Second ITER International Summer School
Kyushu Univ., Kasuga, Japan
2008/07/25

Integrated Modeling of Burning Plasmas

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Acknowledgments
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Outline

1. Introduction
2. Integrated Modeling Code
3. Transport Modeling
4. Source Modeling
5. ITER Modeling
6. Summary

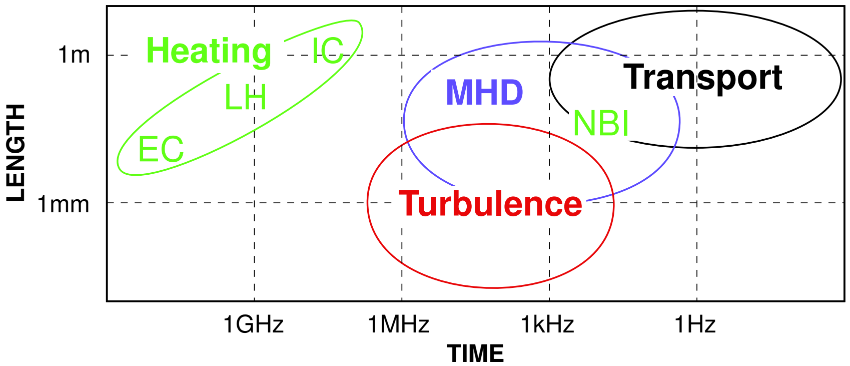
Integrated Simulation of Toroidal Plasmas

- **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

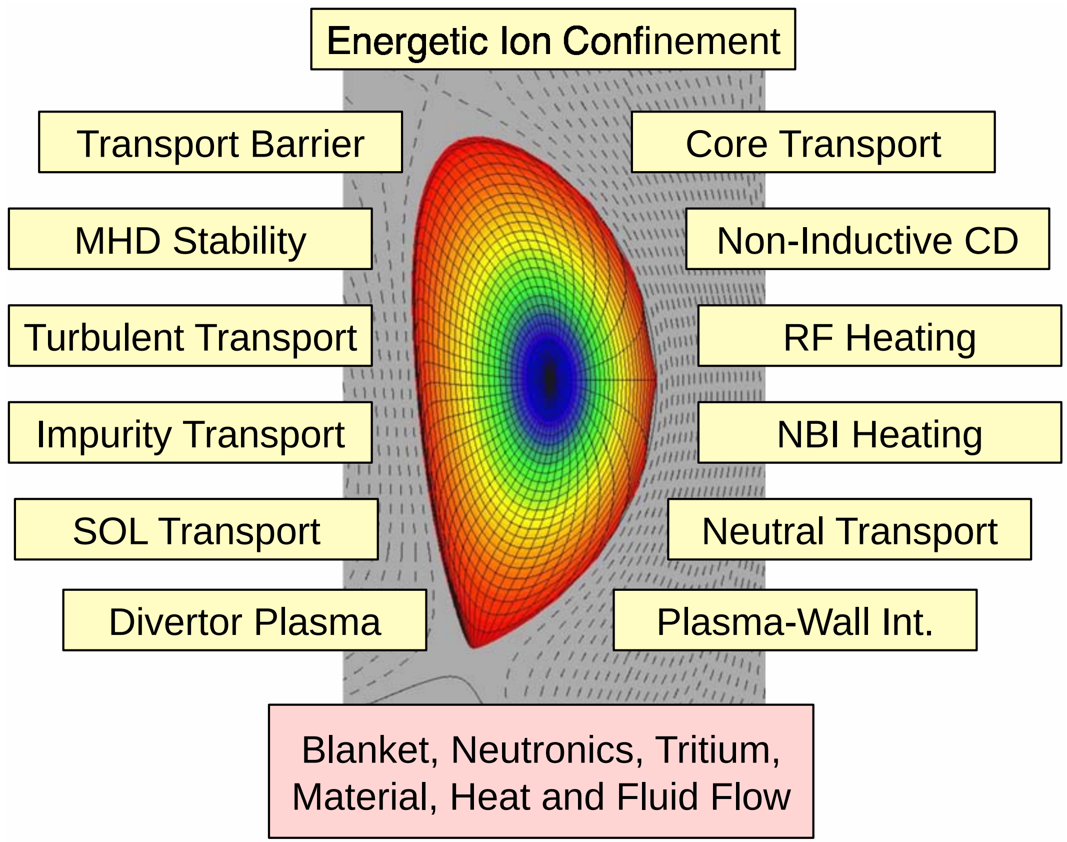
Simulation of Tokamak Plasmas

Broad range of time scale:
100GHz ~ 1000s

Broad range of Spatial scale:
10 μm ~ 10m

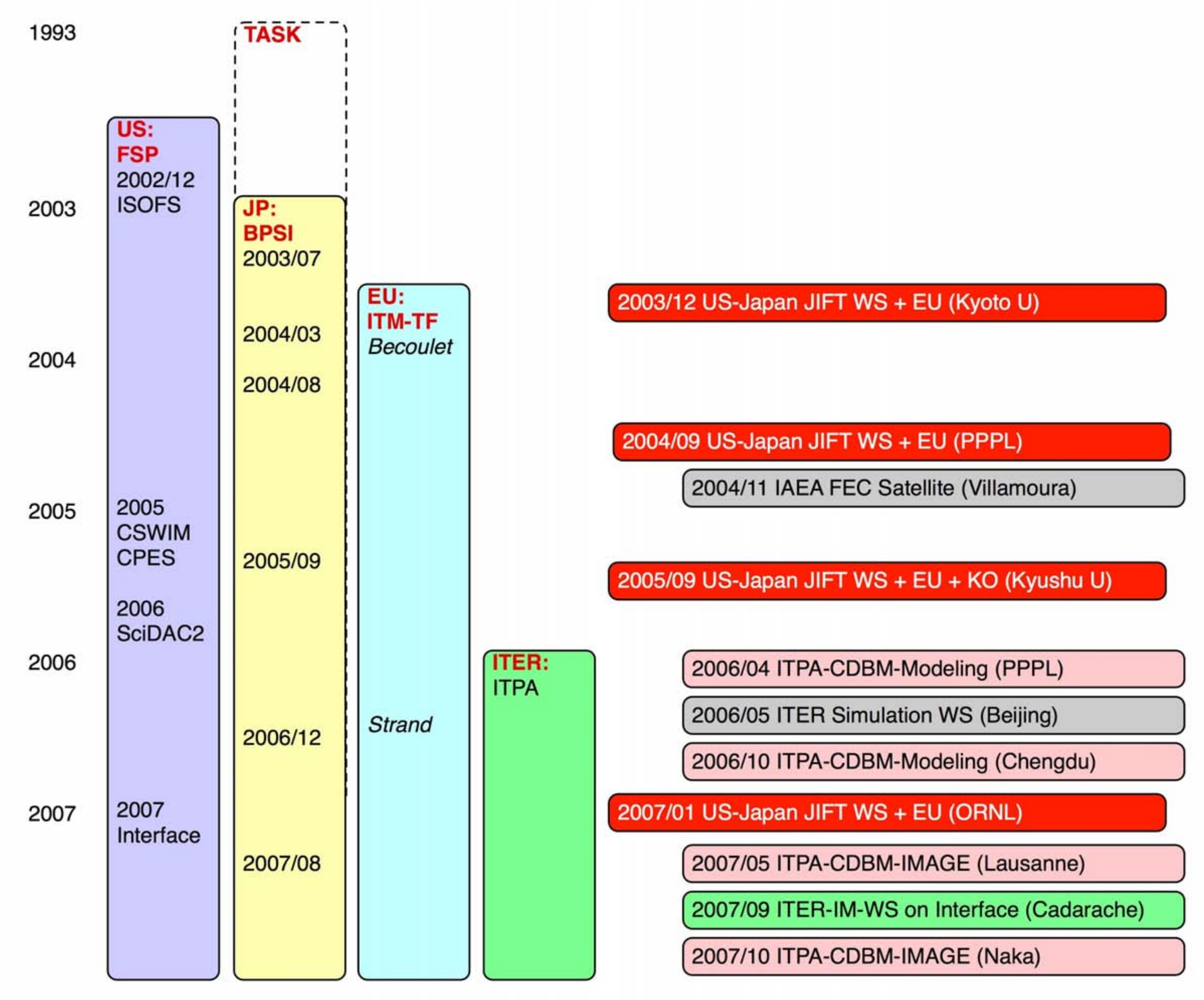


One simulation code never covers all range.



Integrated simulation combining modeling codes interacting each other

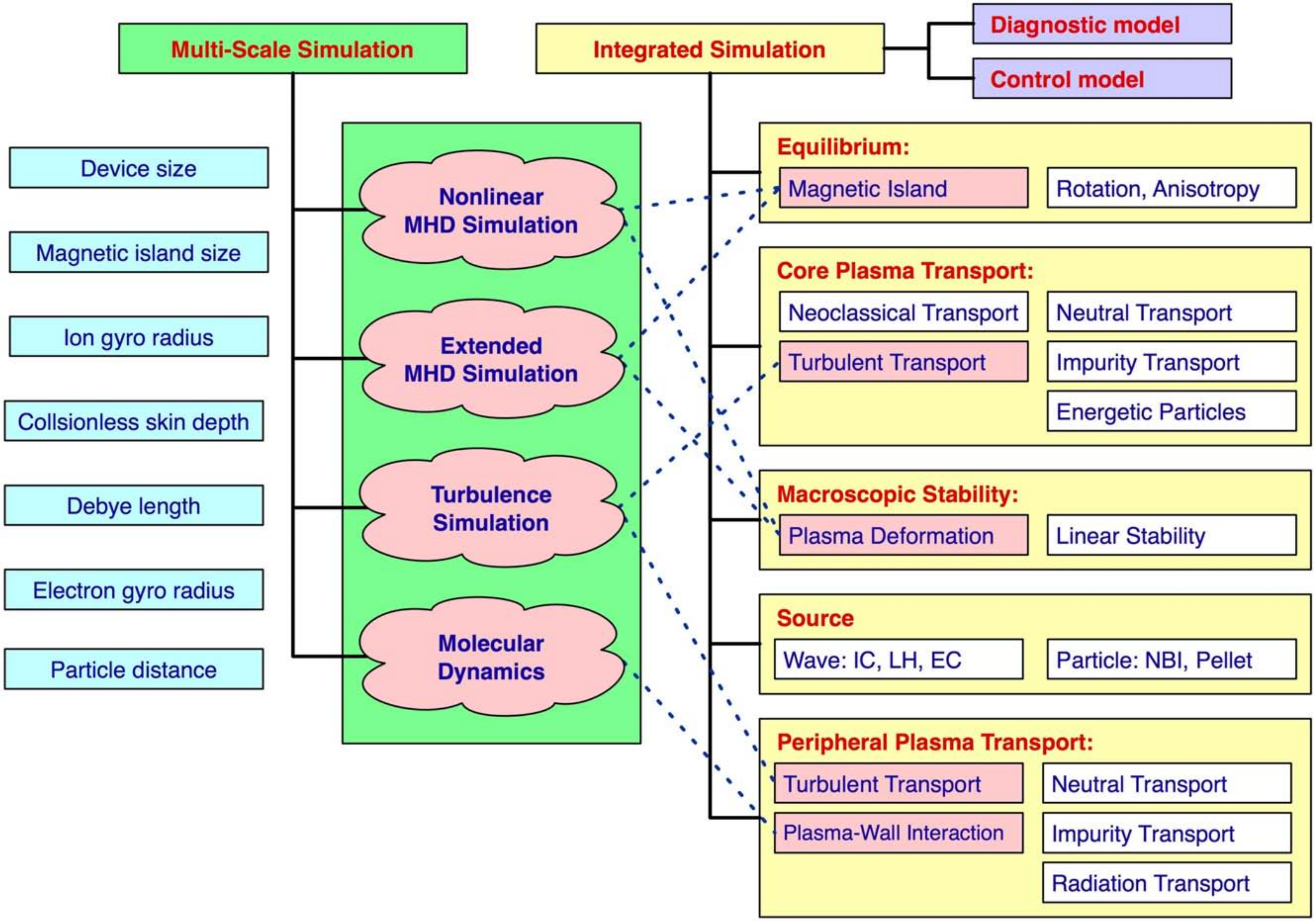
International Integrated Modeling Activity



Integrated Modeling Activities

- **Japan**: **BPSI** (Burning Plasma Simulation Initiative)
  - Research collaboration among universities, NIFS and JAEA
    - Integrated code framework
    - New physics models
    - Advanced computing
- **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) — presently 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)

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

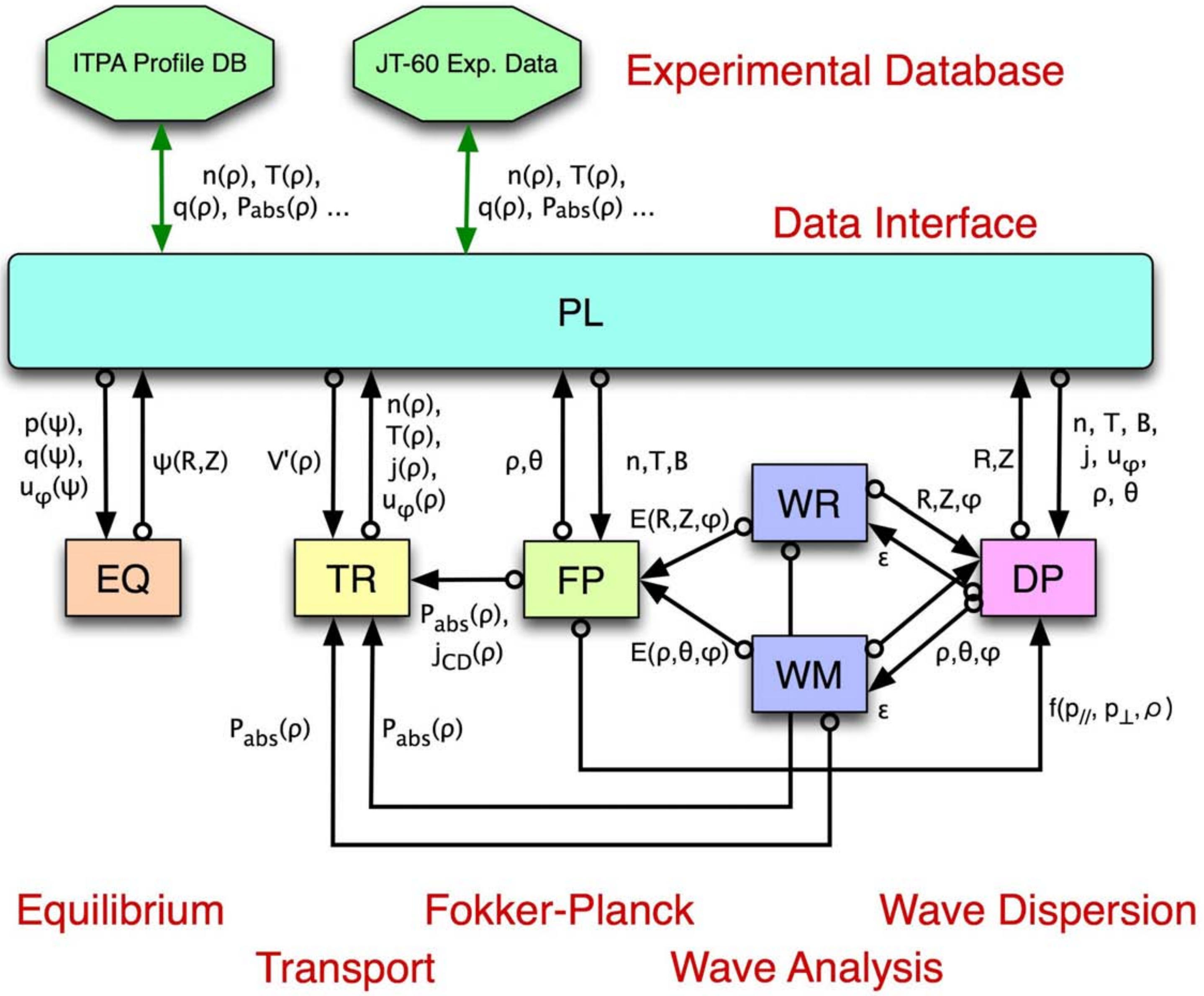
Integrated Modeling Code: TASK

- **T**ransport **A**nalysing **S**ystem for Tokama**K**
  - Developed in **Kyoto University**

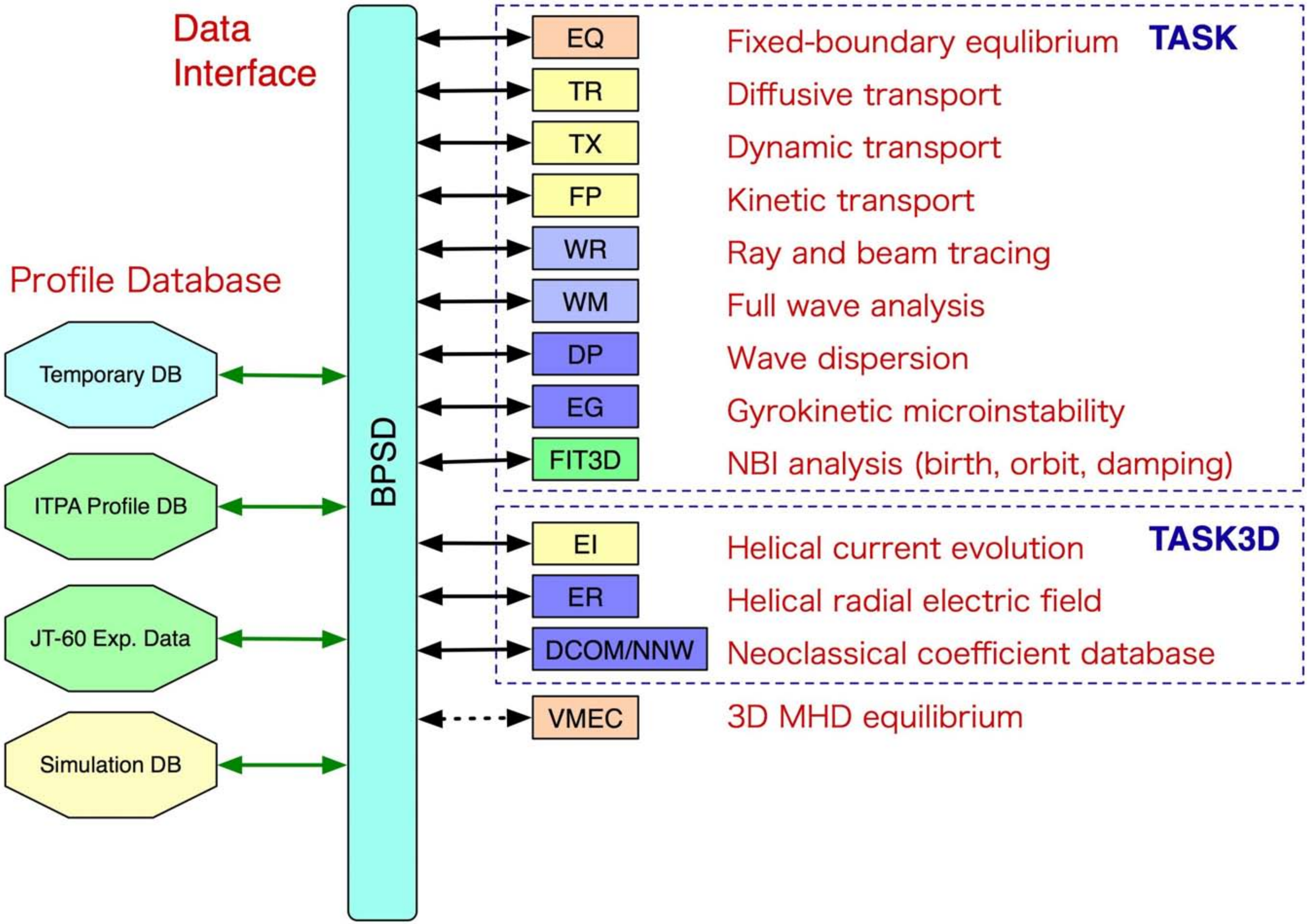
EQ	**2D Equilibrium**	Fixed/Free boundary, Toroidal rotation
TR	**1D Transport**	Diffusive transport, Transport models
TX	**1D Transport**	Dynamic Transport, Rotation and E_r
FP	**3D Fokker-Planck**	Relativistic, Bounce-averaged
WR	**3D Ray tracing**	EC, LH: Ray tracing, Beam tracing
WM	**3D Full wave**	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

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

Original Structure of the TASK code



Present Structure of the TASK code



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	–	–	–	–	–	–	–

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

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

Transport Processes

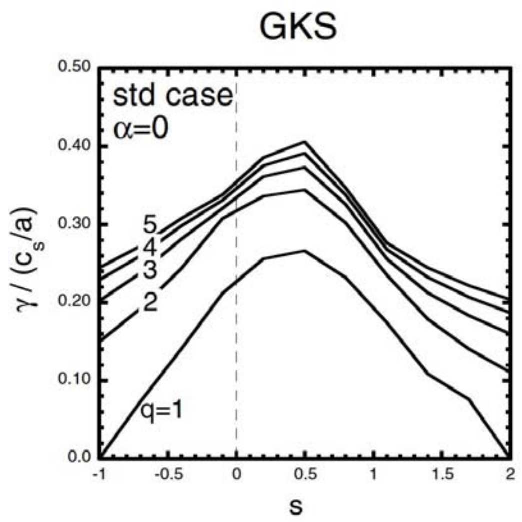
- **Neoclassical transport**
  - Collisional transport in an inhomogeneous magnetic field
  - **Radial diffusion**: usually small compared with turbulent diffusion
  - **Enhanced resistivity**: due to trapped particles
  - **Bootstrap current**: toroidal current driven by radial pressure gradient
  - **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

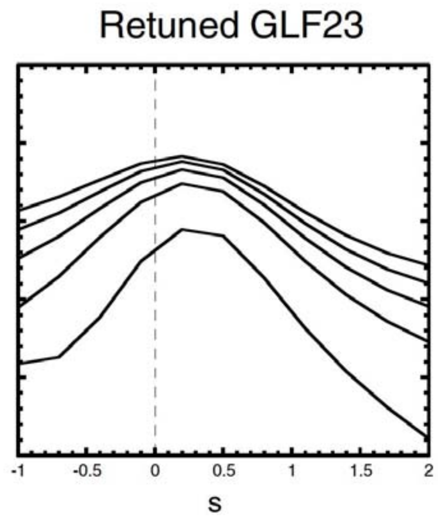
Turbulent Transport Models

- **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

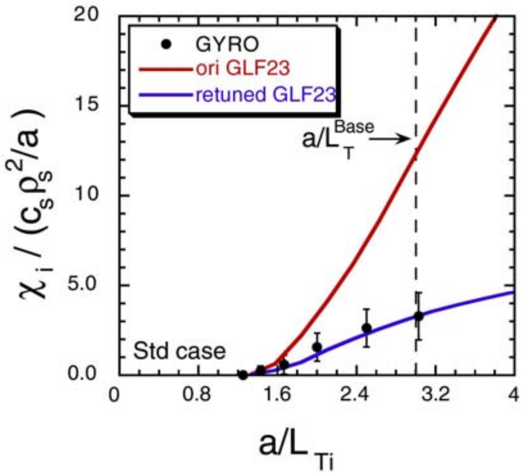
GLF23 Transport Model

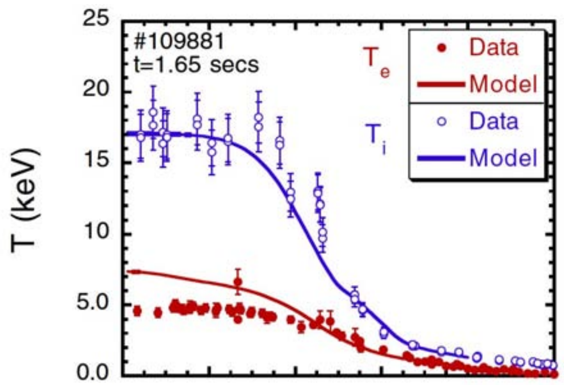
Linear growth rate from gyro-Landau-fluid model





Calibrate coefficients by the nonlinear turbulence code GYRO





Good agreement with experimental data

CDBM Transport Model: CDBM05

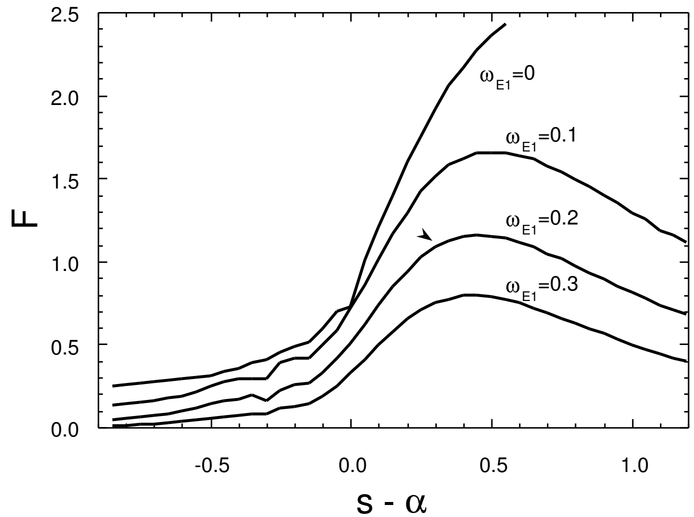
- **Thermal Diffusivity** (Marginal: $\gamma = 0$)

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

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**	$\omega_{\mathrm{E1}} \equiv \dfrac{r^2}{s v_{\mathrm{A}}} \dfrac{\mathrm{d}}{\mathrm{d}r} \dfrac{E}{rB}$

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

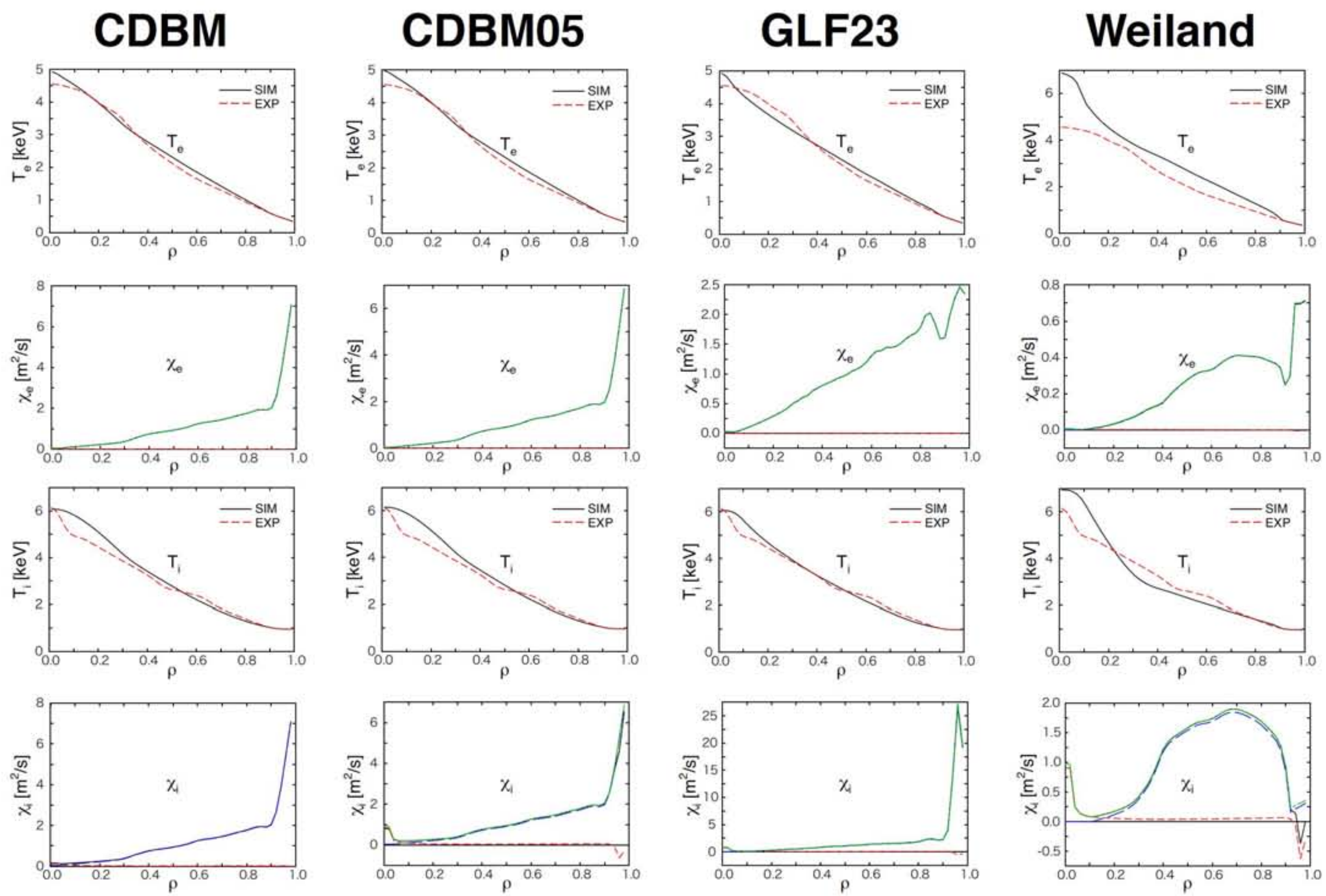
$s - \alpha$ dependence of $F(s, \alpha, \kappa, \omega_{\mathrm{E1}})$



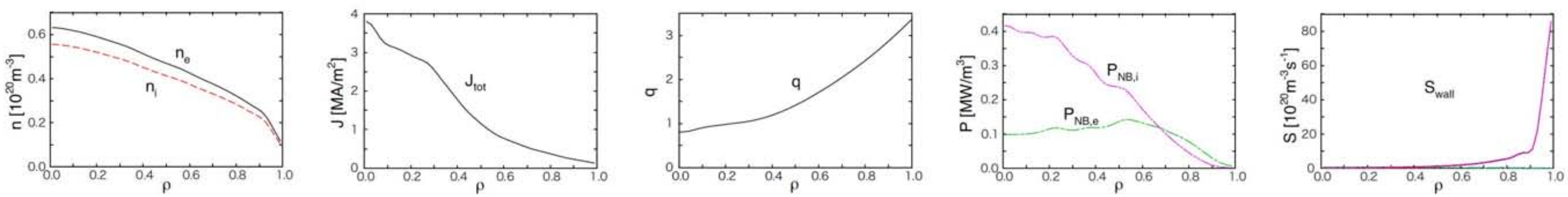
$$F(s, \alpha, \kappa, \omega_{\mathrm{E1}}) = \left(\frac{2\kappa^{1/2}}{1+\kappa^2} \right)^{3/2}$$

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

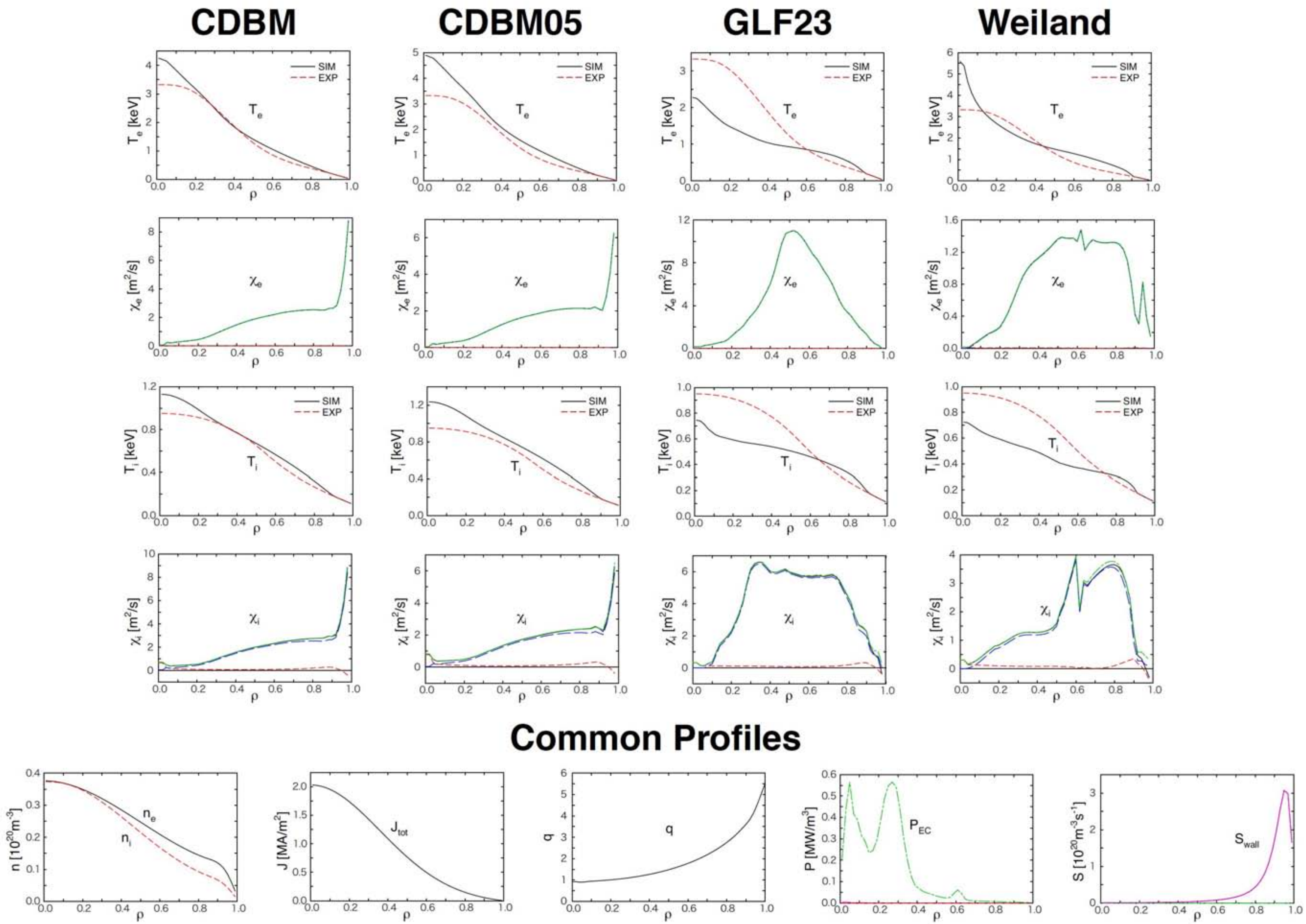
TFTR #88615 (L-mode, NBI heating)



Common Profiles



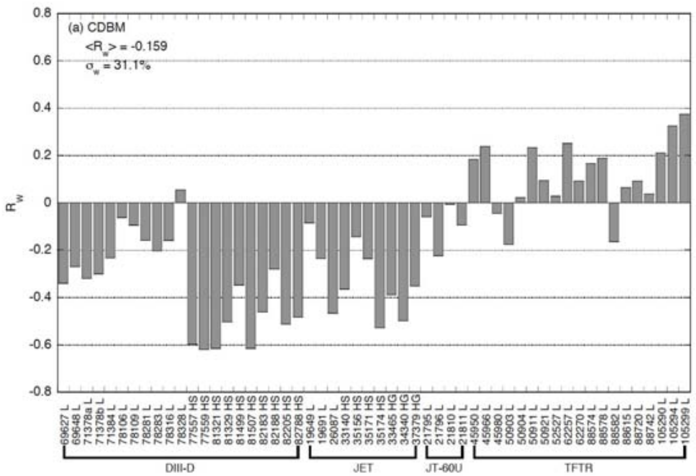
DIII-D #78316 (L-mode, ECH and ICH heatings)



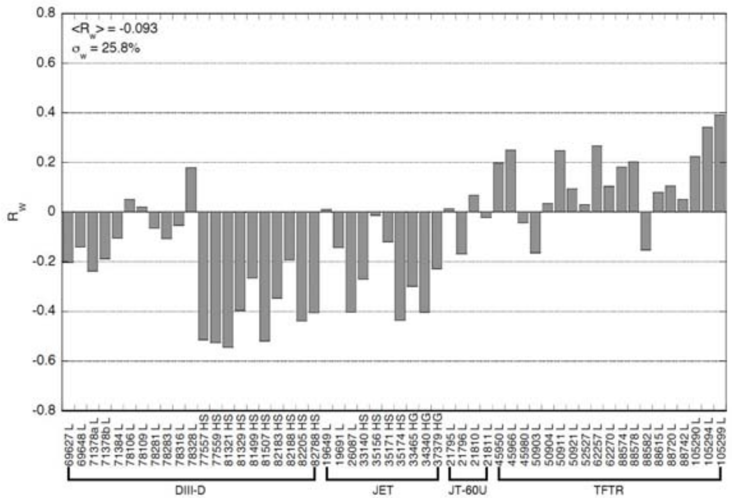
Comparison of Transport Models: ITPA Profile DB

Deviation of Stored Energy

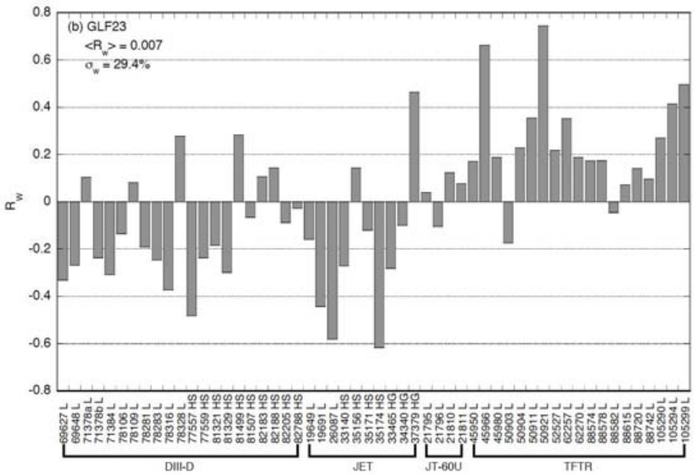
CDBM



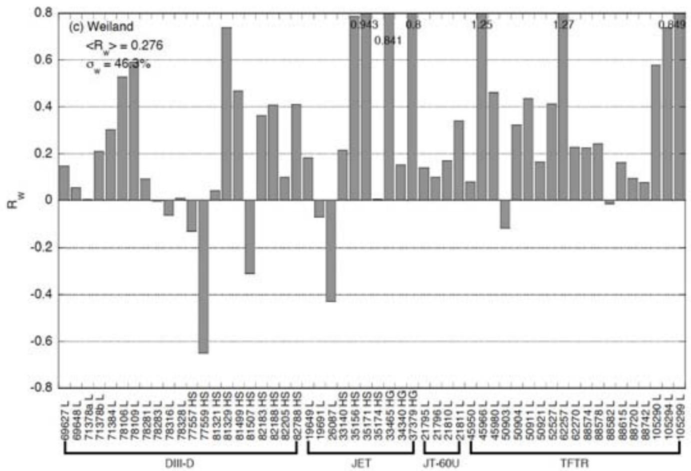
CDBM05



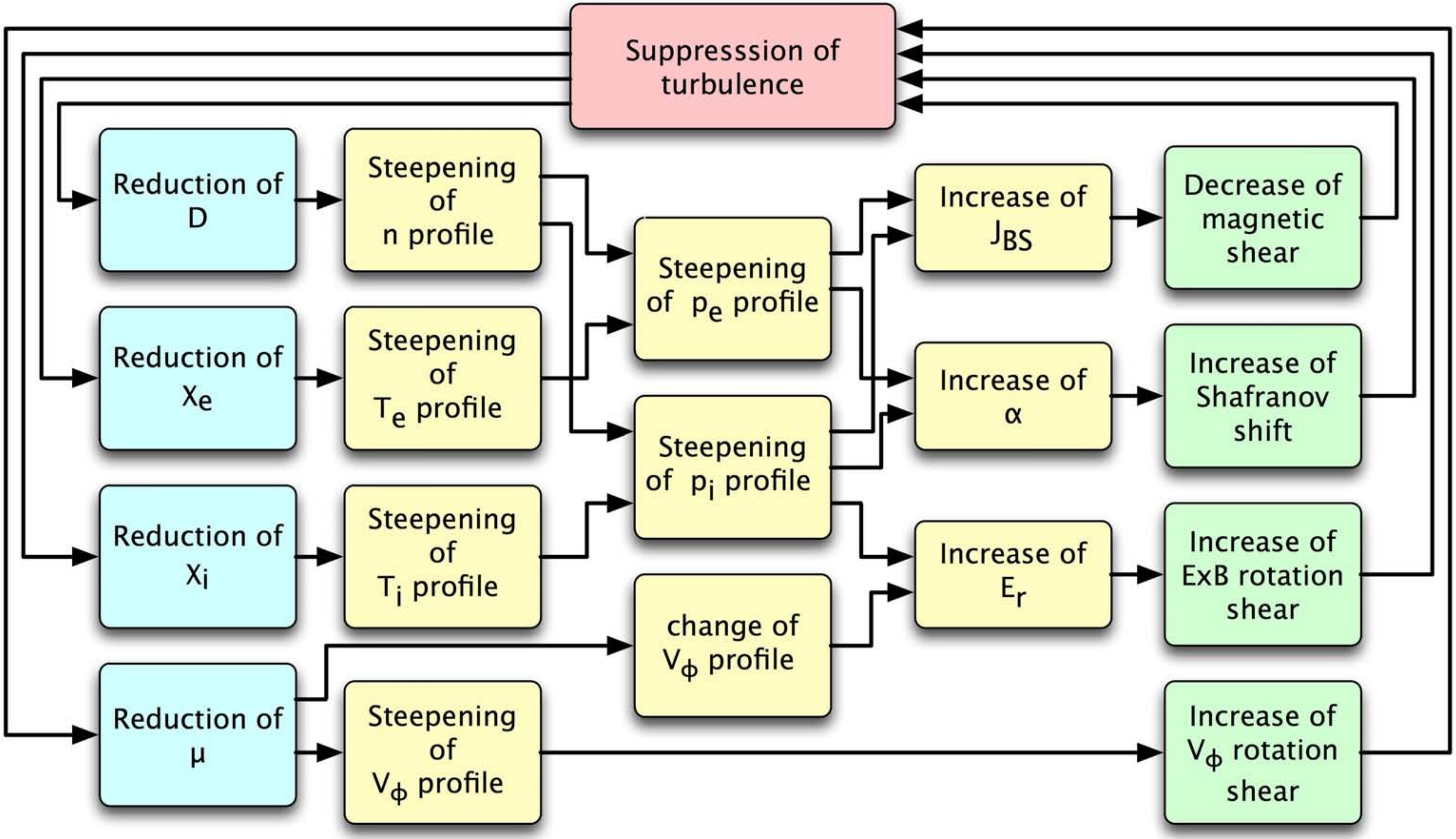
GLF23



Weiland



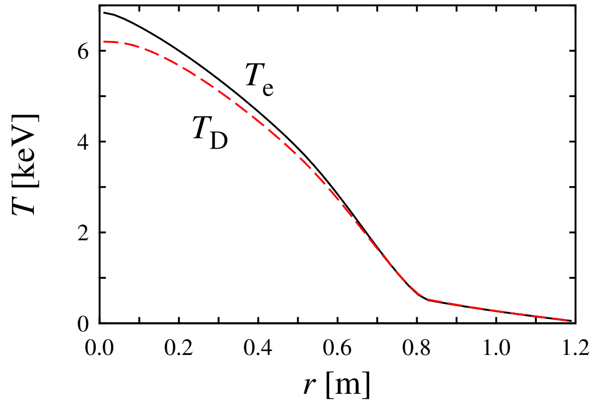
Modeling of Transport Barrier Formation



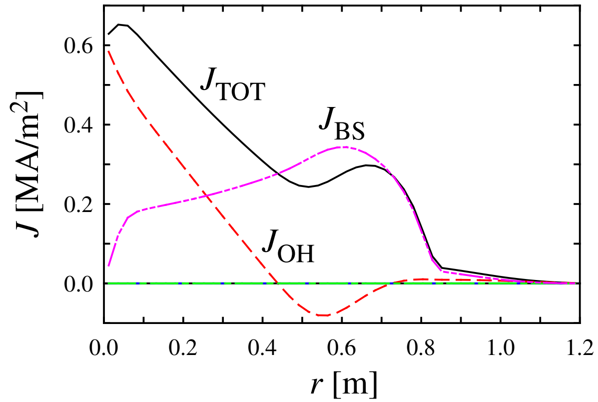
High β_p mode

- $R = 3\,\mathrm{m}$, $a = 1.2\,\mathrm{m}$, $\kappa = 1.5$, $B_0 = 3\,\mathrm{T}$, $I_p = 1\,\mathrm{MA}$
- one second after heating power of $P_H = 20\,\mathrm{MW}$ was switched on

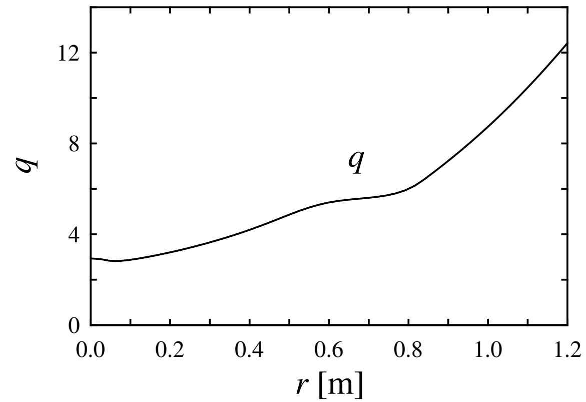
Temperater profile



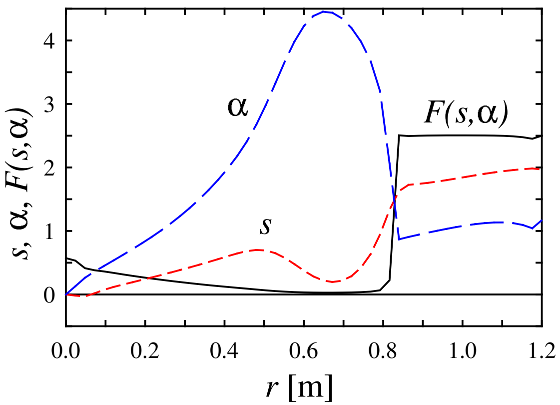
Current profile



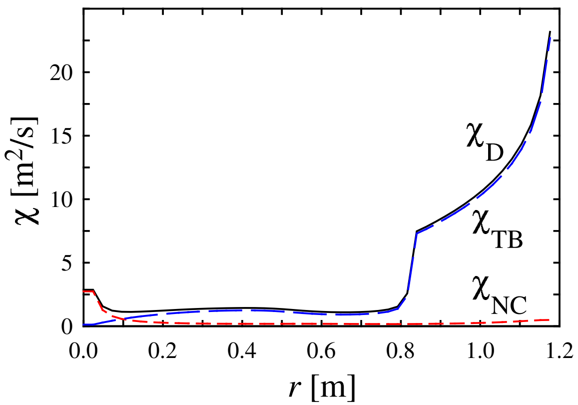
Safety factor



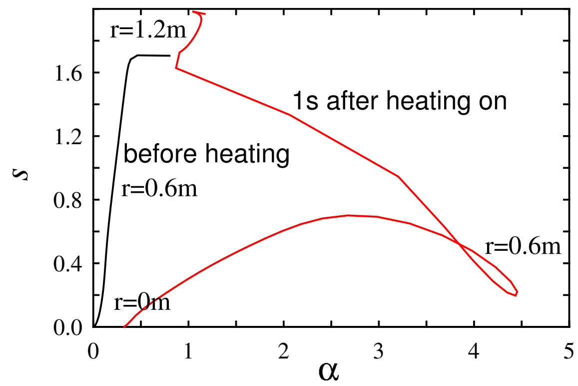
Shear and pressure



Thermal diffusivity



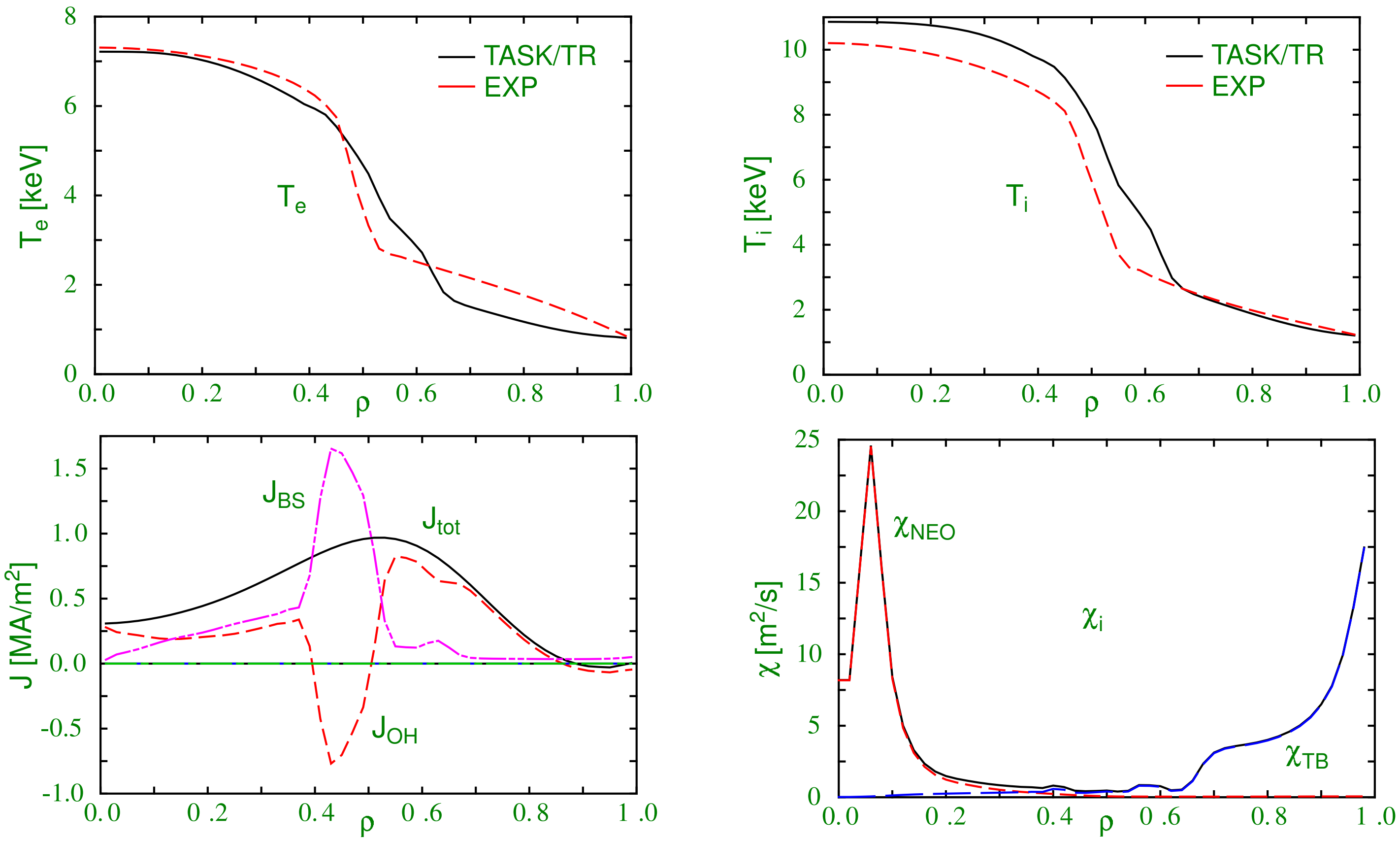
$s - \alpha$ diagram



Steady State ITB Simulation

- CDBM transport model including velocity shearing rate
- Radial electric field calculated from the radial force balance

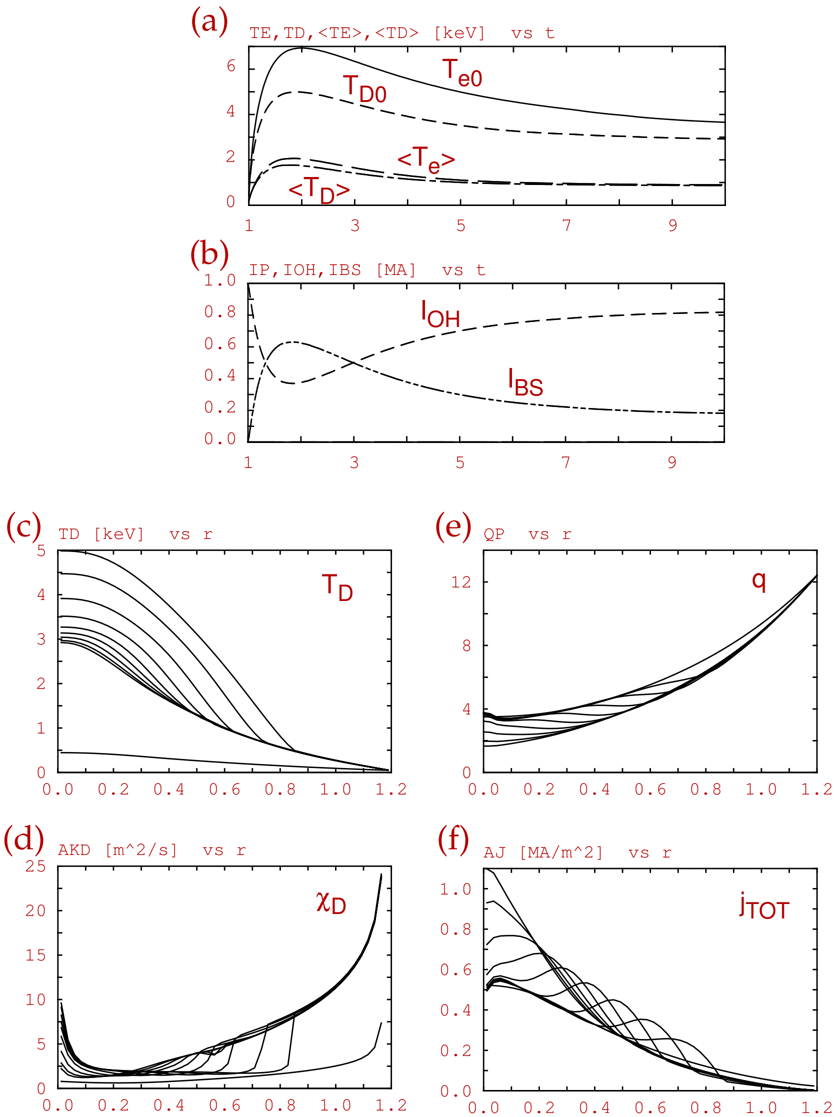
Heat transport simulation for the ITB shot #29728 on the JT-60U Tokamak



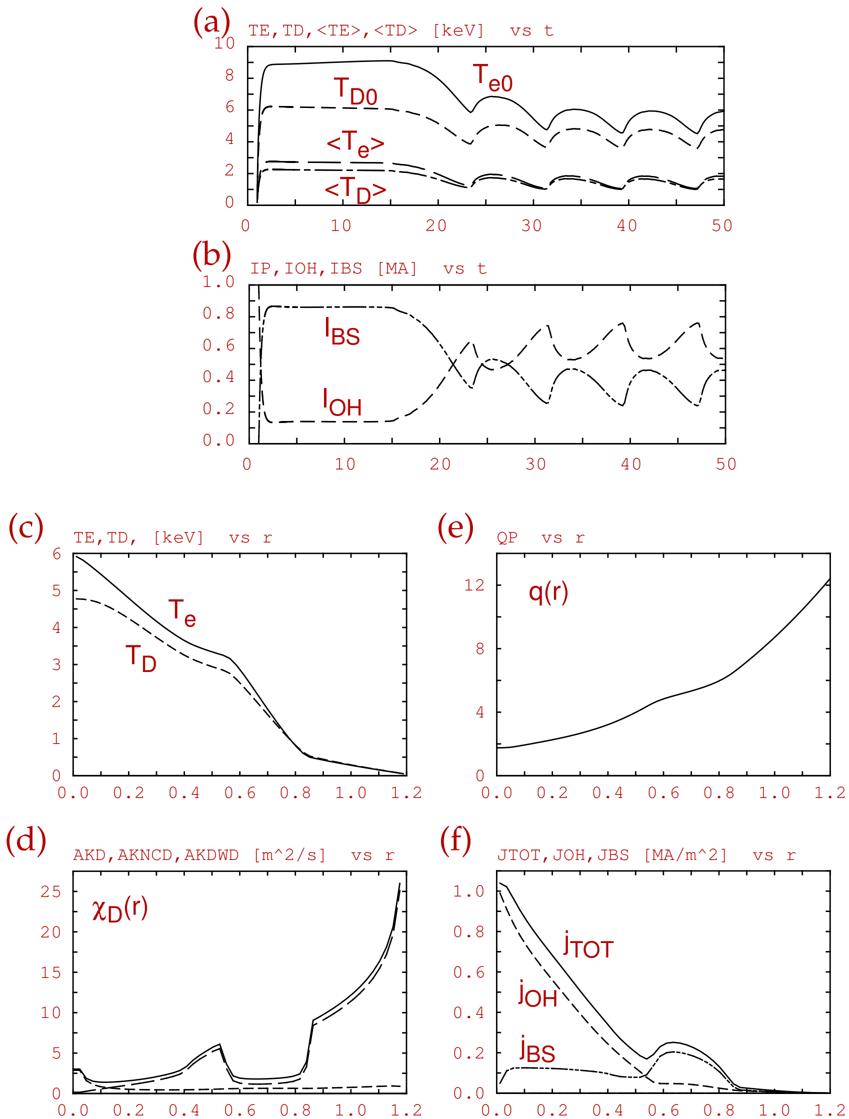
It is generally rather difficult to reproduce ITB formation.

Time Evolution of Internal Transport Barrier

- $P_H = 20\,\mathrm{MW}$



- $P_H = 24.2\,\mathrm{MW}$



Fukuyama et al. NF (1995)

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**:

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

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

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

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

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

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

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

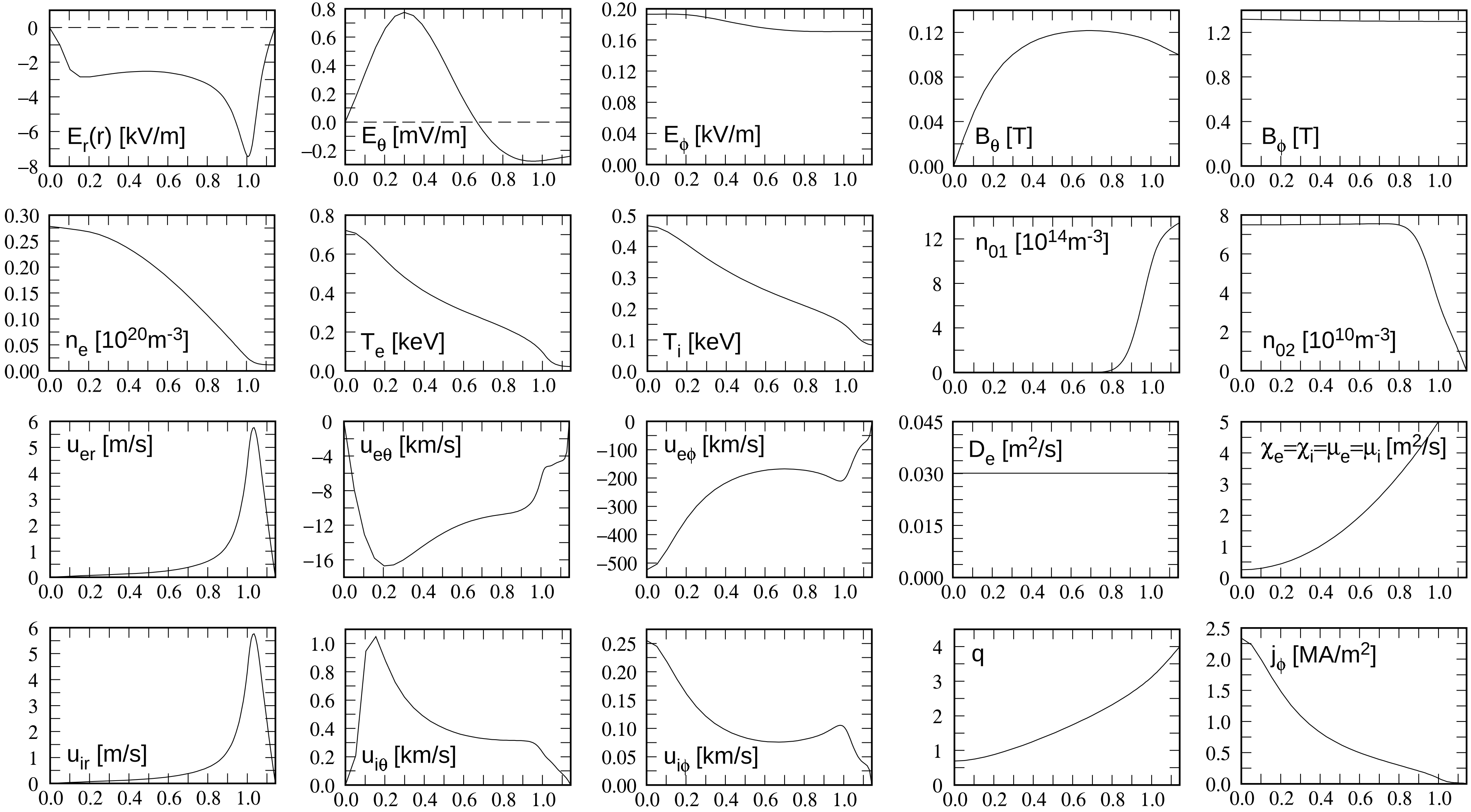
$$+P_s^{\mathrm{C}} + P_s^{\mathrm{L}} + P_s^{\mathrm{H}}$$

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

JFT-2M like plasma composed of electron and hydrogen

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

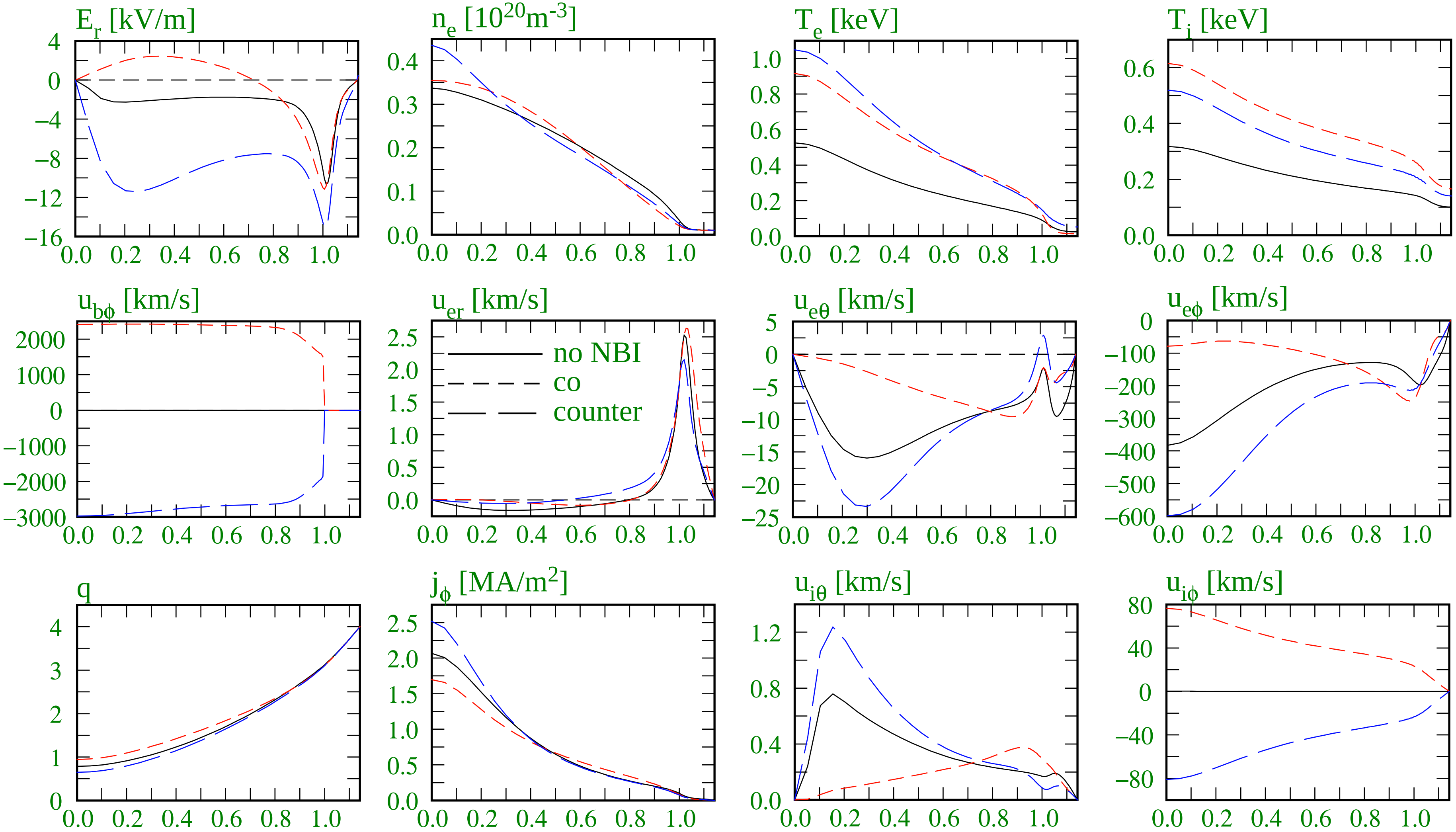
$\gamma = 0.8,\ Z_{\mathrm{eff}} = 2.0$, Fixed turbulent coefficient profile



Density Profile Modification Due to NBI Injection

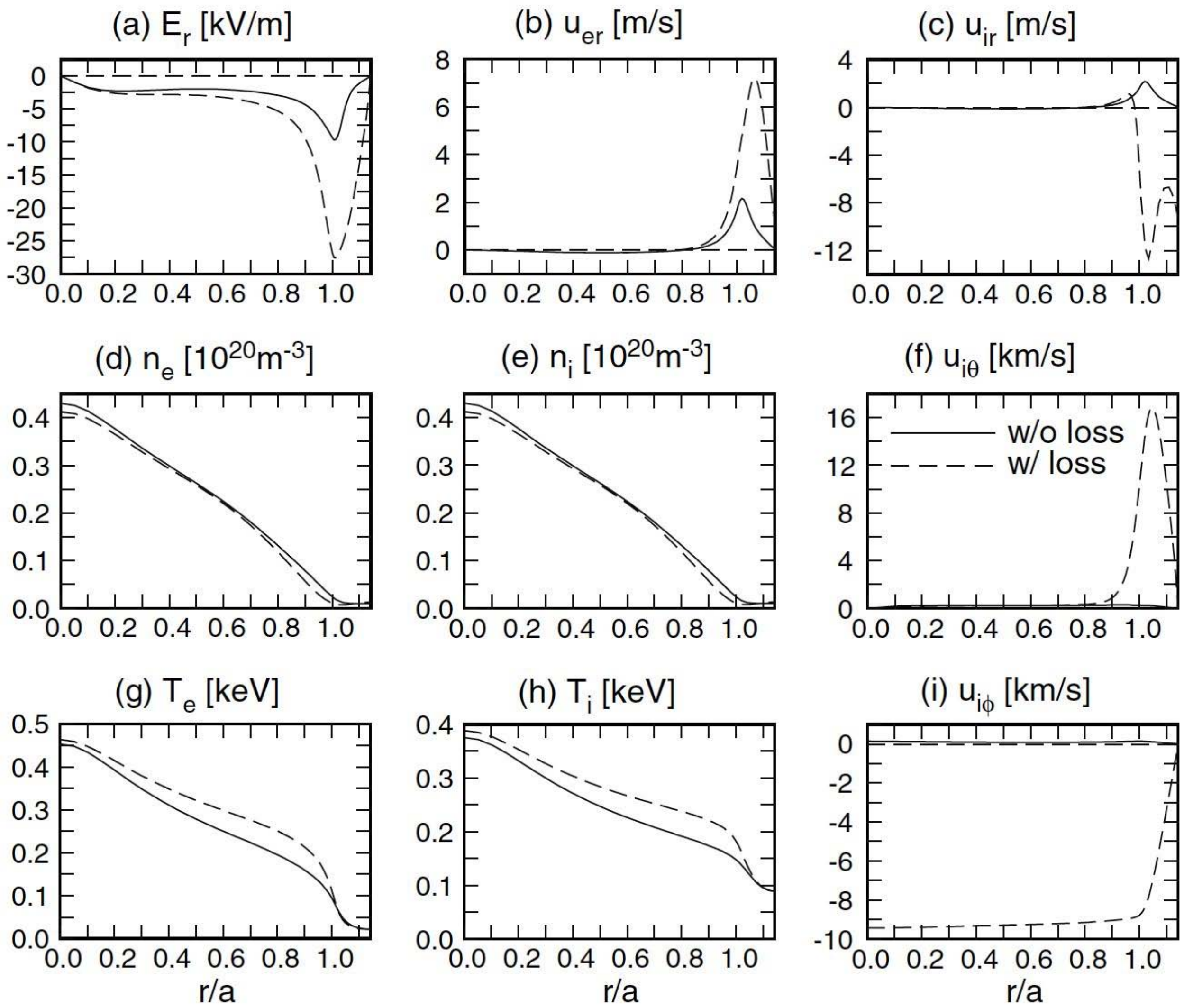
Modification of n and E_r profile depends on the direction of NBI.

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 wave equi-phase surface
- **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
  - Not easy to include kinetic effects in inhomogeneous plasmas

Momentum Distribution Function

- **Fokker-Planck equation**

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

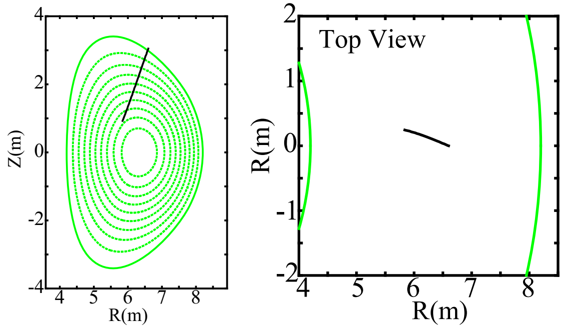
$$\frac{\partial f}{\partial t} = E(f) + C(f) + Q(f) + L(f)$$

  - $E(f)$: 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 the TASK Code

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

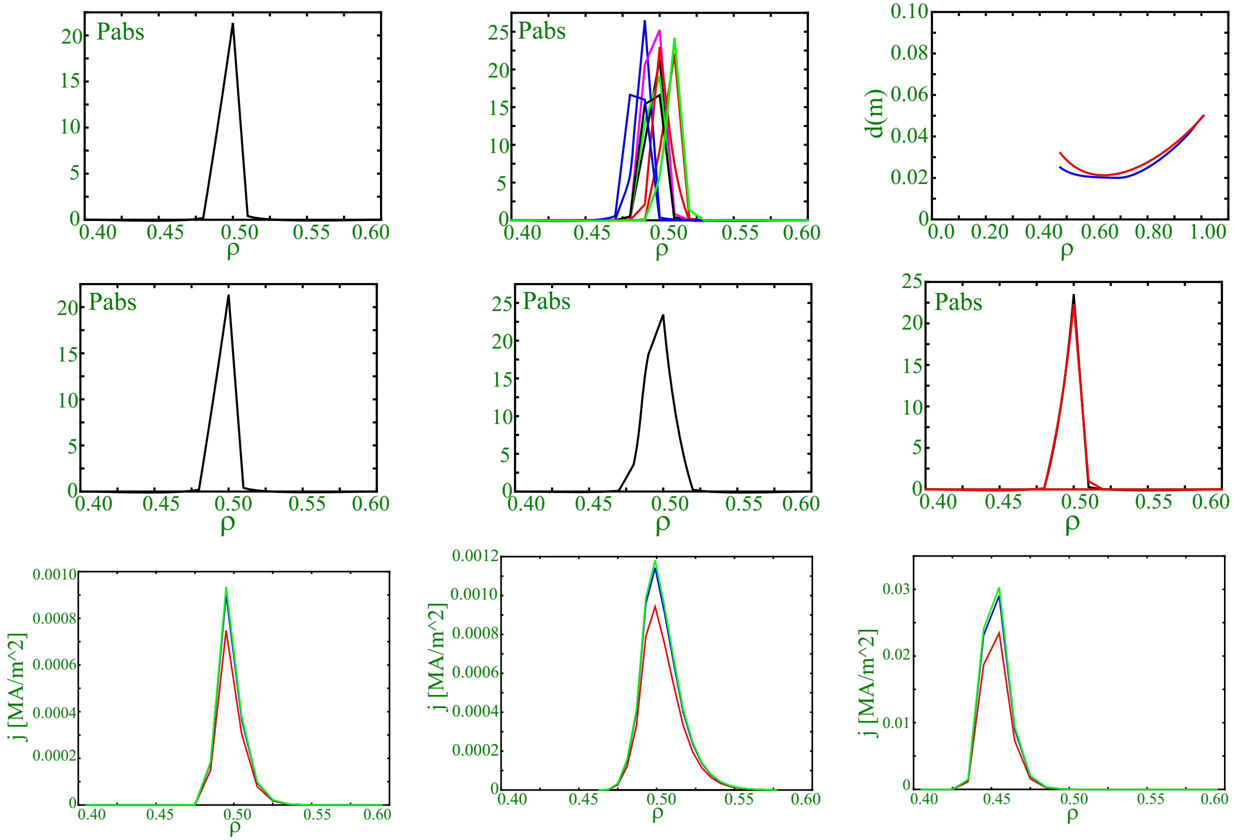


One Ray | **Multi Rays** | **Beam Tracing**

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**

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

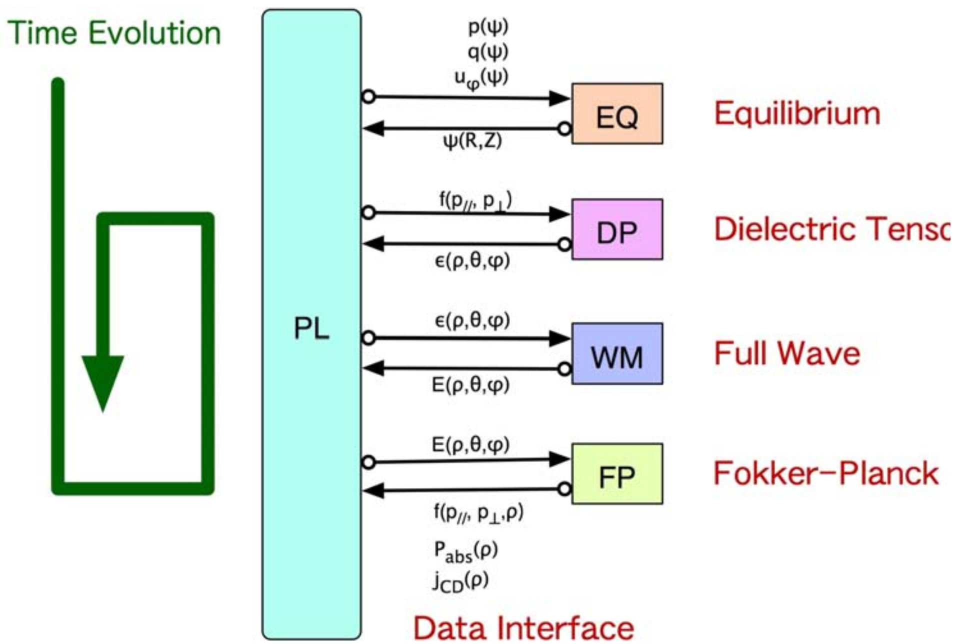
- Kinetic **dielectric tensor**: $\overleftrightarrow{\epsilon}$
  - **Wave-particle resonance**: $Z[(\omega - n\omega_{\mathrm{c}})/k_{\|}v_{\mathrm{th}}]$
  - **Fast ion: Drift-kinetic**

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

- 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

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

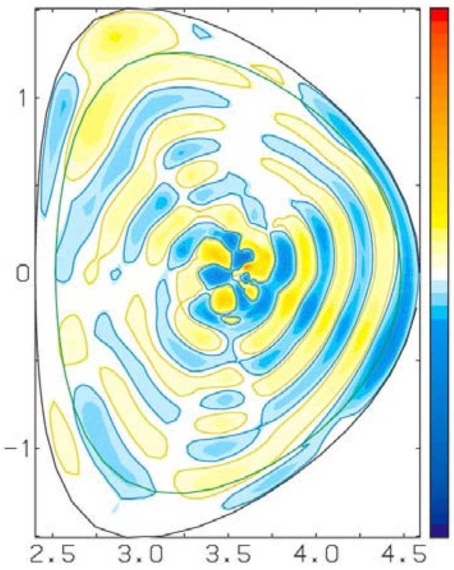
- **Modification of velocity distribution from Maxwellian**
  - Energetic ions generated by ICRF waves
  - Alpha particles generated by fusion reaction
  - Fast ions generated by NB injection
- **Self-consistent wave analysis including modification of $f(v)$**



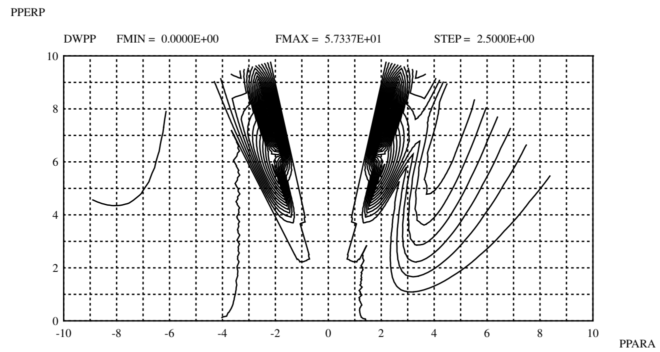
Preliminary Results

- **Tail formation by ICRF minority heating**

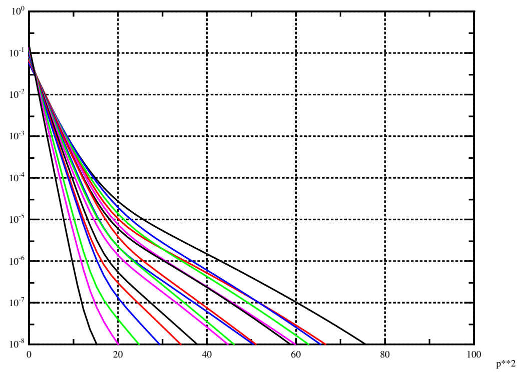
Wave pattern



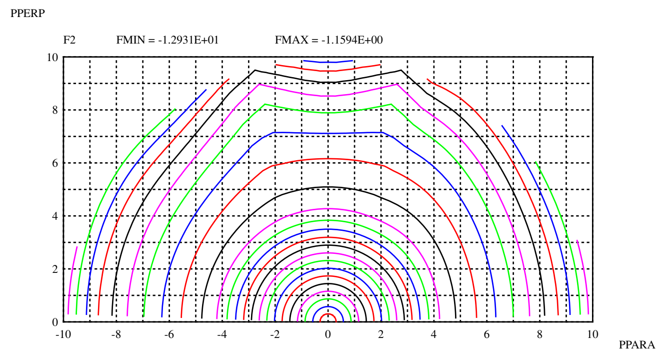
Quasi-linear Diffusion



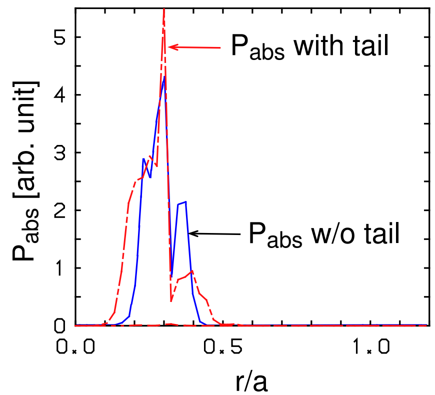
Momentum Distribution



Tail Formation



Power deposition



ITER Modeling Needs

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

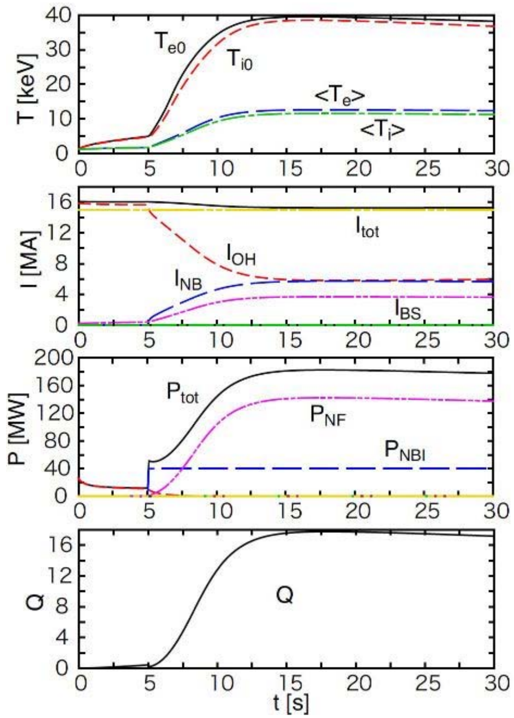
- **Plasma scenario development**:
  - Preparation for operation
- **Detailed design of auxiliary systems**:
  - H&CD, Diagnostics, Fueling, $\cdots$
- **Design of plasma control system**:
  - Development and optimization of integrated control strategies
- **Preparation of ITER operational programme**: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

ITER Plasma Transport Simulation with CDBM05

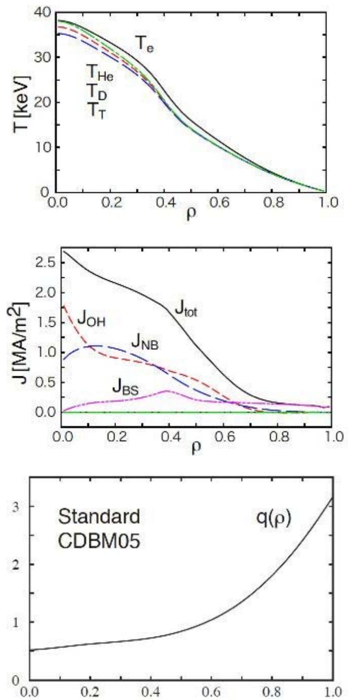
- **Inductive operation**
  - $I_{\mathrm{p}} = 15\,\mathrm{MA}$
  - $P_{\mathrm{NB}} = 40\,\mathrm{MW}$ on axis
  - $\beta_{\mathrm{N}} = 2.65$

- **Hybrid operation**
  - $I_{\mathrm{p}} = 12\,\mathrm{MA}$
  - $P_{\mathrm{NB}} = 33\,\mathrm{MW}$ on axis
  - $\beta_{\mathrm{N}} = 2.68$

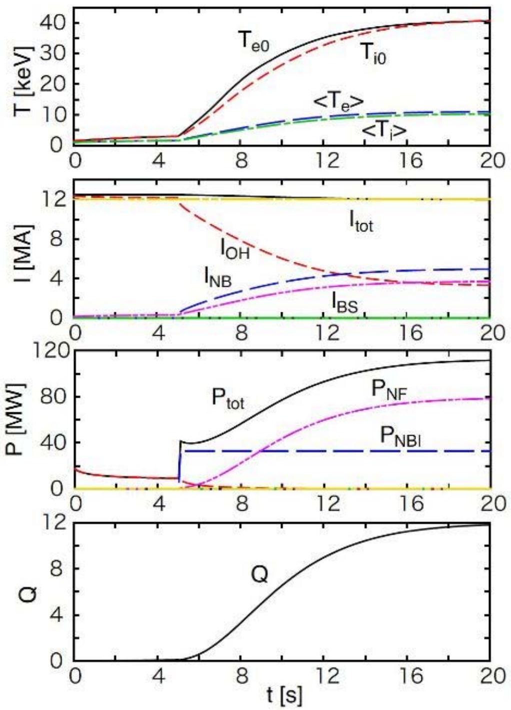
Time evolution



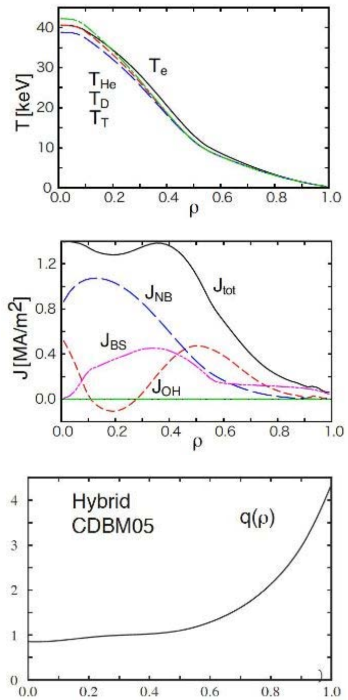
Radial profile



Time evolution



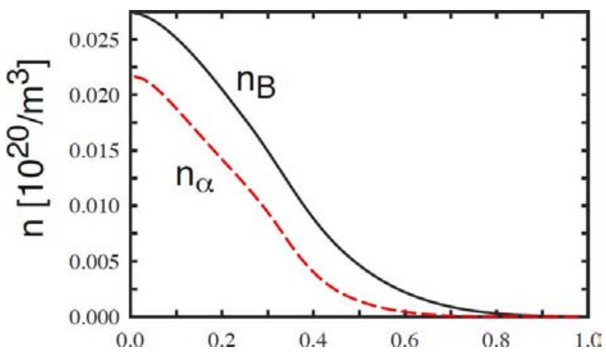
Radial profile



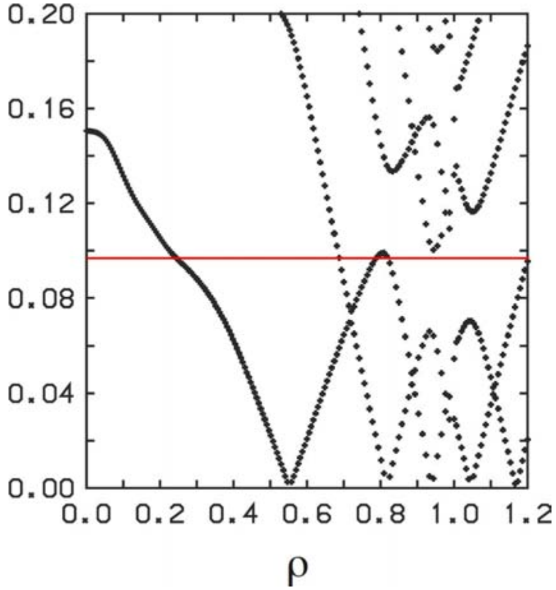
Alfvén Eigenmode Analysis by TASK/WM

- **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 = $(95.95\,\mathrm{kHz}, -1.95\,\mathrm{kHz})$

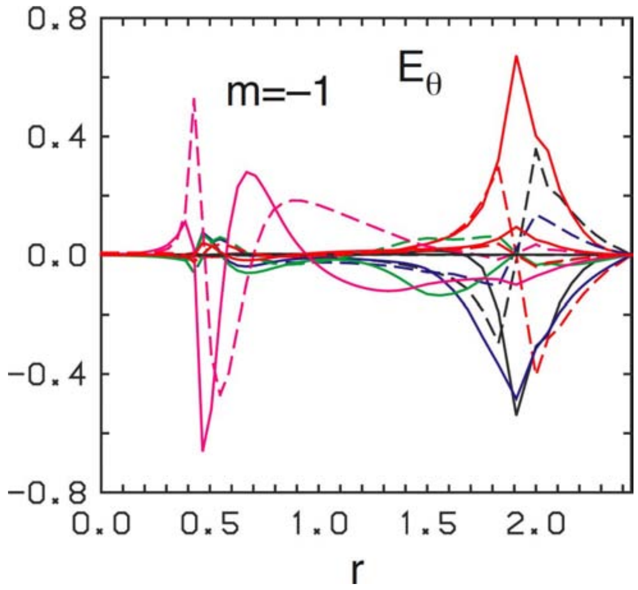
Alpha particle density



Alfvén continuum frequency



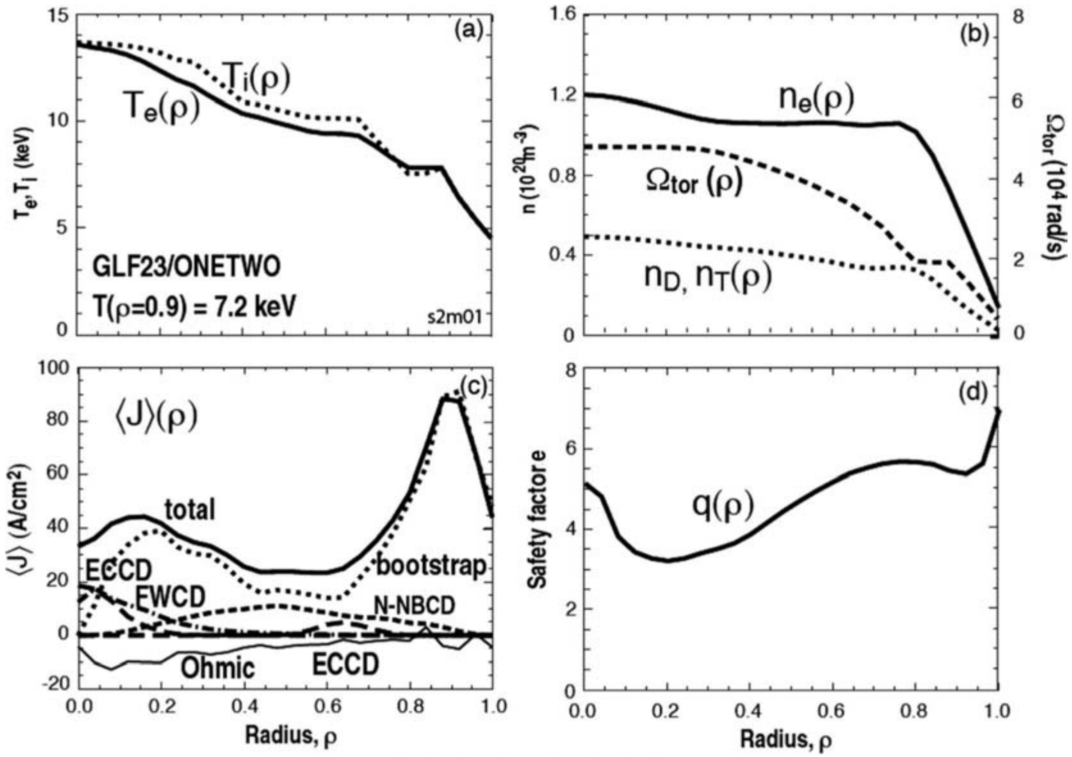
Alfvén eigenmode structure



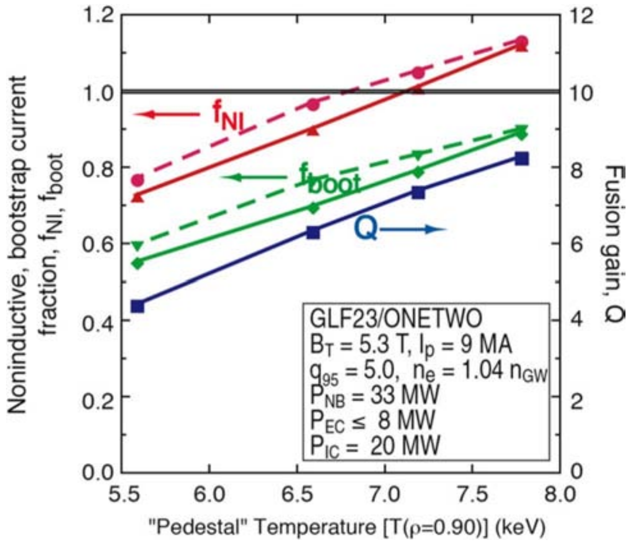
Modeling of Steady-State Operation

Progress in the ITER Physics Basis, NF 47 (2007) S285 - S336

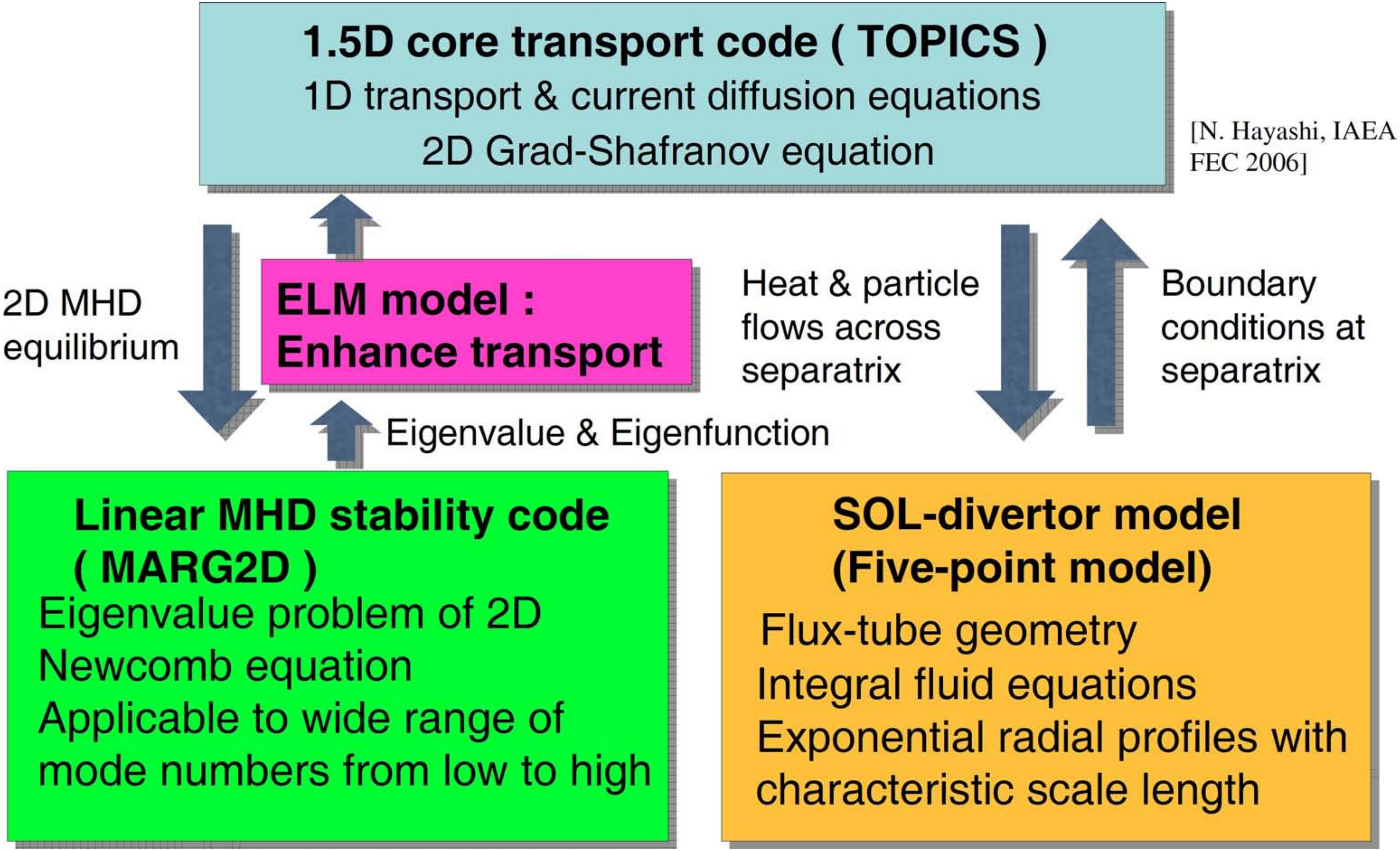
Simulation result by GLF23



Dependence on pedestal temperature

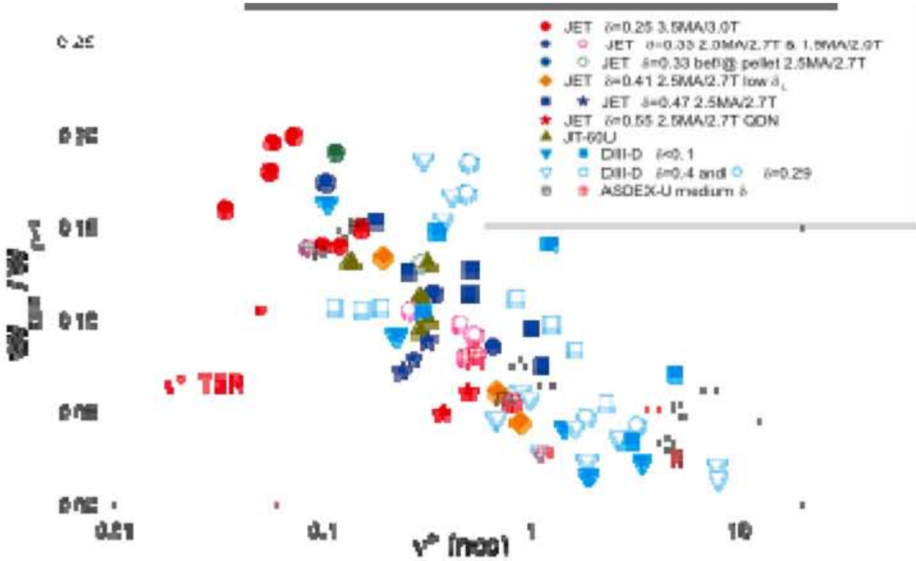


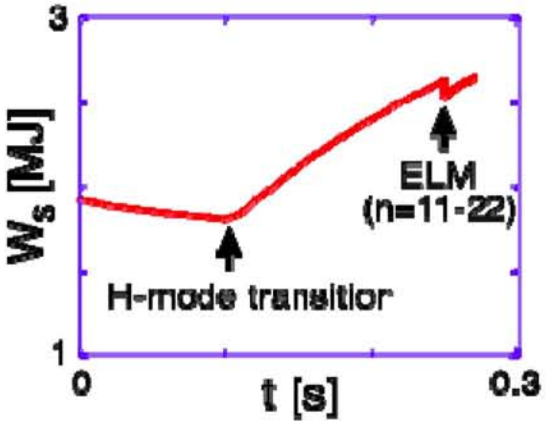
Integrated ELM Modeling by JAEA

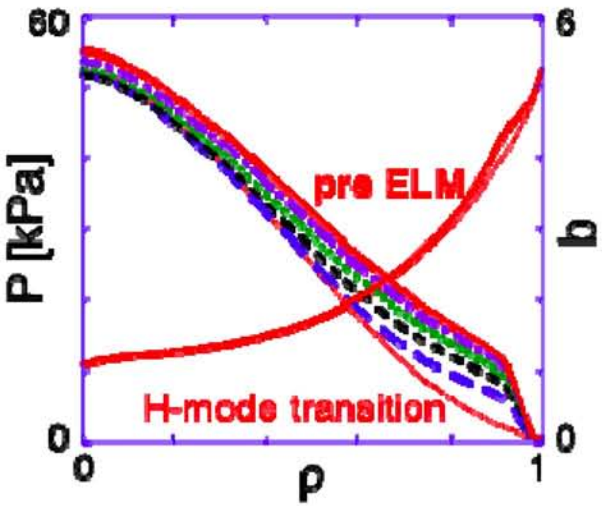


ELM Energy Loss Simulation by JAEA

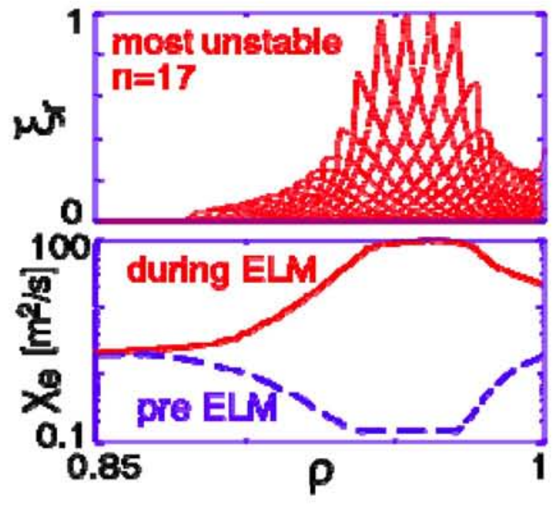
- **Energy loss by ELMs is crucial for reducing the divertor plate lifetime and limiting the plasma confinement.**
- **ELM energy loss was found to decrease with increasing the collisionality in multi-machine experiments.**
- **The collisionality dependence is investigated.**
- **ELM phenomena is simulated in JT-60 parameters.**





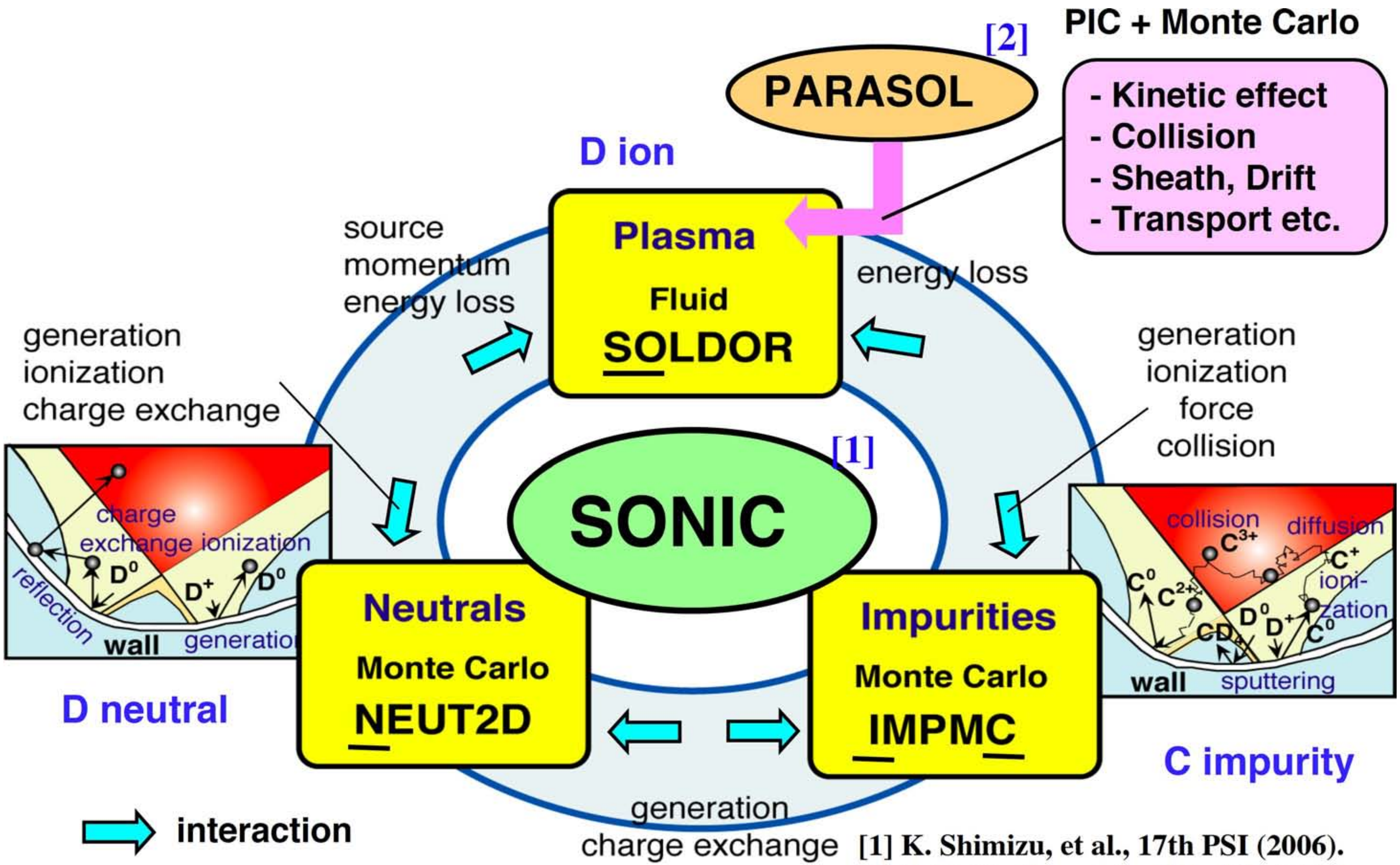


Pedestal formation : Neoclassical transport in peripheral region and anomalous in inside region.



Stabilities of n=1-30 modes are examined in each time step.

Integrated SOL-Divertor Code by JAEA



[1] K. Shimizu, et al., 17th PSI (2006).
[2] T. Takizuka, et al., 15th PSI (2002).

Remaining Issues

- **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.