

# Performance studies for the ITER ECRH launcher

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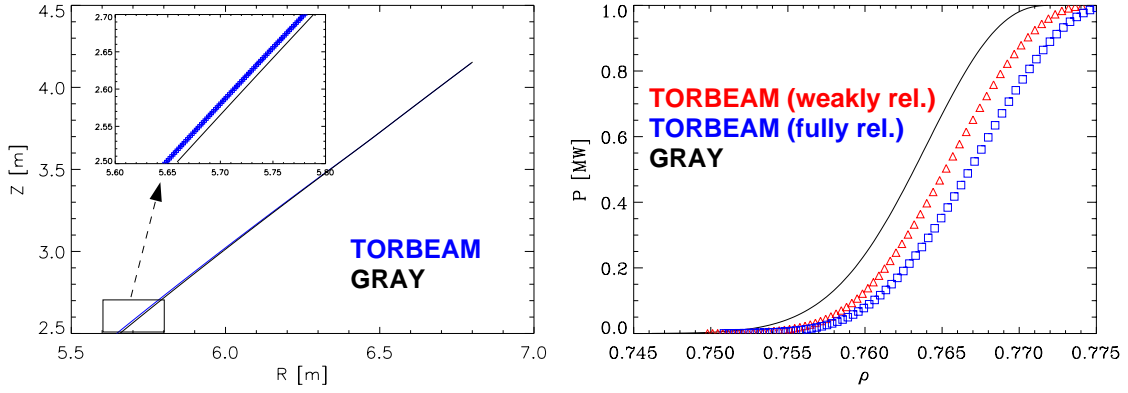
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## INTRODUCTION

The recent benchmarking activity involving ECH codes [1] resulted in a good confidence about the reliability of their results. The beam tracing code TORBEAM [2], as well as GRAY [3], has been used extensively during the past few years to evaluate the performance of different layouts proposed for the upper ECRH launcher for ITER. The better efficiency of the front steering (FS) concept [4] compared to the remote steering (RS) concept [5] in terms of the ratio  $\eta_{ECCD} \equiv j_{ECCD}/j_{bs}$  ( $j_{ECCD}$  being the local ECCD current density and  $j_{bs}$  the unperturbed bootstrap current density at the location where the EC current is deposited) has lead to the choice of the FS launcher as the reference design. The basic physics requirement for the ITER upper launcher, which has the stabilisation of Neoclassical Tearing Modes (NTMs) as its primary objective, is that the figure of merit  $\eta_{ECCD}$  be larger than 1.2 [6]. In this case, a complete stabilisation of the NTM should be possible. However, since the predicted performance of the FS launcher largely exceeds the constraint  $\eta_{ECCD} > 1.2$  [7], it has been proposed to modify the FS design to reach locations down to  $\rho_p \geq 0.4$  (here  $\rho_p$  is the normalised poloidal-flux radius), thus extending its possible applications to the control of FIR-NTMs and sawtooth activity [4], at the expenses of a minor deterioration of  $\eta_{ECCD}$ .

One of the problems which arise in the design of such a launcher is the superposition inside the plasma of different beams injected from the same mirror. In general, since different beams start from slightly different points on the mirror, one can expect that if the beams are launched parallel to each other, they will also have a slightly different absorption location in the plasma. Therefore, one has to look for the best convergence/divergence of the initial beams, which allows the best superposition of the deposition profiles. This requires an accurate modelling of the beam propagation and absorption, since this optimisation must be made at the level of a few percent.

In this paper, the analysis of multi-beam effects on the total current-density profile will be preceded by a review of recent upgrades introduced into the TORBEAM code and of their impact on the present kind of investigations.



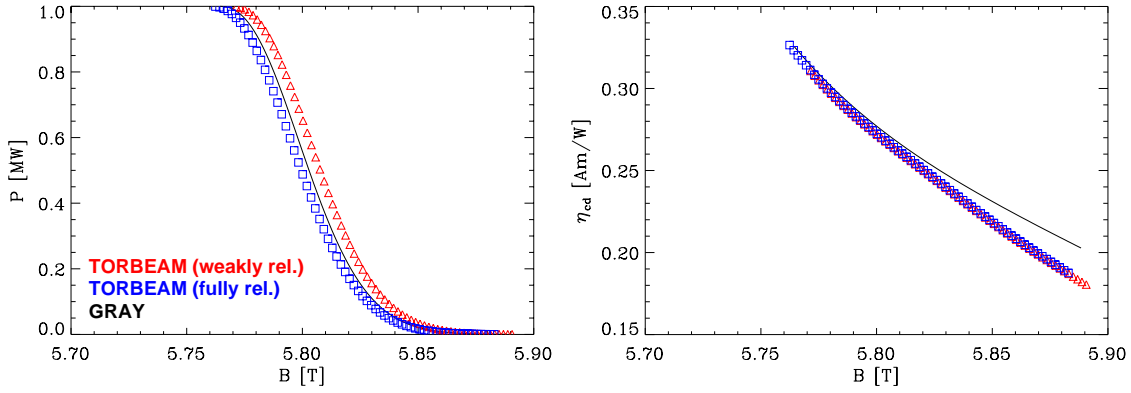
**FIGURE 1.** Beam trajectory and beam power for typical ITER parameters. TORBEAM (red triangles: weakly relativistic absorption; blue squares: fully relativistic absorption) and GRAY (fully relativistic; black solid curve) are compared.

## TORBEAM UPGRADES

TORBEAM integrates the beam tracing equations as obtained within the paraxial WKB method [8]. The EC beam is modelled in terms of a reference ray, which constitutes the “backbone” of the wave beam and evolves according to the usual ray-tracing equations, and of a set of parameters connected to the transverse width of the amplitude profile and to the curvature of the phase front. According to the paraxial expansion, which requires that the inequality  $\lambda \ll W \ll L$  be satisfied (here  $\lambda$  is the wavelength,  $W$  is the beam width and  $L$  is the inhomogeneity scale length of the plasma), the absorption of the beam can be calculated on central ray only, the effects of the finite transverse extension being taken into account geometrically through a projection of the beam onto the resonance. The ratio  $\eta$  between the (surface-averaged) current density driven by the waves  $j$  and the power density  $dP/dV$  delivered to the plasma is calculated using the adjoint method by the routine CURBA [9].

A first point which has been reconsidered in TORBEAM is the calculation of the total driven current. This was computed [2] for each integration step as  $dI = \eta dP / 2\pi R_0$ , where  $R_0$  is the major radius of the tokamak. This formula is exact only in the limit  $\varepsilon \rightarrow 0$  ( $\varepsilon$  being the inverse aspect ratio of the torus). A correct treatment of the flux-surface averages involved in the calculations of  $I$  yields [10]  $dI = \langle B_\phi / R \rangle \eta dP / 2\pi \langle B \rangle$ . This equation is now implemented in the code. Moreover, a routine which calculates the imaginary part of the wave vector employing the fully-relativistic expression for the dielectric tensor has been included in TORBEAM, so that the absorption profile can be compared to the weakly relativistic case already in use. Finally, an inexactness in the calculation of the poloidal angle at which the absorption takes place has been amended.

To evaluate the importance of the modifications mentioned above, a run of TORBEAM has been performed for typical ITER parameters and the results have been compared with those obtained with the GRAY code. The launching point is  $(R, Z) = (6.802, 4.156)$  m, the poloidal injection angle  $\alpha = 54.7^\circ$ , the toroidal injection angle is  $\beta = 20^\circ$ , the wave frequency is  $\omega/2\pi = 170$  GHz and the injected power is  $P = 1$  MW. The total current is  $I = 7.18$  kA for TORBEAM (fully relativistic version) and 7.13 kA

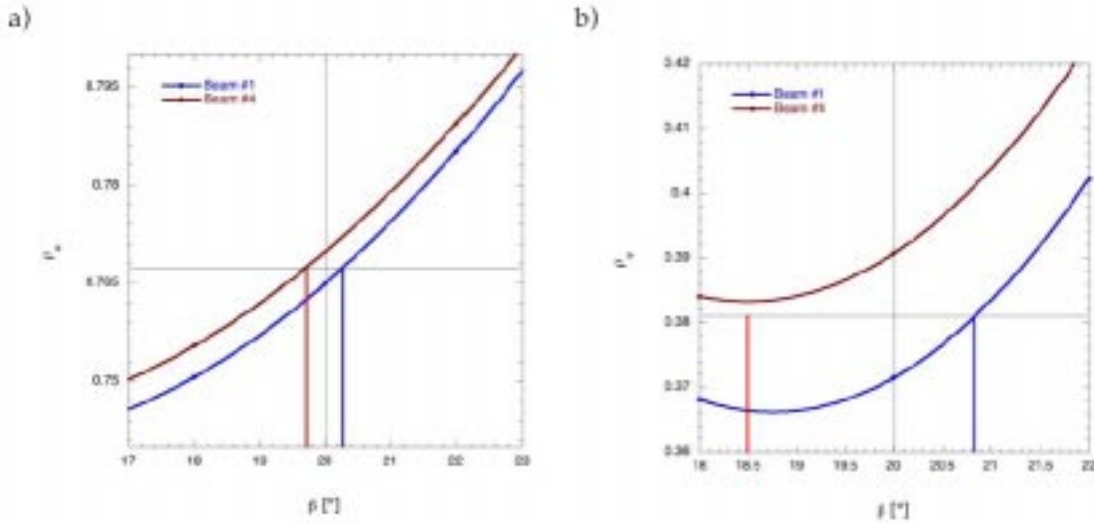


**FIGURE 2.** Beam power and CD efficiency as a function of the magnetic field  $B$  along the ray (symbols as in Fig. 1).

for GRAY. The trajectories of the central ray in the two codes can be seen in Fig. 1a. The small difference that can be observed is probably due to a different implementation of the vacuum-plasma transition. The effect of a fully-relativistic absorption calculation is shown in Fig. 1b. According to the results of multi-code benchmarking [1], one can see that in the weakly-relativistic case, the absorption begins slightly later (i.e., at slightly smaller  $\rho_p$ ). Since the beam trajectories do not exactly overlap, the absorption location in GRAY and TORBEAM differs (by less than 1%). However, as shown in Fig. 2a, the two codes become much closer if the beam power is plotted as a function of the magnetic field experienced by the beam. It is interesting to note that although the difference in the magnetic field between the weakly and the fully relativistic versions of TORBEAM is at a per-mil level, due to the shift of the resonance in velocity space this can have an impact of some percent in the current-drive efficiency (cf. blue and red curves in Fig. 2b and [3]). It is also interesting to note that the CD efficiencies computed by TORBEAM and GRAY do not coincide for  $B \gtrsim 5.8$  T. The origin of this disagreement is that only the leading component of the wave electric field is retained in CURBA, whereas in GRAY the full polarisation term [3, 10] is included. In the example being considered, however, this does not significantly affect the total driven current, since most of the power is absorbed between  $5.70 \text{ T} < B < 5.82 \text{ T}$ , cf. Fig. 2a, where both efficiencies are nearly equal.

## OPTIMISATION OF THE BEAM SUPERPOSITION IN THE ITER UPPER LAUNCHER

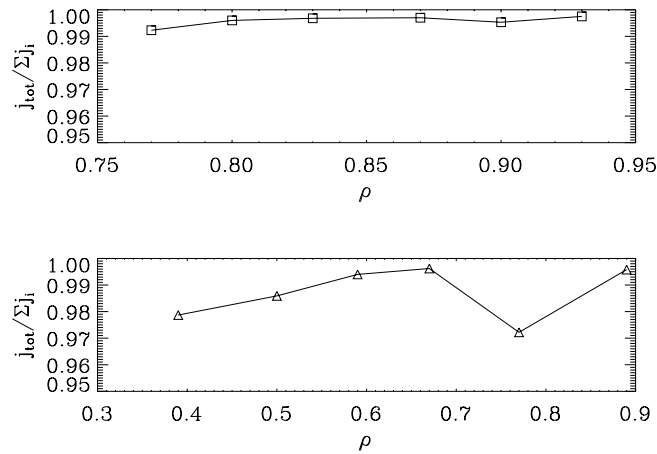
In the FS design, it is foreseen that eight beams are launched from each port. They are arranged in two rows, such that four beams are steered into the plasma by an upper mirror and four by a lower mirror. The best performance in terms of  $\eta_{ECCD}$  can be achieved if the beams have a complete overlap at the deposition location. Since the four beams launched by a given mirror do not have exactly the same initial coordinates, their trajectories do not perfectly coincide. This results in a broadening of the total absorption



**FIGURE 3.** Deposition location for the “extreme” beams launched from the upper mirror (case A), as a function of  $\beta$  for  $\alpha = 57^\circ$  (a) and  $\alpha = 68^\circ$  (b).

profile in the plasma, due to the fact that the maximum absorption does not take place at the same radial location. As mentioned in the introduction, by imposing a proper convergence/divergence of the beams it should be possible to reduce this effect. The issue is investigated using TORBEAM. Even though the difference between the launch coordinates of the beams is small compared to the dimensions of ITER, so that also the spread in the deposition maximum is expected to be also small, it should be stressed that this effect, together with the effect of beam astigmatism [7], could lead to a performance degradation of the order of 10%.

The optimisation is performed for the upper and the lower mirror separately. At the present stage, the lower mirror is designed to aim at a range of flux surfaces in the plasma between  $0.75 \leq \rho_p \leq 0.95$ , whereas the upper mirror is intended for extended physics applications and should reach  $\rho_p = 0.4$ . As a first step to determine the optimum convergence of the four beams for each mirror, one can determine the spread in the deposition location which occurs when they are injected with the same toroidal angle  $\beta$ . An example can be seen in Fig. 3. The deposition locations obtained by scanning the toroidal injection angle from  $18^\circ$  to  $22^\circ$  for a given poloidal injection angle are plotted for the two “extreme” beams on a mirror, i.e. for those beams which have the largest distance between their launch points. This figures allow to guess the injection angles that would lead to the absorption of both beams at the same value of  $\rho_p$ . This angles are different for each poloidal injection angle  $\alpha$  (cf. again Fig. 3). This means that a mirror design for which the optimum convergence is approximately constant for a wide range of  $\alpha$  would be desirable. Two design options have been considered in detail. In the first one (case A), the mirror end far from the steering mechanism is tilted downwards, whereas in the second one (case B) the mirror is horizontal. It has been found that, for case B, a convergence of  $\pm 1^\circ$  for the upper mirror and  $\pm 1.3^\circ$  for the lower mirror



**FIGURE 4.** The ratio between the maximum ECCD current density and the “optimum” current density which would result from a perfect superposition of the beams, for the lower and the upper mirror (case B).

yields a very good superposition over the whole steering range. Fig. 4 shows the ratio between the maximum of the total ECCD current profile (obtained as the sum of the single profiles) and the current density which would result from an exact superposition of the four profiles. As it can be seen, the deterioration due to the different absorption location of the four beams can be kept below 1% for the lower mirror and below 3% for the upper mirror.

## ACKNOWLEDGMENTS

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## REFERENCES

1. R. Prater *et al.*, this conference.
2. E. Poli, A. G. Peeters and G. V. Pereverzev, *Comp. Phys. Comm.* **136**, 90 (2001).
3. D. Farina, this conference.
4. M. A. Henderson *et al.*, this conference.
5. A. G. A. Verhoeven *et al.*, this conference.
6. H. Zohm *et al.*, this conference.
7. G. Ramponi *et al.*, this conference.
8. G. V. Pereverzev, *Phys. Plasmas* **5**, 3529 (1998).
9. R. H. Cohen, *Phys. Fluids* **30**, 2442 (1987); *Phys. Fluids* **31**, 421 (1988).
10. Y. R. Lin-Liu *et al.*, *Phys. Plasmas* **10**, 4064 (2003).