The TORAY Electron Cyclotron Heating and Current Drive Code

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The TORAY ray tracing code computes contributions to electron cyclotron heating (ECH) and RF current–drive (ECCD) sources. Plasma heating and non–inductive current generation by injection of electromagnetic waves in the electron cyclotron frequency range (ECH and ECCD) has been considered an important tool in fusion research. Electron cyclotron current drive (ECCD) is a leading candidate for current profile control in Advanced Tokamak (AT) operation. ECCD has successfully demonstrated that it can help sustain high beta negative central shear (NCS) discharges and suppress neoclassical tearing modes (NTM). TORAY is heavily relied upon by experimentalists at DIII–D and is used elsewhere in the fusion community. The code has a rich history and many authors. Documented here is the TORAY code originating at General Atomics in an attempt to provide the fusion community with a portable well–documented version through the National Transport Code Collaboration Modules Library.

I. INTRODUCTION

The TORAY ray tracing code for electron cyclotron heating (ECH) and current drive (ECCD) originates from the RAYS code developed by D. Batchelor, R. Goldfinger, et al [1,2]. The current version of TORAY described in this document is v1.6 in use at General Atomics.

II. I/O FILES

This section describes the various input and output files associated with TORAY along with there I/O unit numbers assigned internally.

A. Input Files

To run TORAY, the user must supply a 'echin' file and a file containing the MHD equilibrium information. The user may also choose to provide a 'toray.in' namelist file (see Table I) if the default values need to be changed. The 'echin' file (see Table II) contains profile information and various settings. Note that many of the default values are applicable only to the DIII–D tokamak (e.g. **smax** and care should be taken to examine all the input values before applying TORAY to other devices.

The equilibrium information is supplied from some origination of a G-EQDSK file (see the web page $lithos.gat.com/efit/g_eqdsk.html$). That information can be passed to TORAY in 3 ways:

1) Providing an 'mhddat' file which is a binary file created by the GAFIT code and is automatically produced in a ONETWO transport simulation. This is the default mode of operation. Here, **igafit=0**.

2) Providing an ascii file called 'psiin'. This is another processed file created in a ONETWO simulation where the MHD information originates from a G-EQDSK file. To run TORAY using a 'psiin' file instead of a 'mhddat' file, set **igafit=1** in the toray.in namelist file. Also, ipsi is set to zero in the gafit.in namelist file. The default is ipsi=0.

3) Provide a G-EQDSK file. Here, the processed mhddat or psiin files are not needed. The user may simply copy the desired G-EQDSK file to a file called 'eqdskin' and set **igafit=1** in toray.in and set ipsi=1 in 'gafit.in'. Here, psi(rho) is simply obtained from q(psi) and will not give the exact same results for the ECH/ECCD profiles obtained from running TORAY with the mhddat input files.

So, if the user wants to input the equilibrium data to TORAY in any other format than the 'mhddat' file, then the 'toray.in' namelist file must also by supplied with **igafit** set as specified above..

TABLE I. TORAY 'toray.in' Quantities.

Variable	Default	Definition
runid	'ECH and ECCD on DIII-D'	run
igafit	0	Switch to call GAFIT EFIT interface
inang	0	??
ar	0.10	obsolete (cr array now used)
br	0.05	obsolete
smax	150.0	maximum arclength of ray (cm)
ds	0.5	initial step size of arclength (cm)
dsmin	0.5	adjutable step size of arclength (cm) depending on power decreament
fdout	5.0	ray output every fdout step
powinc	1.0e13	used get the J/P profile along a ray for use by CQL3D code
relerr	5.0e-5	relative error tolerance in y-solution vector of ODE solver where abs(local error) $\leq$ abs(y)*relerr + abserr
abserr	5.0e-5	absolute error tolerance in ODE solver
ezeff	2.0	Z_{rmeff}
nharm	2	harmonic number
mn0	32	number of mesh pts in Gaussian integration of Green's function in J/P resonance calculation
bsratio	1	specifies antenna shape (1=circular, ¿1 elongated)
raypatt	'.gauss.'	ray pattern model ('.km.' = old Matsuda model)
gauszone	4	number of annuli for Gaussian ray pattern model
mray(1)	1	number of rays in 1st Gaussian zone
mray(2)	5	number of rays in 2nd Gaussian zone
mray(3)	12	number of rays in 3rd Gaussian zone
mray(4)	12	number of rays in 4th Gaussian zone
mray(5)	20	number of rays in 5th Gaussian zone
mray(6)	24	number of rays in 6th Gaussian zone
mray(7)	26	number of rays in 7th Gaussian zone
cr(1)	0.0	azimuthal phase of ray pattern for 1st zone (radians)
cr(2)	0.1	azimuthal phase of ray pattern for 2nd zone (radians)
cr(3)	0.050	azimuthal phase of ray pattern for 3rd zone (radians)
cr(4)	-0.050	azimuthal phase of ray pattern for 4th zone (radians)
cr(5)	0.050	azimuthal phase of ray pattern for 5th zone (radians)
cr(6)	-0.025	azimuthal phase of ray pattern for 6th zone (radians)
cr(7)	0.025	azimuthal phase of ray pattern for 7th zone (radians)
modelc	4	LinLiu module for ECCD calculation

TABLE II. TORAY 'echin' Quantities.

Variable	Definition
`time12`	profile time (s)
`idamp`	Damping model (see Table VII)
`j12`	number of profile points
`nray`	number of rays (for raypatt=.'km' only)
`nbfld`	equilibrium type (1=concentric circles, 3=EFIT)
`fmu0`	wave frequency (Hz)
`rfmod`	fraction of RF power launched as O–mode
`x00`	major radius of source (cm)
`z00`	height above midplane of source (cm)
`thet`	polar launch angle of central rays (degrees)
`phai`	azimuthal launch angle of central rays (degrees)
`bhalf`	plasma half-width (m)
`bsratio`	aspect rato of the beam, 1.0=circle (for raypatt=.'km' only)
`rmajs`	major radius of magnetic axis, R_o (cm)
`b0`	vacuum toroidal field, B_{To} (Gauss)
`rmins`	toroidal flux at last closed flux surface LCFS, $\rho(a)$ (cm)
`psinrmr(j12)`	normalized toroidal flux, $\rho/\rho(a)$
`zef(j12)`	effective charge, $Z_{\rm eff}$
`ene(j12)`	electron density (cm^{-3})
`ete(j12)`	electron temperature (keV)

Note: this version of TORAY is currently limited to square EFIT (e.g. 65x65) resolution. In principle, the variables nxmx, nzmx, and npsimax in the common block file, paradm.i, can be increased but running TORAY with higher resolution EFITs has not been tested.

B. Output Files

The default output file for the RF deposition profile is an ascii file called 'echout'. This is written each time TORAY is executed. Table III describes the data included in the echout file.

TABLE III. TORAY 'echout' Quantities.

Variable	Definition
`ledge`	number of radial bin boundaries
`xbouni(2:ledge+1)`	normalized poloidal flux of bin boundaries
`voltor/2.`	plasma volume (cm^3)
`2.0*dxi2(2:ledge)`	bin volumes normalized to plasma volume
`weecrh(2:ledge)/2.`	power density in each bin per unit incident power $(W/cm**3perW_{\rm incident})$
`tpowde(2,ledge)`	integrated power per unit incident watt $(W/(W_{\rm incident})$
`wiecrt(2:ledge)`	driven current per normalized bin volume per incident watt $(A/(V_{\rm bin}^{\rm norm} * W_{\rm incident}))$
`tidept(2:ledge)`	integrated current per incident watt $(A/(W_{\rm incident})$

A NetCDF file may also been written that includes ray data and the RF deposition and plasma profiles. To write out the file 'toray.nc', set netcdfdat=.true. in the toray.in input file. Tables IV–V list the various quantities written. It is assumed that an XYZ cartesian coordinate system underlies the calculations, with the Z-axis being the main axis of toroidal symmetry. Positive magnetic field is right handed around Z. The sbtot variable has sign of the vacuum toroidal field. The parallel refractive index, **wnpar**, is positive in the direction of the magnetic field.

TABLE IV. TORAY NetCDF Ray Data Output.

Variable	Definition
`nray`	number of rays
`nharm`	first harmonic number
`freqcy`	wave frequency (Hz)
`x0(nrays)`	launch position for each ray (cm)
`y0(nrays)`	launch position for each ray (cm)
`z0(nrays)`	launch position for each ray (cm)
`angrid1(nrays)`	launch angle, $\vec{k}$ wrt Z-direction (deg)
`angrid2(nrays)`	launch angle, $\vec{k}$ wrt R-direction (deg)
`angrid2(nrays)`	launch angle, $\vec{k}$ wrt R-direction (deg)
`nrayelt(nrays)`	number of ray elements for each ray
`spsi(nrays, neltmax)`	radial-like variable (sqrt(norm poloidal flux))
`ws(nrays, neltmax)`	poloidal distance along a ray (cm)
`wr(nrays, neltmax)`	major radius (cm)
`wz(nrays, neltmax)`	vertical height (cm)
`wphi(nrays, neltmax)`	toroidal angle (radians)
`wnpar(nrays, neltmax)`	parallel refractive index
`wnper(nrays, neltmax)`	perpendicular refractive index
`delpwr(nrays, neltmax)`	power in ray channel (erg/s)
`curds(nrays, neltmax)`	driven current per unit incident Watt per unit ray arc (A/W/cm)
`arcs(nrays, neltmax)`	ray arc length (cm)
`arcds(nrays, neltmax)`	step size along ray arc (cm)
`sdpwri(nrays, neltmax)`	power to ions (if included) (ergs/s)
`cwexde(two, nrays, neltmax)`	complex E_x/E polarization
`cweyde(two, nrays, neltmax)`	complex E_y/E polarization
`cwezde(two, nrays, neltmax)`	complex E_z/E polarization
`fluxn(nrays, neltmax)`	Stix norm, $\lvert E \rvert = 1$ $(ergs/s/cm^2)$
`sedenfac(nrays, neltmax)`	energy density factor relative to free space
`svgrpdc(nrays, neltmax)`	group velocity relative to speed of light
`sbtot(nrays, neltmax)`	magnetic field strength (gauss)
`saspcti(nrays, neltmax)`	inverse aspect ratio $(B_{\max} - B_{\min})/(B_{\max} + B_{\min})$
`sene(nrays, neltmax)`	density along ray $(particles/cm^3)$
`ste(nrays, neltmax)`	temperature along ray (keV)
`salphac(nrays, neltmax)`	collisional damping wavenumber (1/cm)
`salphal(nrays, neltmax)`	linear damping wavenumber (1/cm)

TABLE V. TORAY NetCDF RF Deposition and Plasma Profile Output.

Variable	Definition
`ledge`	Number of radial bin boundaries
`psimag`	Psi at magnetic axis (Volt-s)
`psilim`	Psi at limiting flux surface (Volt-s)
`Raxis`	Magnetic axis R-coord (cm)
`Zaxis`	Magnetic axis Z-coord (cm)
`BTaxis`	Magnetic field at mag axis (tesla)
`volume`	Plasma volume (cm^3)
`xbouni(ledge)`	normalized poloidal flux of bin boundaries
$\mathrm{bin}_{\mathrm{v}}\mathrm{ol}$`(ledgem1)`	normalized bin volumes
`xmrho(ledgem1)`	normalized rho (sqrt(tor flux) of bin center
`xmene(ledgem1)`	density ($1/cm^3$)
`xmete(ledgem1)`	electron temperature (keV)
`xmzeff(ledgem1)`	Z-effective (charge units)
`weecrh(ledgem1)`	power density in each bin per unit incident power ($W/cm**3perW_{\mathrm{incident}}$)
`tpowde(ledgem1)`	integrated power per unit incident watt ($W/(W_{\mathrm{incident}})$
`wiecrt(ledgem1)`	driven current per normalized bin volume per incident watt ($A/(V_{\mathrm{bin}}^{\mathrm{norm}} * W_{\mathrm{incident}})$)
`tidept(ledgem1)`	integrated current per incident watt ($A/(W_{\mathrm{incident}})$

Note that

$$\sum_{k=1}^{nrayelt} curds(k) \times arcds(k) = tidept(ledge) \tag{1}$$

C. I/O Unit Numbers

Table VI lists the assigned unit numbers used for various input and output files in TORAY.

TABLE VI. TORAY I/O Unit Numbers.

Unit Number	Subroutine	Filename
2	echin	echin
3	echout	echout
25	echin	toray.in
2	mgaini	mhddat
1	block data setout, numout	block data setout, numout
6	block data setout, iotty	block data setout, iotty
23	block data setout, io1	ecrh1001
24	block data setout, io2	ecrh2001
25	block data setout, io3	None
26	block data setout, io4	None
27	block data setout, io5	None
28	block data setout, io6	None
29	block data setout, io7	None
30	block data setout, io8	None
31	block data setout, io9	rayec001
32	block data setout, io0	None
96	$\mathrm{chk}_{\mathrm{t}}$rclev	$\mathrm{chk}_{\mathrm{t}}$rclev.out

III. RAY LAUNCHING

To simulate the ray pattern of an actual antenna, a set of rays with a given shape (e.g. Gaussian) is used. Recently, a new ray pattern generator was implemented in TORAY as to make the rays consistent with a Gaussian distribution (raypatt='.gauss.'). The original Matsuda model was not (raypatt='.km.'). The new ray pattern is more flexible, since the old pattern generator was limited to 1, 6, 18, or 30 rays. In some cases, particularly for transport code runs with higher radial resolution than 51 grid points, a larger number of rays is desirable.

The ray pattern subroutine RAYPAT mimics the propagation of a Gaussian beam in the far field region by propagating an array of straight rays emanating from a single point with divergence appropriate to the Gaussian beam. It is assumed that all rays have the same power, and the density of rays is consistent with the power density of an expanding beam with Gaussian fall–off with radius. This approach is inaccurate in the near field region, where the beam may be focusing, but for the DIII–D installation the focus is outside the plasma so the far field approximation is not bad. Note that the single point source lies at the convergence of the far field representation of the rays, not at the focus of the beam or at the waveguide mouth.

The fractional power outside a radius r for a Gaussian distribution is given by

$$f(r) = \exp\left[-2(r/w(z))^2\right] \tag{2}$$

where the waist radius $w(z)$ as a function of distance z is a linear proportion in the far field,

$$w(z) = Dz \tag{3}$$

where the divergence D is the angular dispersion (half angle for e^{-2} in power), or 2.89 degrees for the DIII–D 110 GHz launchers with inside diameter of 2.375 in. (Note: $hlwec$ is the half angle at half power, related to D by $hlwec = D(ln(2)/2)1/2$. For the far field region, D is given by $\lambda/(\pi w_1) = 3.03$ degrees, where λ is the free space wavelength and w_1 is 16.4 mm for the DIII–D geometry, per John Doane [GA–C21242]. For the DIII–D geometry, we use a slightly smaller value of D, 2.89 degrees corresponding to $hlwec = 1.7$ degrees, to better simulate the wave optics in the intermediate distance regime of interest.)

Then for an angle a, the power lying outside that angle is

$$f(a) = \exp\left[-2(a/D)^2\right] \tag{4}$$

The Gaussian distribution can be broken into annular zones, with the boundaries chosen at radii for which the integrated power of each annular zone is proportional to the number of rays in that zone divided by the total number of rays. One central ray is always placed at the center of the distribution, occupying a circular zone. The rays of an annular zone are uniformly spread at the power-weighted center radius for that zone, using an arbitrary number for the orientation of the ray pattern around the central ray. The goal is to find the smallest number of rays for which the power deposition profile is independent of the number of rays, the number of zones, and the orientation of the rays around the cenral ray.

The Gaussian representation for the ray pattern is now the default (raypatt='.gauss.') in the public version of TORAY–GA, identified as version 1.3 or higher in the log file when the code is run. If no toray.in file is found, TORAY–GA will use defaults. Under this condition the value of $nray$ in the ONETWO inone file may be equal to 1 to get 1 ray, and any other value of nray will give 30 rays with the Gaussian pattern. (Previously, $nray$ could be set to 1, 6, 18, or 30, corresponding to 1, 2, 3, or 4 annular non–Gaussian zones.) Studies have shown that the 6 or 18 ray options are too unreliable to be generally useful so these options have been discontinued, although they can be restored if a *toray.in* file is used.

The relevant quantities for the ray pattern are given in the *toray.in* file in the EDATA namelist. The variables and their defaults are given in Table I. Note that if raypatt = .km. then $nray$ determines the number of rays in the pattern using the old ray pattern generator which is limited to a maximum of 30 rays.

IV. RAY TRACING

The ray tracing algorithm uses a modified Adams method to follow the trajectory of rays in the electron cyclotron frequency range $\omega \approx \Omega_e$ as they propagate through the plasma. To compute the absorption along the ray path, several damping models are available. One such commonly used model utilizes Hsu–Matsuda theory, an extension of the Mazzucato formulation, for fundamental cyclotron damping and Batchelor's theory for second harmonic damping. Here, both X–mode and O–mode propagation are included.

The frequency and wave number are related by the dispersion relation

$$D(\mathbf{k}, \omega, \mathbf{x}) = 0 \tag{5}$$

assuming that the background plasma is in steady state in time. The wave trajectory is found by solving the ray equations

$$\frac{d\vec{r}}{ds} = -\frac{\partial D/\partial \vec{k}}{|\partial D/\partial \vec{k}|} \tag{6}$$

$$\frac{d\vec{k}}{ds} = \frac{\partial D/\partial \vec{r}}{|\partial D/\partial \vec{k}|} \tag{7}$$

where s is the arclength along the ray path, $\vec{k}$ is the wavenumber, $\vec{r}$ is the spatial position, and D is the real part determined from the dispersion relation given by a cold or warm plasma approximation. Here, Eqn. 6 can be integrated to trace out the position of the ray along the arclength s and Eqn. 7 integrated to compute the wave number along the ray. The wave front moves with the group velocity along these rays

$$\mathbf{v_g} = \frac{\partial \omega}{\partial \mathbf{k}} = \frac{\partial D/\partial \mathbf{k}}{\partial D/\partial \omega}. \tag{8}$$

The fraction of RF power absorbed by the plasma is given by the integral along the ray path,

$$p(s) = 1 - exp\left(-2\int_0^s Im(\vec{k})\cdot\frac{d\vec{r}}{ds}\right) \tag{9}$$

where the imaginary part of $\vec{k}$ is obtained from the solution of the dispersion relation.

In the TORAY-GA code, the power decrement over some arc length element ds is $Im(\vec{k})$ evaluated at the end of the step multipled by ds. The power in a ray as it propagates in the plasma is calculated using the expression,

$$dP = 2k_i ds cos(\phi) P \tag{10}$$

where dP is the decrement in the power P of a ray in taking a step of size ds along its trajectory, k_i is the imaginary part of the wavevector, and ϕ is the angle between the wavevector and the magnetic field. The crude integration algorithm in TORAY-GA v1.3 and earlier, used the value of k_i determined at the end of a step to use in this expression. This lead to a systematic overestimation of the power decrement and an overestimation of the current drive. An improved trapezoidal integration scheme has been implemented whereby the average k_i is used rather than the value at the end of the step. This is incorporated in v1.4 and is decribed in the DIII–D Physics Memo document $d3dphys_0 201.pdf$.

However, even with this improvement for k_i, the driven current was still found to be overestimated. Assuming that the asymptot is the correct value, the driven current can be reduced more closely to the asymptot by reducing a step size ds. However, too small step size ds can produce too many ray elements along ray trajectory. Therefore, it requires much longer time consumption in running TORAY-GA. In fact, in the very weak absorption region, it is not necessary to use very small step size ds. The further improvement has been made introducing the adjustable step size ds to TORAY-GA(V.1.6), depending on the power decrement along ray trajectory. In the results, the compatible driven current is obtained in both the accuracy and the timings, which is described in detail in DIII-D IMB (Integrated Modeling Branch) Memo 4. Currently, the constant ds scheme is set to be default: ds=0.5cm and dsmin=0.5cm. In order to simulate TORAY-GA(V.1.6) using the adjustable ds scheme, users can change these values in input file "toray.in".

V. ABSORPTION MODELS

The absorption of electromagnetic wave energy along a ray path is computed in TORAY using various damping models that solve the disperion relation in the cold or warm plasma approximation in the vicinity of a desired harmonic [5,4].

TABLE VII. Wave Absorption Models in TORAY.

Model	idamp	validity
None	0	–
Matsuda–Hu	1	near 1st harmonic, weakly relativistic
Matsuda–Hu	2	near 2nd harmonic, weakly relativistic
Matsuda–Hu	3	near 3rd harmonic, weakly relativistic
Matsuda–Hu	7	between 2nd, 3rd harmonics
Mazzucato [4]	8	near 1st harmonic, relativistic

VI. ECCD MODELS

An ECCD module developed by Y.R. LinLiu [6] is incorporated into a new f90 version(v.16) of Toray-Ga. Therefore, two models are available for ECCD calculations.

modelc=3 : Cohen module
modelc=4 : LinLiu module

The default is given as "modelc=4" for LinLiu's ECCD module.

VII. CURRENT DRIVE

The electron cyclotron current drive (ECCD) is computed using a formulation by Cohen [3] and includes relativistic, electron–ion collisions, and trapped particle effects. The current drive efficiency, J/P_d, is the ratio of the driven current to the deposited power and is computed in subroutine **curba**. Here, J/P_d normalized to $e/(m\nu v_{\rm th})$, where $\nu = 4\pi n_e^4 (log\lambda)/m^2 v_{\rm th}^3$, and $v_{\rm th} = \sqrt{2T/m}$.

Output to the *echout* file includes *wiecrt*, which is the driven current (A) per normalized bin volume per incident power (W), and *tidept* which is the integrated current (A) per incident power (W).

In a recent DIIID Physics Memo, Y. R. Lin-Liu showed that proper flux surface averaging of the output J/P from the subroutine which calculates the ECCD requires division by $< B >$ where TORAY-GA had divided by $B_{\rm min}$. This was approximately corrected by dividing J/P by $1+\epsilon$, where ϵ is the inverse magnetic aspect ratio $(B_{\rm max} B_{\rm min})/(B_{\rm max} + B_{\rm min})$, since $< B >$ is not presently available to TORAY-GA. This effect reduces the calculated current.

Another revision to the code has been made with regards to how the cosine of the poloidal angle is computed for ECCD. For circular flux surfaces the low beta approximation, $R_{\rm loc} = R_0 + acos\theta_p = R_0(1+\epsilon cos\theta_p)$. Taking $B \propto 1/R$ gives

$$cos\theta_p = \frac{B_{\rm max} + B_{\rm min} - 2B_{\rm max} B_{\rm min} B_{\rm loc}}{B_{\rm min} - B_{\rm max}} \tag{11}$$

However, subroutine *currn* used

$$cos\theta_p = \frac{B_{\rm max} + B_{\rm min} - 2B_{\rm loc}}{B_{\rm min} - B_{\rm max}} \tag{12}$$

which is incorrect in the large aspect ratio limit. It has been found that correcting this introduces a change in the poloidal angle of up to 10 degrees and results in an increase in the computed ECCD.

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