Location and Quantification of non-absorbed EC-power in ITER

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Electron cyclotron resonance heating will be an essential heating system for ITER [1]. Although the single pass absorption reaches nominally 100%, stray radiation may be due to a non-negligible fraction of cross polarization as well as due to operation very early in the start-up phase or due to heating at the 3rd harmonic of the electron cyclotron frequency (1/3 of full magnetic field). These cases require to model where the non-absorbed power hits in-vessel components and in particular with which power density. Such information may even be required in real time to protect sensitive components. As a starting point, fig. 1 shows the power densities expected when injecting into the empty vessel. Note that metallic surfaces do reflect up to 99% of the power such that there is no general conflict, since ITER's first wall is designed for several MW/m^2. Potential issues may arise in the early operational phases and for remote, more sensitive components. In contrary to smaller machines in operation nowadays, ITER will be safe with respect to cut-offs of the heating beams, since the ratio B_t^2/n_e is much higher. Still a cut-off

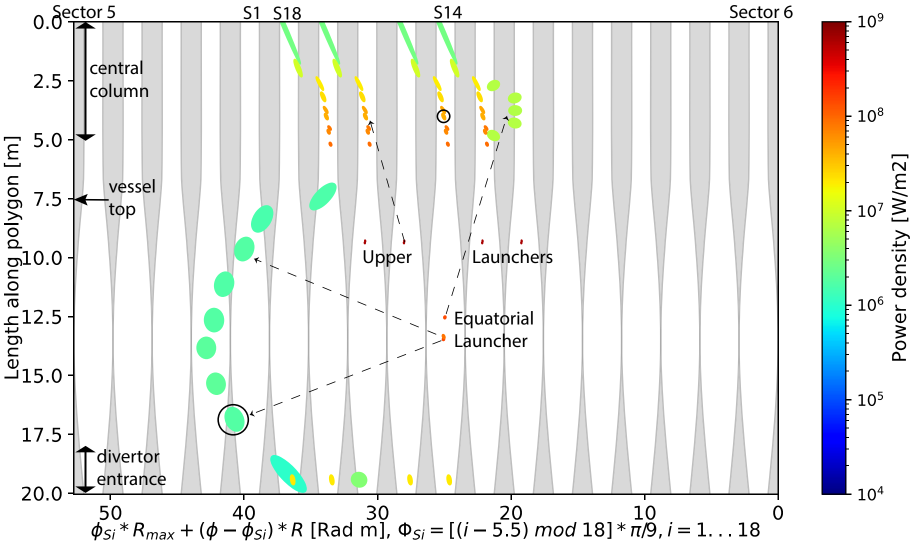

Figure 1: *Power impinging on ITER first wall by EC injection of 1 MW beams into the empty vessel. Shown are projections of the 18 sectors connected at the largest major radius using a rotated poloidal polygon as first wall proxy (see text and fig. 2). Beam intensities are projected into the tangential planes at the crossing of the central beam, where they form ellipses. The color coding corresponds to the max. power density in the center, it drops by one order of magnitude towards the edge of the ellipse. For one beam per mirror the entry (launching) and exit (immission) ellipses are shown; they are connected by dashed arrows. Launcher angles are varied in 5 steps over the full ranges.*

situation will occur for the cross polarization, when heating ITER at full field (5.3 T) with the ordinary (O-)mode at the fundamental EC resonance, the case further discussed in this paper.

To estimate these vessel loads the beam-tracing code TORBEAM [2] is used within the IMAS suite [3] as a post processor to a Q=10 modelling-scenario from the ITER IMAS scenario database [4]. If a significant part of the injected power leaves the plasma, the Gaussian beam parameters are stored in an IDS, so anyone interested in impact of stray radiation can use this IDS to reconstruct the Gaussian beam and its impact on any R,Φ, z coordinate. In order to visualize trends we calculate here the immission on the surface of a rotational poloidal polygon (known at ITER as wall2D).

The immission without plasma is of course reduced introducing the plasma as an absorber. Fig. 2 shows O-mode absorption at two time points in the ramp-up for two extreme beams (encircled in fig. 1), one launched by the middle steering mirror (MSM) of the equatorial launcher (EL) crossing the plasma on a long path and 2 resonance (red line) crossings, the other launched off-axis by the L(ower)SM of an upper launcher (UL). At 24 s, non-absorbed power is observed for both cases, i.e. 17% / 37% of the injected power. At the later time only the off-axis launcher has minor impact (< 0.2% non-absorbed power) also vanishing further into the ramp-up. The vacuum-footprint in the background is shown for power reference and to indicate the moderate beam bending (central density profiles (not shown) are flat).

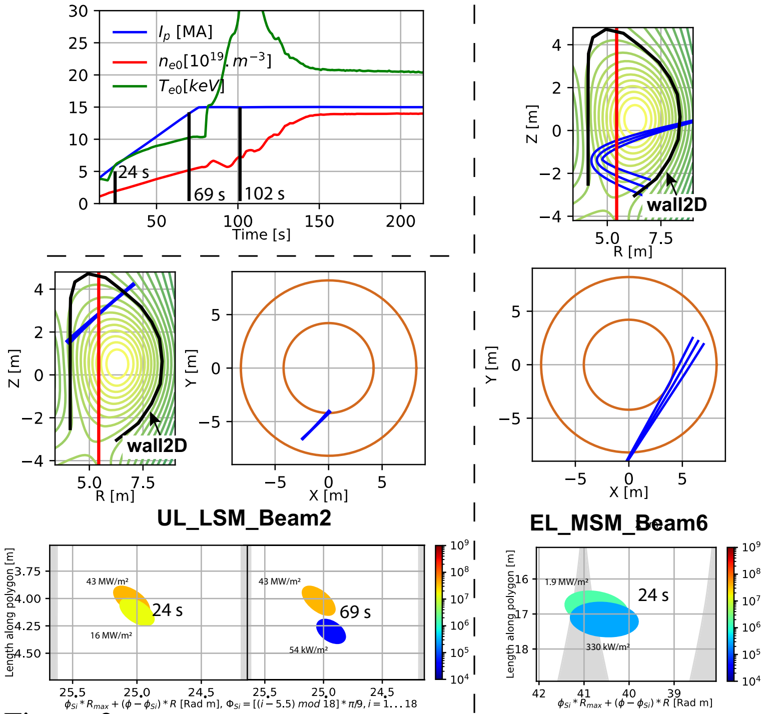

Figure 2: *O-mode transmission for two selected beams (encircled in fig. 1) at 24 s and 69 s in the ramp-up. The beam trajectories are shown in poloidal- and top-view at 24 s. The vacuum transmission is shown for reference behind the O-mode pattern. For the mid-plane launched beam, no transmission was observed at 69 s within the given scale. (Time point 102 s see fig. 3.)*

With respect to cross polarization, additional TORBEAM runs with the orthogonal polarization are required. O-Mode at higher harmonics can be treated as a heating beam since no cut-offs are expected and absorption will only occur at high plasma temperatures. Deviations from the vacuum beam are small. The situation is very different for the above mentioned X-mode cutoff in case of O1-heating. It occurs when the heating frequency ω corresponds to the right hand (RH) cut-off. Assuming $B \propto 1/R$ leads to a condition for the radial position of the cut-off : $R_{RH} = R_{CR}/(1-\omega_p^2/\omega^2)$ with the plasma frequency ω_p, $\omega_p^2 \propto n_e$ and R_{CR} the major radius of the cold first harmonic resonance. As the density increases the cut-off moves from the cold resonance to the plasma edge. The density for which the cut-off reaches the separatrix depends on R at which the specific beam enters the separatrix and is thus higher for the equatorial launcher than for the upper launchers, which inject beams closer to the top of the plasma at lower R, which can be very close to R_{CR} for max. upwards inclined mirrors. Fig.3 illustrates the situation for an intermediate time point in the density ramp up. A cut-off in the scrape-off layer (SOL) poses a problem for codes describing wave propagation, which require a smooth variation of the refractive index as the cut-off is approached. Since the density in the models is often not defined outside the separatrix, it has to be extended in the SOL. Here a *tanh* + exponential decay is used. Additionally a linear term inside the separatrix adjusts the slope towards the center (fig.3, top).

With this extension, TORBEAM was used to trace the reflection of the beams, and at the bottom of fig.3 the movement of the footprints along the vessel walls can be seen which move towards the launching points as the RH-resonance moves outward with increasing density. At the density flattop (burning plasma phase) the power densities are close to the ones launched. In this example for which a conservative number of 5% cross polarization is assumed power density in this phase can be as high as 50 MW/m^2 (UL) and 5 MW/m^2 (EL). As mentioned above, a metallic surface cooled to the ITER specs shall be able to handle this. This study was driven by concerns for sensitive components like diagnostics or the IC antennas in the vicinity of the EC launchers. The IC antennas are indicated as rectangles in the figure. The study shows that the IC antenna in S(ector)13 may be hit by beams from the USM of UL/S12 and from the T(op)SM of the EL, while beams from the two other EL mirrors may reach the IC antenna in S15. Consequences are under investigation.

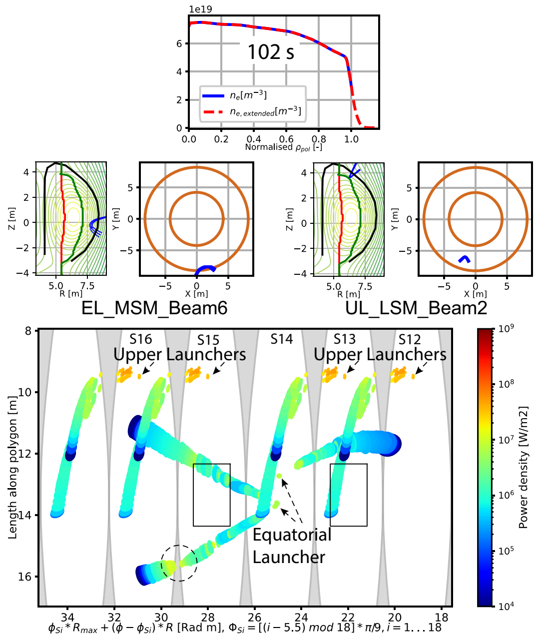

Figure 3: *X-mode reflections at the RH cut-off (dark green line in the poloidal views), assuming 5% cross polarisation. See text for details. The beams used for the middle row are the same as in fig. 2.*

The usage of beam tracing in the vicinity of a cut-off may violate premises for its applicability, i.e. the refractive index and the elements of the conductivity matrix should vary smoothly over a scale of a few beam widths. The validity of the paraxial WKB approximation implemented in TORBEAM has been analyzed in the past for the case of 2D propagation [6, 7, 5]. The main source of disagreement between the beam tracing results and the exact (analytical or numerical) solution of the full-wave equation stems from the fact that the beam tracing solution does not account for the interference pattern occurring where the beam is reflected. This results in an faulty estimate of the position of the amplitude maximum and of the beam size around the turning point, and in general to a wider beam width after reflection. Both these inaccuracies become less and less evident the shallower the incidence angle. According to the analyses performed so far, it is reasonable to assume that TORBEAM can reproduce correctly at least the order of magnitude of the power density impinging on the wall. On the other hand, in some numerically challenging scenarios, the code gives unreliable results. Indeed we find that the intensities of the reflections do not always increase monotonically as the cut-off layer moves outward (as indicated by the dashed circle in fig. 3). A quantitative interpretation of a single result can be misleading and should be either checked by a density variation or by inspecting the beam trajectory, which shows peculiarities in these cases. An example is shown in fig. 4, where TORBEAM exhibits an non-physical necking of the beam at the plasma exit, while a nearly constant width should be expected, as demonstrated by a WKBeam [8] run for the same case. This failure is probably due to a pile-up of numerical inaccuracies in the equations for the Gaussian envelope, which involve second derivatives of the background quantities. Improvement in the numerical schemes are under way to stabilize the integration of the beam shape under these extreme conditions.

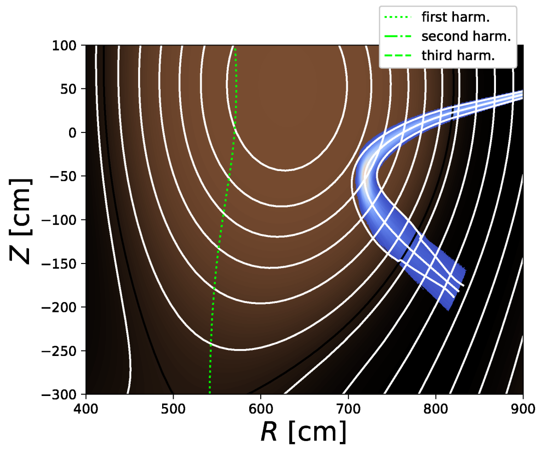

Figure 4: *Beam trajectory for a critical case as calculated by TORBEAM (white trajectory) and WK-Beam (color scale).*

The views and opinions expressed herein do not necessarily reflect those of the ITER Organization.

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