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モジュール間連携機構を用いたトカマク統合シミュレーション

Integrated Tokamak Simulation Using Inter-Module Collaboration

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- トカマク統合シミュレーション
- TASK コード，モジュール間連携機構
- 解析例：EQ+TR, DP+WM+FP
- まとめ

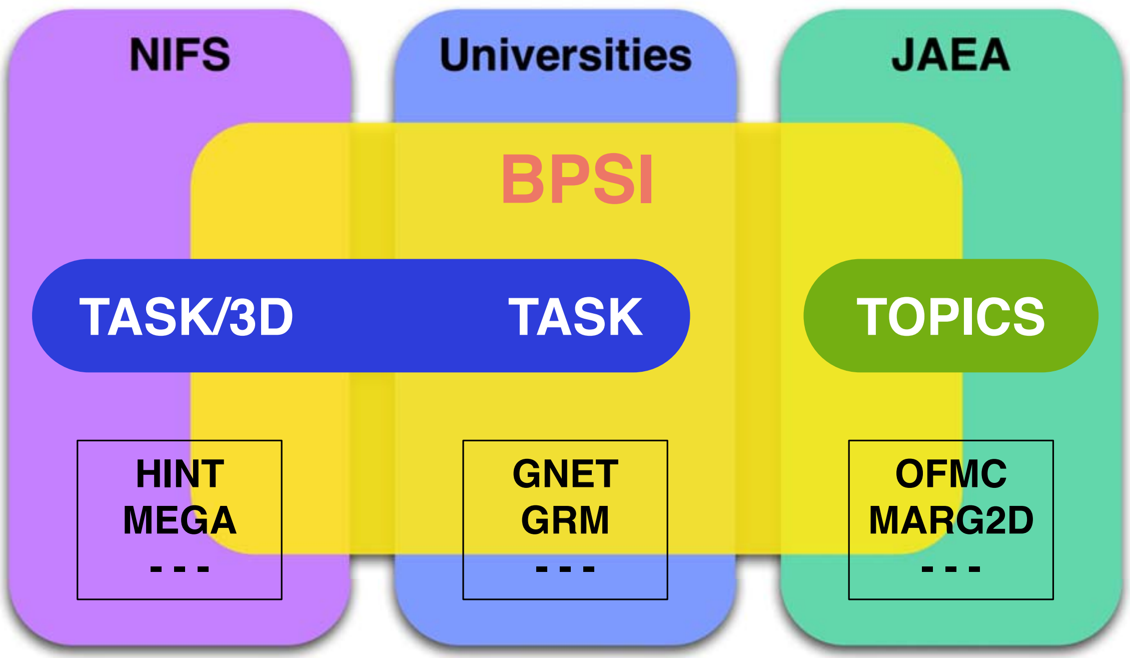
Integrated Tokamak Simulation

- **Purpose**
  - To predict the behavior of burning plasmas
  - To develop reliable and efficient schemes to control them
  - To contribute to reactor design
- **Simulation describing various phenomena in a tokamak plasma:**
  - **Whole plasma** (core & edge & divertor & wall-plasma)
  - **Whole discharge** (startup & sustainment & termination)
  - **Reasonable accuracy** (validation with experimental data)
  - **Reasonable computer resources** (still limited)
- **Strategy of integrated modeling**
  - **Development and assembly of necessary modeling codes**
  - **Organized development of simulation system**

BPSI: Burning Plasma Simulation Initiative

- **Research Collaboration among Universities, NIFS and JAEA**
- **Targets of BPSI**
  - **Framework** for collaboration of various plasma simulation codes
  - **Physics integration** with different time and space scales
  - **Advanced technique** of computer science

Integrated code: TASK and TOPICS



TASK Code

- **Transport Analysing System for TokamaK**
- **Features**
  - **A core of integrated modeling code in BPSI**
    - — Modular structure
    - — Reference code for data interface and standard data set
  - **Various heating and current drive scheme**
    - — EC, LH, IC, AW, NB
  - **Advanced transport modeling**
    - — Diffusive, Dynamic, Kinetic
  - **High portability**
  - **Open source** (V1.0: Fortran95, **http://bpsi.nucleng.kyoto-u.ac.jp/task/**)
  - **Parallel processing using MPI library**
  - **Extension to toroidal helical plasmas**

Modules of TASK

EQ	**2D Equilibrium**	Fixed/Free 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, Eigenmode
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**	LIB, MTX, MPI

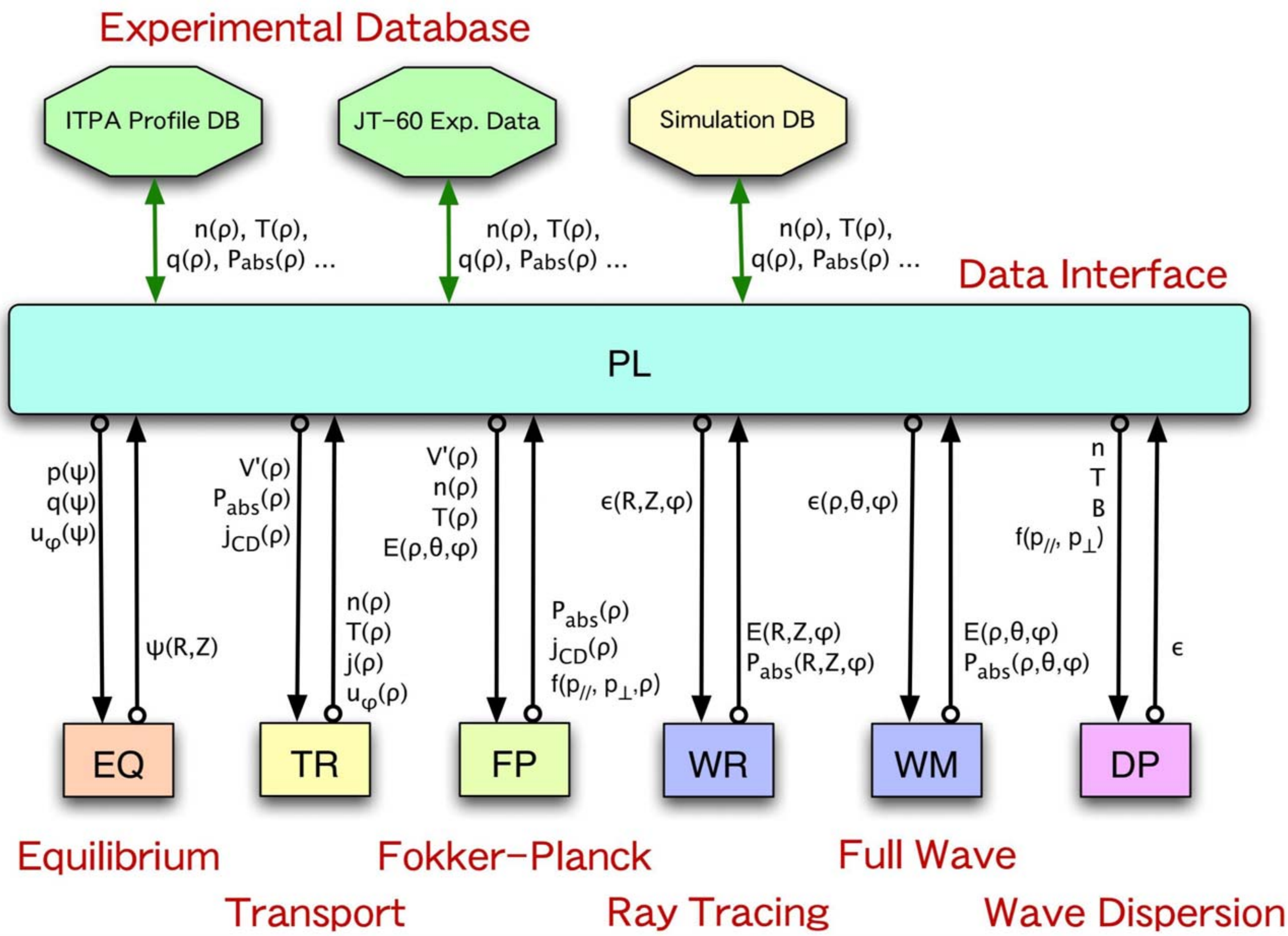
Under Development

TX	Transport analysis including plasma rotation and E_r

Collaboration with TOPICS

EQU	Free boundary equilibrium
NBI	NBI heating

Modular Structure of TASK



Inter-Module Collaboration Interface: TASK/PL

- **Purpose of the interface**
  - **Data exchange**:
    - — Standard dataset
    - — Data exchange interface
  - **Execution control**:
    - — Sequential control of module execution
    - — Uniform user interface

- **Role of Data Interface Layer: TASK/PL**
  - **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

Standard Dataset (interim)

Shot data

Machine ID, Shot ID, Model ID

Device data: (Level 1)

RR	R	m	Geometrical major radius
RA	a	m	Geometrical minor radius
RB	b	m	Wall radius
BB	B	T	Vacuum toroidal mag. field
RKAP	κ		Elongation at boundary
RDLT	δ		Triangularity at boundary
RIP	I_{p}	A	Typical plasma current

Equilibrium data: (Level 1)

PSI2D	$\psi_{\mathrm{p}}(R,Z)$	Tm^2	2D poloidal magnetic flux
PSIT	$\psi_{\mathrm{t}}(\rho)$	Tm^2	Poloidal magnetic flux
PSIP	$\psi_{\mathrm{p}}(\rho)$	Tm^2	Poloidal magnetic flux
ITPSI	$I_{\mathrm{t}}(\rho)$	Tm	Poloidal current: $B_\phi R$
IPPSI	$I_{\mathrm{p}}(\rho)$	Tm	Toroidal current
PPSI	$p(\rho)$	MPa	Plasma pressure
QINV	$1/q(\rho)$		Inverse of safety factor

Metric data

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

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

3D: 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	$u_{s\phi}(\rho)$	$\mathrm{m/s}$	Toroidal rotation velocity
QINV	$1/q(\rho)$		Inverse of safety factor

Kinetic plasma data

FP	$f(p,\theta_p,\rho)$		momentum dist. fn at $\theta=0$

Dielectric tensor data

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

Full wave field data

CE	$\boldsymbol{E}(\rho,\chi,\zeta)$	$\mathrm{V/m}$	Complex wave electric field
CB	$\boldsymbol{B}(\rho,\chi,\zeta)$	$\mathrm{Wb/m}^2$	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	$\boldsymbol{E}(\ell)$	$\mathrm{V/m}$	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	$\boldsymbol{v}(\ell)$	$1/\mathrm{m}$	Beam curvature at length ℓ

Data Exchange Interface

- **Data structure**: **Derived type** (Fortran95): structure type

time	`plasmaf%time`
number of grid	`plasmaf%nrmax`
square of grid radius	`plasmaf%s(nr)`
plasma density	`plasmaf%data(nr)%pn`
plasma temperature	`plasmaf%data(nr)%pt`

- **Program interface**

Initialize	`bpsd_init_plasmaf(ierr)`
Set data	`bpsd_set_plasmaf('plasmaf',plasmaf,ierr)`
Get data	`bpsd_set_plasmaf('plasmaf',plasmaf,ierr)`

- **Other functions**:
  - Save data into a file, Load data from a file, Plot data

Execution Control Interface

- **Example for TASK/TR**

`TR_INIT`	Initialization (Default value)	`BPSX_INIT('TR')`
`TR_PARM(ID,PSTR)`	Parameter setup (Namelist input)	`BPSX_PARM('TR',ID,PSTR)`
`TR_PROF(T)`	Profile setup (Spatial profile, Time)	`BPSX_PROF('TR',T)`
`TR_EXEC(DT)`	Exec one step (Time step)	`BPSX_EXEC('TR',DT)`
`TR_GOUT(PSTR)`	Plot data (Plot command)	`BPSX_GOUT('TR',PSTR)`
`TR_SAVE`	Save data in file	`BPSX_SAVE('TR')`
`TR_LOAD`	load data from file	`BPSX_LOAD('TR')`
`TR_TERM`	Termination	`BPSX_TERM('TR')`

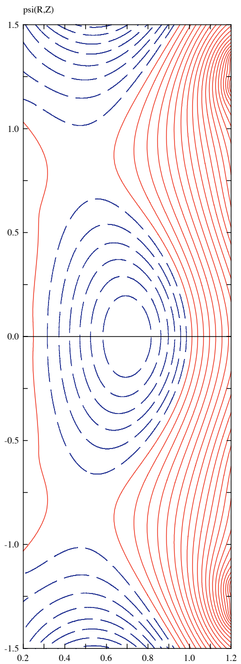
- **Module registration**

```
TR_STRUCT%INIT=TR_INIT
TR_STRUCT%PARM=TR_PARM
TR_STRUCT%EXEC=TR_EXEC
  ...
BPSX_REGISTER('TR',TR_STRUCT)
```

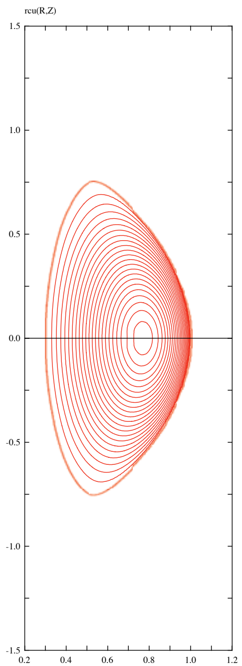
Example: Coupling of TASK/TR and TOPICS/EQU

- **TOPICS/EQU**: Free boundary 2D equilibrium
- **TASK/TR** Diffusive 1D transport (CDBM + Neoclassical)
- **QUEST** parameters:
  - $R = 0.64\,\mathrm{m}$, $a = 036\,\mathrm{m}$, $B = 0.64\,\mathrm{T}$, $I_\mathrm{p} = 300\,\mathrm{kA}$, OH+LHCD

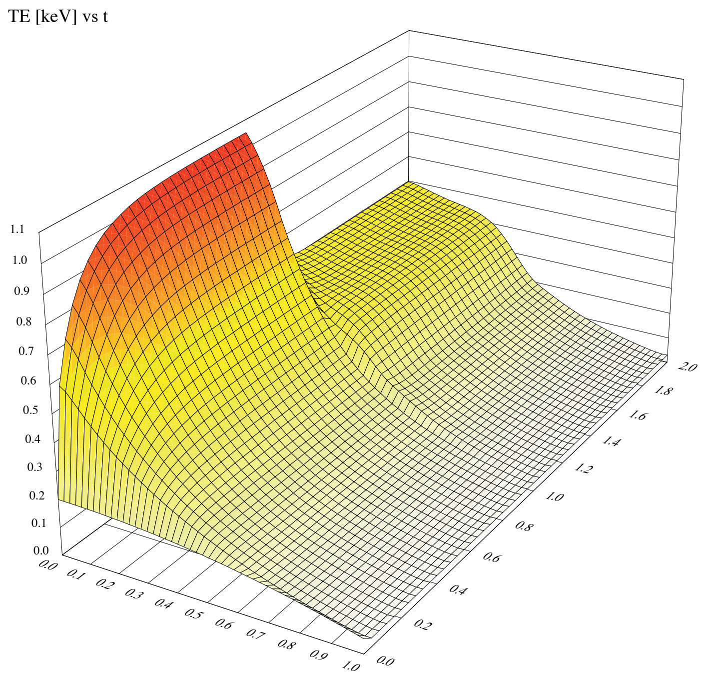
$\psi_\mathrm{p}(R, Z)$



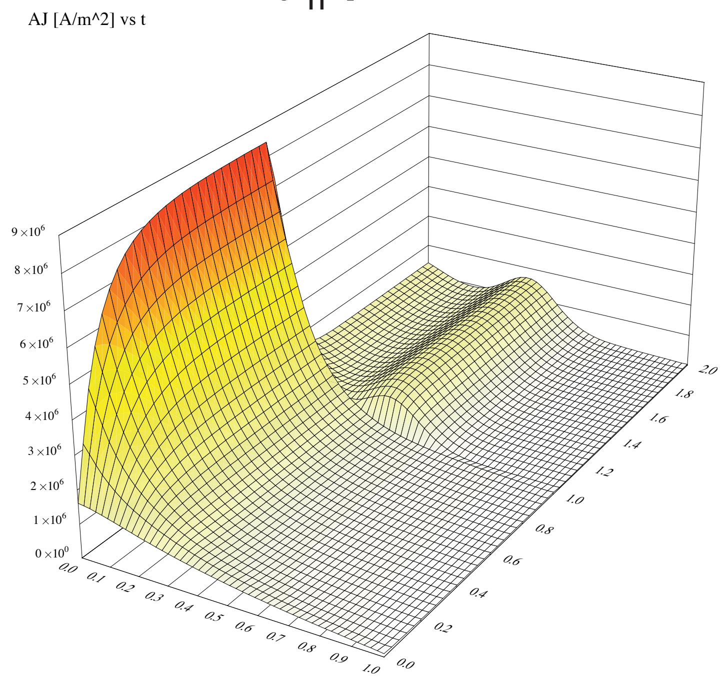
j_ϕ



$T_\mathrm{e}(\rho, t)$

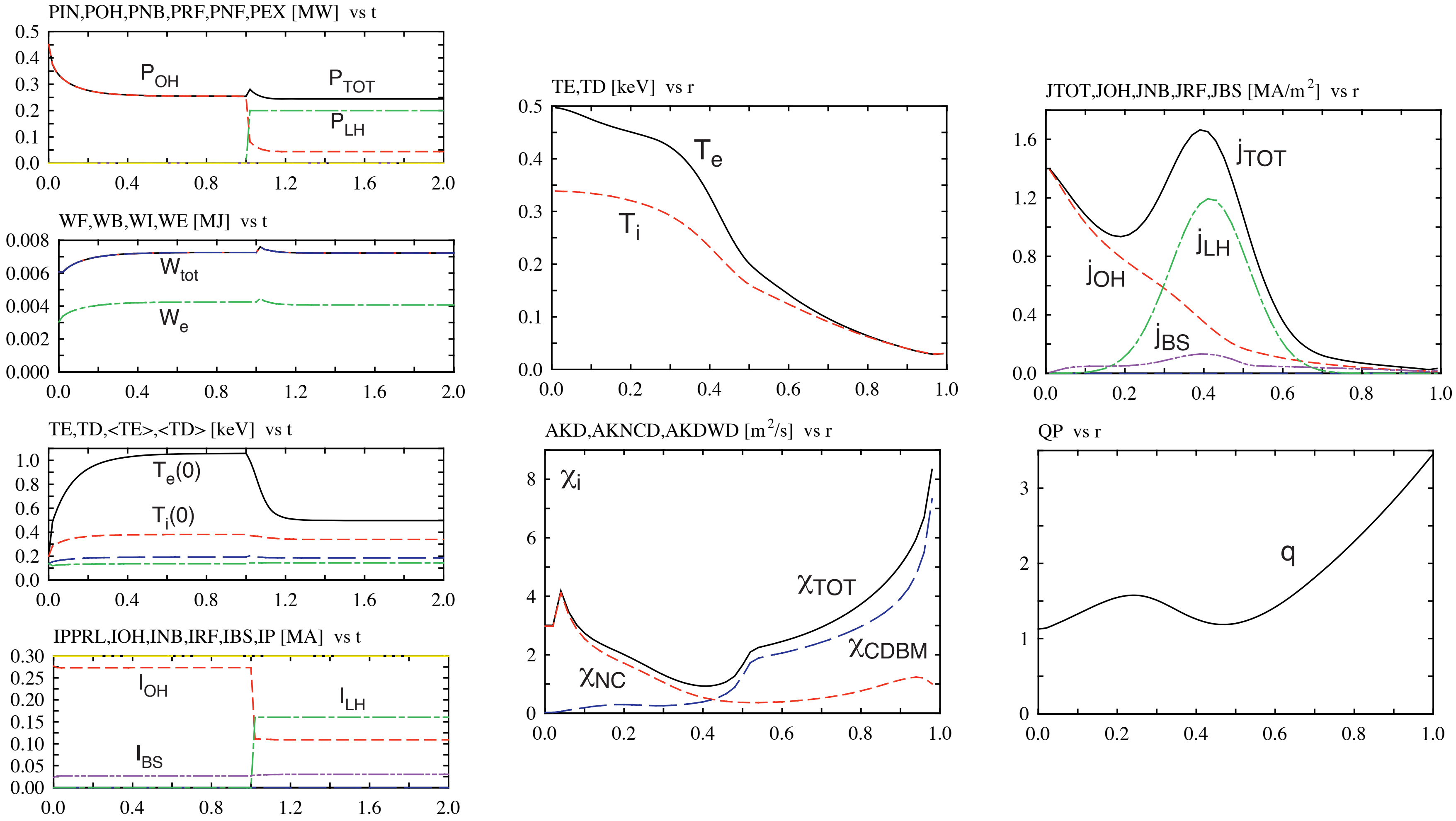


$j_{||}(\rho, t)$



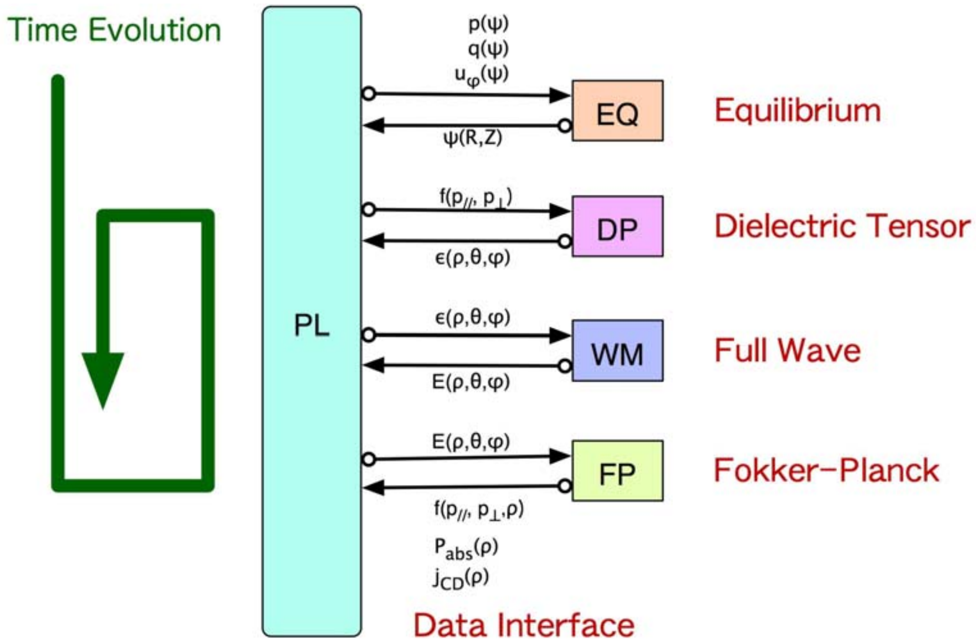
Transport simulation

- **OH + off-axis LHCD**: 200 kW
- **Formation of internal transport barrier** (equilibrium not solved)



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

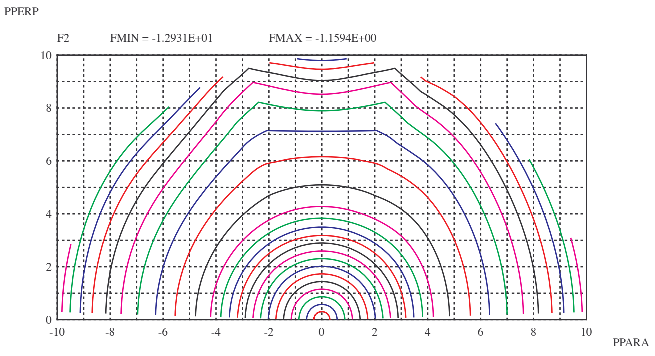
- **Modification of velocity distribution from Maxwellian**
  - Absorption of ICRF waves in the presence of energetic ions
  - Current drive efficiency of LHCD
  - NTM controllability of ECCD (absorption width)
- **Self-consistent wave analysis including modification of $f(v)$**



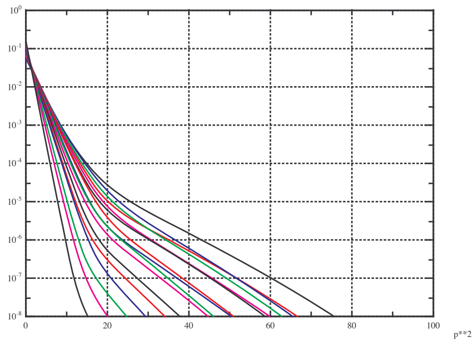
Self-Consistent ICRF Minority Heating Analysis

- **Analysis in TASK**
  - Dielectric tensor for arbitrary $f(v)$
  - Full wave analysis with the dielectric tensor
  - Fokker-Plank analysis of full wave results
  - Self-consistent iterative analysis: **Preliminary**
- **Energetic ion tail formation**
  - **Broadening of power deposition profile**

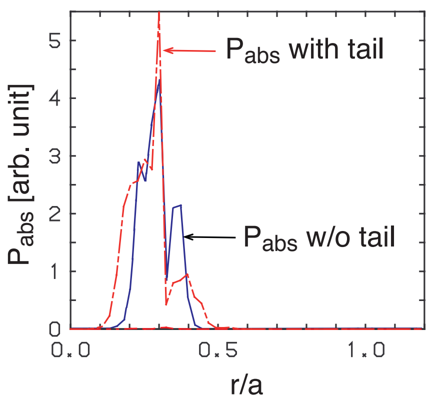
Momentum Distribution



Tail Formation



Power deposition



Summary

- We are developing module interfaces for integrated modeling of toroidal plasmas using the **TASK** code as a reference.
- The standard dataset, data exchange interface, and execution interface have been developed.
- The equilibrium code was extracted from the **TOPICS** code and coupled with the transport code in TASK using the module interface.
- Preliminary results of **self-consistent analysis of wave heating and current drive** describing the time evolution of the momentum distribution function and its influence on the wave propagation and absorption have been obtained.

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

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** $f(\boldsymbol{v})$, relativistic)
  - Gyro-kinetic plasma model (Maxwellian)
  - **Gyro-kinetic plasma model (Arbitrary** $f(\boldsymbol{v})$**, non-relativistic)**
- **Arbitrary** $f(\boldsymbol{v})$**:**
  - **Relativistic Maxwellian**
  - **Output of TASK/FP**