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Integrated Torus Plasma Modeling by TASK code

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- Modules of TASK codes
- Recent results of TASK code
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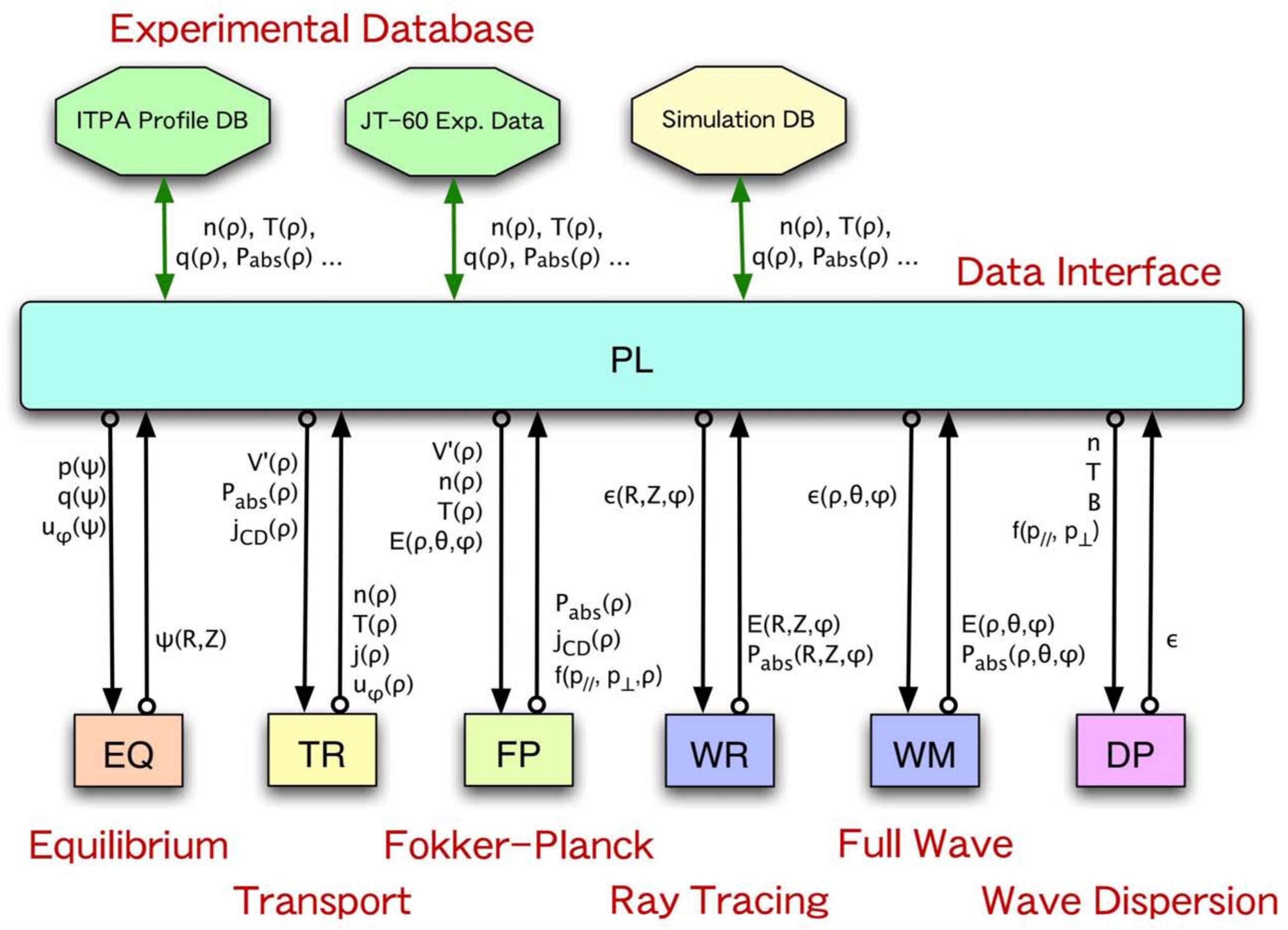
TASK Code

- Transport Analysing System for TokamaK
- Features
  - Core of Integrated Modeling Code in BPSI
  - Modular Structure
  - Various Heating and Current Drive Scheme
  - High Portability
  - Development using CVS
  - Open Source
  - Parallel Processing using MPI Library
  - Extension to Toroidal Helical Plasmas

Modular Structure of TASK



Data Interface Layer PL

- **Role of Interface Layer**
  - To keep the present status of plasma
  - To store the history of plasma
  - Interface to file system
  - Interface to experimental profile database
  - Interface to simulation profile database

- **Data to be stored**
  - **Standard dataset**
    - Shot data, Device data
    - Equilibrium data, Metric data
    - Fluid plasma data, Kinetic plasma data
    - Dielectric tensor data, Full wave data, Ray/Beam tracing data
  - **User-defined data**

Standard Dataset (interim)

Shot data

Machine ID, Shot ID, Model ID

Device data: (Level 1)

RR	R	m	Geometrical major radius
RA	a	m	Average minor radius $(R_{\max} - R_{\min})/2$
RB	b	m	Wall radius
BB	B	T	Vacuum toroidal magnetic field at $(RR, 0)$
RKAP	κ		Elongation at boundary
RDLT	δ		Triangularity at boundary
RIP	$I_{\rm p}$	A	Typical plasma current

Equilibrium data: (Level 1)

PSIP	$\psi_{\rm p}(R,Z)$	Tm^2	2D poloidal magnetic flux
PSIR	$\psi(\rho)$	Tm^2	Poloidal magnetic flux
PPSI	$p(\rho)$	MPa	Plasma pressure
TPSI	$T(\rho)$	Tm	$B_\phi R$
QPSI	$1/q(\rho)$		Safety factor
JPAV	$j_{\parallel}^{\rm ave}(\rho)$		Averaged parallel current density

Metric data

1D: $V'(\rho)$, $\langle \nabla\rho \rangle(\rho)$, $\cdots$

2D: g_{ij}, $\cdots$

Fluid plasma data

NSMAX	s		Number of particle species
PA	A_s		Atomic mass
PZ0	Z_{0s}		Charge number
PZ	Z_s		Charge state number
PN	$n_s(\rho)$	m^3	Number density
PT	$T_s(\rho)$	eV	Temperature
PU	$u_{s\phi}(\rho)$	m/s	Toroidal rotation velocity

Kinetic plasma data

FP	$f(p, \theta_p, \rho)$		momentum distribution at $\theta = 0$

Dielectric tensor data

CEPS	$\overleftrightarrow{\epsilon}(\rho, \chi, \xi)$		Local dielectric tensor

Full wave field data

CE	$\boldsymbol{E}(\rho, \chi, \xi)$	V/m	Complex wave electric field
CB	$\boldsymbol{B}(\rho, \chi, \xi)$	$\mathrm{Wb/m}^2$	Complex wave magnetic field

Ray/Beam tracing field data

RRAY	$R(\ell)$	m	R of ray at length ℓ
ZRAY	$Z(\ell)$	m	Z of ray at length ℓ
PRAY	$\phi(\ell)$	rad	ϕ of ray at length ℓ
CERAY	$\boldsymbol{E}(\ell)$	V/m	Wave electric field at length ℓ
PWRAY	$\boldsymbol{P}(\ell)$	W	Wave power at length ℓ
DRAY	$\boldsymbol{d}(\ell)$	m	Beam radius at length ℓ
VRAY	$\boldsymbol{v}(\ell)$	1/m	Beam curvature at length ℓ

Geometrical Optics: TASK/WR

- **Ray Tracing**: 6 equations
  - Ray position $\boldsymbol{r}_0$, wave number $\boldsymbol{k}^0$
- **Beam Tracing**: 18 equations
  - **Beam shape** : Weber function (Hermite polynomial: H_n)

$$\boldsymbol{E}(\boldsymbol{r}) = \mathrm{Re}\left[\sum_{mn} C_{mn}(\delta^2 \boldsymbol{r})\boldsymbol{e}_{mn}(\delta^2 \boldsymbol{r}) H_m(\delta\xi_1) H_n(\delta\xi_2)\, \mathrm{e}^{\,\mathrm{i}\, s(\boldsymbol{r})-\phi(\boldsymbol{r})}\right]$$

— Amplitude : C_{mn}, Polarization : $\boldsymbol{e}_{mn}$, Phase : $s(\boldsymbol{r}) + \mathrm{i}\,\phi(\boldsymbol{r})$

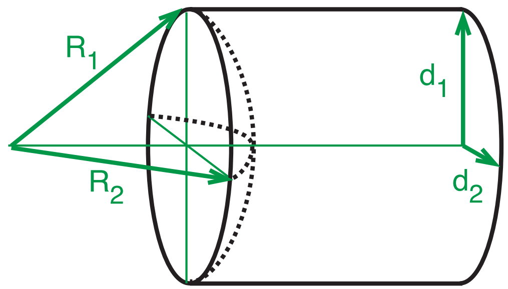
$$s(\boldsymbol{r}) = s_0(\tau) + k^0_\alpha(\tau)[r^\alpha - r^\alpha_0(\tau)] + \frac{1}{2} s_{\alpha\beta}[r^\alpha - r^\alpha_0(\tau)][r^\beta - r^\beta_0(\tau)]$$

$$\phi(\tau) = \frac{1}{2}\phi_{\alpha\beta}[r^\alpha - r^\alpha_0(\tau)][r^\beta - r^\beta_0(\tau)]$$

— **Curvature radius** of equi-phase surface:

$$R_\alpha = 1/\lambda s_{\alpha\alpha}$$

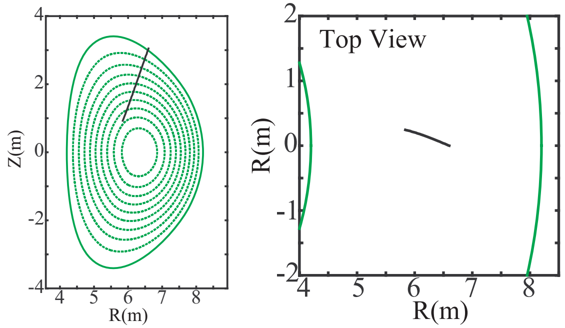
— **Beam radius**: $d_\alpha = \sqrt{2/\phi_{\alpha\alpha}}$



  - Gaussian beam : case with $m = 0,\ n = 0$

Analysis of ECCD by TASK Code

Poloidal angle	70°
Toroidal angle	20°
Initial beam radius	0.05 m
Initial beam curvature	2 m

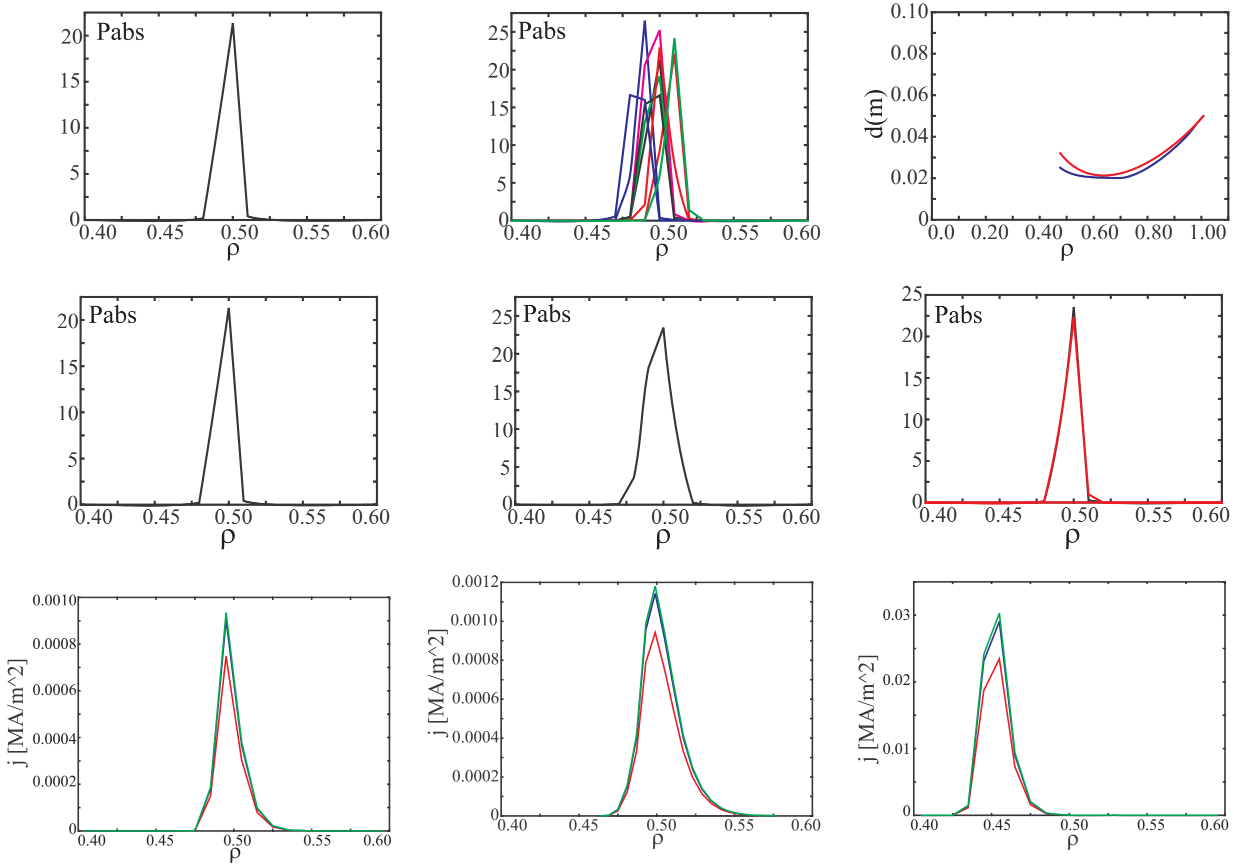


One Ray | **Multi Rays** | **Beam Tracing**

Ray/Beam Profile

P_{abs} Profile

j_{CD} Profile



Full wave analysis: TASK/WM

- **magnetic surface coordinate**: (ψ, θ, φ)
- Boundary-value problem of **Maxwell's equation**

$$\nabla \times \nabla \times \boldsymbol{E} = \frac{\omega^2}{c^2} \overleftrightarrow{\epsilon} \cdot \boldsymbol{E} + \mathrm{i}\,\omega\mu_0 \boldsymbol{j}_{\mathrm{ext}}$$

- Kinetic **dielectric tensor**: $\overleftrightarrow{\epsilon}$
  - **Wave-particle resonance**: $Z[(\omega - n\omega_{\mathrm{c}})/k_{\|}v_{\mathrm{th}}]$
  - **Fast ion: Drift-kinetic**

$$\left[\frac{\partial}{\partial t} + v_{\|}\nabla_{\|} + (\boldsymbol{v}_{\mathrm{d}} + \boldsymbol{v}_{\mathrm{E}}) \cdot \nabla + \frac{e_\alpha}{m_\alpha}(v_{\|}E_{\|} + \boldsymbol{v}_{\mathrm{d}} \cdot \boldsymbol{E})\frac{\partial}{\partial \varepsilon}\right] f_\alpha = 0$$

- Poloidal and toroidal **mode expansion**
  - **Accurate estimation of $k_{\|}$**
- Eigenmode analysis: **Complex eigen frequency** which maximize wave amplitude for fixed excitation proportional to electron density

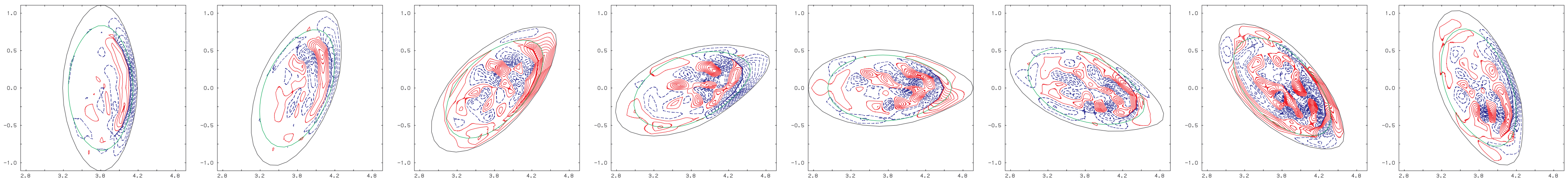
ICRF Waves in Toroidal Helical Plasmas (Cold Plasma Model)

LHD ($B_0 = 3\,\mathrm{T}$, $R_0 = 3.8\,\mathrm{m}$)

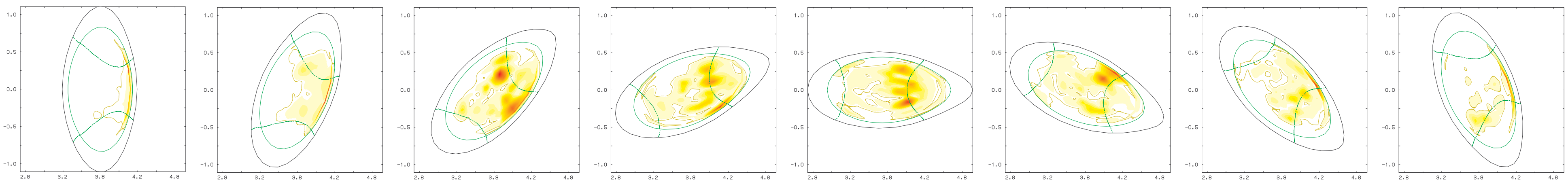
$f = 42\,\mathrm{MHz}$, $n_{\phi 0} = 20$, $n_{e0} = 3 \times 10^{19}\,\mathrm{m}^{-3}$, $n_{\mathrm{H}}/(n_{\mathrm{He}} + n_{\mathrm{H}}) = 0.235$,

$N_{\mathrm{rmax}} = 100$, $N_{\theta\mathrm{max}} = 16$ ($m = -7 \ldots 7$), $N_{\phi\mathrm{max}} = 4$ ($n = 10, 20, 30$)

Wave electric field (imaginary part of poloidal component)



Power deposition profile (minority ion)



Fokker-Planck Analysis : TASK/FP

- **Fokker-Planck equation**

  for **velocity distribution function** $f(p_{\|}, p_{\perp}, \psi, t)$

$$\frac{\partial f}{\partial t} = E(f) + C(f) + Q(f) + L(f)$$

  - $E(f)$: Acceleration term due to DC electric field
  - $C(f)$: Coulomb collision term
  - $Q(f)$: Quasi-linear term due to wave-particle resonance
  - $L(f)$: Spatial diffusion term

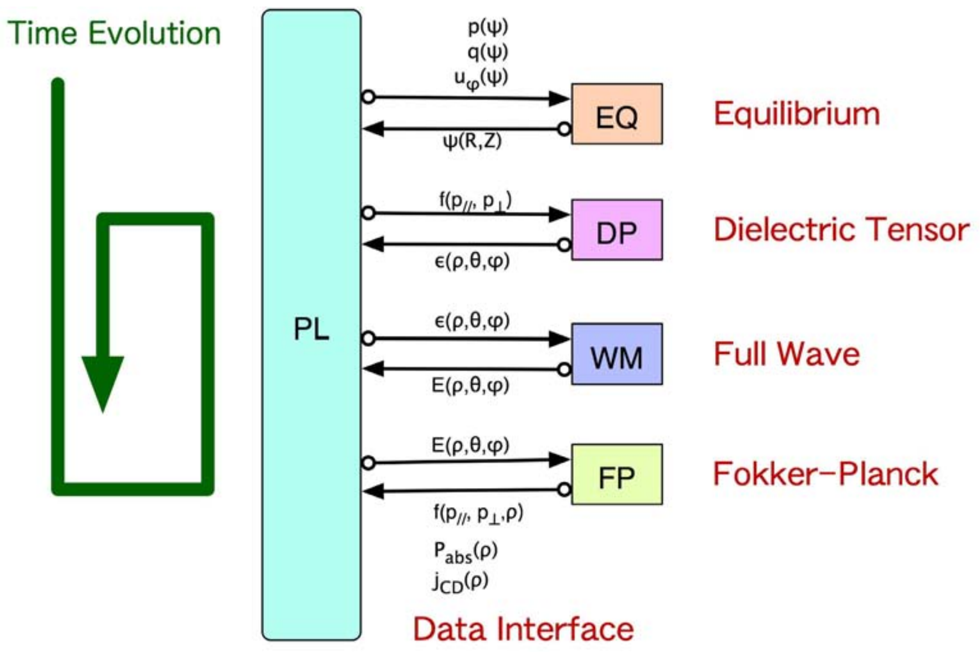
- **Bounce-averaged**: Trapped particle effect, zero banana width
- **Relativistic**: momentum $\boldsymbol{p}$, weakly relativistic collision term
- **Nonlinear collision**: momentum or energy conservation
- **Three-dimensional**: spatial diffusion (neoclassical, turbulent)

Wave Dispersion Analysis : TASK/DP

- **Various Models of Dielectric Tensor $\overleftrightarrow{\epsilon}(\omega, \boldsymbol{k}; \boldsymbol{r})$:**
  - Resistive MHD model
  - Collisional cold plasma model
  - Collisional warm plasma model
  - Kinetic plasma model (Maxwellian, non-relativistic)
  - Kinetic plasma model (Arbitrary $f(v)$, relativistic)
  - Gyro-kinetic plasma model (Maxwellian)
  - Gyro-kinetic plasma model (Arbitrary $f(v)$, non-relativistic)
- **Arbitrary $f(v)$:**
  - Relativistic Maxwellian
  - Output of TASK/FP

Self-Consistent Wave Analysis with Modified $f(v)$

- **Modification of velocity distribution from Maxwellian**
  - Absorption of ICRF waves in the presence of energetic ions
  - Current drive efficiency of LHCD
  - NTM controllability of ECCD (absorption width)
- **Self-consistent wave analysis including modification of $f(v)$**

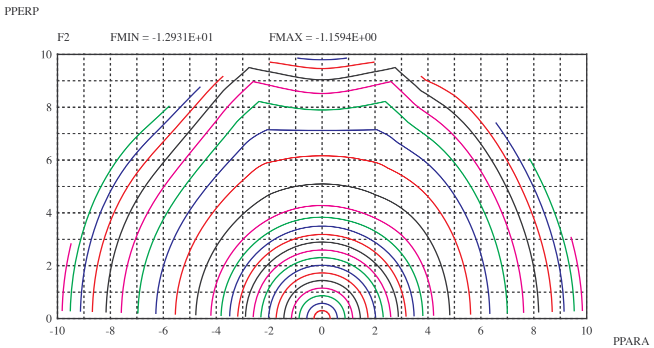


Development of Self-Consistent Wave Analysis

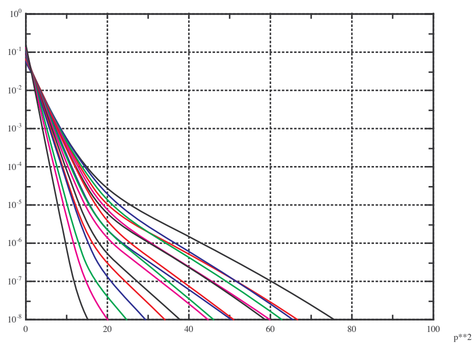
- **Code Development in TASK**
  - Ray tracing analysis with arbitrary $f(v)$: **Already done**
  - Full wave analysis with arbitrary $f(v)$: **Completed**
  - Fokker-Plank analysis of ray tracing results: **Already done**
  - Fokker-Plank analysis of full wave results: **Almost competed**
  - Self-consistent iterative analysis: **Preliminary**

- **Tail formation by ICRF minority heating**

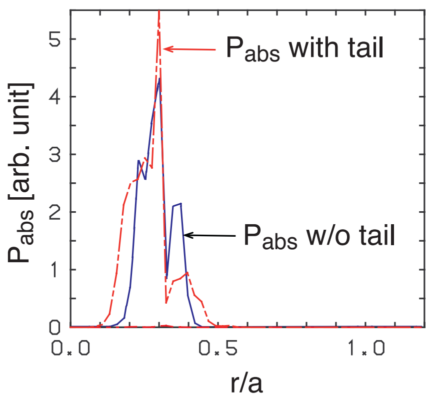
Momentum Distribution



Tail Formation



Power deposition



Integrated Analysis of AE in ITER Plasma

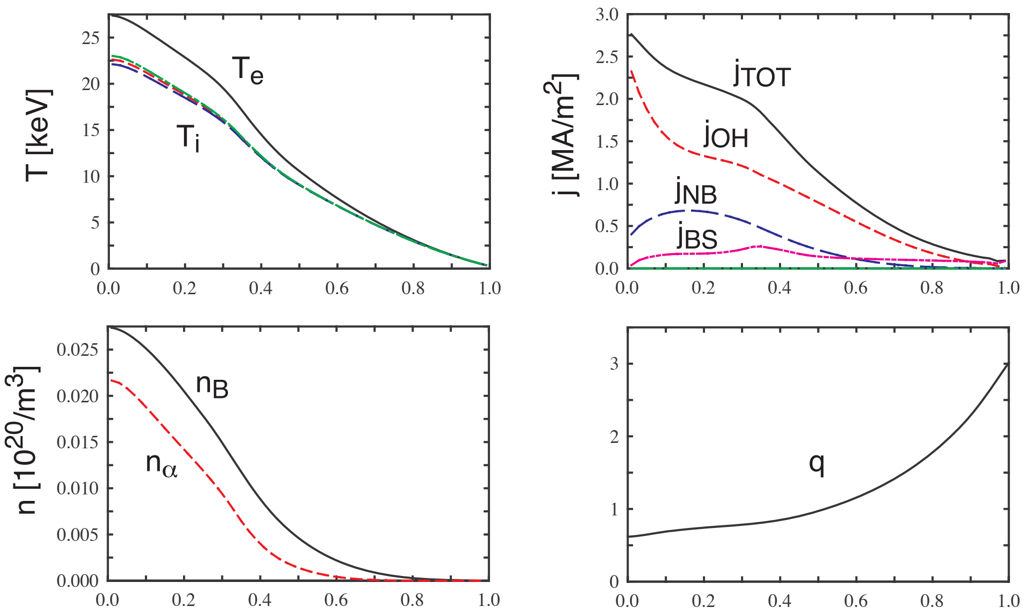
- **Combined Analysis**
  - **Equilibrium**: TASK/EQ
  - **Transport**: TASK/TR
    - — Turbulent transport model: CDBM
    - — Neoclassical transport model: NCLASS (**Houlberg**)
    - — Heating and current profile: given profile
  - **Full wave analysis**: TASK/WM
- **Stability analysis**
  - Standard H-mode operation: $I_\mathrm{p} = 15\,\mathrm{MA}$, $Q \sim 10$
  - Hybrid operation: $I_\mathrm{p} = 12\,\mathrm{MA}$, flat q profile above 1
  - Steady-state operation: $I_\mathrm{p} = 9\,\mathrm{MA}$, reversed shear

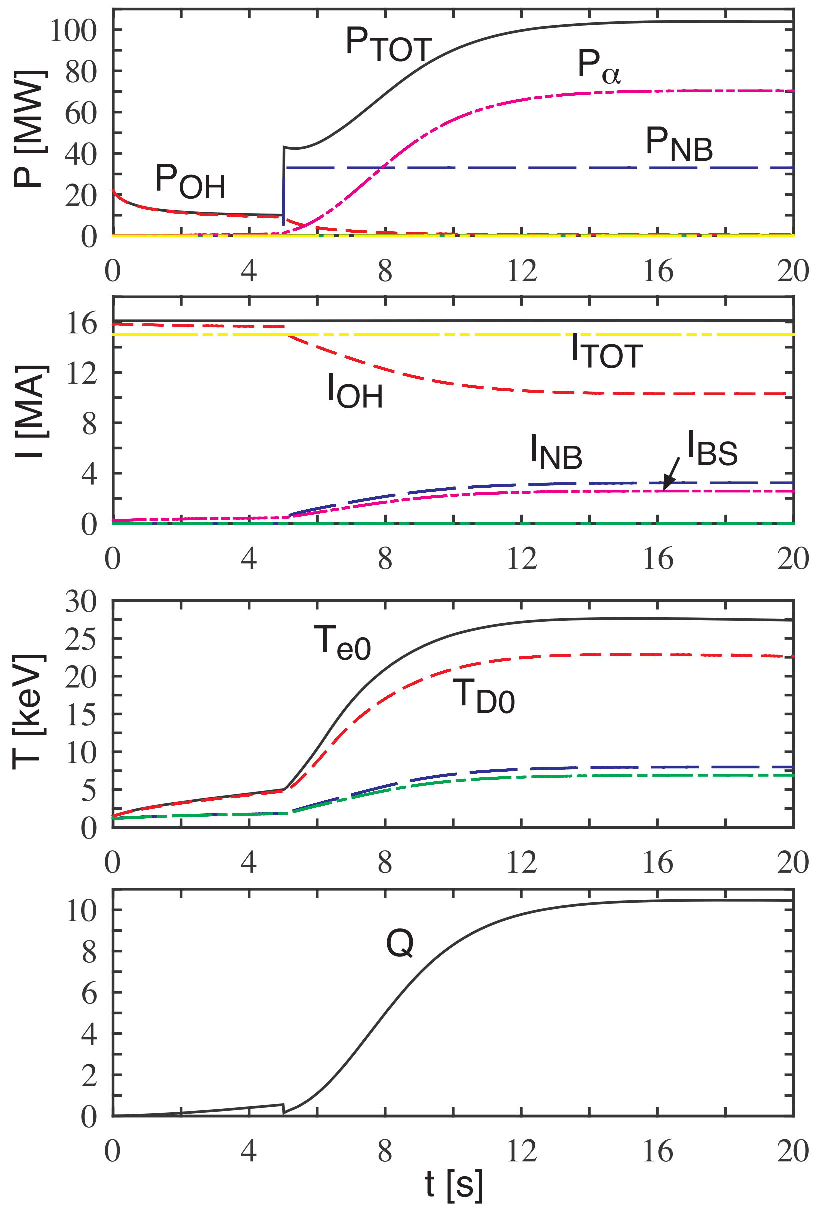
Diffusive Transport Analysis: TASK/TR

- **Transport Equation Based on Gradient-Flux Relation**
  - **Multi thermal species**: e.g. Electron, D, T, He
    — Density, thermal energy, (toroidal rotation)
  - **Two beam components**: Beam ion, Energetic α
    — Density, toroidal rotation
  - **Neutral**: Two component (cold and hot), Diffusion equation
  - **Impurity**: Thermal species or fixed profile
- **Transport Model**
  - **Neoclassical**: Wilson, Hinton & Hazeltine, Sauter, NCLASS
  - **Turbulent**: CDBM (current diffusive ballooning mode), GLF23 (V1.61), IFS/PPPL, Weiland
- **Interface to Experimental Data**
  - UFILE (ITPA profile DB)

Standard H-mode Operation

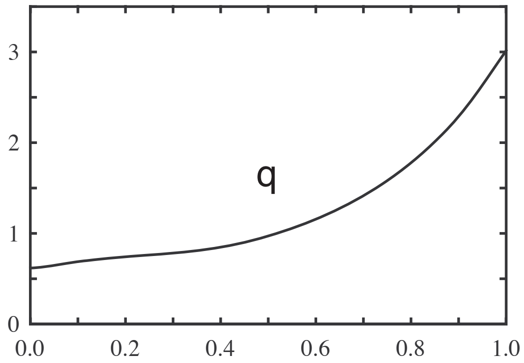
- $I_p = 15\,\mathrm{MA}$
- $P_{NB} = 33\,\mathrm{MW}$
- $\beta_N = 1.3$



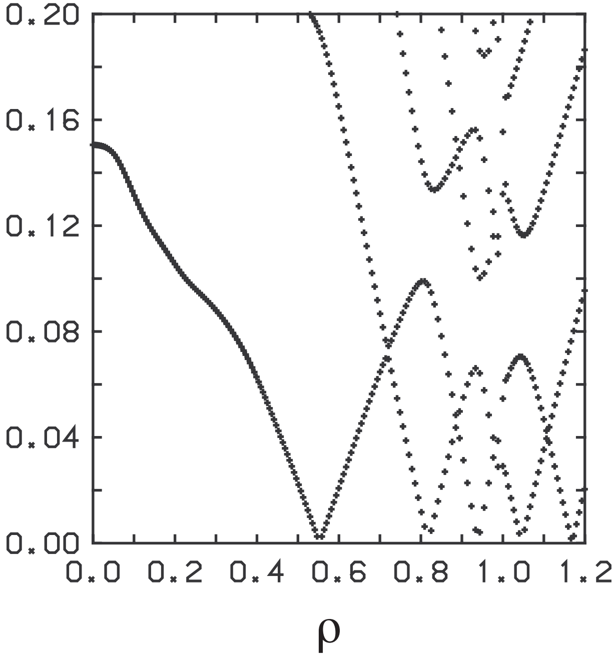


AE in Standard H-mode Operation

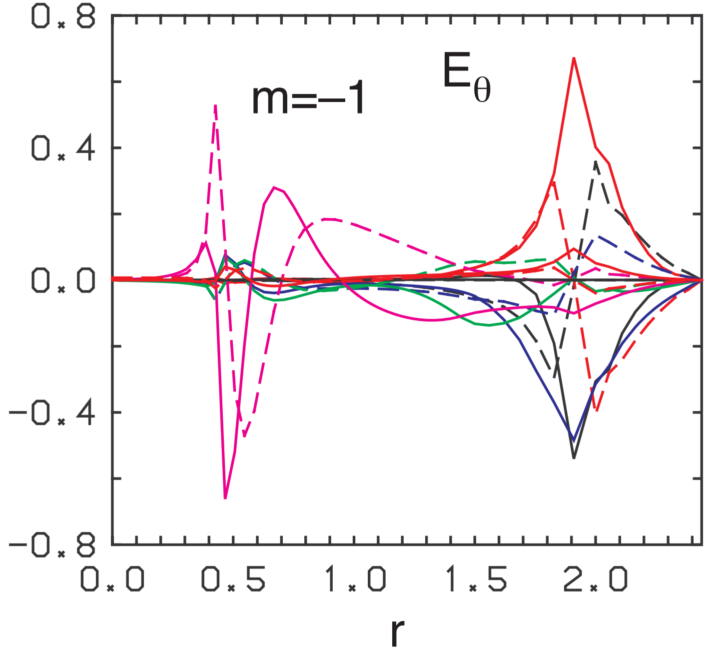
q profile



Alfvén Continuum



Mode structure ($n = 1$)



$f_r = 95.95\,\text{kHz}$

$f_i = -1.95\,\text{kHz}$

Stabilization due to $q = 1$

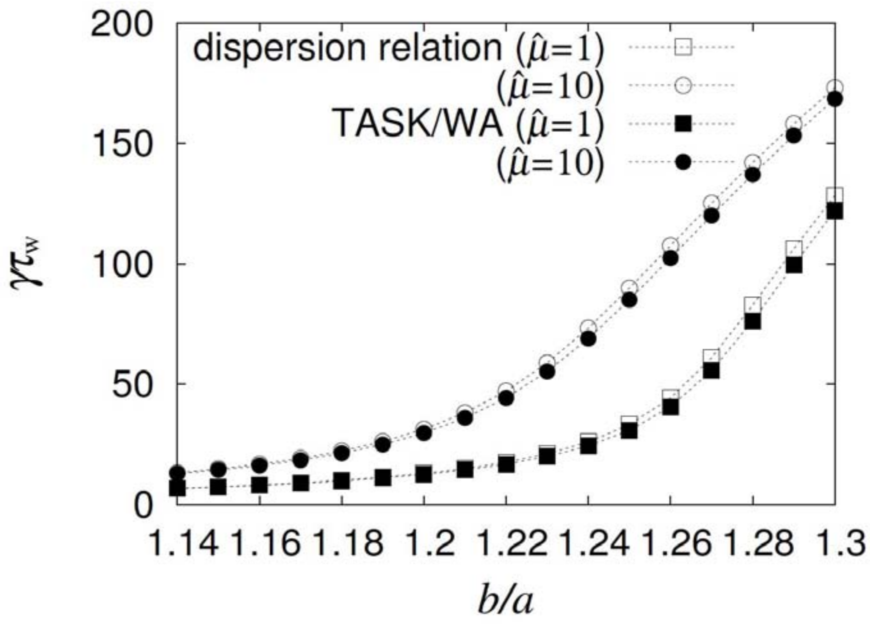
Full Wave Analysis of RWM (TASK/WA)

- **Full wave analysis**: solving Maxwell's equation

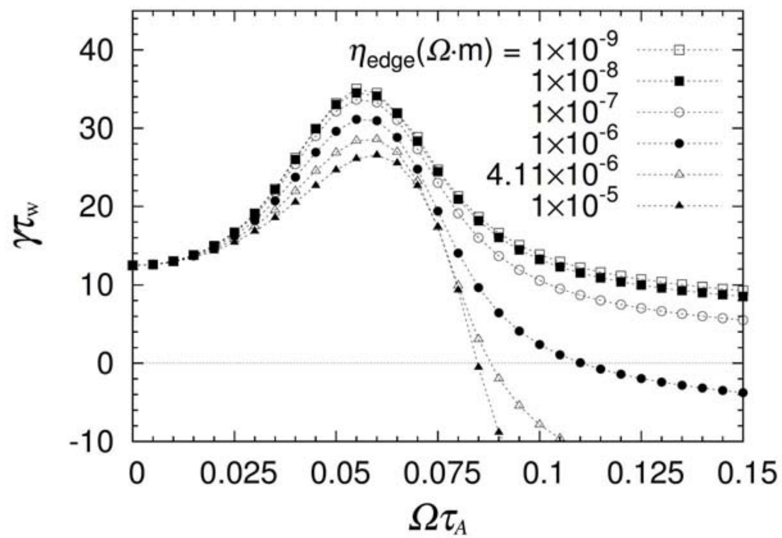
$$\nabla \times \nabla \times \boldsymbol{E} = \frac{\omega^2}{c^2} \overleftrightarrow{\epsilon} \cdot \boldsymbol{E} + \mathrm{i}\,\omega\mu_0 \boldsymbol{j}_{\mathrm{ext}}$$

- **Resistive MHD dielectric tensor including diamagnetic flow**
- **Ferromagnetic Resistive wall**

b/a dependence



Rotation dependence



Access to TASK code

- **Required Environment**
  - Unix-like OS (Linux, Mac OSX, $\cdots$)
  - X-window system
  - Fortran95 compiler
- **Source code**
  - **Stable version**: Web site (http://bpsi.nucleng.kyoto-u.ac.jp/task/)
  - **Latest version**: CVS tree (Read only) [password required]
  - **Developer**: CVS tree (R/W) [account required]
- **User support**
  - Uniform user interface
  - English guidebook in preparation: by the end of 2006

Summary

- We are developing **TASK** code as a reference core code for burning plasma simulation based on transport analysis.

- **Standard dataset** and **module interface** are still under discussion. They will be implemented by the end of this summer.

- The integrated code TASK is open source and easy to use, though more modules are required.

- **Future work for TASK**
  - Improvement of the modules: Full modular structure, Fortran95
  - Improvement of the models: Edge plasma, Sawtooth, ...
  - Systematic comparison with experimental data
  - Integrated simulation with other code: Stability, Peripheral, ...