Integrated Tokamak Code: TASK

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Acknowledgments
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Outline

1. Integrated Simulation of Fusion Plasmas
2. Integrated Tokamak Modeling Code: TASK
3. Transport Modeling
4. Source Modeling
5. ITER Modeling
6. Summary

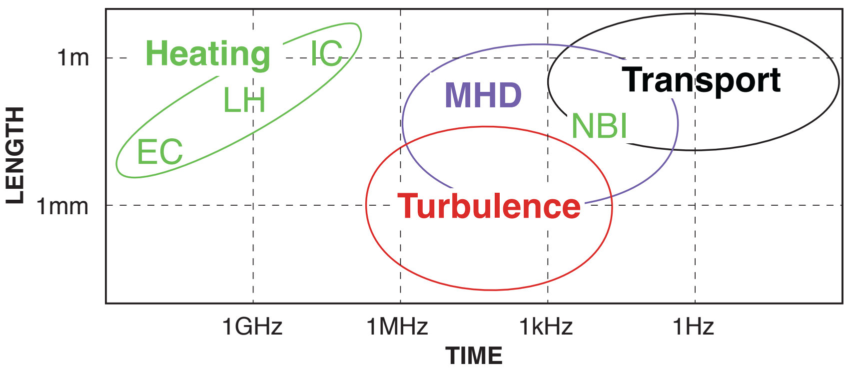
Integrated Simulation of Toroidal Plasmas

- **Why needed?**
  - To predict the behavior of burning plasmas in tokamaks
  - To develop reliable and efficient schemes to control them
- **What is needed?**
  - **Simulation describing:**
    - **Whole plasma** (core & edge & divertor & wall-plasma)
    - **Whole discharge**
      (startup & sustainment & transients events & termination)
    - **Reasonable accuracy** (validation by experiments)
    - **Reasonable computer resources** (still limited)
- **How can we do?**
  - Gradual increase of understanding and accuracy
  - Organized development of simulation system

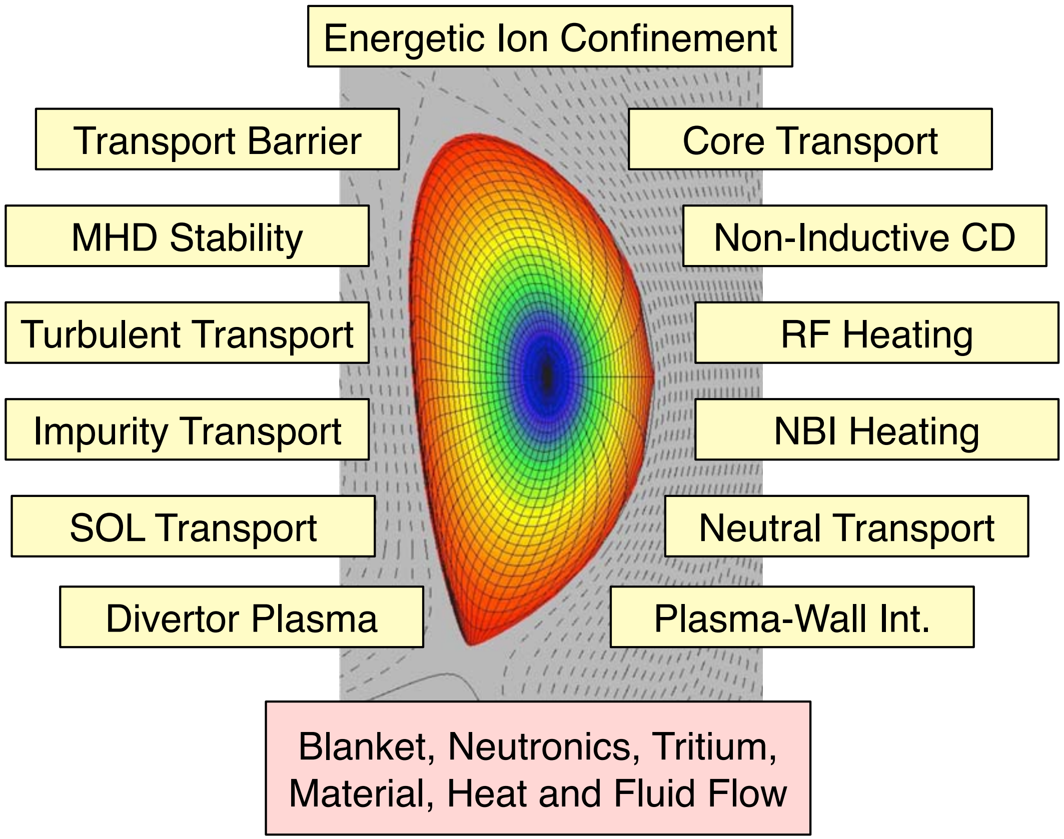
Simulation of Tokamak Plasmas

Broad range of time scale:
100GHz $\sim$ 1000s

Broad range of Spatial scale:
10 μm $\sim$ 10m

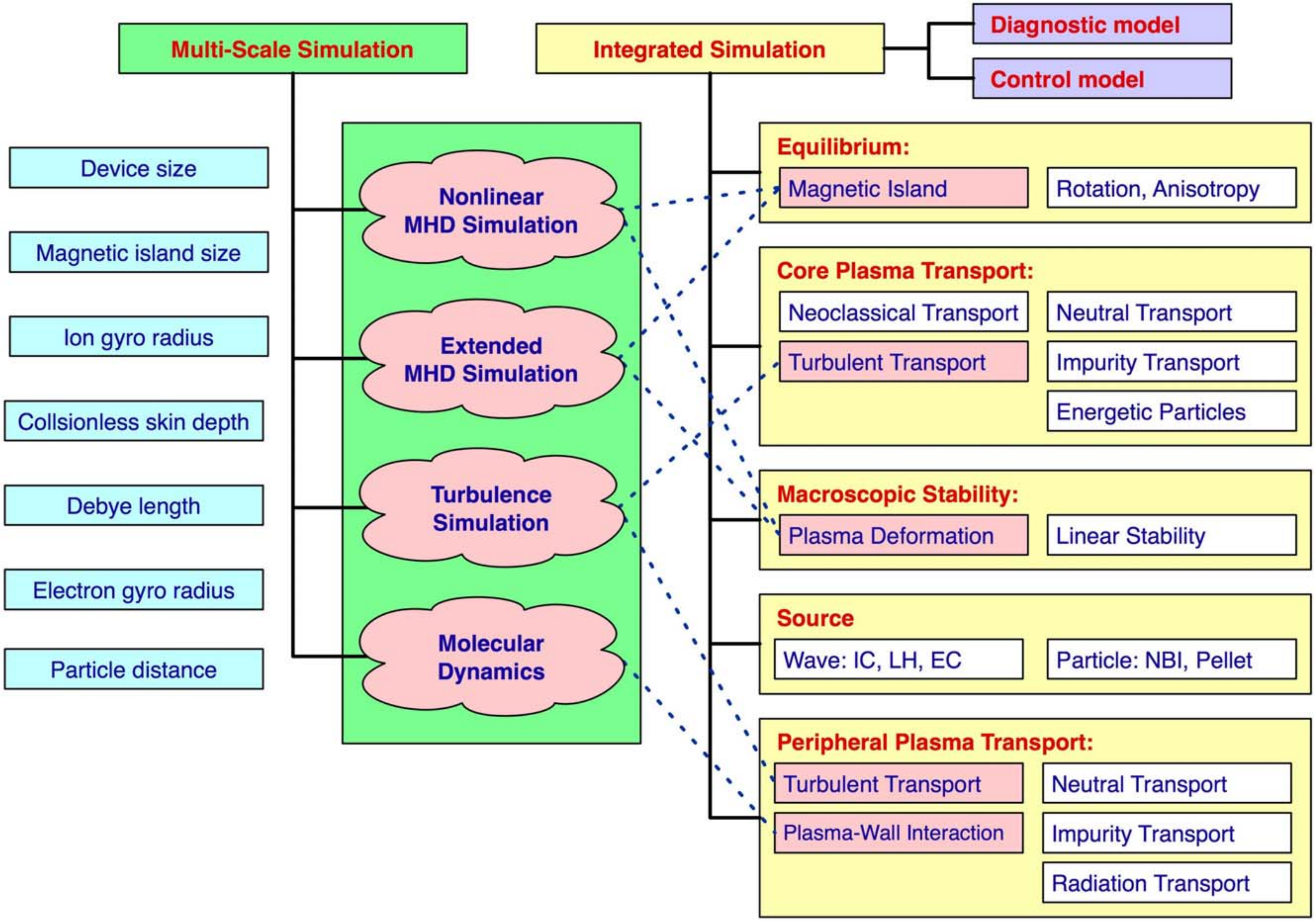


One simulation code never covers all range.



Integrated simulation combining modeling codes interacting each other

Integrated Tokamak Simulation



Desired Features of Integrated Modeling Code

- **Modular structure**: for flexible extension of analyses
  - **Core modules** (equilibrium, transport, source, stability)
  - **Various levels of models** (quick, standard, precise, rigorous)
  - **New physics models** (easier development)
- **Standard module interface**: for efficient development-of modules
- **Interface with experimental data**: for validating physics models
- **Unified user interface**: for user-friendly environment
- **Scalability in parallel processing** of time consuming modules
- **High portability**
- **Open source** of core modules
- **Visualization** included

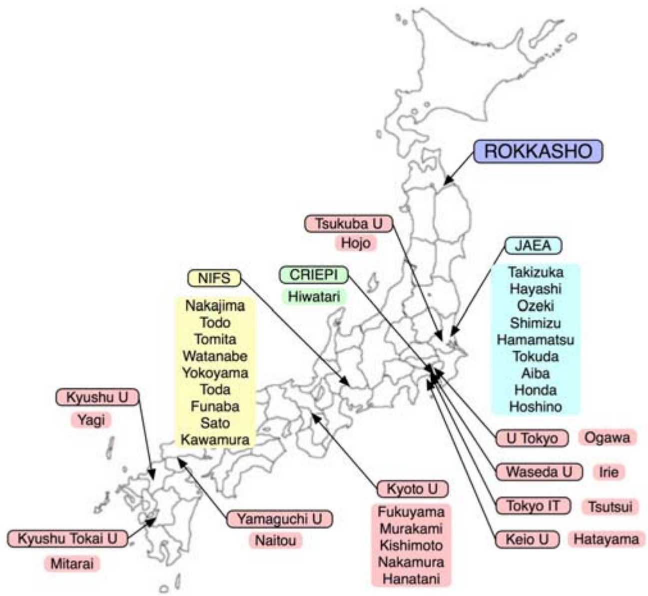
Integrated Modeling Activities

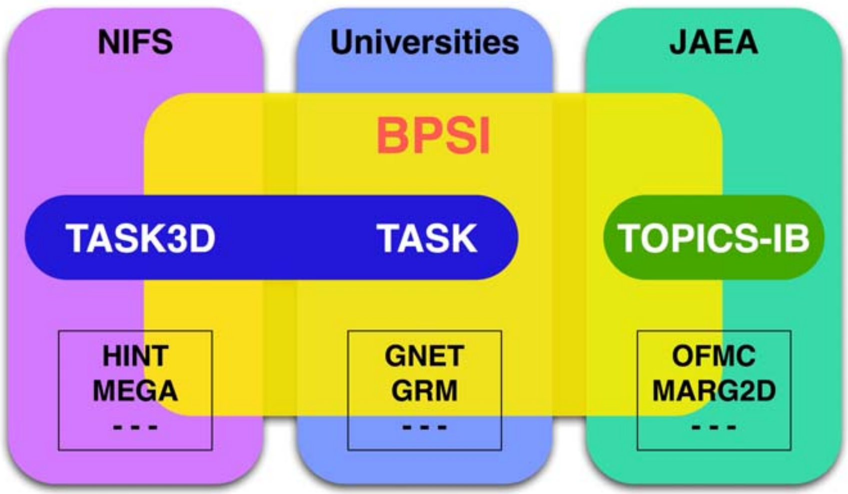
- **Japan**: **BPSI** (Burning Plasma Simulation Initiative)
  - Research collaboration among universities, NIFS and JAEA
    - Framework for code integration
    - Physics integration
    - Advanced computing technology
- **EU**: **ITM-TF** (EFDA Task Force: Integrated Transport Modeling)
  - Code Platform Project: code interface, data structure
  - Data Coordination Project: verification and validation
  - Five Integrated Modeling Projects: EQ, MHD, TR, Turb., Source
- **US**: **FSP** (Fusion simulation project) — a part of SciDAC
  - Simulation of Wave Interactions with Magnetohydrodynamics (SWIM)
  - Center for Plasma Edge Simulation (CPES)
  - Framework Application for Core-Edge Transport Simulations (FACETS)
- **ITER**: **IMEG** (Integrated Modeling Expert Group)

BPSI: Burning Plasma Simulation Initiative

Research Collaboration of 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





All Japan collaboration **Integrated code development**

Integrated Modeling Code: TASK

- **Transport Analysing System for TokamaK**
- **Features**
  - Core of Integrated Modeling Code in BPSI
    - Modular structure
    - Reference imprementation of standard data set and interface
  - Various Heating and Current Drive Scheme
    - EC, LH, IC, AW, NB
  - High Portability
    - Most of library routines included (except LAPACK, MPI, MDS+)
    - Original graphic libraries (X11, Postscript, OpenGL)
  - Development using CVS (Version control)
  - Open Source: **http://bpsi.nucleng.kyoto-u.ac.jp/task/**)
  - Parallel Processing using MPI Library (partially)

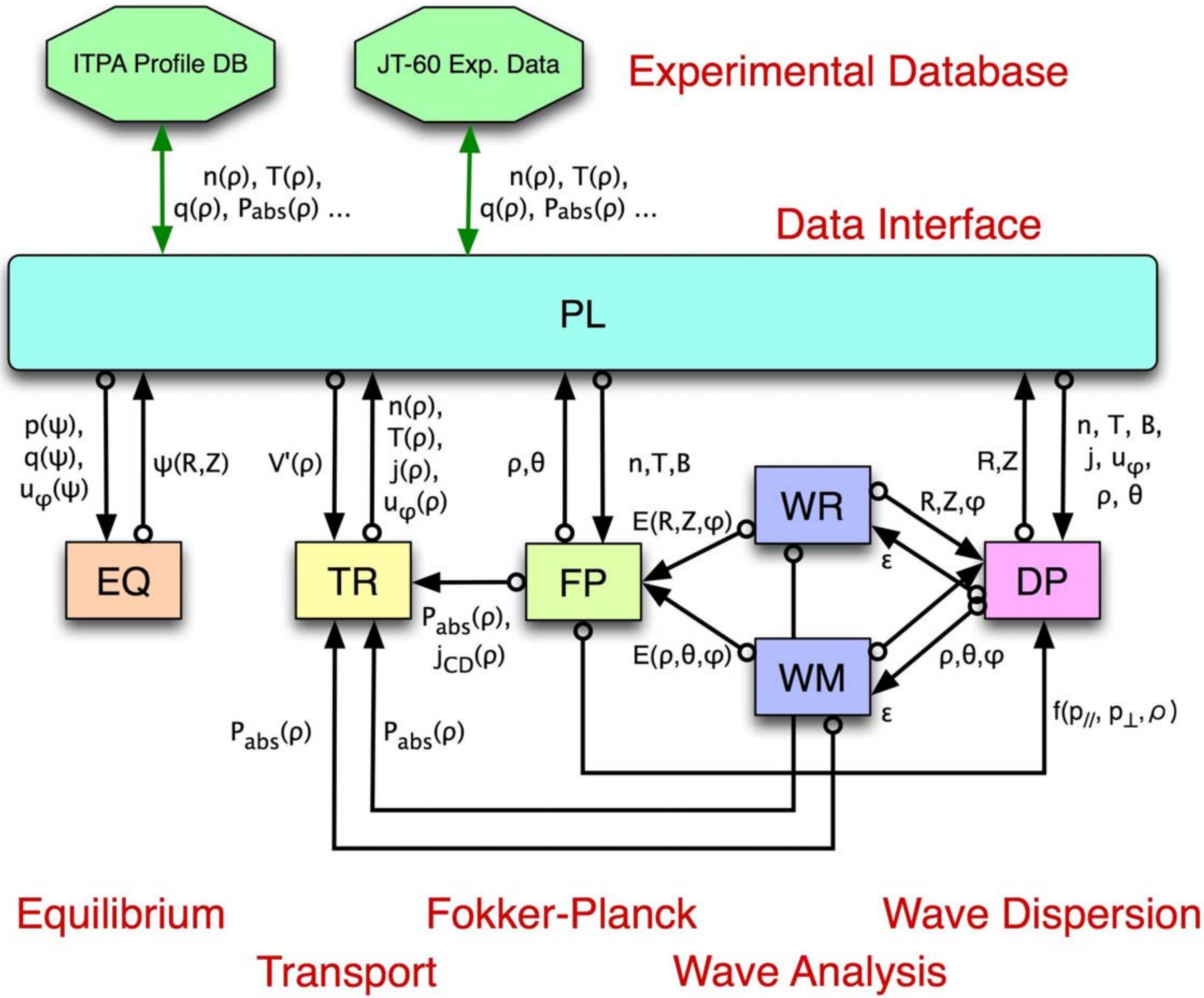
Components of the TASK Code

- **Developed since 1992, now in Kyoto University**

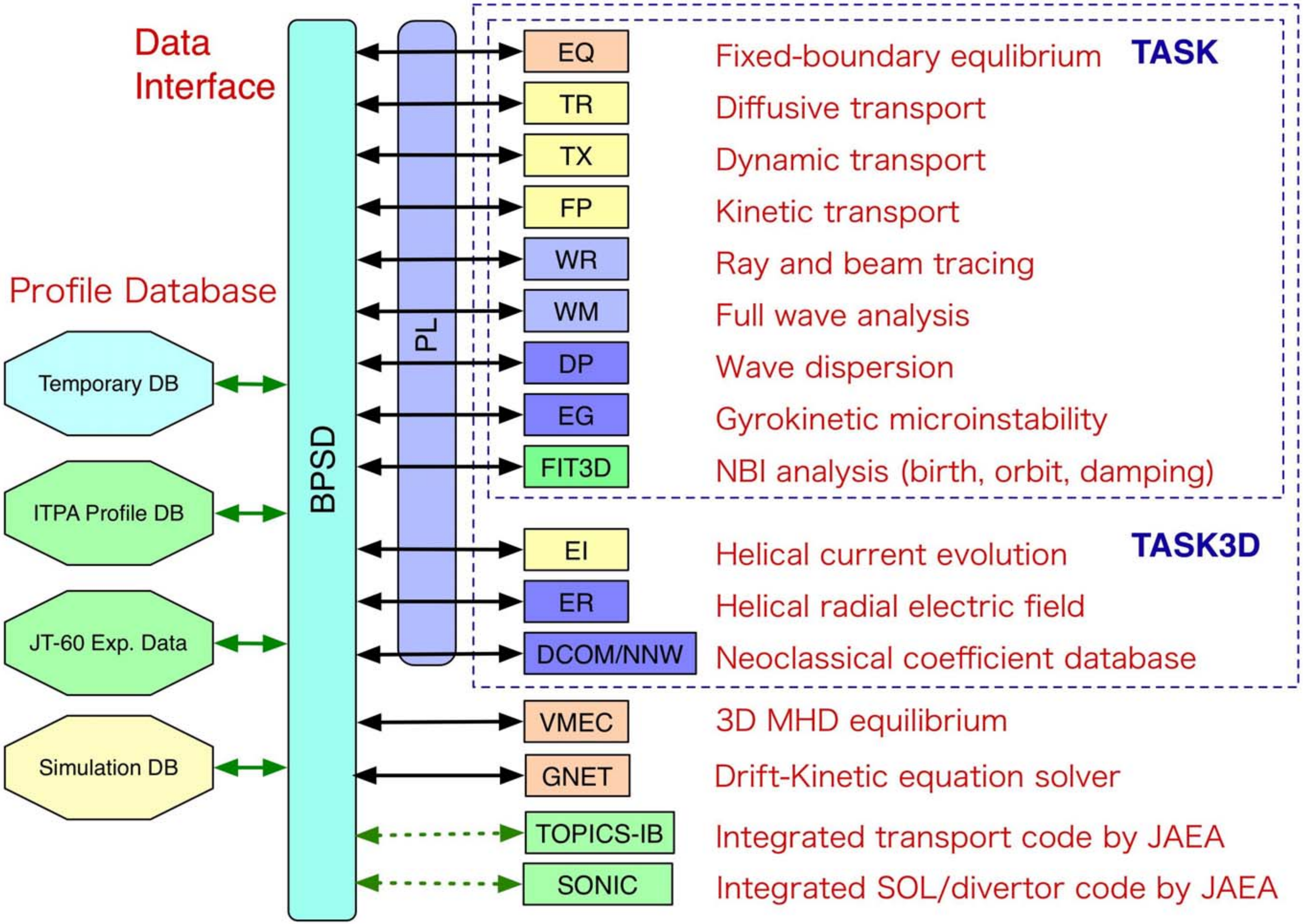
BPSD	**Data Exchange**	Standard data set, Program interface
EQ	**2D Equilibrium**	Fixed boundary, Toroidal rotation
TR	**1D Transport**	Diffusive transport, Transport models
TX	**1D Transport**	Dynamic Transport, Rotation and E_r
FP	**3D Fokker-Planck**	Relativistic, Bounce-averaged
WR	**3D Ray Tracing**	EC, LH: Ray tracing, Beam tracing
WM	**3D Full Wave**	IC: Antenna excite, Alfvén Eigenmode
DP	**Wave Dispersion**	Dielectric tensor, Arbitrary $f(\boldsymbol{v})$
FIT3D	**NBI Physics**	Birth, Orbit width, Deposition
PL	**Utilities**	Interface to BPSD and profile database
LIB	**Libraries**	Common libraries, MTX, MPI
GSAF	**Graphics**	Original graphic library for Fortran

- **TASK3D**: Extension to 3D Helical Plasmas (**NIFS and Kyoto U**)

Original Structure of the TASK code



Present Structure of TASK and Related Codes in BPSI



Inter-Module Collaboration Interface

- **Role of Module Interface**
  - **Data exchange between modules**: **BPSD**
    - **Standard dataset**: Specify set of data
    - **Specification of data exchange interface**: set/get/load/save
  - **Execution control**: **BPSX**
    - **Specification of execution control interface**: initialize, setup, exec, visualize, terminate
    - **Uniform user interface**: parameter input, graphic output
- **Role of data exchange interface**
  - **Keep present status of plasma and device**
  - **Save into file and load from file**
  - **Store history of plasma**
  - **Interface to experimental data base**

Policies of BPSD

- **Minimum and Sufficient Dataset**
  - **To minimize the data to be exchanged**
  - **Mainly profile data**
  - **Routines to calculate global integrated quantities**
    - separately provided
- **Minimum Arguments in Interfaces**
  - **To maximize flexibility**
  - **Use derived data type or struct**
  - **Only one dataset in the arguments of an interface**
- **Minimum Interfaces**
  - **To make modular programming easier**
  - **Use function overloading**

Data Exchange Interface: BPSD

- **Standard dataset**: Specify data to be stored and exchanged
  - **Data structure**: Derived type (Fortran95): structured type

e.g.

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

- **Specification of API**:
  - **Program interface**

e.g.

Set data	`bpsd_set_data(plasmaf,ierr)`
Get data	`bpsd_get_data(plasmaf,ierr)`
Save data	`bpsd_save(ierr)`
Load data	`bpsd_load(ierr)`

BPSD Standard Dataset (version 0.6)

Category	Name	EQ	TR	TX	FP	WR	WM	DP
Shot data	bpsd_shot_type	–	–	–	–	–	–	–
Device data	bpsd_device_type	in	in	in	in			
1D equilibrium data	bpsd_equ1D_type	out	in	in	in			
2D equilibrium data	bpsd_equ2D_type	out			in	in	in	in
1D metric data	bpsd_metric1D_type	out	in	in	in			
2D metric data	bpsd_metric2D_type	out			in	in	in	in
Plasma species data	bpsd_species_type	in	in	in	in			in
Fluid plasma data	bpsd_plasmaf_type	in	out	out	i/o			in
Kinetic plasma data	bpsd_plasmak_type				out			in
Transport matrix data	bpsd_trmatrix_type		i/o					
Transport source data	bpsd_trsource_type		i/o	i/o	i/o	out	out	
Dielectric tensor data	bpsd_dielectric_type					in	in	out
Full wave field data	bpsd_wavef_type				in	out		
Ray tracing field data	bpsd_waver_type				in		out	
Beam tracing field data	bpsd_waveb_type				in		out	
User defined data	bpsd_0/1/2ddata_type	–	–	–	–	–	–	–

Execution Control Interface

- **BPSX**: not yet decided
  - **Monolithic integrated code**
  - **Script-driven element codes**
  - **MPI-2 driven element codes**

- **Example of element codes for TASK/TR**

`TR_INIT`	Initialization (Default value)
`TR_PARM(ID,PSTR)`	Parameter setup (Namelist input)
`TR_SETUP(T)`	Profile setup (Spatial profile, Time)
`TR_EXEC(DT)`	Exec one step (Time step)
`TR_GOUT(PSTR)`	Plot data (Plot command)
`TR_SAVE`	Save data in file
`TR_LOAD`	load data from file
`TR_TERM`	Termination

Equilibrium Analysis

- **Shape of an axisymmetric plasma**: poloidal magnetic flux $\psi(R,Z)$
- **Grad-Shafranov equation**

$$R\frac{\partial}{\partial R}\frac{1}{R}\frac{\partial\psi}{\partial R}+\frac{\partial^2\psi}{\partial Z^2}=-\mu_0 R^2\frac{\mathrm{d}p(\psi)}{\mathrm{d}\psi}-F(\psi)\frac{\mathrm{d}F(\psi)}{\mathrm{d}\psi}$$

  - **Pressure profile**: $p(\psi)$
  - **Poloidal current density profile**: $F(\psi)$
  - **Plasma boundary shape** (fixed boundary) or **Poloidal coil current** (free boundary)

  determines the poloidal plasma shape.

- **Coupling with transport analysis**
  - **Input**: $p(\psi)$, $q(\psi)=F\dfrac{\mathrm{d}V}{\mathrm{d}\psi}\left\langle\dfrac{1}{R^2}\right\rangle$
  - **Output**: Metric quantities, Flux surface averaged quantities

Various Levels of Transport Modeling

Fluid model

Diffusive transport equation	$n(\rho,t)$, $T(\rho,t)$	TR
Dynamic transport equation	$n(\rho,t)$, $\mathbf{u}(\rho,t)$, $T(\rho,t)$, $\mathbf{q}(\rho,t)$	TX

Kinetic model

Bounce-averaged gyrokinetic equation	$f(p, \theta_p, \rho, t)$	FP
Axisymmetric gyrokinetic equation	$f(p, \theta_p, \rho, \chi, t)$	
Gyrokinetic equation	$f(p, \theta_p, \rho, \chi, \zeta, t)$	
Full kinetic equation	$f(p, \theta_p, \phi_g, \rho, \chi, \zeta, t)$	

Transport Modeling in the TASK code

- **Diffusive transport equation**: **TASK/TR**
  - Diffusion equation for plasma density
  - Flux-Gradient relation
  - Conventional transport analysis
- **Dynamical transport equation: TASK/TX**:
  - Continuity equation and equation of motion for plasma density
  - Flux-averaged fluid equation
  - Plasma rotation and transient phenomena
- **Kinetic transport equation: TASK/FP**:
  - Gyrokinetic equation for momentum distribution function
  - Bounce-averaged Fokker-Plank equation
  - Modification of momentum distribution

Diffusive Transport Equation: TASK/TR

- **Transport Equation Based on Gradient-Flux Relation**:

$$\boldsymbol{\Gamma} = \overleftrightarrow{M} \cdot \partial \boldsymbol{F}/\partial\rho$$

where 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**

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

Transport Processes

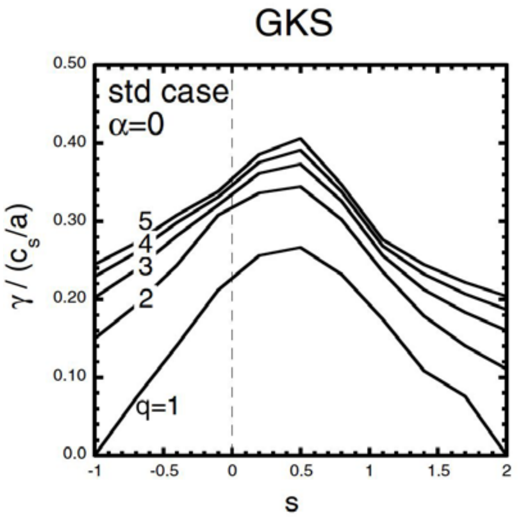
- **Neoclassical transport**
  - Collisional transport in an inhomogeneous magnetic field
  - **Radial diffusion**: usually small compared with turbulent diffusion
  - **Enhanced resistivity**: due to trapped particles
  - **Bootstrap current**: toroidal current driven by radial pressure gradient
  - **Ware pinch**: Radial particle pinch driven by toroidal electric field
- **Turbulent transport**
  - Various transport models: GLF23, CDBM, Weiland, $\cdots$
- **Atomic transport**: charge exchange, ionization, recombination
- **Radiation transport**
  - Line radiation, Bremsstrahlung, Synchrotron radiation
- **Parallel transport**: along open magnetic field lines in SOL plasmas

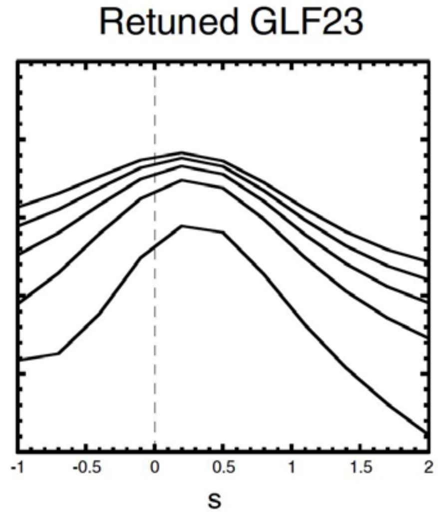
Turbulent Transport Models

- **CDBM model**: current diffusive ballooning mode turbulence model
  - **developed by K. Itoh et al.**
  - Marginal stability condition of the current diffusive ballooning mode including turbulent transport coefficients as parameters
- **GLF23 model**: Gyro-Landau-Fluid turbulence model
  - **developed by Waltz and Kinsey (GA)**
  - Linear growth rate from gyro-Landau-fluid model (ITG, TEM, ETG)
  - Evaluate transport coefficients based on mixing length estimate
  - Calibrate coefficients by the linear stability code GKS
  - Calibrate coefficients by the nonlinear turbulence code GYRO
- **Weiland model**:
  - **developed by J. Weiland**
  - Based on ITG turbulence model

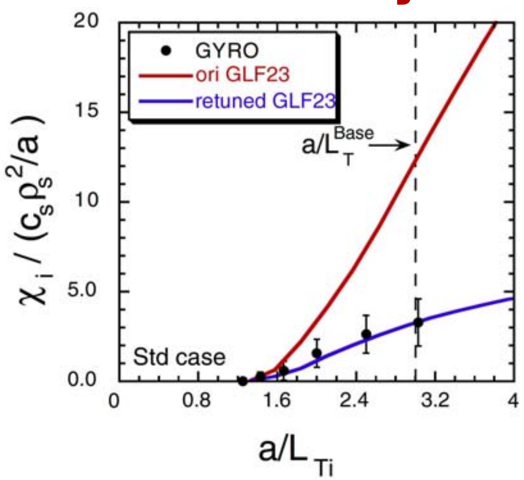
GLF23 Transport Model

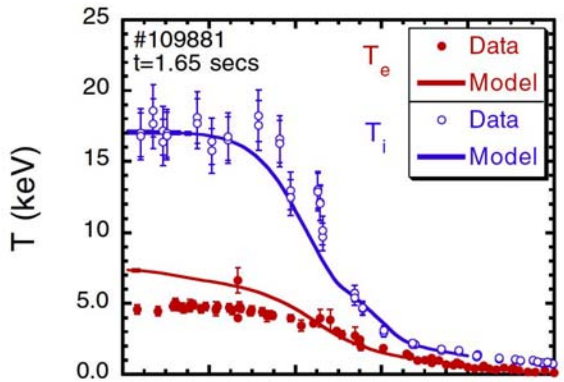
Linear growth rate from gyro-Landau-fluid model





Calibrate coefficients by the nonlinear turbulence code GYRO





Good agreement with experimental data

CDBM Transport Model: CDBM05

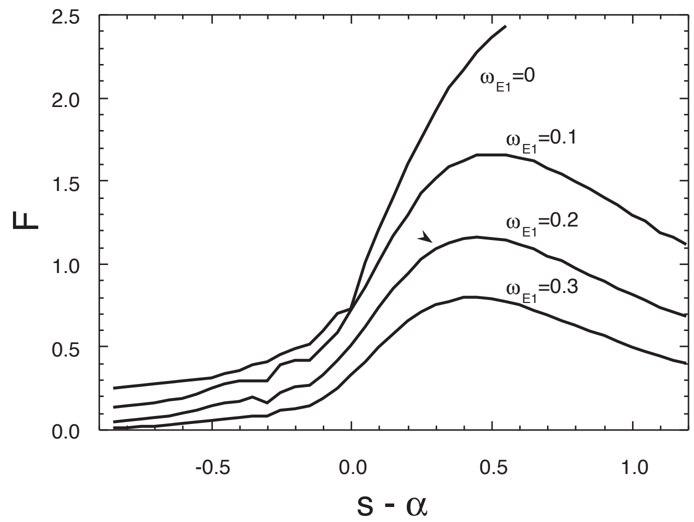
- **Thermal Diffusivity** (Marginal: $\gamma = 0$)

$$\chi_{\rm TB} = F(s, \alpha, \kappa, \omega_{\rm E1})\, \alpha^{3/2} \frac{c^2}{\omega_{\rm pe}^2} \frac{v_{\rm A}}{qR}$$

Magnetic shear	$s \equiv \dfrac{r}{q}\dfrac{\mathrm{d}q}{\mathrm{d}r}$
Pressure gradient	$\alpha \equiv -q^2 R \dfrac{\mathrm{d}\beta}{\mathrm{d}r}$
Elongation	$\kappa \equiv b/a$
$E \times B$ **rotation shear**	$\omega_{\rm E1} \equiv \dfrac{r^2}{s v_{\rm A}} \dfrac{\mathrm{d}}{\mathrm{d}r} \dfrac{E}{rB}$

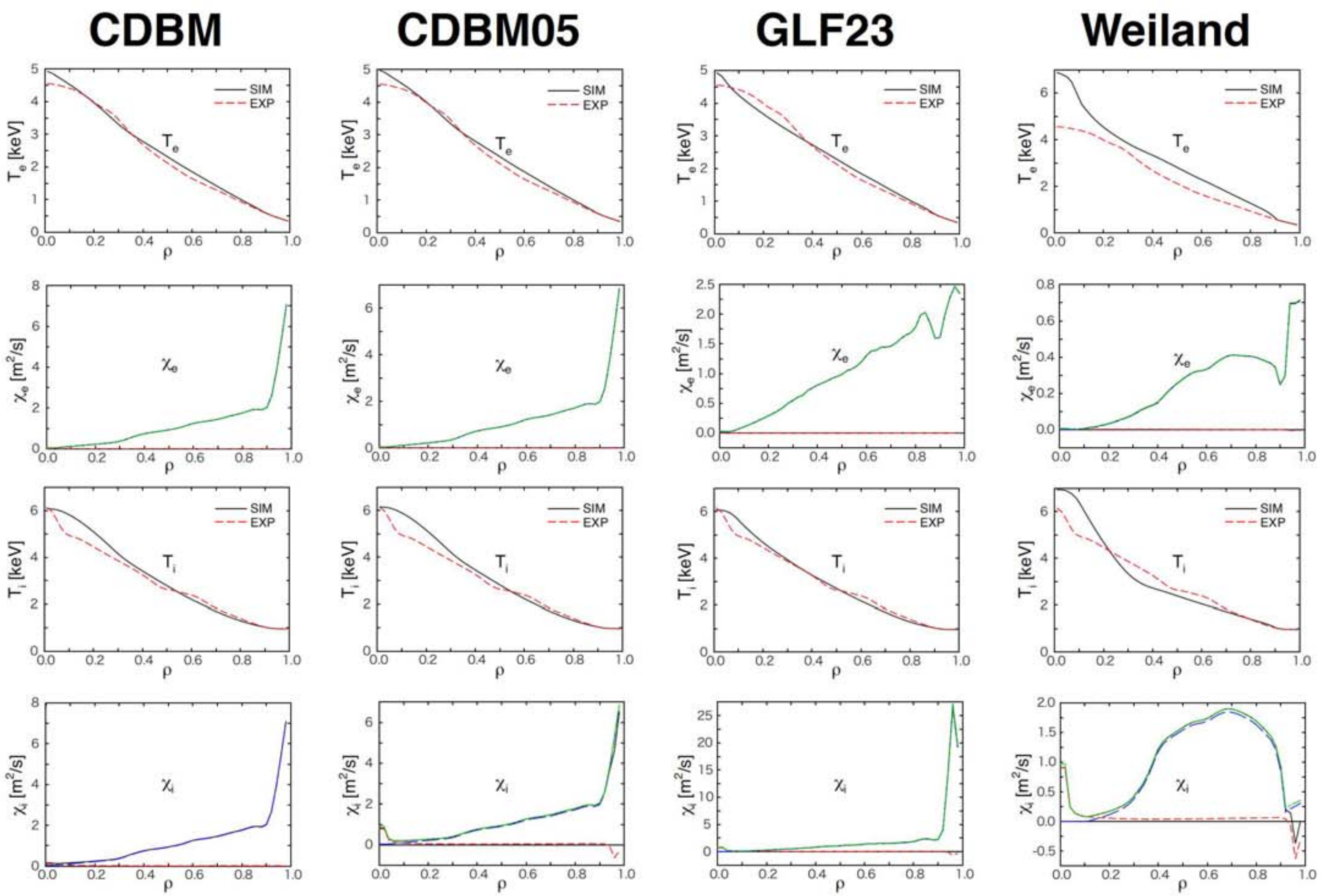
- **Weak and negative magnetic shear,**
  Shafranov shift, elongation,
  and $E \times B$ rotation shear
  reduce thermal diffusivity.

$s - \alpha$ dependence of $F(s, \alpha, \kappa, \omega_{\rm E1})$

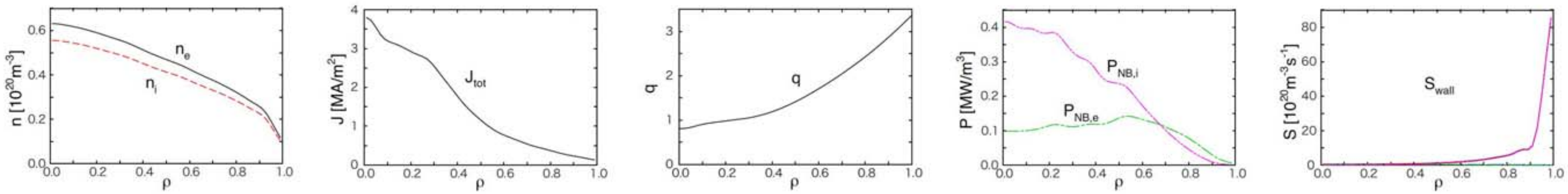


$$F(s, \alpha, \kappa, \omega_{\rm E1}) = \left(\frac{2\kappa^{1/2}}{1+\kappa^2}\right)^{3/2} \times \begin{cases} \dfrac{1}{1+G_1\omega_{\rm E1}^2} \dfrac{1}{\sqrt{2(1-2s')(1-2s'+3s'^2)}} & \text{for } s' = s - \alpha < 0 \\[2ex] \dfrac{1}{1+G_1\omega_{\rm E1}^2} \dfrac{1+9\sqrt{2}s'^{5/2}}{\sqrt{2}(1-2s'+3s'^2+2s'^3)} & \text{for } s' = s - \alpha > 0 \end{cases}$$

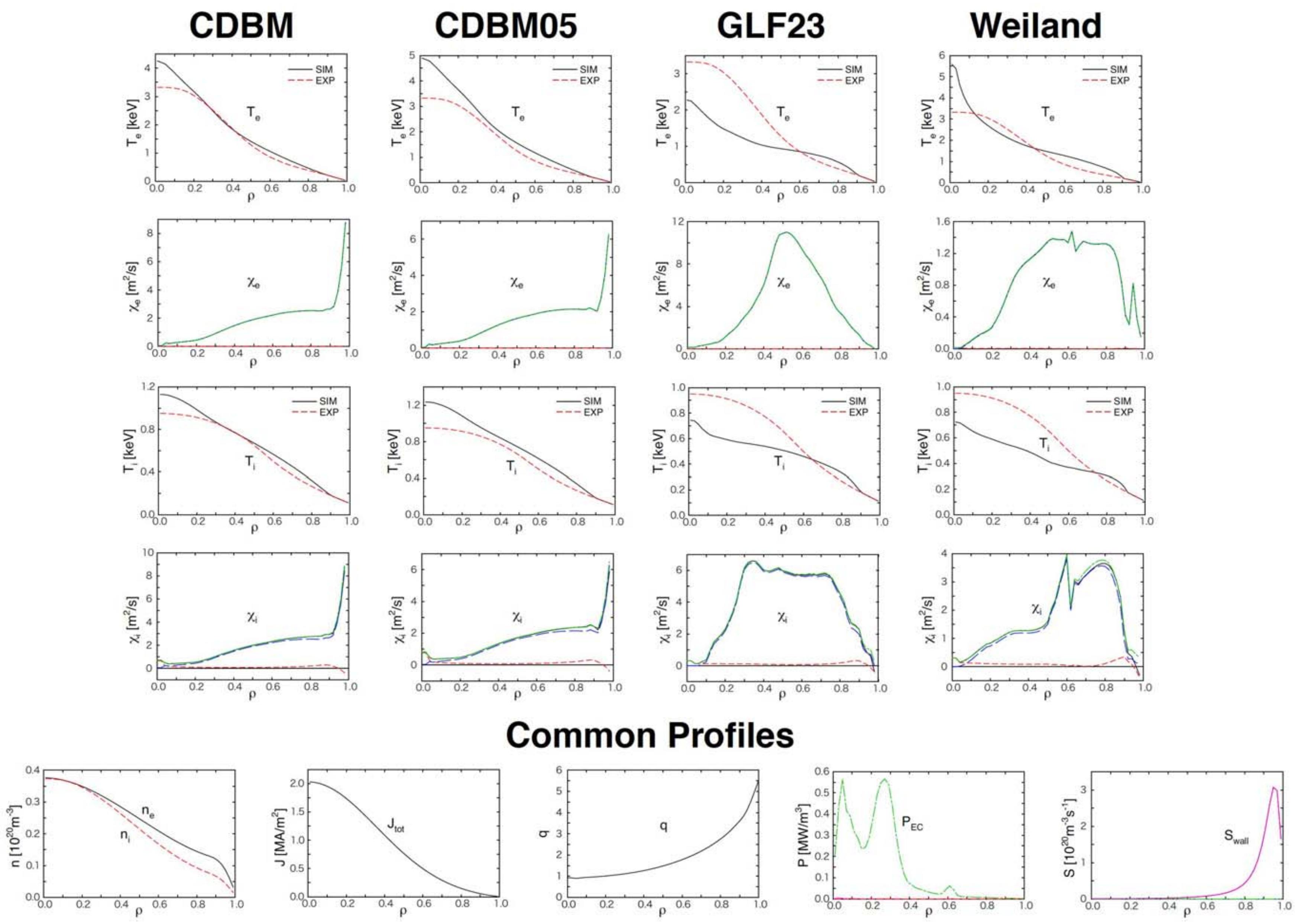
TFTR #88615 (L-mode, NBI heating)



Common Profiles



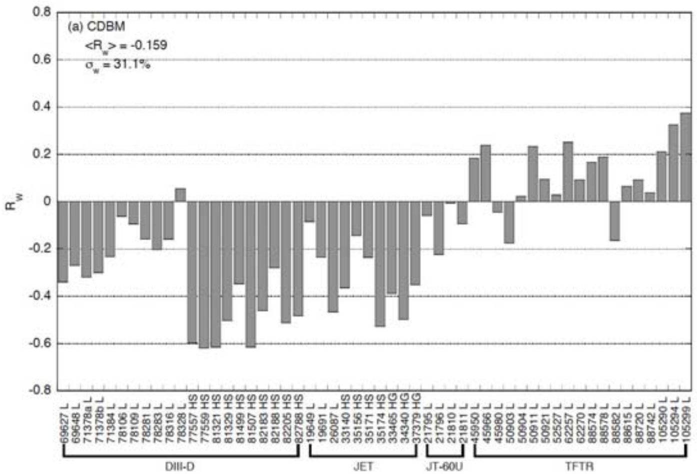
DIII-D #78316 (L-mode, ECH and ICH heatings)



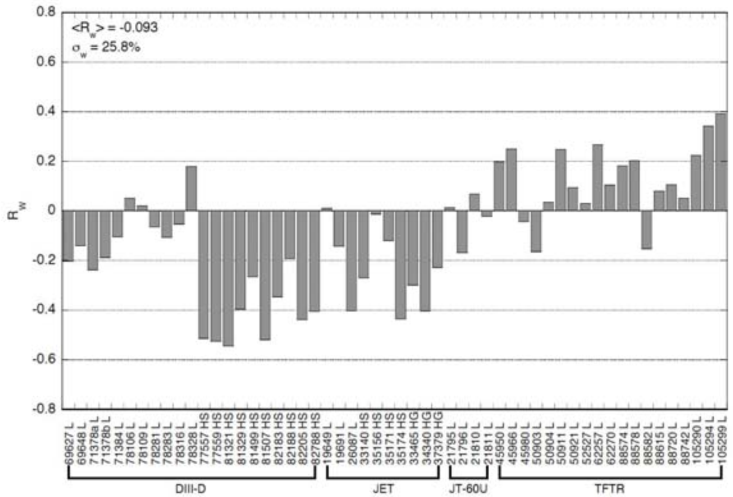
Comparison of Transport Models: ITPA Profile DB

Deviation of Stored Energy

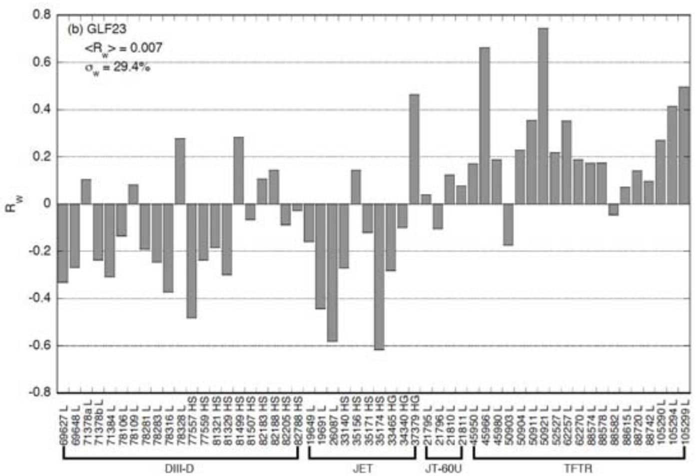
CDBM



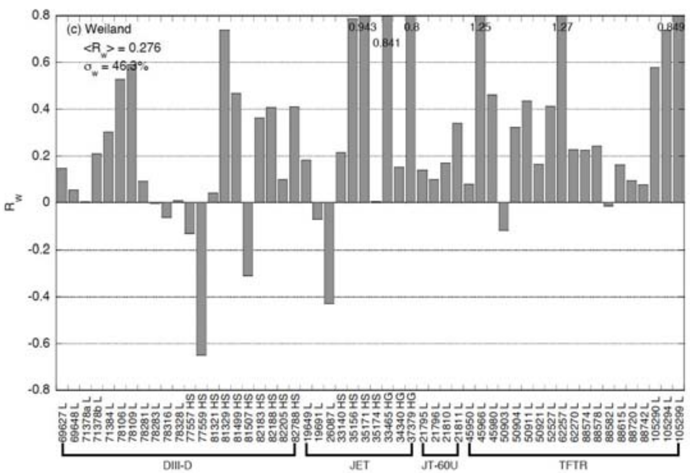
CDBM05



GLF23



Weiland



1D Dynamic Transport Code: TASK/TX

- **Dynamic Transport Equations** (TASK/TX)

  M. Honda and A. Fukuyama, JCP 227 (2008) 2808

  – **A set of flux-surface averaged equations**
  – **Two fluid equations for electrons and ions**
    ◦ Continuity equations
    ◦ Equations of motion (radial, poloidal and toroidal)
    ◦ Energy transport equations
  – **Maxwell's equations**
  – **Slowing-down equations for beam ion component**
  – **Diffusion equations for two-group neutrals**
- **Self-consistent description of plasma rotation and electric field**
  – Equation of motion rather than transport matrix
- **Quasi-neutrality is not assumed.**

Model Equation of Dynamic Transport Simulation

- **Flux-surface-averaged multi-fluid equations**:

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

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

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

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

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

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

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

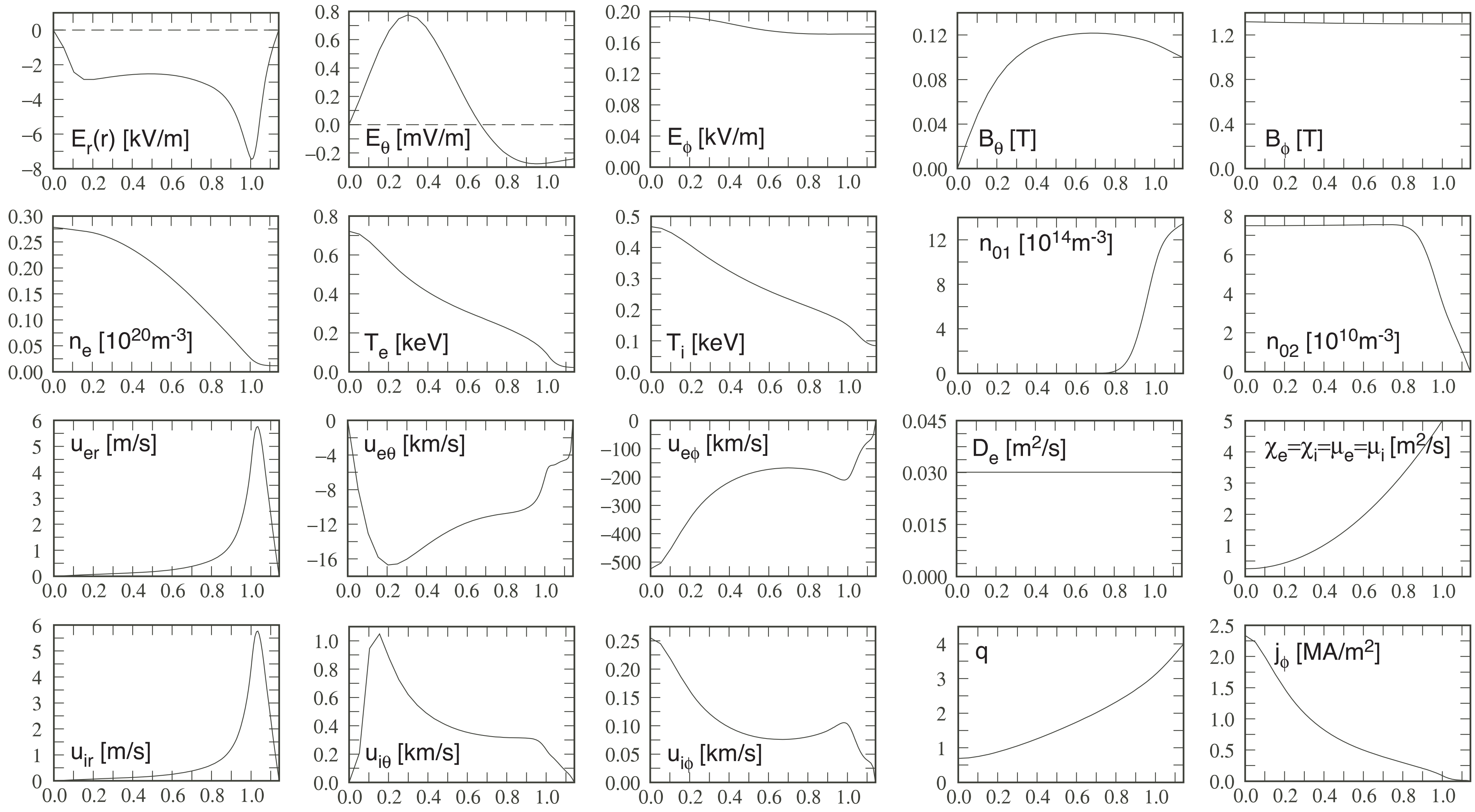
$$+P_s^{\mathrm{C}} + P_s^{\mathrm{L}} + P_s^{\mathrm{H}}$$

Typical Ohmic Plasma Profiles at $t = 50\,\mathrm{ms}$

JFT-2M like plasma composed of electron and hydrogen

$R = 1.3\,\mathrm{m}$, $a = 0.35\,\mathrm{m}$, $b = 0.4\,\mathrm{m}$, $B_{\phi b} = 1.3\,\mathrm{T}$, $I_p = 0.2\,\mathrm{MA}$, $S_{\mathrm{puff}} = 5.0 \times 10^{18}\,\mathrm{m}^{-2}\mathrm{s}^{-1}$

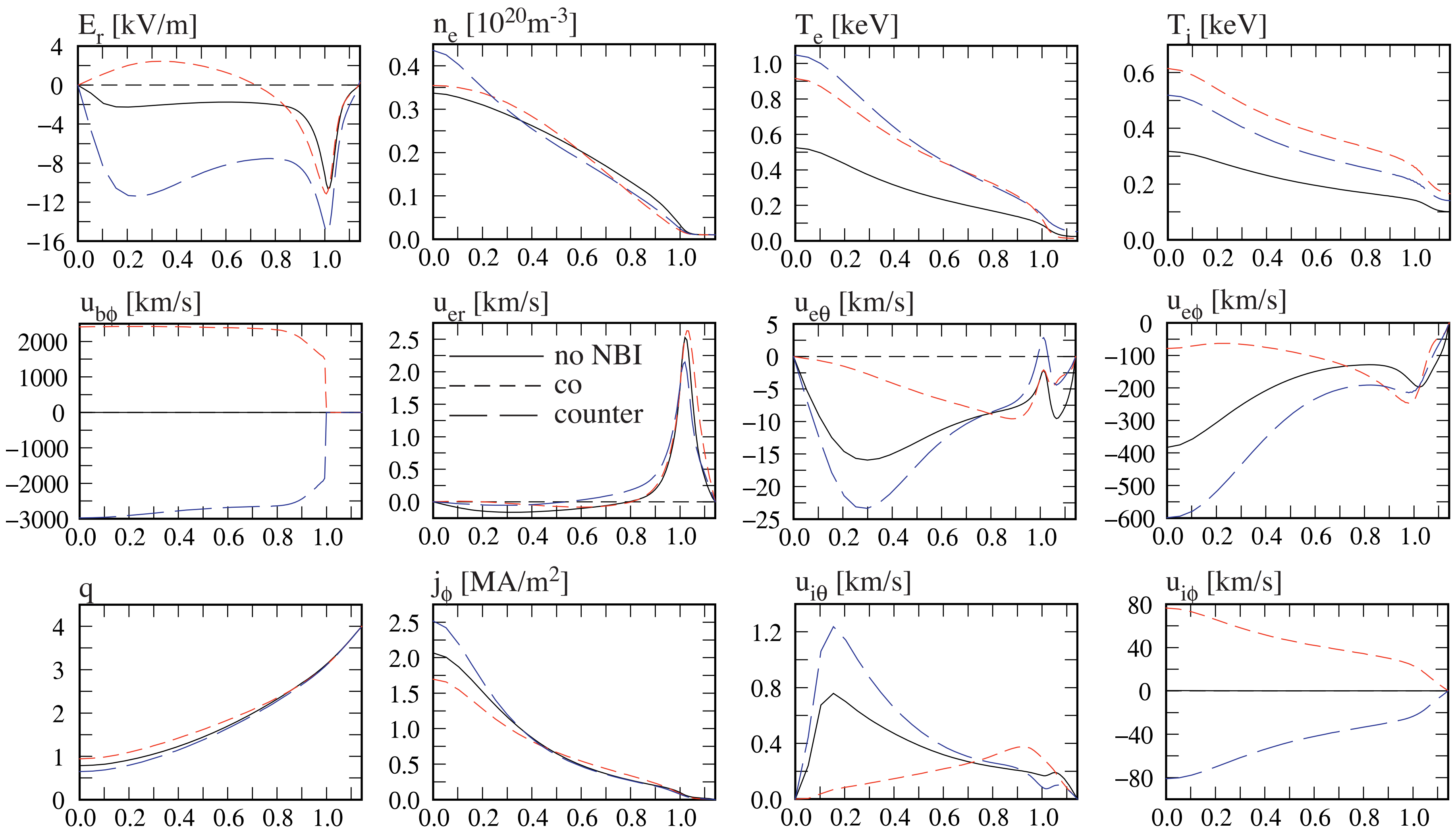
$\gamma = 0.8$, $Z_{\mathrm{eff}} = 2.0$, Fixed turbulent coefficient profile



Density Profile Modification Due to NBI Injection

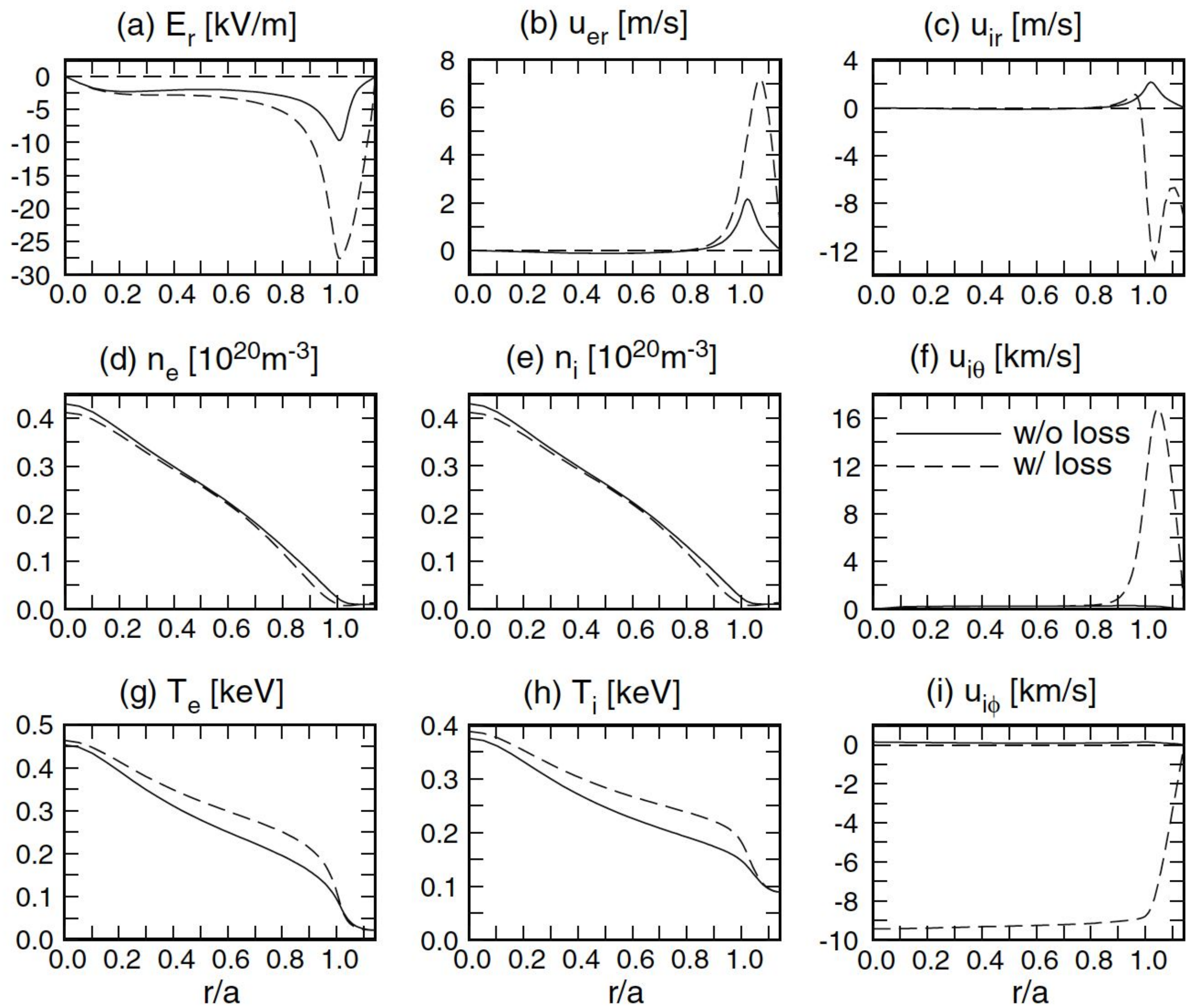
Modification of n and E_r profile depends on the direction of NBI.

Co/Counter with I_p: Density flattening/peaking



Toroidal Rotation Due to Ion Orbit Loss

- **Ion orbit loss near the edge region drives toroidal rotation**



Ref. M. Honda et al., NF (2008) 085003

Source Modeling

- **Heat and momentum sources**:
  - **Alpha particle heating**:
    - sensitive to fuel density and momentum distribution
  - **Neutral beam injection**:
    - birth profile, finite size orbit, deposition to bulk plasma
  - **Waves**:
    - IC ($\sim 50\,\mathrm{MHz}$): fuel ion heating, current drive, rotation drive(?)
    - LH ($\sim 10\,\mathrm{GHz}$): current drive
    - EC ($\sim 170\,\mathrm{GHz}$): current drive, pre-ionization
- **Particle source**
  - **Gas puff, recycling**:
  - **Neutral beam injection**:
  - **Pellet injection**: penetration, evaporation, ionization, drift motion

Wave Modeling

- **Ray tracing**: **EC, LH**
  - Spatial evolution of ray position and wave number
  - Wave length λ much less than scale length L: $\lambda \ll L$
  - Beam size d is sufficiently large (**Fresnel condition**): $L \ll d^2/\lambda$
- **Beam tracing**: **EC**
  - New variables: beam radius, curvature of equi-phase surface
- **Beam propagation**: **EC**
  - Under development: Time evolution of $\boldsymbol{E}(\boldsymbol{r}, t)\,\mathrm{e}^{\,\mathrm{i}\,\omega t}$
- **Full wave analysis**: **IC, AW, MHD**
  - Stationary Maxwell's equation as a boundary problem
  - Wave length λ comparable with scale length L
  - Evanescent region, strong absorption, coupling with antenna

Wave Dispersion Analysis : TASK/DP

- **Various Models of Dielectric Tensor** $\overleftrightarrow{\epsilon}(\omega, \boldsymbol{k}; \boldsymbol{r})$:
- **Analytic model**
  - Resistive MHD model
  - Collisional cold plasma model
  - Collisional warm plasma model
  - Kinetic model (Maxwelian, non-relativistic)
  - Drift-kinetic model (Maxwellian, inhomogeneity)
  - Hamiltonian formulation (cyclotron, bounce, precession)
- **Numerical integrateion**
  - Kinetic model (Relativistic, Maxwellian)
  - Kinetic model (Relativistic, arbitrary $f(\boldsymbol{v})$)
  - Drift-kinetic model (Inhoogeneity, arbitrary $f(\boldsymbol{v})$)
  - Hamiltonian formulation (arbitrary $f(\boldsymbol{v})$)

Ray Tracing: TASK/WR

- **Geometrical Optics**
  - Wave length $\lambda \ll$ Characteristic scale length L of the medium
  - Plane wave: Beam size d is sufficiently large
    - **Fresnel condition is well satisfied**: $L \ll d^2/\lambda$

- **Evolution along the ray trajectory τ**
  - Wave packet position $\boldsymbol{r}$, wave number $\boldsymbol{k}$, dielectric tensor K
  - **Ray tracing equation**:

$$\frac{\mathrm{d}\boldsymbol{r}}{\mathrm{d}\tau} = \frac{\partial K}{\partial \boldsymbol{k}} \Big/ \frac{\partial K}{\partial \omega}$$

$$\frac{\mathrm{d}\boldsymbol{k}}{\mathrm{d}\tau} = -\frac{\partial K}{\partial \boldsymbol{r}} \Big/ \frac{\partial K}{\partial \omega}$$

  - **Equation for wave energy** W, group velocity $\boldsymbol{v}_{\mathrm{g}}$, damping rate γ

$$\boldsymbol{\nabla} \cdot \left(\boldsymbol{v}_{\mathrm{g}} W\right) = -2\gamma W$$

Beam Tracing: TASK/WR

- Beam size perpendicular to the beam direction: first order in ϵ
- **Beam shape** : Hermite polynomial: H_n)

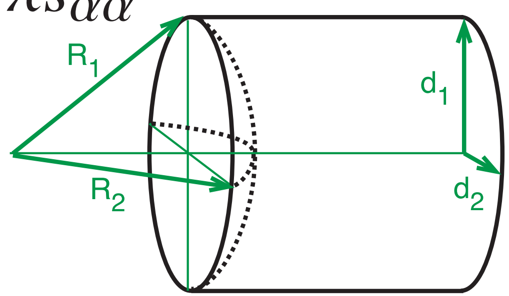
$$\boldsymbol{E}(\boldsymbol{r}) = \mathrm{Re}\left[\sum_{mn} C_{mn}(\epsilon^2\boldsymbol{r})\boldsymbol{e}(\epsilon^2\boldsymbol{r})H_m(\epsilon\xi_1)H_n(\epsilon\xi_2)\,\mathrm{e}^{\,\mathrm{i}\,s(\boldsymbol{r})-\phi(\boldsymbol{r})}\right]$$

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

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

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

  - Position of beam axis : $\boldsymbol{r}_0$, Wave number on beam axis: $\boldsymbol{k}^0$
  - **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 $m = 0$, $n = 0$

Beam Propagation Equation

- **Solvable condition for Maxwell's equation with beam field**

$$\frac{\mathrm{d}r_0^\alpha}{\mathrm{d}\tau} = \frac{\partial K}{\partial k_\alpha}$$

$$\frac{\mathrm{d}k_\alpha^0}{\mathrm{d}\tau} = -\frac{\partial K}{\partial r^\alpha}$$

$$\frac{\mathrm{d}s_{\alpha\beta}}{\mathrm{d}\tau} = -\frac{\partial^2 K}{\partial r^\alpha \partial r^\beta} - \frac{\partial^2 K}{\partial r^\beta \partial k_\gamma} s_{\alpha\gamma} - \frac{\partial^2 K}{\partial r^\alpha \partial k_\gamma} s_{\beta\gamma} - \frac{\partial^2 K}{\partial k^\gamma \partial k^\delta} s_{\alpha\gamma} s_{\beta\delta} + \frac{\partial^2 K}{\partial k^\gamma \partial k^\delta} \phi_{\alpha\gamma}\phi_{\beta\delta}$$

$$\frac{\mathrm{d}\phi_{\alpha\beta}}{\mathrm{d}\tau} = -\left(\frac{\partial^2 K}{\partial r^\alpha \partial k^\gamma} + \frac{\partial^2 K}{\partial k^\gamma \partial k_\delta} s_{\alpha\delta}\right)\phi_{\beta\gamma} - \left(\frac{\partial^2 K}{\partial r^\beta \partial k^\gamma} + \frac{\partial^2 K}{\partial k^\gamma \partial k_\delta} s_{\beta\delta}\right)\phi_{\alpha\gamma}$$

- By integrating this set of 18 ordinary differential equations, we obtain trace of the beam axis, wave number on the beam axis, curvature of equi-phase surface, and beam size.
- **Equation for the wave amplitude** C_{mn}

$$\nabla \cdot \left(\boldsymbol{v}_{\mathrm{g}0}|C_{mn}|^2\right) = -2\left(\gamma |C_{mn}|^2\right)$$

Group velocity: $\boldsymbol{v}_{\mathrm{g}0}$, Damping rate: $\gamma \equiv (\boldsymbol{e}^* \cdot \overleftrightarrow{\epsilon}_{\mathrm{A}} \cdot \boldsymbol{e})/(\partial K/\partial\omega)$

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 **multi-species velocity distribution function**: $f_s(p_\parallel, p_\perp, \psi, t)$

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

  - $E(f)$: 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 and energy conservation
- **Multi-species**: conservation between species
- **Three-dimensional**: spatial diffusion (neoclassical, turbulent)

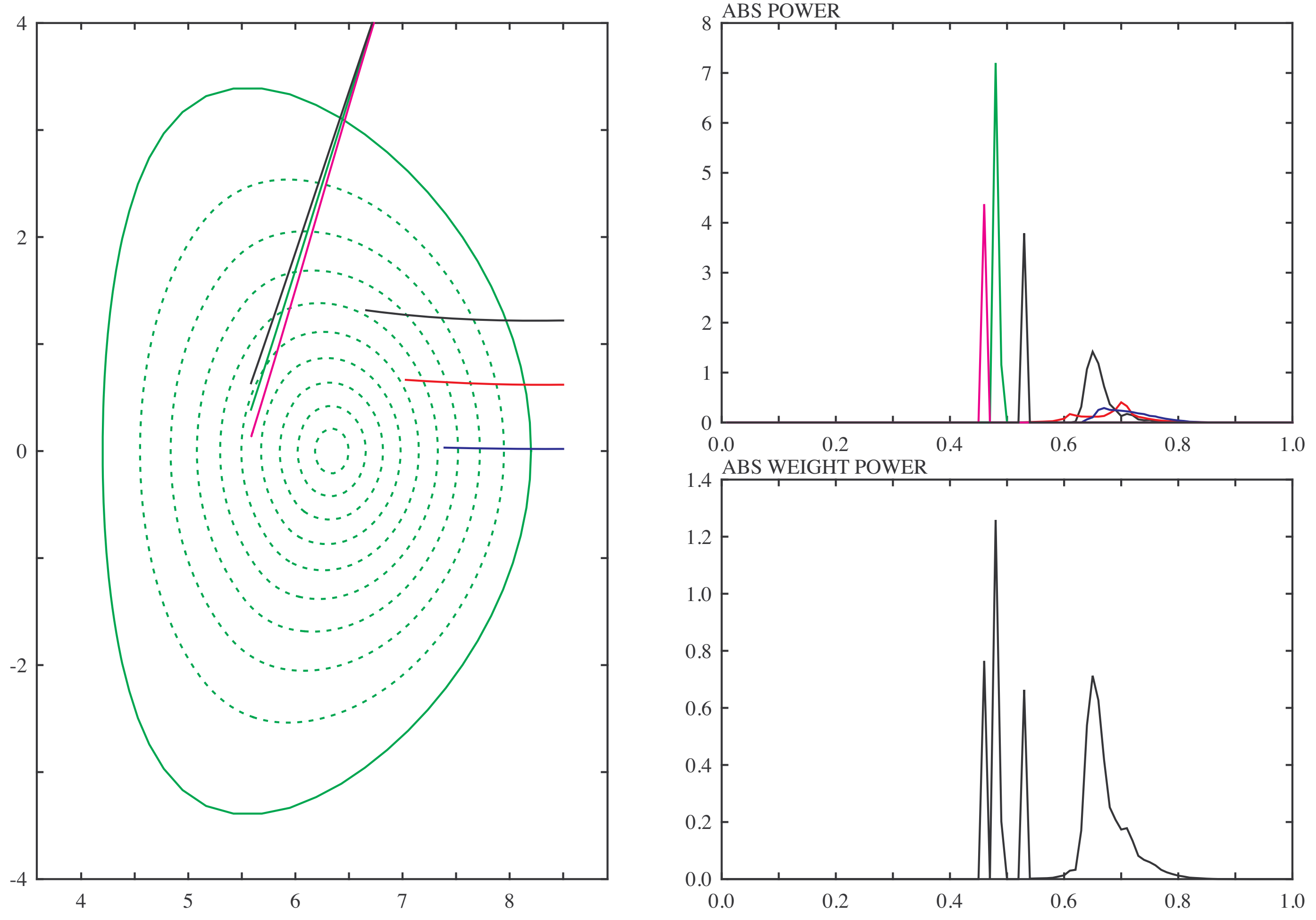
ITER Modeling Needs

based on Dr. Campbell' talk at Cadarache, Sept 2007

- **Plasma scenario development**:
  – Preparation for operation
- **Detailed design of auxiliary systems**:
  – H&CD, Diagnostics, Fueling, $\cdots$
- **Design of plasma control system**:
  – Development and optimization of integrated control strategies
- **Preparation of ITER operational programme**:
  – End-to-end scenario development
  – Detailed pulse definition
- **Experimental data evaluation**:
  – Pulse characterization and physics analysis
  – Refinement of operation scenario and performance predictions

Analysis of EC propagation in ITER

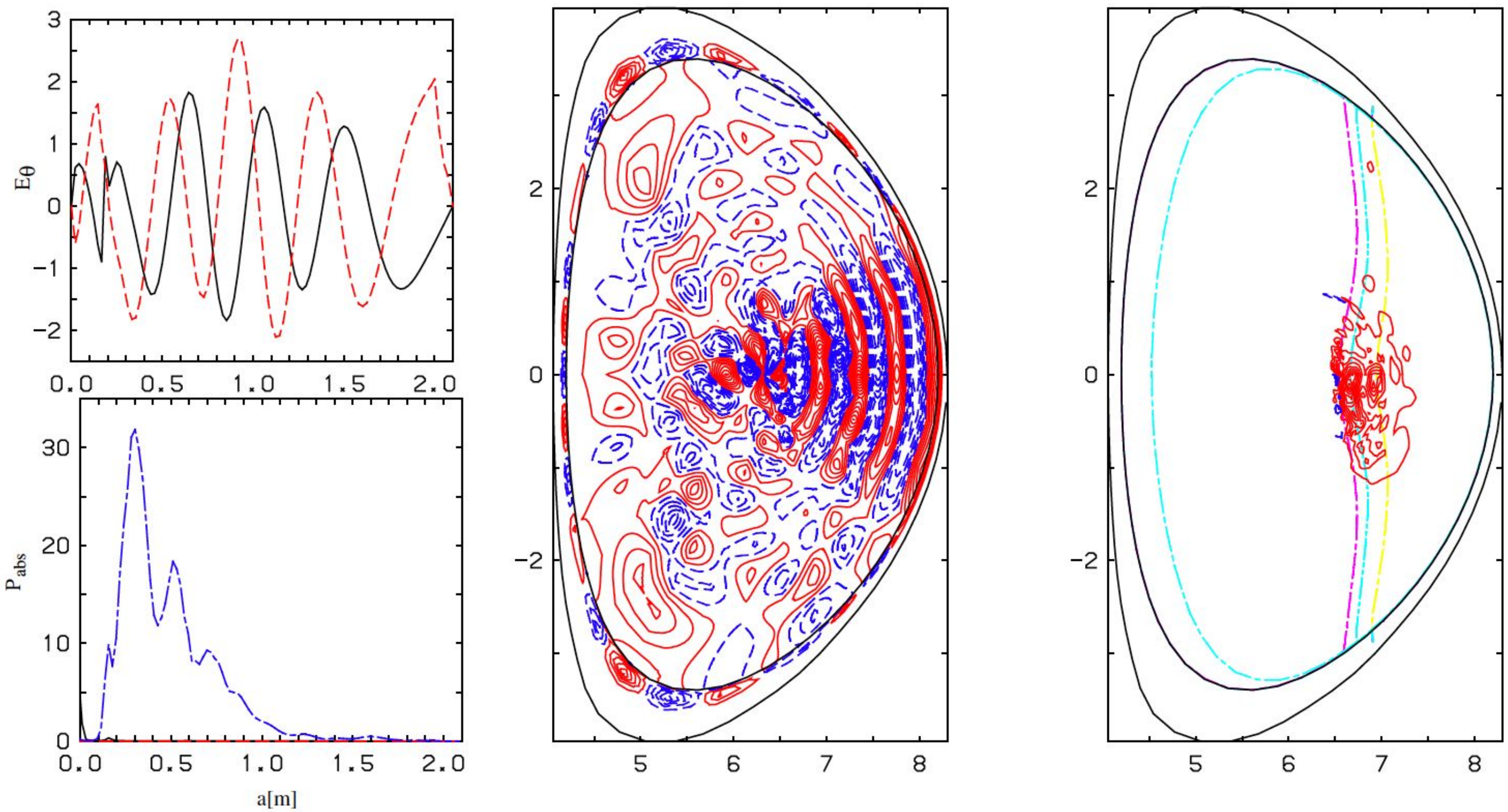
BB = 5.300	Q0 = 1.000	PA(1) = 0.0005	PTPR(1)= 20.0000	PA(2) = 2.0000	PTPR(2)= 20.0000
RR = 6.200	QA = 3.000	PZ(1) = -1.0000	PTPP(1)= 20.0000	PZ(2) = 1.0000	PTPP(2)= 20.0000
RA = 2.000	RF = 1.700E+05	PN(1) = 0.8000	PTS(1) = 0.0500	PN(2) = 0.4000	PTS(2) = 0.0500
RKAP = 1.700	NPHII= -0.1177	PNS(1) = 0.0100	MODELP1= 25.	PNS(2)= 0.0050	MODELP2= 1.



Analysis of IC propagation in ITER

- **Minority heating in D phase**: D + H

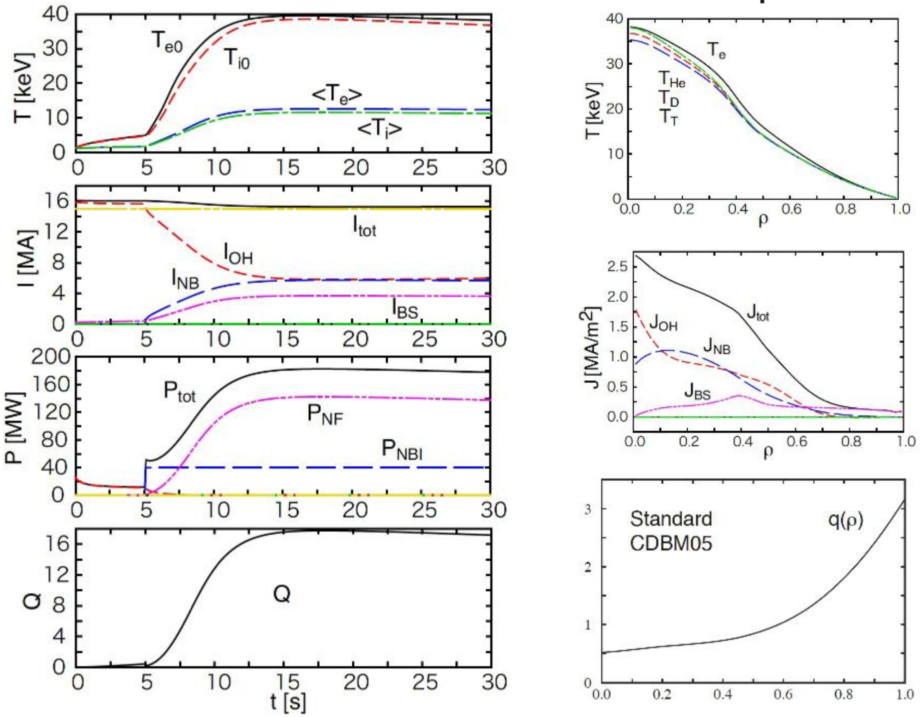
Radial profile　　Wave electric field　　P_{abs} by minority ion



ITER Plasma Transport Simulation with CDBM05

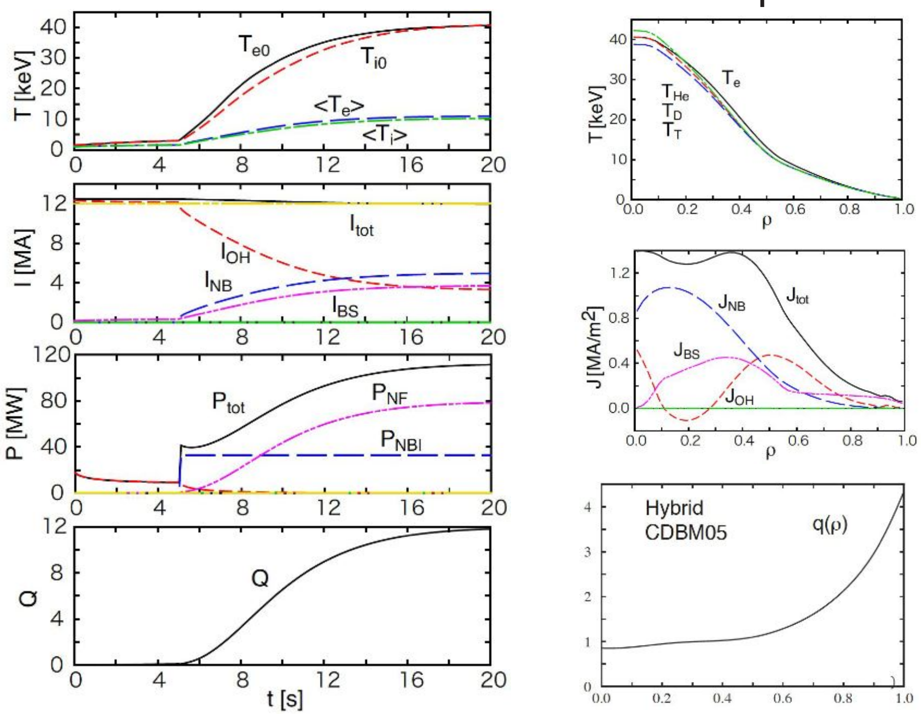
- **Inductive operation**
  - $I_p = 15\,\mathrm{MA}$
  - $P_{NB} = 40\,\mathrm{MW}$ on axis
  - $\beta_N = 2.65$

Time evolution Radial profile



- **Hybrid operation**
  - $I_p = 12\,\mathrm{MA}$
  - $P_{NB} = 33\,\mathrm{MW}$ on axis
  - $\beta_N = 2.68$

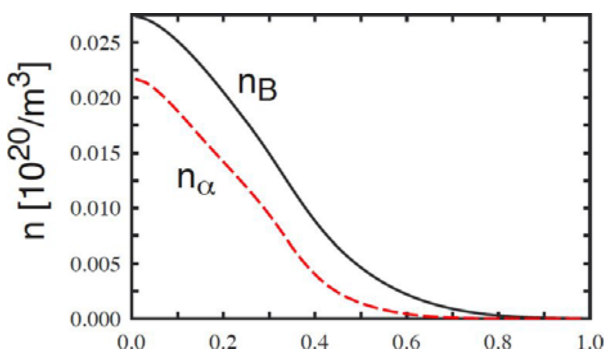
Time evolution Radial profile



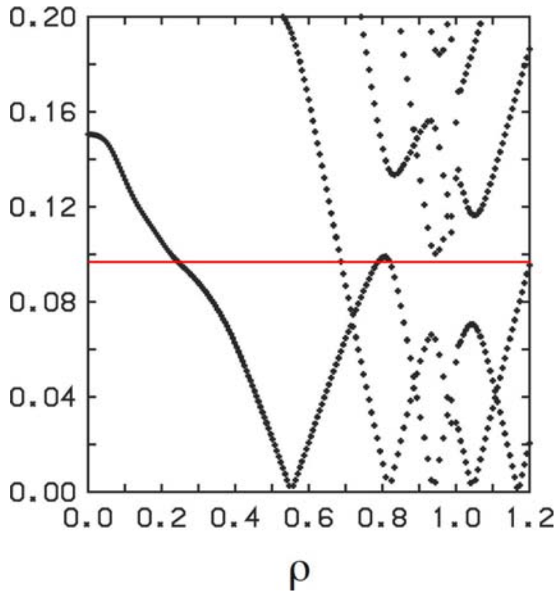
Alfvén Eigenmode Analysis by TASK/WM

- **Alfvén eigenmode driven by alpha particles**
  - Calculated by the full wave module TASK/WM
  - Toroidal mode number: $n = 1$
  - TAE is stable: Eigen mode frequency = $(95.95\,\mathrm{kHz}, -1.95\,\mathrm{kHz})$

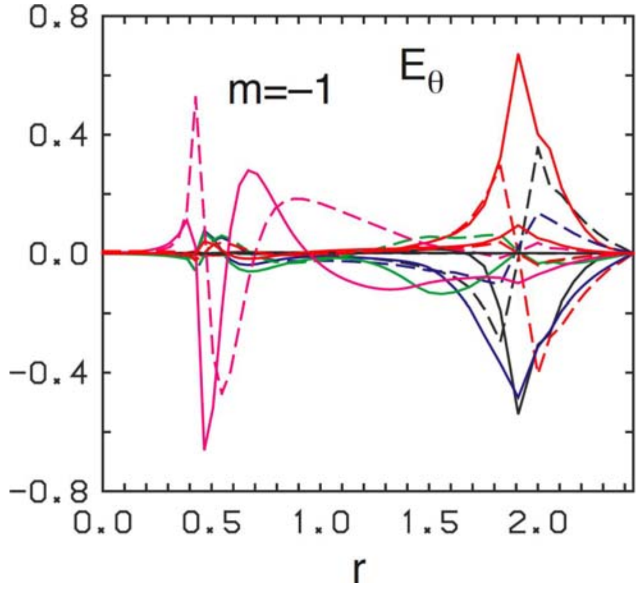
Alpha particle density



Alfvén continuum frequency

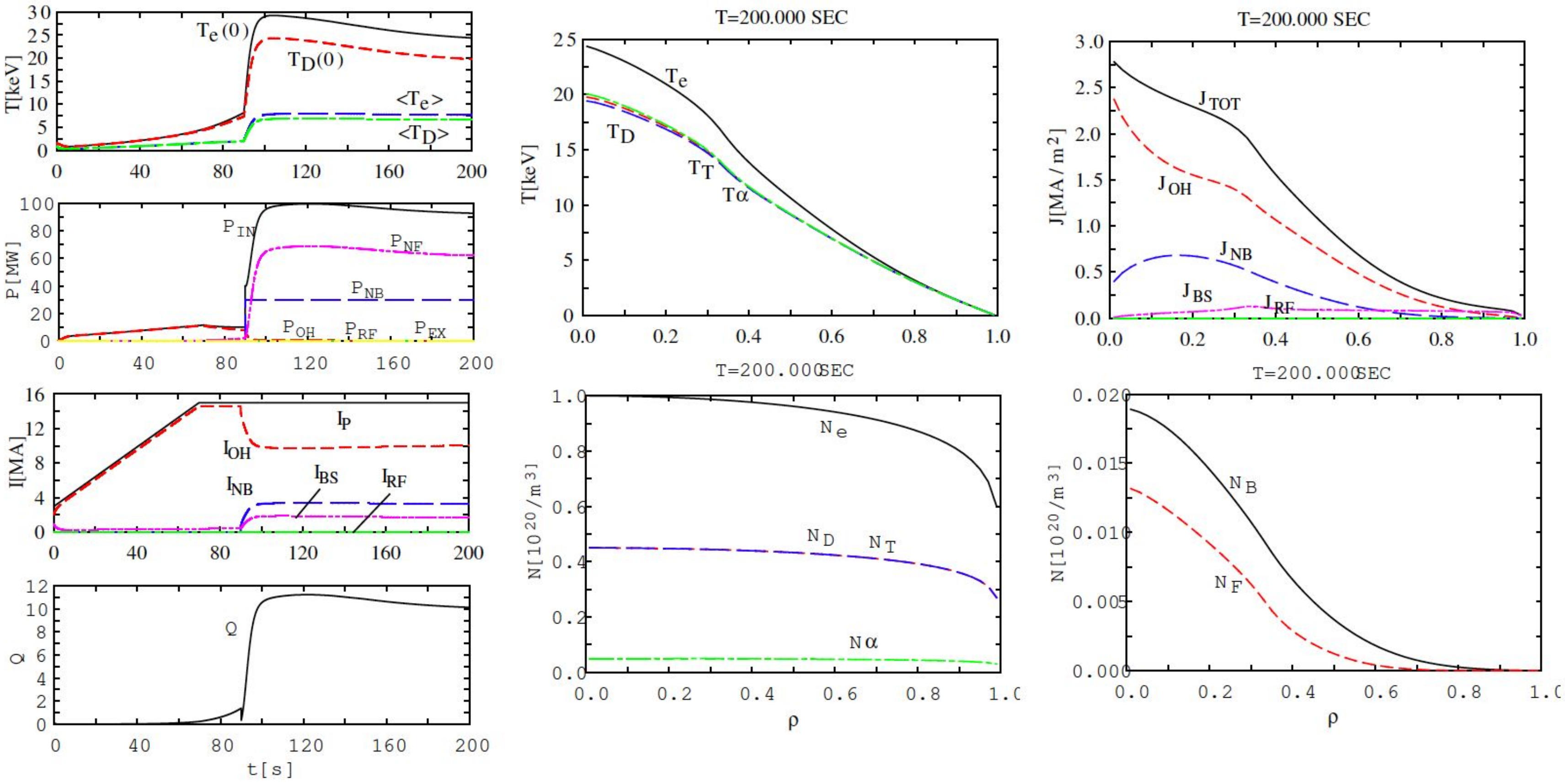


Alfvén eigenmode structure



ITER Inductive Operation

- **15 MA Current rise in 70 s**



- Behavior of plasma depends on timing of heating

Future Plan of the TASK code

	Present Status	In 2 years	In 5 years
Equlibrium	Fixed/Free Boundary	Equilibrium Evolution	Start Up Analysis
Core Transport	1D Diffusive TR	Kinetic TR	2D Fluid TR
	1D Dynamic TR		
SOL Transport		2D Fluid TR	Plasma-Wall Interaction
Neutral Tranport	1D Diffusive TR	Orbit Following	
Energetic Ions	Kinetic Evolution	Orbit Following	
Wave Beam	Ray/Beam Tracing	Beam Propagation	
Full Wave	Kinetic ε	Gyro Integral ε	Orbit Integral ε
Stabilities	Sawtooth Osc.	Tearing Mode	Systematic Stability Analysis
	ELM Model	Resistive Wall Mode	
Turbulent Transport	CDBM Model	Linear GK + ZF	Nonlinear ZK + ZF
		Diagnostic Module	
		Control Module	

Remaining Issues in Tokamak Plasma Modling

- **Pedestal temperature**: modeling of L/H transition
- **Transport barrier formation**: turbulence transport model
- **ELM physics**: nonlinear behavior of ELM on transport
- **Nonlinear MHD events**: modeling of plasma profile change
- **Energetic-ion driven phenomena**: coupling of Alfvén mode and drift waves
- **Kinetic analysis of transport and MHD phenomena**: non-Maxwellian distribution
- **Wave physics**: full wave analysis of Bernstein waves
- **Divertor plasma**: plasma-wall interaction
- **Start up**: Rapid change of equilibrium and control

and so on...

Summary

- **Integrated modeling of burning plasmas** is indispensable for exploiting optimized operation scenario of ITER and reliable design of DEMO.

- Discussion on **international collaboration** for the development of **integrated ITER modeling** is on going.

- There are **many remaining issues** in **constructing comprehensive integrated code**; especially, L/H transition mechanism, turbulent transport model, ELM physics, nonlinear MHD events, energetic particle driven phenomena and plasma wall-interactions.

- Solving those remaining issues requires not only **large-scale computer simulations** but also **intensive modeling efforts** based on experimental observations.