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Integrated Tokamak Plasma Simulation with TASK Code

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- TASK: **T**ransport **A**nalysing **S**ystem for tokama**K**
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Background

- **Experiments**: **Significant Progress in Diagnostics**
  - High resolution in space and time
  - Electromagnetic field in plasmas
- **Theory**: **Better Understanding of Nonlinear Physics**
  - Structure formation, zonal flow, . . .
- **Simulation**: **Detailed Simulation of Individual Phenomenon**
  - Exponential growth of computation resources and network speed
  - Progress in computation science
  - Lack of methodology to describe multi-scale physics
- **Target of TASK code development**
  - **Framework of code integration**
  - **Standard dataset for data exchange**
  - **Common interface for data transfer and execution control**

TASK Code

- **Transport Analysing System for TokamaK**
- **Features**
  - **A Core of Integrated Modeling Code in BPSI**
    - Modular Structure
    - Reference Data Interface
  - **Various Heating and Current Drive Scheme**
    - EC, LH, IC, AW, (NB)
  - **High Portability**
    - Most of Library Routines Included (except LAPACK and MPI)
    - Own Graphic Libraries (gsaf, gsgl)
  - **Development using CVS** (Concurrent Version System)
    - Open Source (by the end of 2004)
  - **Parallel Processing using MPI Library**
  - **Extension to Toroidal Helical Plasmas**

Modules of TASK

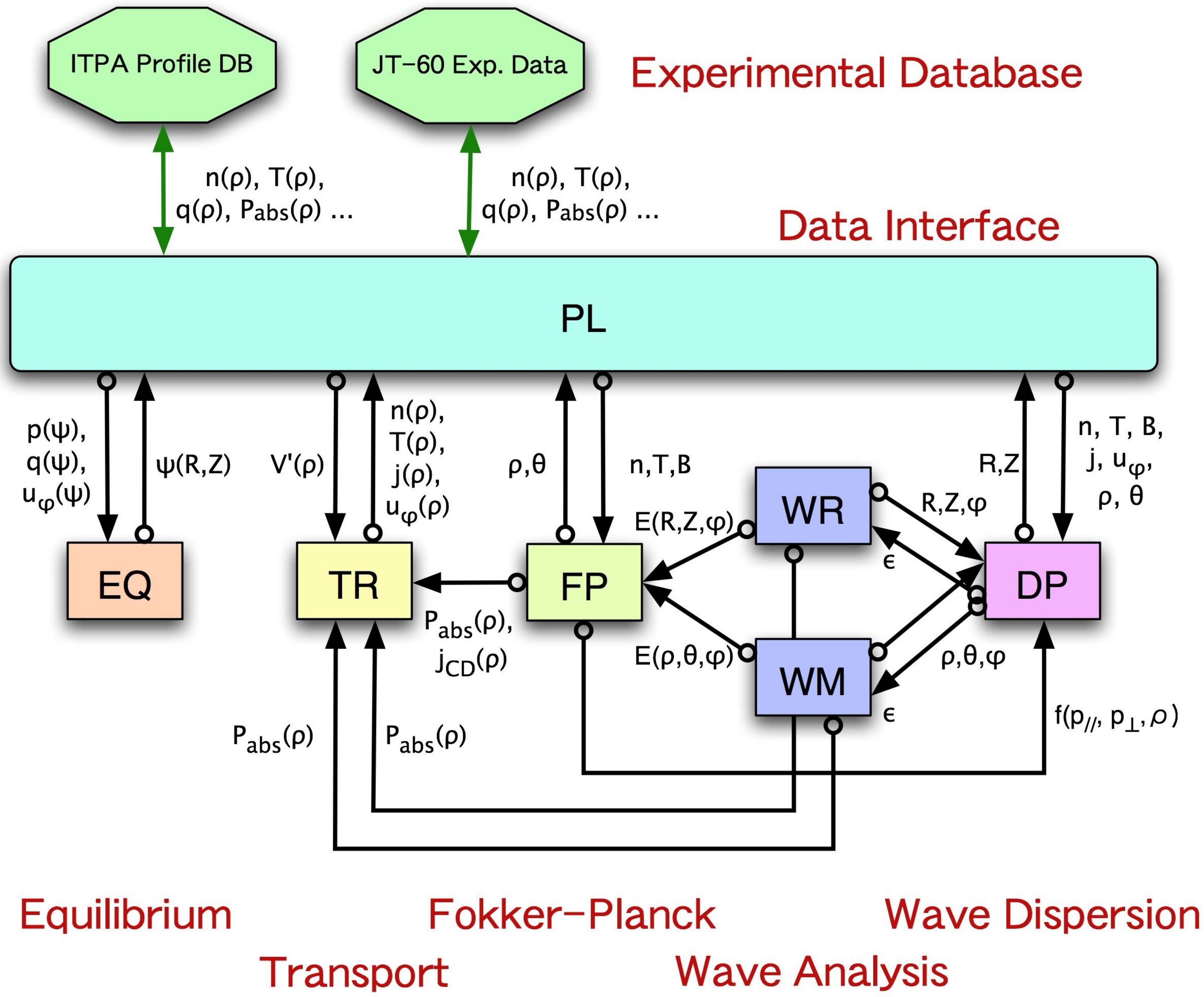
EQ	**2D Equilibrium**	Fixed boundary, Toroidal rotation
TR	**1D Transport**	Diffusive Transport, Transport models
WR	**3D Geometr. Optics**	EC, LH: Ray tracing, Beam tracing
WM	**3D Full Wave**	IC, AW: Antenna excitation, Eigen mode
FP	**3D Fokker-Planck**	Relativistic, Bounce-averaged
DP	**Wave Dispersion**	Local dielectric tensor, Arbitrary $f(\boldsymbol{v})$
PL	**Data Interface**	Data conversion, Profile database
LIB	**Libraries**	

Associated Libraries

GSAF	2D Graphic library for X Window and EPS
GSGL	3D Graphic library using OpenGL

All developed in Kyoto U

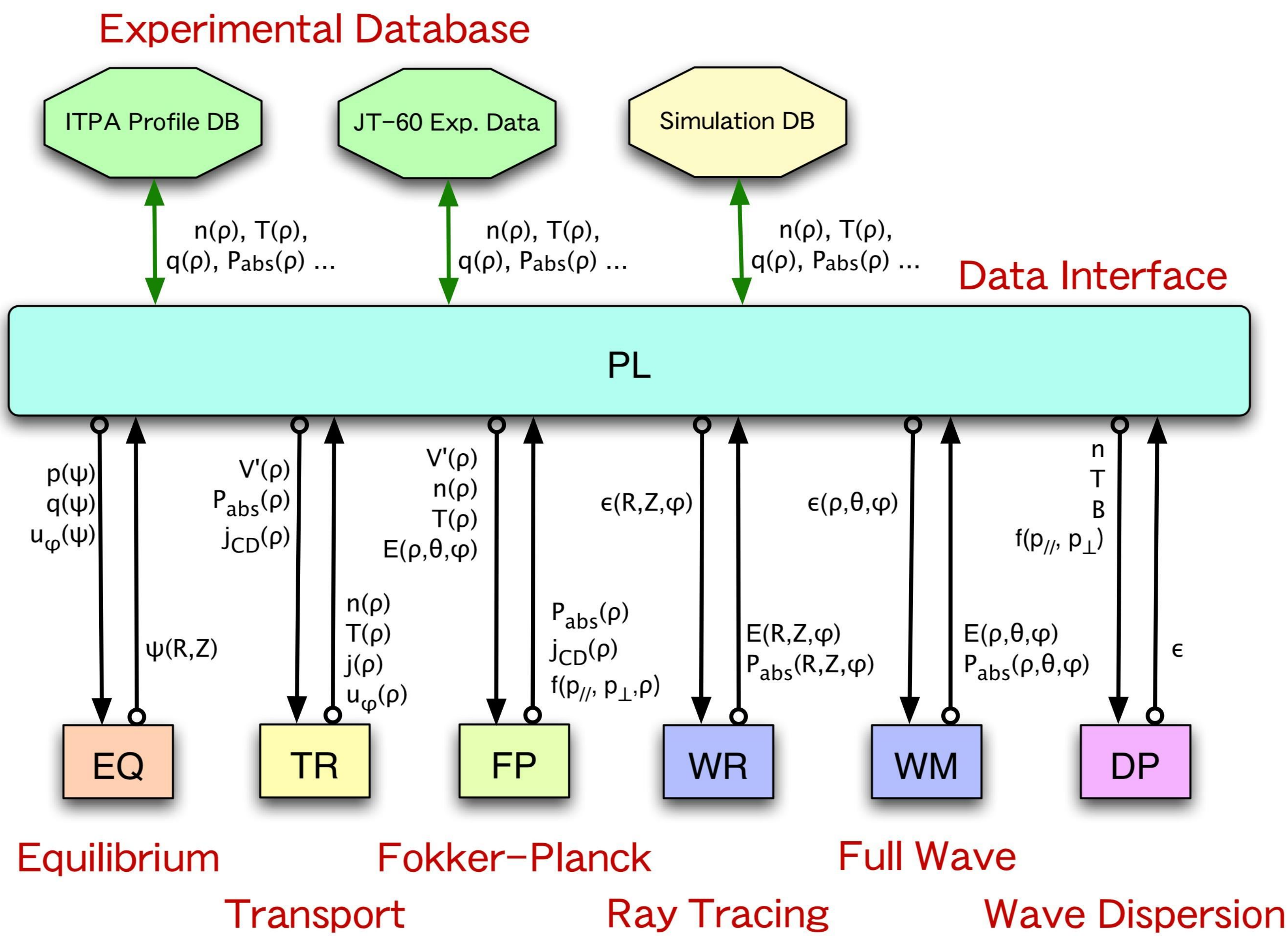
Present Structure of TASK



Under Development

- **New Modules**
  - **EX**: 2D equilibrium with free boundary
  - **TX**: Transport analysis based on flux-averaged fluid equation
  - **WA**: Global linear stability analysis
  - **WI**: Integro-differential wave analysis (FLR, $\boldsymbol{k} \cdot \nabla B \neq 0$)
- **Extension to 3D Helical System**
  - **3D Data Structure**
  - **3D Equilibrium**: VMEC, HINT
  - **Wave Analysis**: Already 3D
  - **Transport Analysis**: New transport model
- **New Modular Structure**

New Modular Structure of TASK



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** $f(\boldsymbol{v})$, relativistic)
  - **Gyro-kinetic plasma** model (Maxwellian)
- **Numerical Integration in momentum space**: **Arbitrary** $f(\boldsymbol{v})$
  - Relativistic Maxwellian
  - Output of TASK/FP: Fokker-Planck code

Geometrical Optics: TASK/WR

- **Ray Tracing** (Geometrical Optics)
  - Wave length $\lambda \ll$ Characteristic scale length L of the medium
  - Propagation of plane wave

    — Spatial evolution of beam position and wave number
  - Assumption of plane wave:

    — Beam size d is sufficiently large: **Fresnel condition**: $L \ll d^2/\lambda$
  - Beam : Diffraction effect determines the beam size d

- **Beam Tracing**
  - Propagation of beam with finite size

    — Spatial evolution of beam size and curvature radius

Fokker-Planck Analysis : TASK/FP

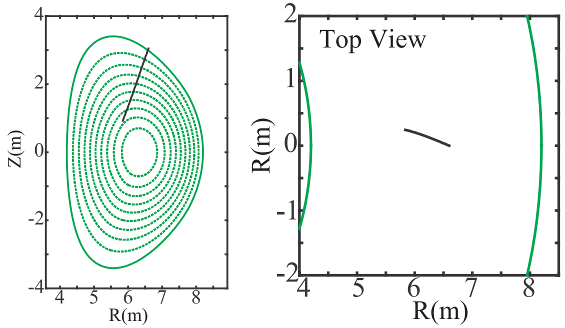
- **Fokker-Planck equation**
  for **velocity distribution function** $f(p_{||}, p_\perp, \psi, t)$

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

  - $E(f)$: 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)

Analysis of ECCD by TASK Code

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

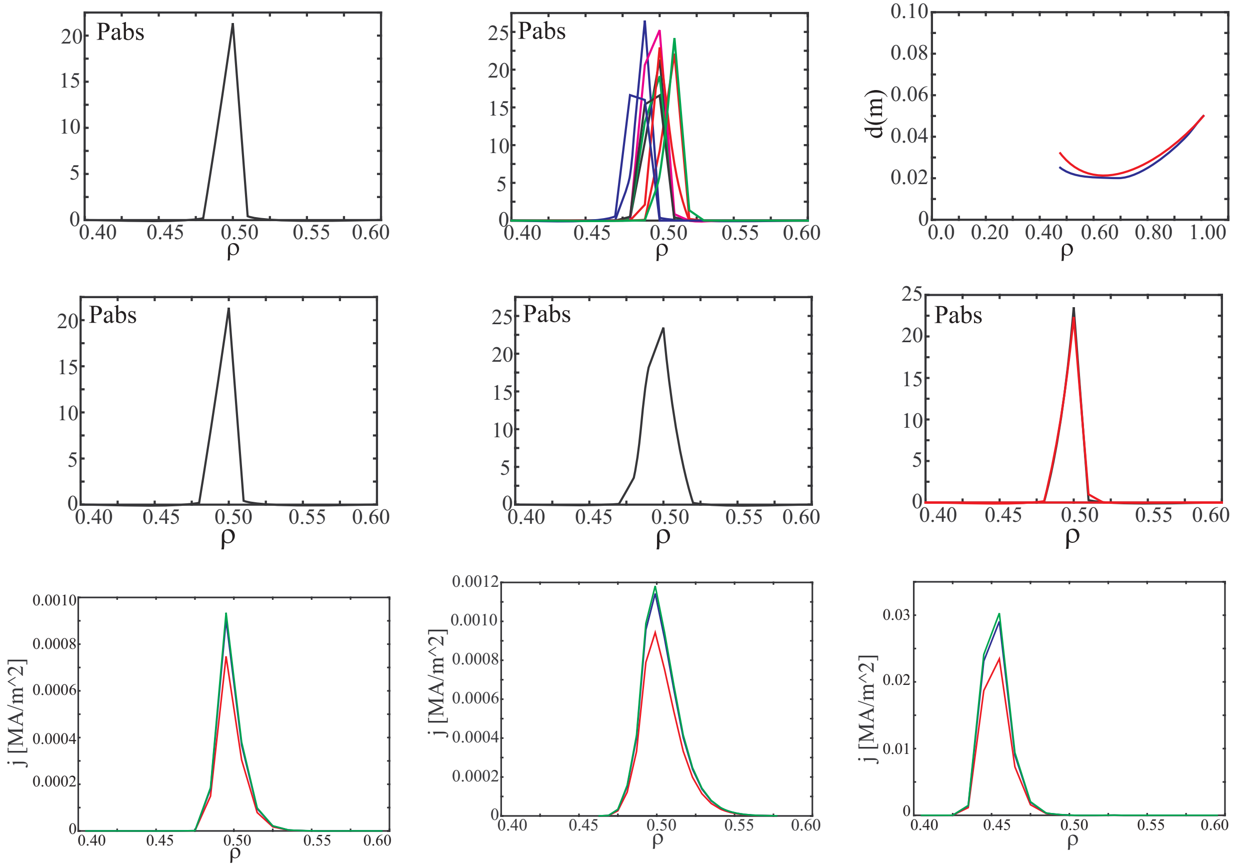


One Ray | Multi Rays | Beam Tracing

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**: $Z[(\omega - n\omega_{\mathrm{c}})/k_{\parallel} v_{\mathrm{th}}]$
  - **Fast ion: Drift-kinetic**

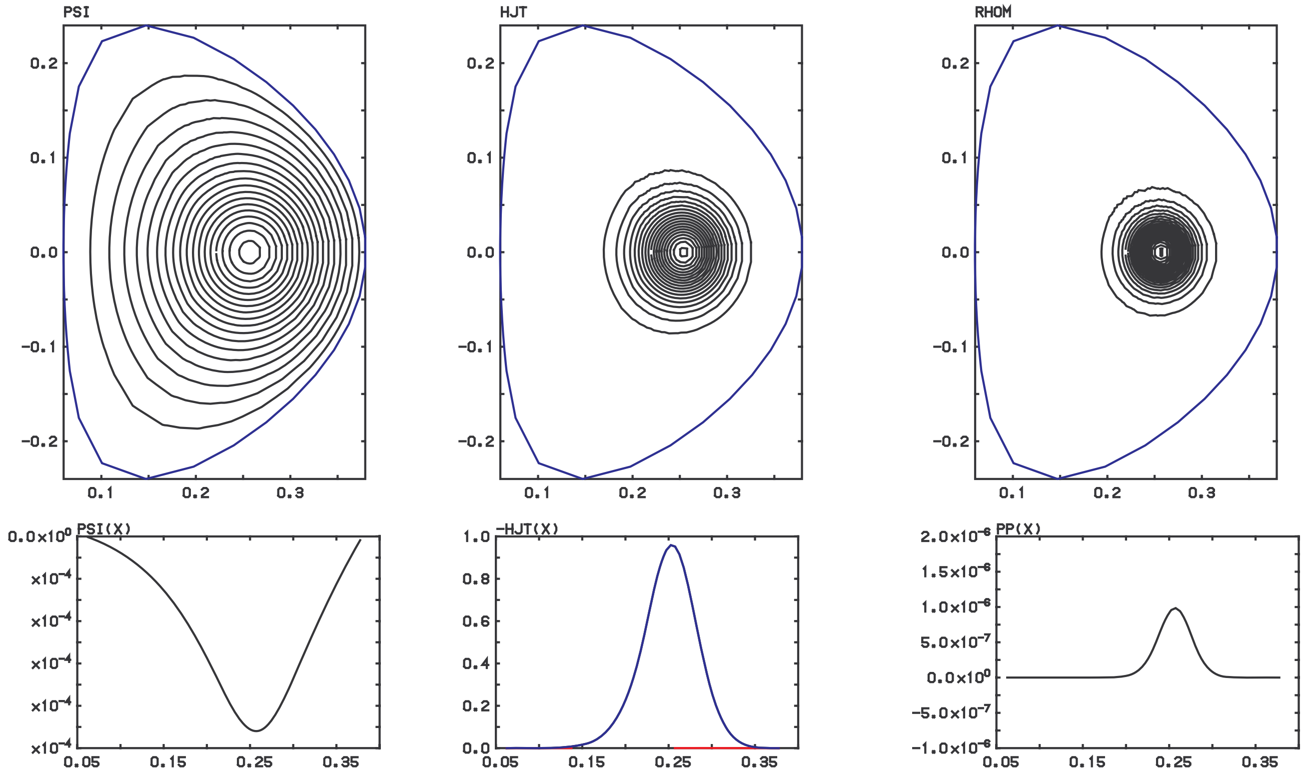
$$\left[\frac{\partial}{\partial t} + v_{\parallel}\nabla_{\parallel} + (\boldsymbol{v}_{\mathrm{d}} + \boldsymbol{v}_{\mathrm{E}}) \cdot \nabla + \frac{e_\alpha}{m_\alpha}(v_{\parallel}E_{\parallel} + \boldsymbol{v}_{\mathrm{d}} \cdot \boldsymbol{E})\frac{\partial}{\partial \varepsilon}\right] f_\alpha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

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

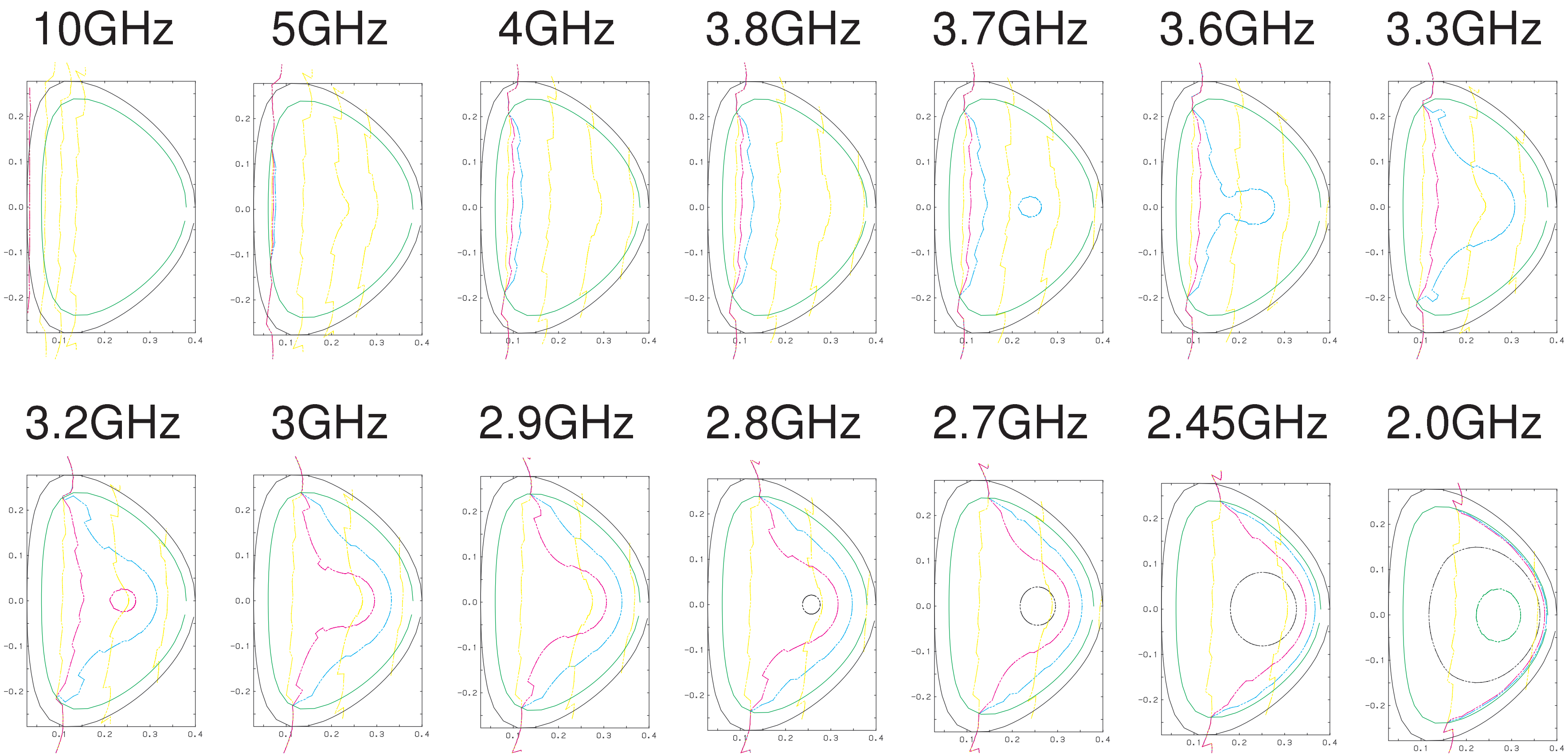
Full Wave Analysis of ECH in Small-Size ST (1)

- **Small-size spherical tokamak: LATE** (Kyoto University)
  - **T. Maekawa et al., Proc. 20th IAEA Fusion Energy Conf., IAEA-CN-116/EX/P4-27 (Vilamoura, Portuga, 2004)**
  - $R = 0.22\,\mathrm{m}$, $a = 0.16\,\mathrm{m}$, $B_0 = 0.0552\,\mathrm{T}$, $I_p = 6.25\,\mathrm{kA}$, $\kappa = 1.5$

Poloidal Flux   Current Density   Number Density



Full Wave Analysis of ECH in Small-Size ST (2)

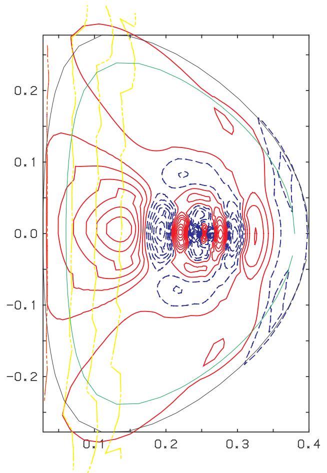


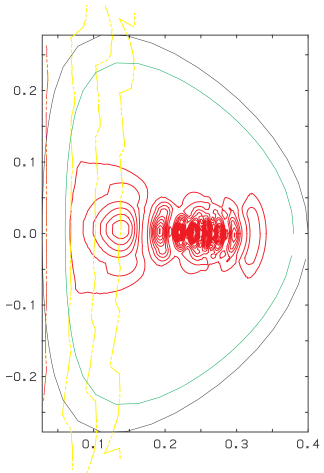
Line color	Large Location
Yellow	n-th EC harmonics
Violet	Upper hybrid resonance
Blue	RHS cyclotron cutoff
Green	LHS cyclotron cutoff
Black	Plasma cutoff / resonance

Full Wave Analysis of ECH in Small-Size ST (3)

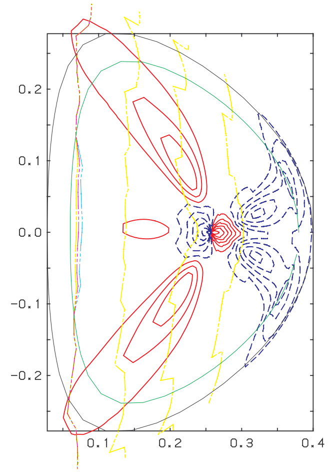
- **Standard density:** $10^{17}\,\mathrm{m}^{-3}$: **Extra-ordinary wave excitation**

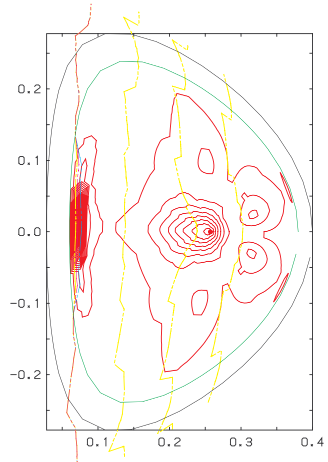
E_θ 10GHz $P_{\rm abs}$



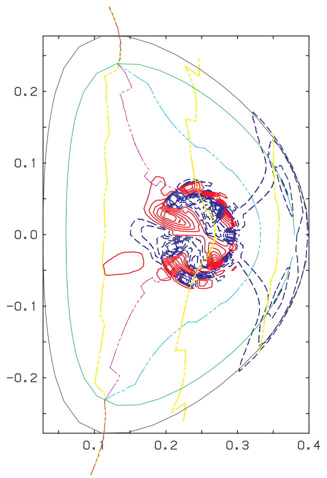


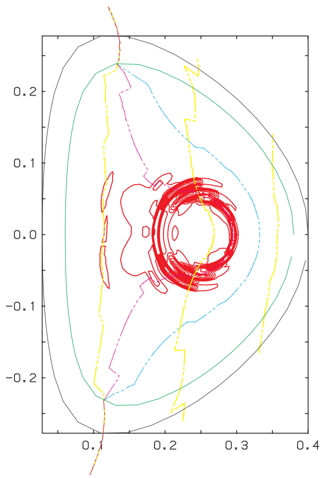
E_θ 5GHz $P_{\rm abs}$



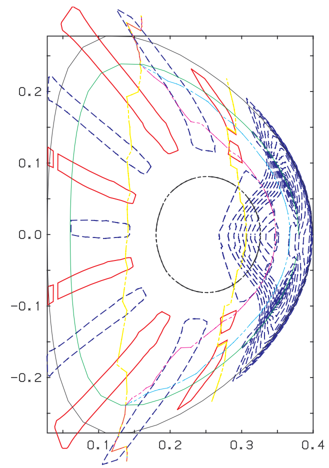


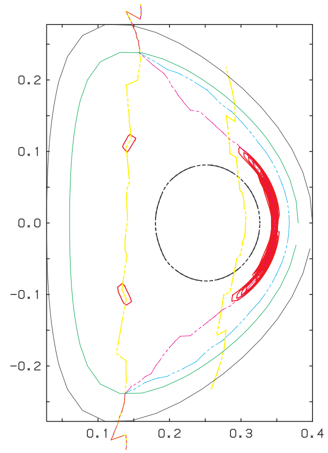
E_θ 3GHz $P_{\rm abs}$





E_θ 2.45GHz $P_{\rm abs}$

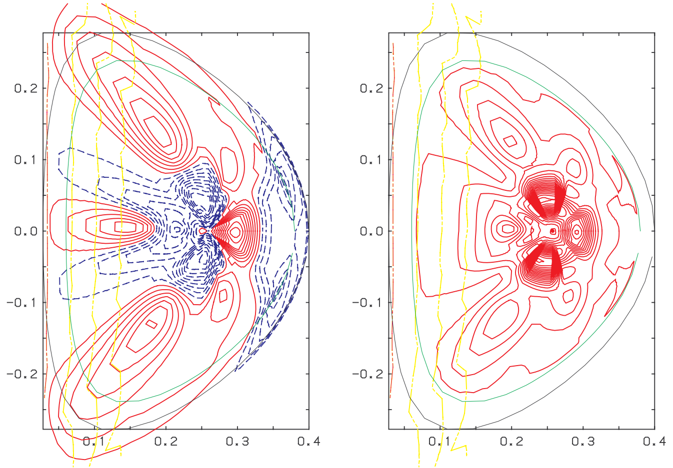




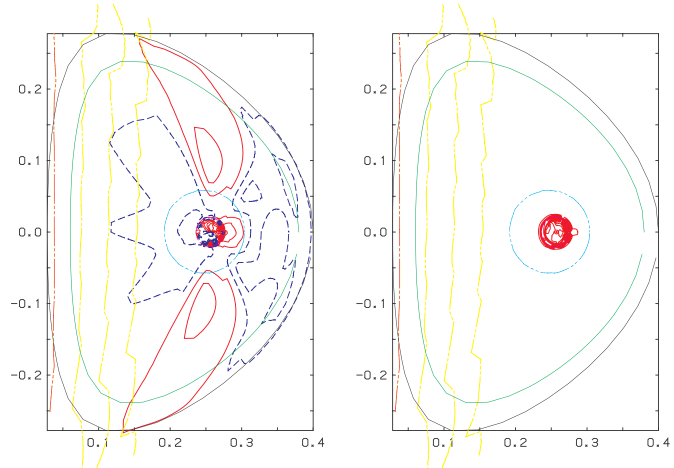
Full Wave Analysis of ECH in Small-Size ST (4)

- **High density:** $10^{18}\,\mathrm{m}^{-3}$: **Extra-ordinary wave excitation**

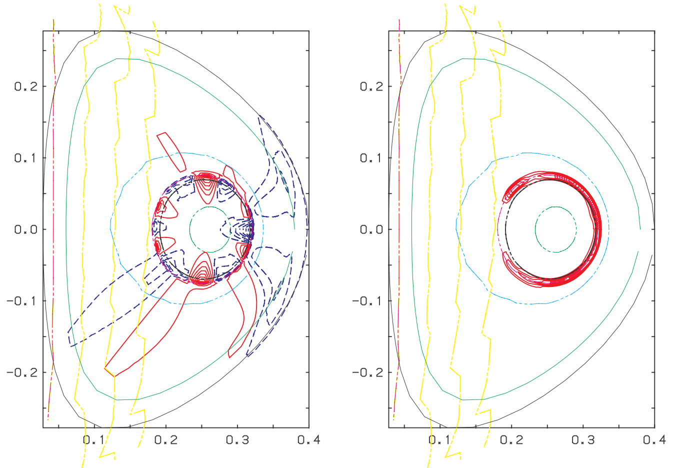
E_θ 10GHz P_{abs}



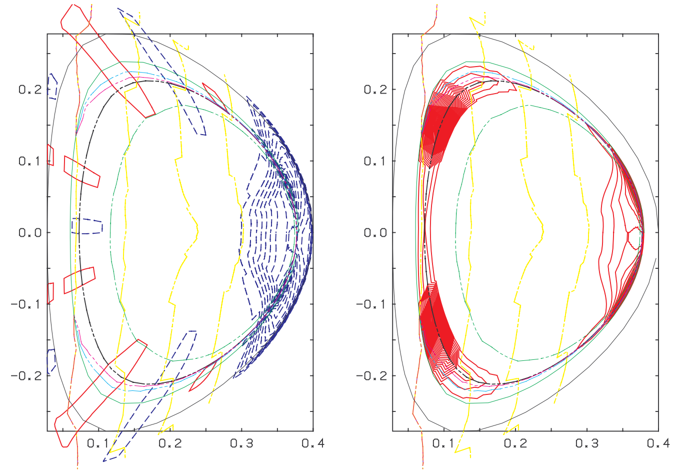
E_θ 9GHz P_{abs}



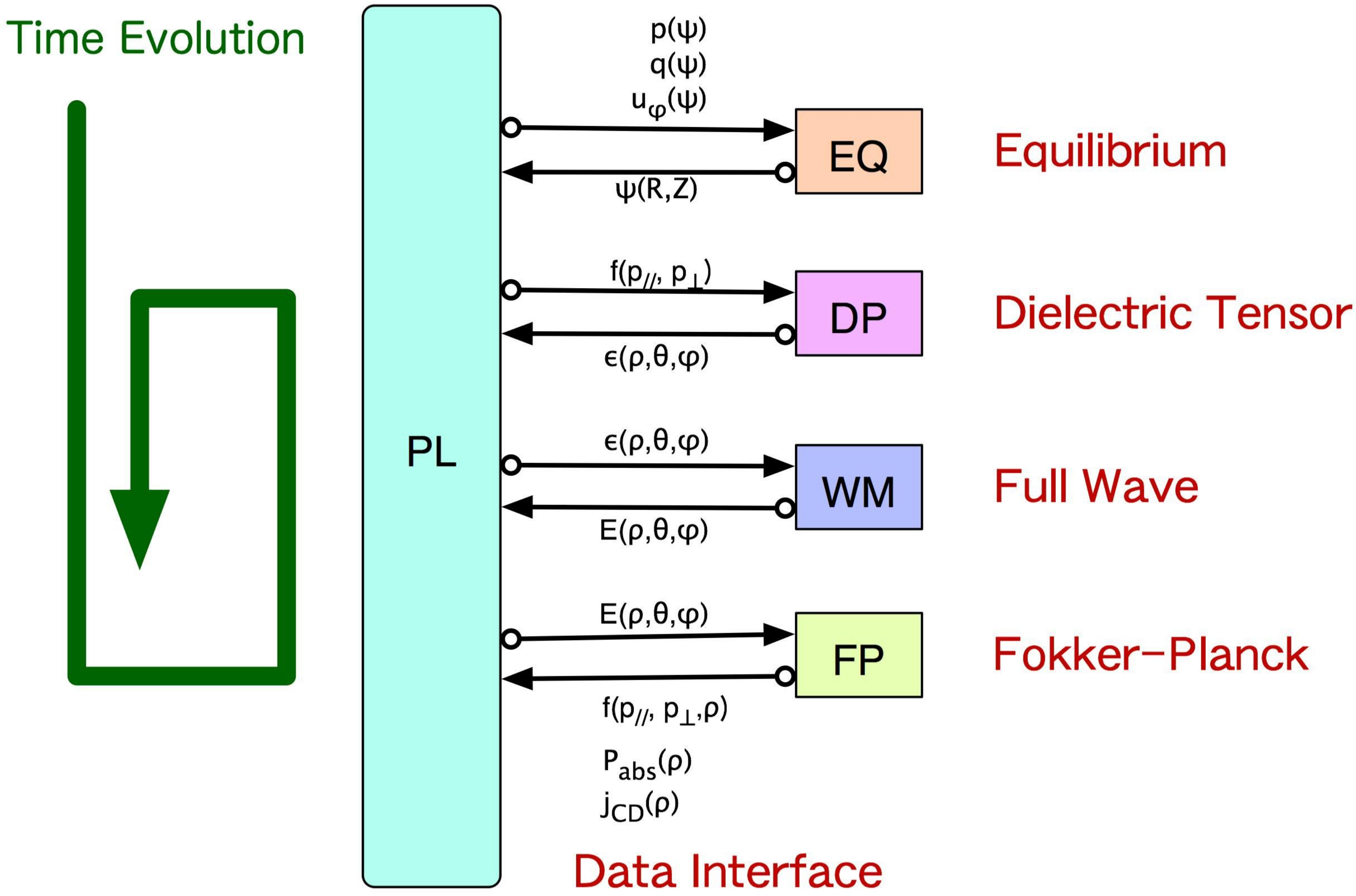
E_θ 8GHz P_{abs}



E_θ 5GHz P_{abs}



Self-consistent Full Wave Analysis



Summary of Self-Consistent Wave Analysis

- **Deviation of velocity distribution from Maxwellian may strongly affect**
  - Power absorption of ICRF waves in the presence of energetic ions
  - Current drive efficiency of LHCD
  - NTM controllability of ECCD
- **Systematic analyses including the modification of velocity distribution by TASK code is under way.**
- **Quantitative analysis will require integro-differential analysis including FLR effects.**

Summary (1)

- We are developing TASK code as a reference core code for burning plasma simulation based on transport analysis.
- The TASK code is composed of modules: equilibrium, transport, wave analysis, velocity space analysis, and data interface.
- Ray tracing analysis using TASK/WR/DP/FP was applied to ECCD on ITER and Full wave analysis using TASK/EQ/WM was applied to ECH on a small-size spherical tokamak.
- Self-consistent analysis of RF heating and current drive including the modification of velocity distribution function is still under development.

Summary (2)

- To Dos
  - Open source: Removing proprietary subroutines
  - Improvement of modules: Fully modular structure
  - Standard data interface with other simulation code
  - Systematic comparison with experimental data
  - Development of new modules: WA, TX, WI, EQX