

## **Modelling of Electron Cyclotron Radiative Transport in Fusion Plasmas: The new Code RAYTEC (Approach and Applications)**

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As it was recognised that local electron cyclotron (EC) wave power losses can be a competitive contribution to the 1D electron power balance for reactor-grade tokamak plasmas with core temperatures of 35 keV or higher as anticipated for steady-state operation in ITER and DEMO <sup>1</sup> and, therefore, have an impact on the temperature profile of these plasmas, a systematic effort is ongoing to improve the modelling capability for the radial profile of EC wave emission. This effort aims at generating and validating a hierarchy of codes that cover the non-local behaviour of EC wave transport with good accuracy and also provide sufficient computational efficiency for being usable in 1D transport studies <sup>2</sup>.

To cover the effects of a non-circular plasma cross-section and of toroidicity for plasmas with arbitrary density and temperature profile, a new code, RAYTEC, which traces the change of the EC radiation intensity along the rays, has been developed and applied to ITER-like plasmas <sup>3</sup>. The motivation for this work was to provide an alternative to SNECTR which is no longer in active use. In its present form, the code addresses specular reflection (which allows tracing rays without having to rely on Monte-Carlo methods as does SNECTR) of straight rays at an ideally toroidal wall with elliptical cross section, and covers plasmas in thermodynamic equilibrium. The efficiency of the computations was enhanced by adopting Robinson's approach <sup>4,5,6</sup> for the calculation of the EC absorption coefficient as well as by an appropriate modelling of the inner hot plasma for the lower frequencies for which the plasma effectively behaves as a black body and which contributes little to the net EC wave power density  $dP/dV$  that is emitted from the plasma.

RAYTEC has been used to (i) investigate to which extent elongation of the plasma cross section and toroidicity affect the angular distribution of the radiation field  $I$ , (ii) determine the radial profile of the net EC wave power density  $dP/dV$  that is emitted from the plasma for

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ITER-like plasma parameters and profiles, study the impact of elongation and toroidicity on  $dP/dV$  and compare with profiles generated by the frequently used simpler models for  $dP/dV$ , viz., CYTRAN<sup>7</sup> and EXACTEC<sup>8</sup>, as well as with an explicit analytical expression for  $dP/dV$  in terms of local and global plasma parameters that has been generated by Locally Applying Trubnikov's Formula (to be referred to as LATF) for the total EC power loss<sup>9, 10</sup> and (iii) consider the total EC power loss and its dependence on both the plasma geometry and the shape of the plasma temperature profile as following from this local analysis and also compare these results with those obtained from the total power loss formulae given by Albajar et al.<sup>11</sup> and by Fidone et al.<sup>12</sup>.

As a result, elongation and toroidicity by themselves do not lead to a sizeable isotropisation of the radiation intensity  $I$ . For this, a significant diffusive component in the reflection at the wall is necessary. The impact of elongation, for specular wall reflection, is generally found to be weak: for constant area of the plasma cross section, there is a slight tendency for the specific intensity to decrease with increasing elongation, corresponding to a decrease of the effective optical thickness of the system. Toroidicity, due to the variation of the angle between the ray direction and the magnetic field, tends to mitigate the angular dependence of  $I$ , in particular for rays propagating at a small angle with respect to the magnetic field, but also introduces abrupt changes of  $I$  when the path length towards the last wall reflection point (and possibly previous ones) discontinuously changes and the optical distance to that reflection point is not large compared to 1.

In the hot core, for ITER-like conditions, elongation and toroidicity are found to enhance the net losses due to EC waves typically by 25% with respect to the equivalent circularly cylindrical plasma. This is not far from what is found to occur also through isotropisation of the wave field, e.g., by a strong diffuse component in wall reflection<sup>2</sup>. Hence RAYTEC can be used with good accuracy (certainly considerably better than 25% locally) in 1D plasma transport calculations for ITER and DEMO. While there are significant differences in details of the profiles of the net EC wave power density  $dP/dV$  obtained from RAYTEC and from the more simplified models underlying the computationally faster codes CYTRAN and EXACTEC as well as from the explicit LATF expression, overall these latter models do not deviate by more than about 20% from RAYTEC results (see Figs.1) and, hence, provide still quite adequate approximations although they do not describe geometry and profile effects accurately.

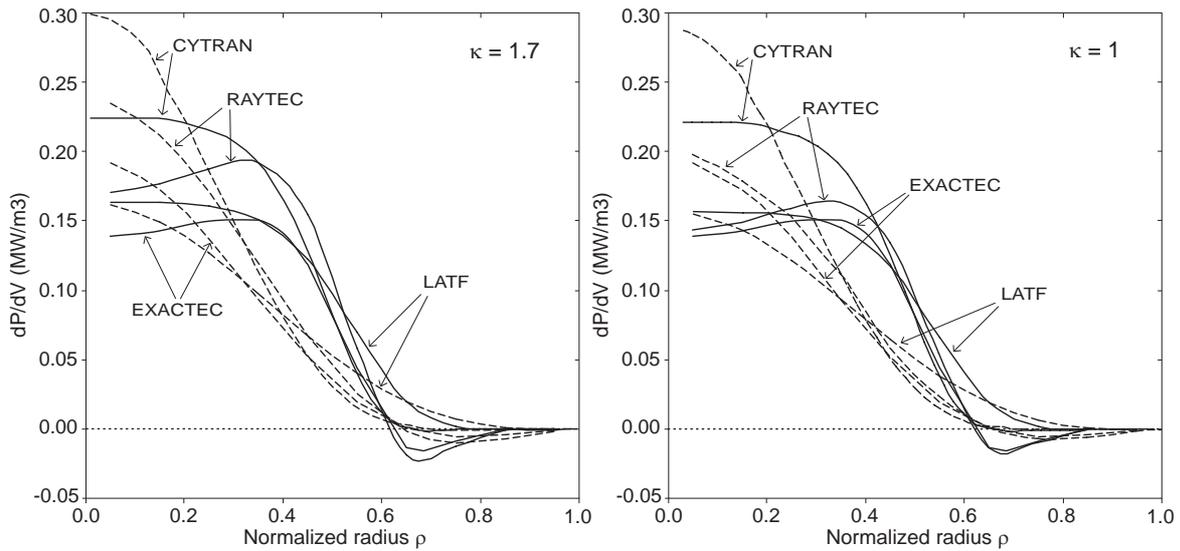


Figure 1a. Comparison of CYTRAN, EXACTEC and LATF results for  $dP/dV$  with those obtained from RAYTEC for ITER-like parameters. The aspect ratio is  $A = 3.1$ ; two temperature profiles are considered that both have, respectively, a peak and a volume average temperature of 45 keV and 18 keV: an “advanced” profile characterised by a wide hot core (solid curves) and a parabola-like one (dashed curves); the left plot shows the results for a plasma elongation  $\kappa = 1.7$  while the right plot refers to a circular plasma ( $\kappa = 1$ ); the wall reflection coefficient is  $R_w = 0.8$ .

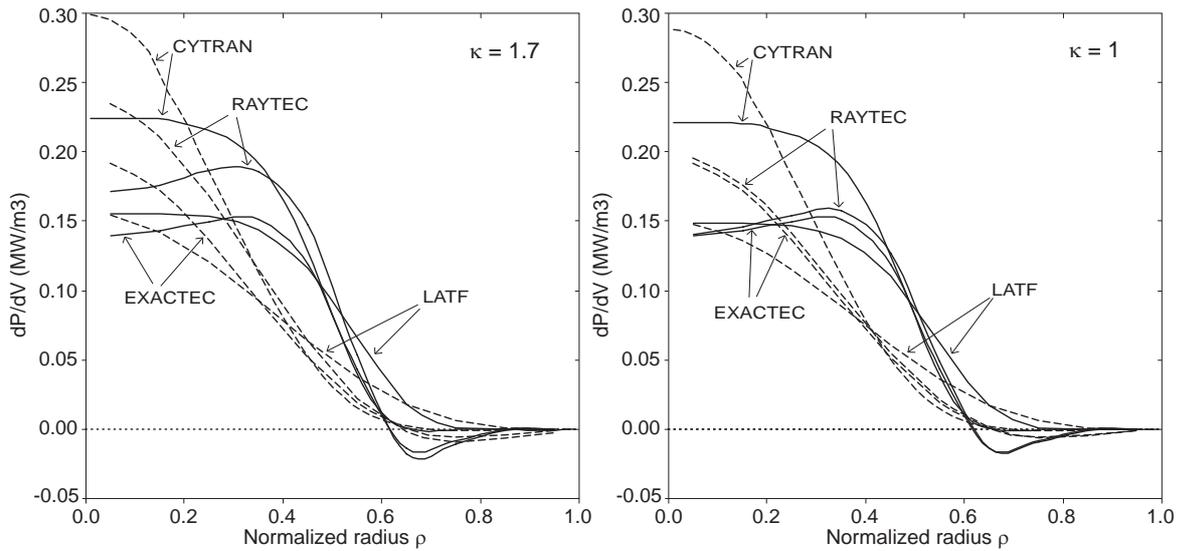


Figure 1b. Same as figure 1a, but for a large aspect ratio ( $A = 4.5$ ).

The analysis of the total EC power loss obtained by volume integration of the local EC wave losses  $dP/dV$  as calculated using RAYTEC shows trends with varying toroidicity and plasma elongation similar to those found for  $dP/dV$ . The values calculated from  $dP/dV$  as obtained using CYTRAN, EXACTEC and LATF as well as those from the explicit expressions due to Albajar et al and Fidone et al and one that has been constructed on the basis of the LATF approach (which separates profile effects from those of geometry and the global plasma parameters) again are within 25% of the RAYTEC results, but there are noteworthy differences in the dependencies on aspect ratio and elongation (see Figs.2).

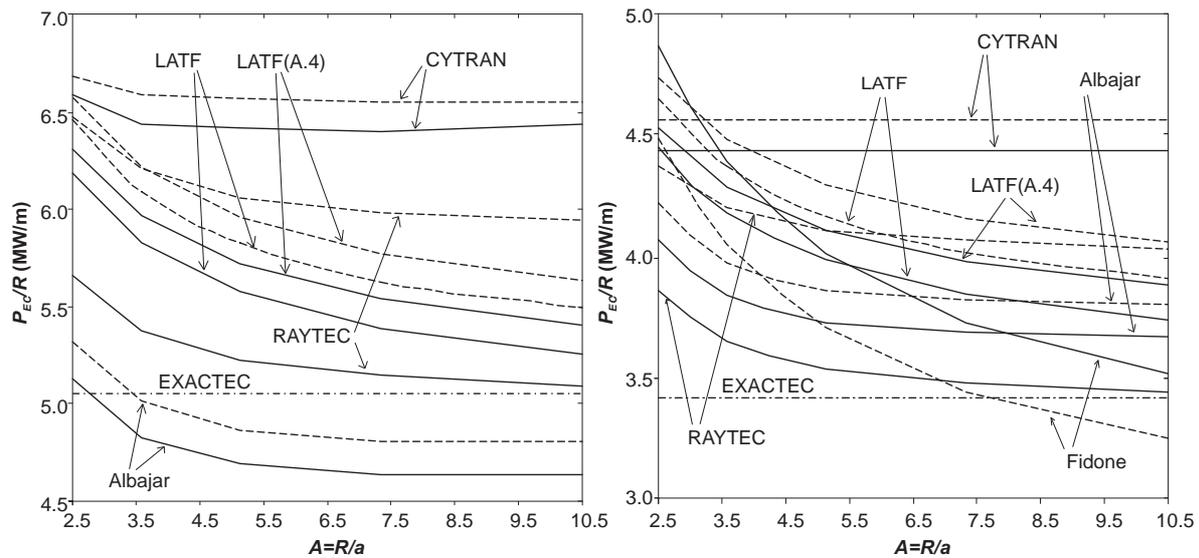


Figure 2a. Comparison of the total EC wave power emitted per toroidal unit length  $P_{EC}/R$  versus aspect ratio  $A$  as obtained by integrating  $dP/dV$  calculated using CYTRAN, EXACTEC and LATF numerically over the plasma volume, as well as that derived from the global formulae given by Albajar et al and by Fidone et al and from an approximate analytical expression based on LATF, with the volume-integrated RAYTEC results for ITER-like parameters and both circular cross section (solid curves) and a plasma elongation  $\kappa = 1.7$  (dashed curves); left plot: “advanced” temperature profile, right plot: parabola-like temperature profile.

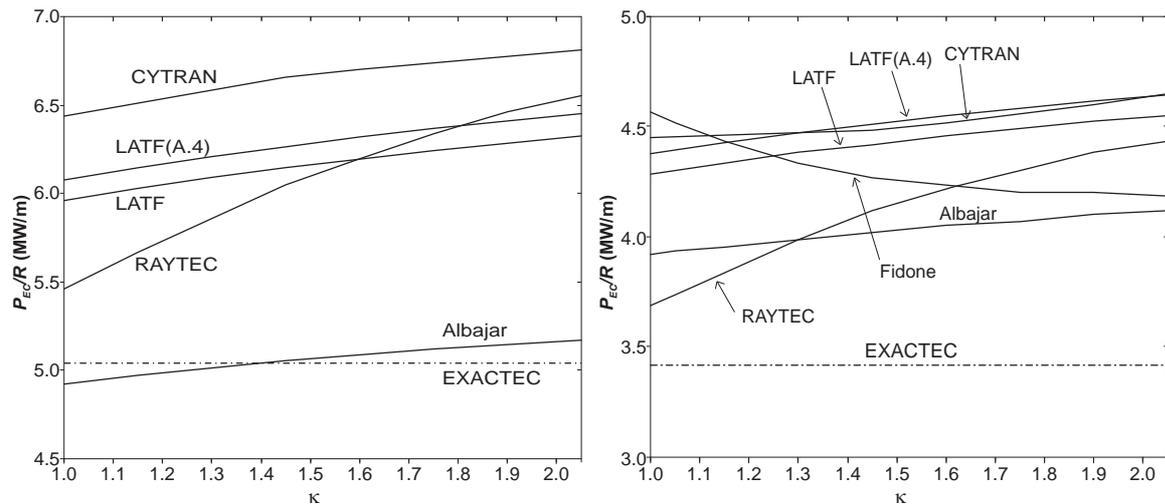


Figure 2b. Same as figure 2a, but for the dependence on elongation  $\kappa$  at fixed  $A = 3.1$ .

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