Meeting on Impurity Modeling
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NIFS

Present Status of Integrated Tokamak Transport Code: TASK

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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

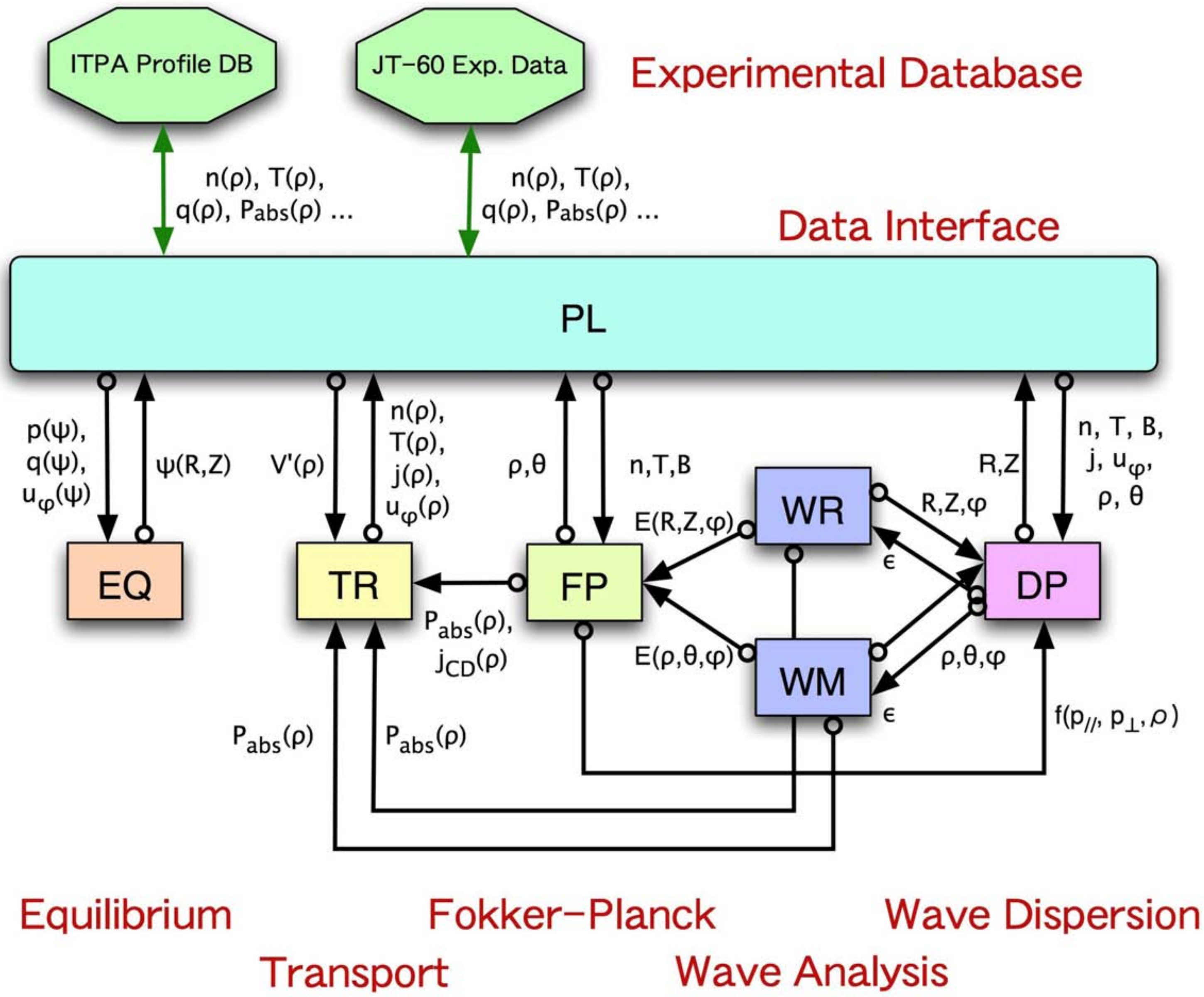
EQ	**2D Equilibrium**	Fixed boundary, Toroidal rotation
TR	**1D Transport**	Diffusive Transport, Transport models
WR	**3D Geometr. Optics**	EC, LH: Ray tracing, Beam tracing
WM	**3D Full Wave**	IC, AW: Antenna excitation, Eigen mode
FP	**3D Fokker-Planck**	Relativistic, Bounce-averaged
DP	**Wave Dispersion**	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

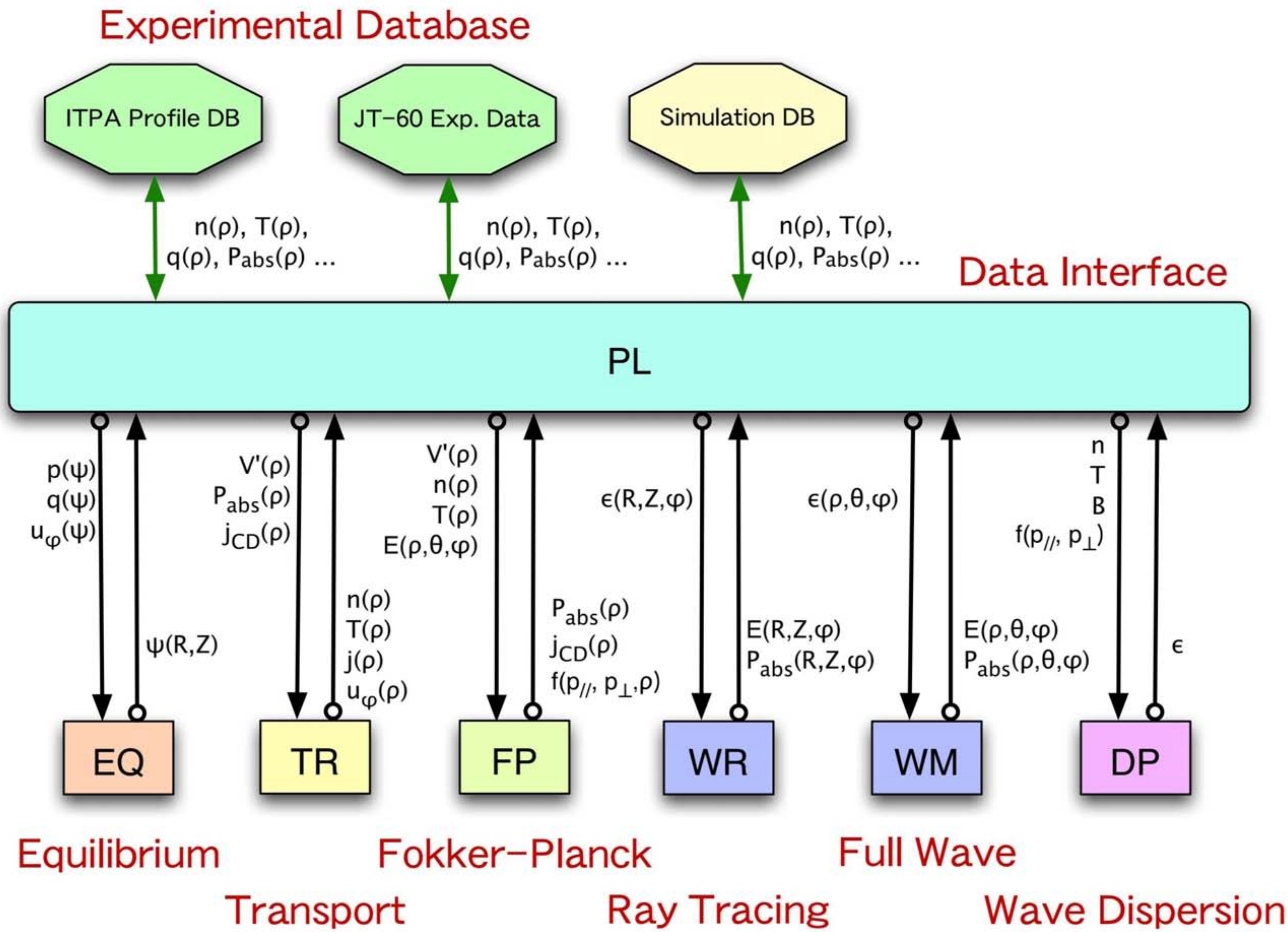
Present Structure of TASK



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



Transport Analysis

- **Level of Analysis**:
  - **TASK/TR**: Diffusive transport equation:
    — Flux-Gradient relation
    — Conventional transport analysis
  - **TASK/TX**: Dynamical transport equation:
    — Flux-averaged fluid equation
    — Plasma rotation and transient phenomena
  - **TASK/FP**: Kinetic transport equation:
    — Bounce-averaged Fokker-Plank equation
    — Modification of momentum distribution

Diffusive Transport Model

- **Transport Equation**: V: Volume, ρ: Normalized radius, $V' = \mathrm{d}V/\mathrm{d}\rho$
  - **Particle transport**

$$\frac{1}{V'}\frac{\partial}{\partial t}(n_s V') = -\frac{\partial}{\partial \rho}\left(V'\langle|\nabla\rho|\rangle n_s V_s - V'\langle|\nabla\rho|^2\rangle D_s \frac{\partial n_s}{\partial \rho}\right) + S_s$$

  - **Toroidal momentum transport**

$$\frac{1}{V'}\frac{\partial}{\partial t}(n_s u_{\phi s} V') = -\frac{\partial}{\partial \rho}\left(V'\langle|\nabla\rho|\rangle n_s u_{\phi s} V_{Ms} - V'\langle|\nabla\rho|^2\rangle n_z \mu_s \frac{\partial u_{\phi s}}{\partial \rho}\right) + M_s$$

  - **Heat transport**

$$\frac{1}{V'^{5/3}}\frac{\partial}{\partial t}\left(\frac{3}{2} n_s T_s V'^{5/3}\right) = -\frac{1}{V'}\frac{\partial}{\partial \rho}\left(V'\langle|\nabla\rho|\rangle \frac{3}{2} n_s T_s V_{Es} - V'\langle|\nabla\rho|^2\rangle n_s \chi_s \frac{\partial T_s}{\partial \rho}\right) + P_s$$

  - **Current diffusion**

$$\frac{\partial B_\theta}{\partial t} = \frac{\partial}{\partial \rho}\left[\frac{\eta}{F R_0 \langle R^{-2}\rangle}\frac{R_0 F^2}{\mu_0}\frac{\partial}{V' \partial \rho}\left(\frac{V' B_\theta}{F}\left\langle\frac{|\nabla\rho|^2}{R^2}\right\rangle\right) - \frac{\eta}{F R_0 \langle R^{-2}\rangle}\langle \boldsymbol{J}\cdot\boldsymbol{B}\rangle_{\mathrm{ext}}\right]$$

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)

Modeling of ETB Formation

- **Transport Simulation including Core and SOL Plasmas**
- **Role of Separatrix**
  - Closed magnetic surface $\Longleftrightarrow$ Open magnetic field line
  - Difference of dominant transport process
- **Radial Electric Field**
  - Poloidal rotation, Toroidal rotation
  - Polarization current
  - Poisson equation
- **Atomic Processes**
  - Ionization, Charge exchange, Recycling

Dynamical Transport Model: TASK/TX

- **1D Transport code** (TASK/TX) *Ref. Fukuyama et al.*
- **Two fluid equation for electrons and ions**
  - Flux surface average
  - Coupled with Maxwell equation
  - Neutral diffusion equation
- **Neoclassical transport**
  - Included as a poloidal viscosity term
  - Diffusion, resistivity, bootstrap current, Ware pinch
- **Anomalous transport**
  - Current diffusive ballooning mode
  - Ambipolar diffusion through poloidal momentum transfer
  - Perpendicular viscosity

Model Equation (1)

- **Fluid equations** (electrons and ions)

$$\frac{\partial n_s}{\partial t} = -\frac{1}{r}\frac{\partial}{\partial r}(r n_s u_{sr}) + S_s$$

$$\frac{\partial}{\partial t}(m_s n_s u_{sr}) = -\frac{1}{r}\frac{\partial}{\partial r}(r m_s n_s u_{sr}^2) + \frac{1}{r} m_s n_s u_{s\theta}^2 + e_s n_s(E_r + u_{s\theta} B_\phi - u_{s\phi} B_\theta) - \frac{\partial}{\partial r} n_s T_s$$

$$\frac{\partial}{\partial t}(m_s n_s u_{s\theta}) = -\frac{1}{r^2}\frac{\partial}{\partial r}(r^2 m_s n_s u_{sr} u_{s\theta}) + e_s n_s(E_\theta - u_{sr} B_\phi) + \frac{1}{r^2}\frac{\partial}{\partial r}\left(r^3 n_s m_s \mu_s \frac{\partial}{\partial r}\frac{u_{s\theta}}{r}\right)$$

$$+F_{s\theta}^{\mathrm{NC}} + F_{s\theta}^{\mathrm{C}} + F_{s\theta}^{\mathrm{W}} + F_{s\theta}^{\mathrm{X}} + F_{s\theta}^{\mathrm{L}}$$

$$\frac{\partial}{\partial t}\left(m_s n_s u_{s\phi}\right) = -\frac{1}{r}\frac{\partial}{\partial r}(r m_s n_s u_{sr} u_{s\phi}) + e_s n_s(E_\phi + u_{sr} B_\theta) + \frac{1}{r}\frac{\partial}{\partial r}\left(r n_s m_s \mu_s \frac{\partial}{\partial r} u_{s\phi}\right)$$

$$+F_{s\phi}^{\mathrm{C}} + F_{s\phi}^{\mathrm{W}} + F_{s\phi}^{\mathrm{X}} + F_{s\phi}^{\mathrm{L}}$$

$$\frac{\partial}{\partial t}\frac{3}{2} n_s T_s = -\frac{1}{r}\frac{\partial}{\partial r} r\left(\frac{5}{2} u_{sr} n_s T_s - n_s \chi_s \frac{\partial}{\partial r} T_{\mathrm{e}}\right) + e_s n_s(E_\theta u_{s\theta} + E_\phi u_{s\phi})$$

$$+P_s^{\mathrm{C}} + P_s^{\mathrm{L}} + P_s^{\mathrm{H}}$$

Model Equation (2)

- **Neutral Transport**

$$\frac{\partial n_0}{\partial t} = -\frac{1}{r}\frac{\partial}{\partial r}\left(-rD_0\frac{\partial n_0}{\partial r}\right) + S_0$$

- **Maxwell equations**

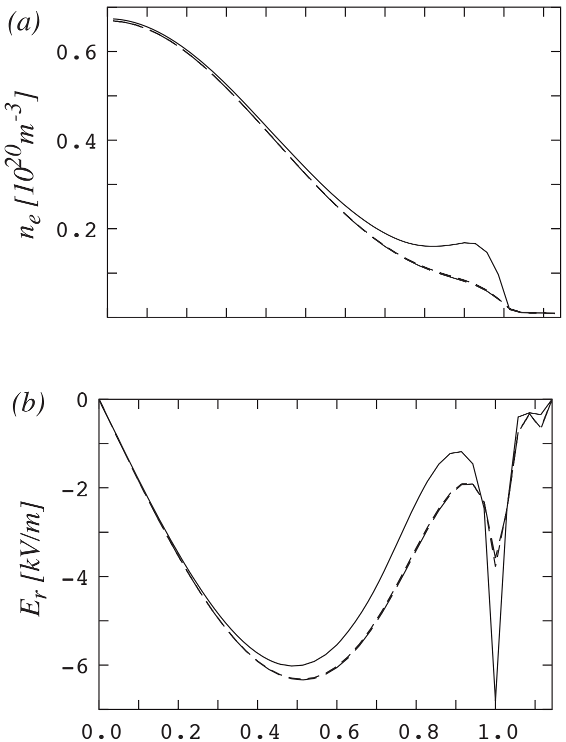
$$\frac{1}{r}\frac{\partial}{\partial r}(rE_r) = \frac{1}{\epsilon_0}\sum_s e_s n_s$$

$$\frac{\partial B_\theta}{\partial t} = \frac{\partial E_\phi}{\partial r}, \qquad \frac{\partial B_\phi}{\partial t} = -\frac{1}{r}\frac{\partial}{\partial r}(rE_\phi)$$

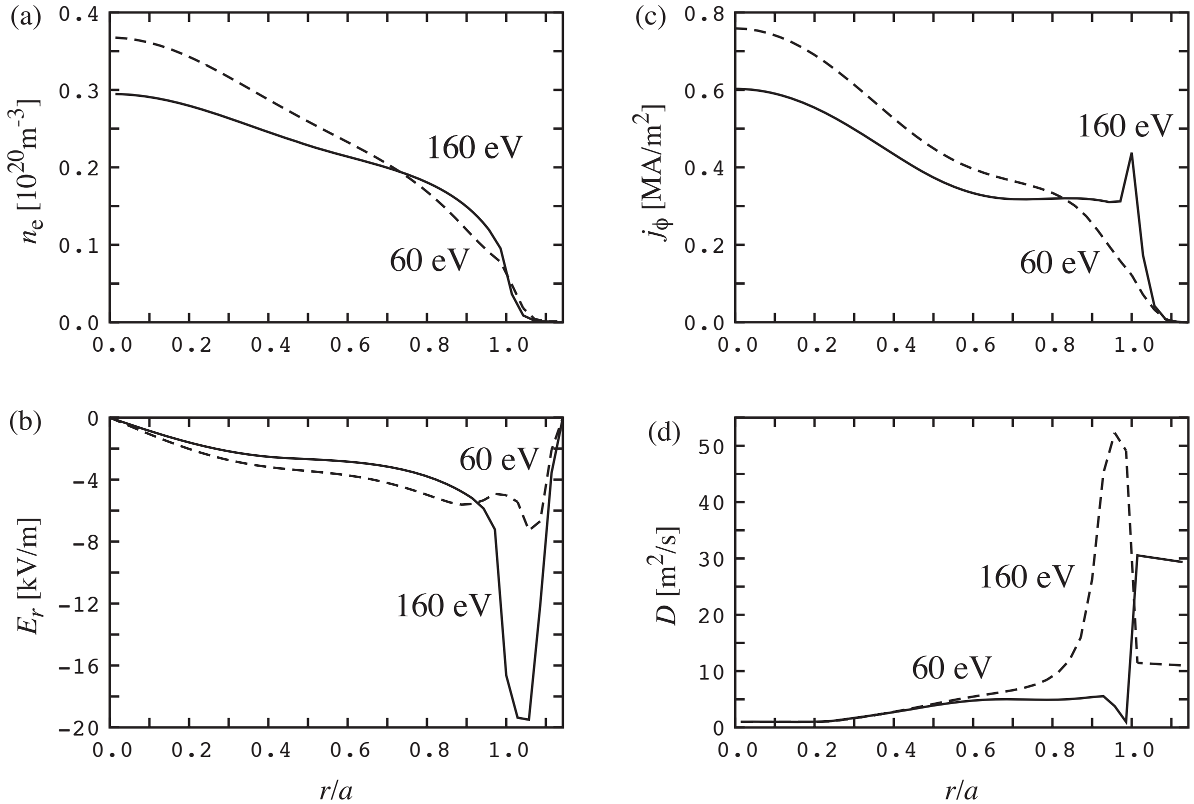
$$\frac{1}{c^2}\frac{\partial E_\theta}{\partial t} = -\frac{\partial}{\partial r}B_\phi - \mu_0\sum_s n_s e_s u_{s\theta}, \qquad \frac{1}{c^2}\frac{\partial E_\phi}{\partial t} = \frac{1}{r}\frac{\partial}{\partial r}(rB_\theta) - \mu_0\sum_s n_s e_s u_{s\phi}$$

Typical Profiles

$D_{\mathrm{TB}} = 0$



Edge Temperature Dependence



Impurity Modeling

1. **Simplest Model**: Originally implemented in TASK/TR
   - Fixed profile proportional to nne profile
   - Charge state and radiation power as a function of $T_{\rm e}$
2. **Diffusive Transport for Average Charge State**
   - Diffusive transport equation of one component for one impurity species
   - Charge state and radiation power as a function of $T_{\rm e}$
   - Complicated to keep charge neutrality
3. **Diffusive Transport for Each Charge State**
   - Diffusive transport equation of multi component for one impurity species
   - Ionization, recombination, radiation as a function of $T_{\rm e}$
   - Requires large computational power
4. **Coupling with Impurity Code**

Interface with Impurity Code

- **Standard data set to describe plasma status**
  - device data, magnetic data, metric data, fluid data, kinetic data, ray tracing data, full wave data
  - Structured data (Fortran 95)
- **Standard data interface to exchange data**
  - Data transfer through subroutine arguments
  - Without common for data transfer between modules
- **Standard execution interface to control modules**
  - Initialization, parameter input, execution, output

Standard Dataset (draft)

- **Normalized minor radius**: $\rho = \sqrt{\psi_{\rm t}/\psi_{\rm ta}}$
- **Device data**: $R_0,\ a,\ b,\ B_0,\ \kappa,\ \delta,\ I_{\rm p}$
- **Equilibrium data**: $\psi_{\rm p}(R,Z),\ \psi_{\rm p}(\rho),\ p(\rho),\ I_\theta(\rho),\ q(\rho),\ j_{\|{\rm AV}}(\rho)$
- **Metric data**: $\langle 1/R^2\rangle,\ \langle|\nabla\rho|^2/R^2\rangle,\ \langle|\nabla\rho|\rangle,\ \langle|\nabla\rho|^2\rangle,\ {\rm d}V/{\rm d}\rho,\ \ldots,\ g_{ij}$
- **Fluid plasma data**: $A_s,\ Z_s,\ n_s(\rho),\ T_s(\rho),\ u_{\phi s}(\rho)$
- **Kinetic plasma data**: $f(p,\theta_p,\rho)$
- **Ray tracing data**: $R_{\rm ray}(\ell),\ Z_{\rm ray}(\ell),\ \phi_{\rm ray}(\ell),\ \boldsymbol{E}(\ell)$
- **Full Wave data**: $\boldsymbol{E}(\rho,\chi,\xi),\ \boldsymbol{B}(\rho,\chi,\xi),\ P_{\rm abs}(\rho,\chi,\xi)$

- **Data Exchange Interface**
  - Structured data (Fortran95)
  - `BPSI_GET('FL1D',BPSI_FL1D)`: `BPSI_FL1D%PS(NS)%PT(NR)`
  - `BPSI_SET('FL1D',BPSI_FL1D)`

Execution Control Interface

- **Common Control Interface** (tentative)
  - `XX=PL or EQ or TR or DP or WR or WM or FP`

`XXINIT`	Initialization (default value, parameter file)
`XXPARM(ID,P)`	Parameter input (namelist, text, file)
`XXPROF`	Setup initial profile
`XXEXEC(DT)`	Execution (calculation or one time step)
`XXGOUT(P)`	Graphic output (command text)
`XXSAVE`	File output of calculation results
`XXLOAD`	File input of calculation results
`XXTERM`	Termination

Summary

- 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.
- Works in progress
  - Open source: Removing proprietary subroutines
  - Improvement of modules: Fully modular structure
  - Standard data interface with other simulation code
- Welcome to integrate Impurity module

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