces. Moreover, by launching the power with $\beta \sim 26^\circ$-$28^\circ$ would also lead to increased CD efficiency as well as to larger values of the peak current densities.

For $4 \, T > B \geq 3.1 \, T$, first harmonic cold resonance is out of the plasma, while second harmonic enters, and this is still in the low field side.

For $B=2.95 \, T$, the current may be driven at relevant surfaces by injecting the power as X2-mode, but the peak current densities are not well above the local bootstrap current density, unless the toroidal launch angle $\beta$ becomes smaller than the nominal one. This is related to the fact that the second harmonic resonance at this field is at a relatively ‘small’ distance from the radial location of the launcher, requiring quasi-vertical trajectories for large $\beta$.

For $B=2.68 \, T$, being the cold resonance as second harmonic located very close to that of first harmonic for the reference case, also the trajectories of the X2-mode are nearly the same. As far the peak current densities are concerned, they have been founded to be about 1.6 times larger than in the reference case, as a consequence of our choice of scaling the electron density and temperature by taking $v^* = \text{const}$.

Finally, we note that qualitatively similar results for NTMs stabilization are obtained even if a different scaling for the electron temperature and density had been chosen (e.g., $n/n_0 = \text{const}$), although not so favorable as far as the CD efficiency is concerned.

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