Electron Cyclotron Heating, Current Drive, and Emission Applications of the GENRAY Ray Tracing Code

R.W. Harvey[1], A.P. Smirnov[2], R. Prater, M.E. Austin[3]

General Atomics, P.O. Box 85608, San Diego, California 92186-5698, USA
[1]CompX, P.O. Box 2672, Del Mar, CA 92014-5672, USA
[2]Moscow State University, Moscow, Russia
[3]University of Texas, Austin, TX, USA

Abstract

We report benchmarking of EC absorption and CD from the GENRAY ray tracing code against results from the well-known TORAY ray tracing code for ITER and DIII-D conditions. The code is then applied to calculate nonthermal cyclotron emission from the DIII-D tokamak for high power, low density discharges, using CQL3D distributions functions. Radiation temperature is four times the Thomson temperature.

The GENRAY ray tracing code [1,2] is an all-frequencies ray tracing code in three dimensional geometry. Presently, the ray tracing uses toroidal equilibria as specified by the EQDSK format, with optional toroidal variations in magnetic field and plasma parameters. Several alternative wave dispersion calculations are supported, including the fully relativistic relation of Mazzucato-Fidone-Granata[3]. Current drive is obtained with the Cohen adjoint module[4]. For modeling of high power RF injection, GENRAY is coupled to the CQL3D Fokker-Planck code[5].

GENRAY builds on the experience of the TORAY[6] and Brambilla LH/FW ray tracing[7] codes. Calculations are performed in a R,Φ,Z-cylindrical coordinate system. Numerical integration of the ray tracing equations is with Runge-Kutta techniques. Capabilities have been developed to readily incorporate any dispersion relation solver: the required derivatives with respect to wave frequency and wavenumber are obtained by numerical differentiation.

In addition, GENRAY calculates nonthermal cyclotron emission resulting from analytically or numerically specified distributions. The radiation transport equation is solved following along EC rays, in the manner of the prior HORACE code[8]. Coefficients of emission and absorption are then calculated at necessary points along the ray trajectories terminating at the detector, enabling solution of the radiation transport equation along the ray trajectory from the plasma to the detector. The coefficients are based on various model distribution functions, or are taken from results of the CQL3D.

In the following, we report results of benchmarking GENRAY against the well-tested[9] TORAY-CQL3D codes, for EC waves in ITER and in DIII-D. Following this, an ECE simulation of a high power ECH, low density DIII-D shot is reported.

The canonical ITER ECCD test case has been reported upon by Prater[10], benchmarking several ray tracing and ECCD calculations within the international community. Figure 1 shows the ITER plasma cross-section with the poloidal projection of EC rays from GENRAY superimposed. Launch is from R=6.4848m, Z=4.1100m, with toroidal launch angle $\phi = 137.840$deg measured from the major radius direction through the source about a vertical line, and poloidal launch angle $\theta = 146.075$deg polar angle. The rays (48 in this case) are launched each with equal power, but in a pattern which is spead out angularly to represent a Gaussian power pattern[11]. The half-width at half-power of the simulated beam, in this case, is 1.177 deg.

Figure 1 shows trajectories projected on to the poloidal plane, for the ITER test case. Figures 2 compare the major radius and vertical position of several rays in the bundle. Cold plasma rays are used. The figure, and a similar one for the vertical position of the rays, shows close overlap of the GENRAY and TORAY rays, indicating that the geometry, ray starting conditions, plasma profiles, and dispersion relation are in close agreement. Figure 3 shows power absorbed along the ray, from GENRAY, TORAY, and CQL3D. GENRAY and TORAY use versions of the fully-relativistic Mazzucato-Fidone-Granata dispersion relation solver to calculate damping at each point, given the $n_{\|}$-values along the ray from the cold-plasma ray tracing. The CQL3D damping calculation is independent, and is proportional to the integral over momentum space of energy times $\partial f/\partial t|_{QL}$, the the QL diffusion operator. The necessary polarizations and wavenumbers to calculate the QL operator are from Mazzucato[3], and are obtained at each point along the ray[5]. The resulting EC driven current from each of these codes is: 7.805 kA/MW (GENRAY), 7.824 kA/MW (TORAY), 8.83kA/MW (CQL3D). GENRAY and TORAY agree well, and CQL3D gives 12 percent greater current attributable to using a momentum-conserving electron-electron collision operator not in the Cohen model[4].

A DIII-D test case was chosen to be near the X2 cutoff density at 110 GHz, $n_{\rm cutoff} = 7.5 \cdot 10^{13}\rm cm^{-3}$. The rays penetrate to the shoulder of the density distribution at 5.9e13 density shown in Fig. 4. The traces of R and Z versus poloidal distance along the ray overlap for each of the rays, as for the above ITER case. Power deposition profiles versus poloidal distance overlap, as shown in Fig. 5. Current drive efficiency is 12.94 kA/MW (GENRAY), 13.08 kA/MW (TORAY), 16.9 kA/MW (CQL3D). Genray and toray agree to 1 percent, and the more accurate momentum-conserving CQL3D calculation is 30 percent greater.

The GENRAY-CQL3D suite provides a means to estimate the nonthermal enhancement of ECE resulting from auxiliary heating and transport. Here we report agreement between a DIII-D observation of ECE radiation temperature enhanced a factor of 4 over the Thomson scattering measured temperature with calculations. Shot 11522 plasma profiles are shown in Fig. 6. This is a particularly low density shot with central density $0.6 \cdot 10^{13}/\mathrm{cm}^3$, increasing to $1.0 \cdot 10^{13}/\mathrm{cm}^3$at $\rho = 0.4\mathrm{a}$, then decreasing. The 2.4 MW of EC power give intense central deposition of $3.0\,\mathrm{W}/\mathrm{cm}^3$. Figure 7 shows contours of the electron distribution in the high RF power region near the plasma center calculated for this shot using the CQL3D Fokker-Planck code. Spacing of the contours is equispaced for a Maxwellian, and thus there is a substantial flattening of the distribution at low velocities. Figure 8 shows the resulting spectrum of EC radiation calculated from the CQL3D electron distributions, with intensity converted to radiation temperature. A reasonable EC radiation reflection coefficient (0.9) has increased the central radiation temperature from 24 keV to 27 keV. There is excellent agreement with the experimentally measured value.

A similar ECE calculation result for T-10 was reported at the EC-9 Meeting, Hefei, China [12], giving a factor of 1.5 enhancement of the EC radiation temperature over the bulk temperature. Perpendicular ECH heating of T-10 flattened the distribution at low velocities, the electrons to which ECE is sensitive. Similar results have been reported for the FTU tokamak[13].

One caveat concerning the low velocity electron modeling, is that the Fokker-Planck code is being operated in a mode whereby radial transport effects are approximately modeled by the Fokker-Plank'd electrons colliding on the self-consistent electron distribution except that the isotropic part of the distribution is held fixed in velocity space as a Maxwellian at the temperature measured by the Thomson scattering. An improved model would have an actual radial transport term in the Fokker-Planck equation[14], although the appropriate velocity dependence of such a term is not well-studied. Future work will address these questions.

In conclusion: (1) GENRAY ray tracing and current drive calculations have been sucessfully benchmarked against the well-know TORAY code results; (2) The GENRAY-CQL3D suite of codes provides a model for DIII-D ECE measurement which is four times higher than the neighboring Thomson scattering temperature.

PostScript

Recent work[15] on GENRAY includes calculation of EC ray absorption accounting for a lowest order non-Hermitian part of the dielectric tensor, following work by Westrhof[16] and Tokman[17].

Acknowledgements

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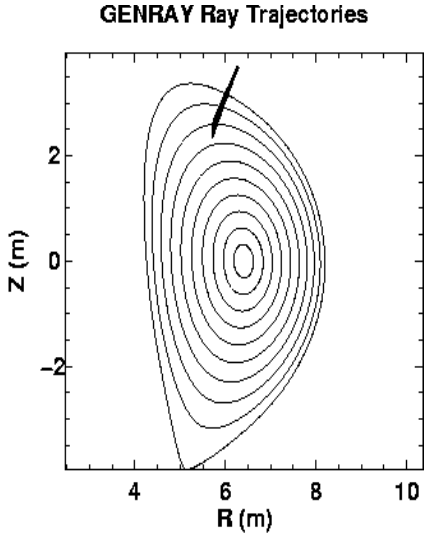

Figure 1: Cross-section of toroidal plasma showing ray cones and heating regions for ITER test case.

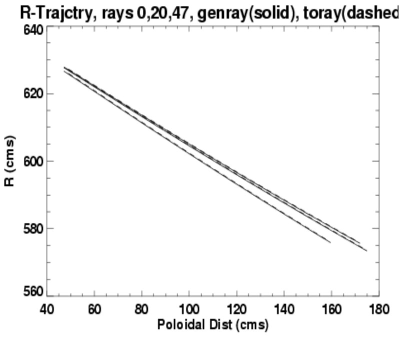

Figure 2: Major radius of three typical ray trajectories, which overlap.

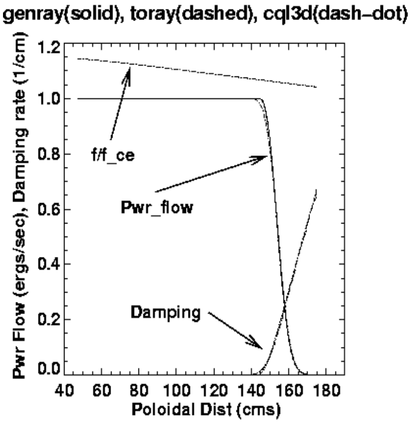

Figure 3: Flow of power along the central ray, showing close overlap of GENRAY, TORAY, and CQL3D deposition. Also shown is the spatial damping rate from genray and cql3d. The ratio (f/f_ce) gives proximity to the cyclotron layer.

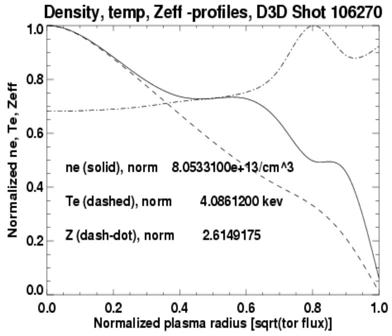

Figure 4: High density DIII-D ECH heated plasma. The solid line shows density profile with a shoulder at $5.9 \cdot 10^{13} \mathrm{cm}^{-3}$.

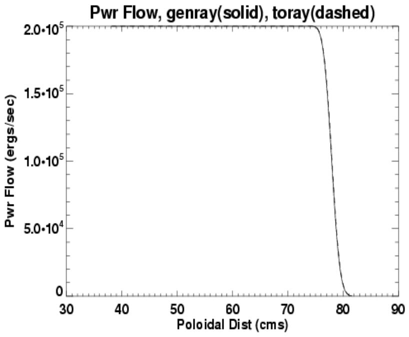

Figure 5: Power flow in the central ray from the GENRAY and TORAY codes. The lines from the two codes overlap, showing close agreement of the geometry and absorption.

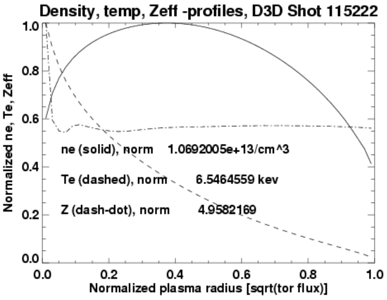

Figure 6: Low density DIII-D shot for which observed central ECE radiation temperature is approximately four times the Thomson temperature.

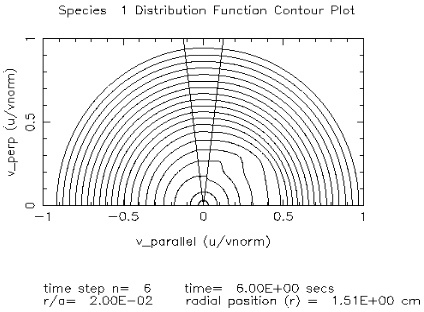

Figure 7: The 2D electron distribution function near the plasma center. The contour values are such as to be equi-spaced for a Maxwellian distribution.

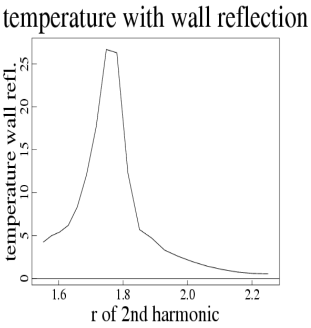

Figure 8: Computed ECE radiation temperature giving a central value of 27 keV, in agreement with experimental observations. The central Thomson temperature is 6.5 keV.