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Modeling of Transport and Barrier Formation in Toroidal Plasmas

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- Transport Modeling: CDBM Transport Model
- Modeling of Internal Transport Barrier
- Modeling of Edge Transport Barrier
- Modeling of Transport in Helical Plasmas
- Summary

Transport Modeling

- **Recent progress of plasma operation and diagnostic technique in torus plasma experiments has revealed various improved confinement mode.**
- **Reliable transport model should reproduce experimental observations:**
  - **Global confinement time scaling**
  - **Nonlinear relation between heat flux and temperature gradient**
  - **Radial profile data base**
  - **Fluctuation type and level**
  - **Formation of transport barrier**

Modeling of Transport Barrier Formation (1)

- **Mechanism of Turbulence Suppression**
  - $E \times B$ **rotation shear**

— E_r **generation through radial force balance**

$$E_r = -u_\theta B_\phi + u_\phi B_\theta + \frac{1}{e_s}\frac{\mathrm{d}}{\mathrm{d}r}P$$

— $E \times B$ **shearing rate (Hahm and Burrel)**

$$\omega_E = \frac{RB_\theta}{B}\frac{\mathrm{d}}{\mathrm{d}r}\left(\frac{E_r}{RB_\theta}\right)\frac{k_\theta}{k_r}$$

— **Criteria for suppression**

$$\omega_E > \gamma_{\mathrm{Lin}}$$

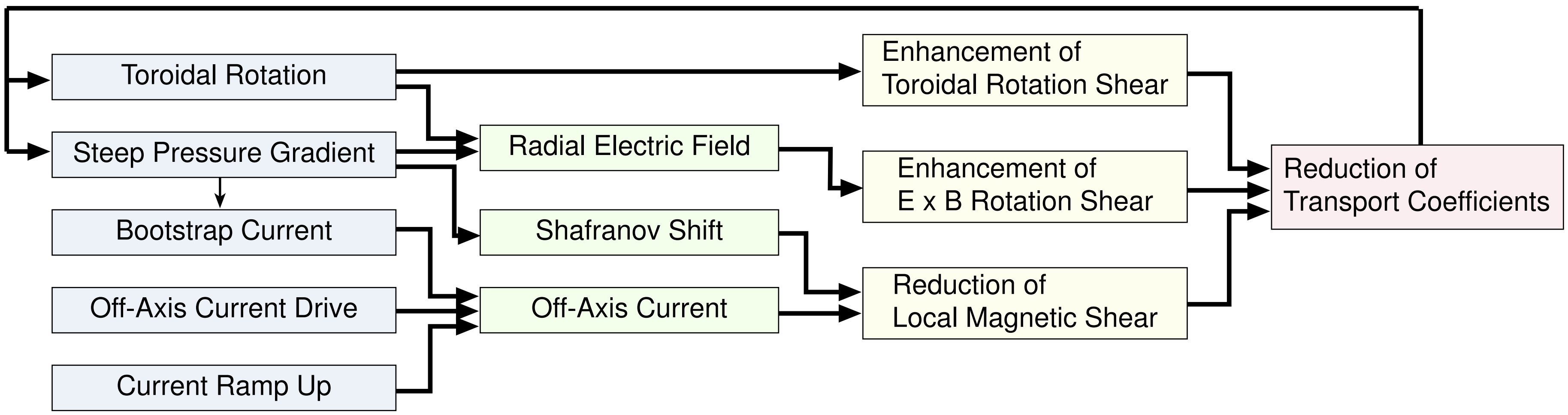
  - **Magnetic shear s and normalized pressure gradient α**

— **Marginal stability of self-sustained turbulence (CDBM model)**

— **Thermal diffusivity χ as a function of s and α**

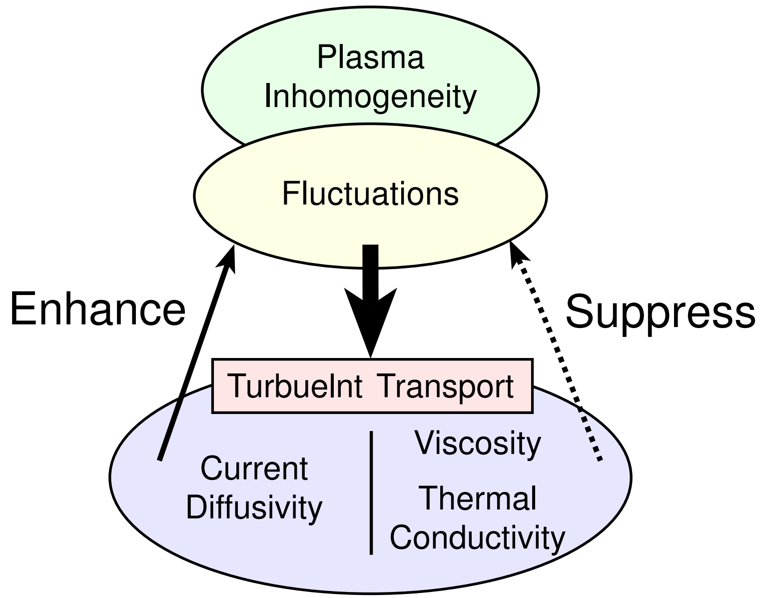
Modeling of Transport Barrier Formation (1)

- **Positive feedback of pressure gradient increase**
  - **In both models, χ depends on the pressure gradient. χ.**



CDBM Transport Model

- **Self-Sustained Turbulence Theory**
  - **Turbulence sustained by the enhancement of transport coefficients due to the turbulence itself**



- **Current-Diffusive Ballooning Mode**
  - **Ballooning mode: MHD mode localized in bad curvature region**

— **Ideal ballooning mode (second stability)**

— **Resistive ballooning mode (plasma near edge)**

— **Current-diffusive ballooning mode (core plasma)**

CDBM Turbulence Model

- **Marginal Stability Condition** ($\gamma = 0$)

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

Magnetic shear $\quad s \equiv \dfrac{r}{q}\dfrac{\mathrm{d}q}{\mathrm{d}r}$

Pressure gradient $\quad \alpha \equiv -q^2 R \dfrac{\mathrm{d}\beta}{\mathrm{d}r}$

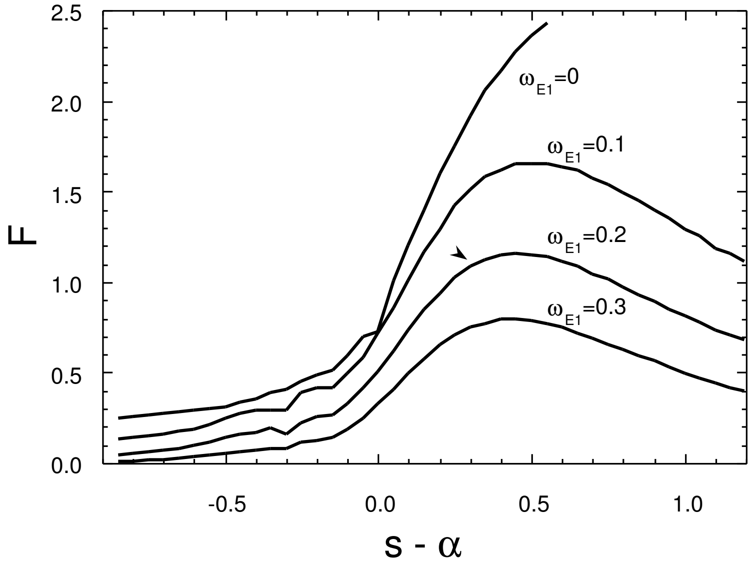
Magnetic curvature $\quad \kappa \equiv -\dfrac{r}{R}\left(1 - \dfrac{1}{q^2}\right)$

***E* × *B* rotation shear** $\quad \omega_{\mathrm{E1}} \equiv \dfrac{r^2}{s v_{\mathrm{A}}} \dfrac{\mathrm{d}}{\mathrm{d}r} \dfrac{E}{rB}$

- **Weak and negative magnetic shear,**
  Shafranov shift and
  ***E* × *B* rotation shear**

reduce thermal diffusivity.

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



Fitting Formula

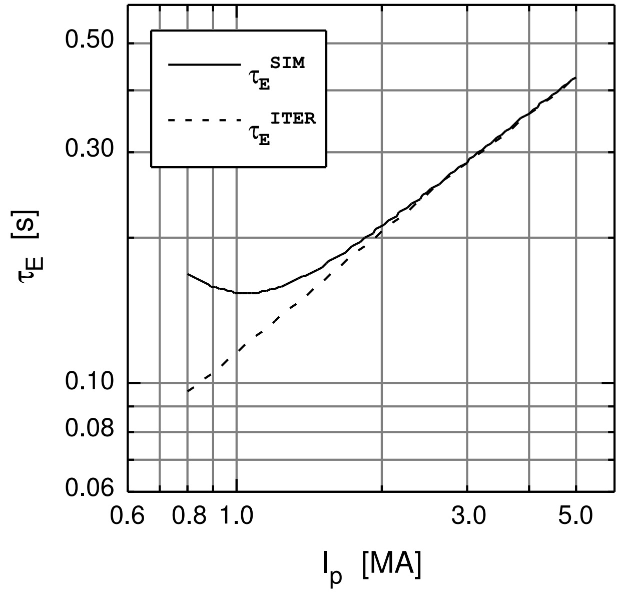
$$F = \begin{cases} \dfrac{1}{1 + G_1 \omega_{\mathrm{E1}}^2} \dfrac{1}{\sqrt{2(1-2s')(1-2s'+3s'^2)}} & \textbf{for} \quad s' = s - \alpha < 0 \\[2ex] \dfrac{1}{1 + G_1 \omega_{\mathrm{E1}}^2} \dfrac{1 + 9\sqrt{2} s'^{5/2}}{\sqrt{2}(1 - 2s' + 3s'^2 + 2s'^3)} & \textbf{for} \quad s' = s - \alpha > 0 \end{cases}$$

Simulation of L-mode and Improved Confinement

- **Zero-Dimensional Analysis with fixed $F(s, \alpha, \kappa)$ (gyro-Bohm scaling)**

$$\tau_E \propto F^{-0.4} A_i^{0.2} I_P^{0.8} n^{0.6} B^0 a^{1.0} R_0^{1.2} P^{-0.6}$$

- **Deviation from L-mode scaling at low I_p**
  - **Increase of P_{in}**
  - **Increase of pressure gradient**
    $\longrightarrow$ Increase of α
  - **Increase of bootstrap current**
    $\longrightarrow$ Decrease of s
  - **Reduction of χ**

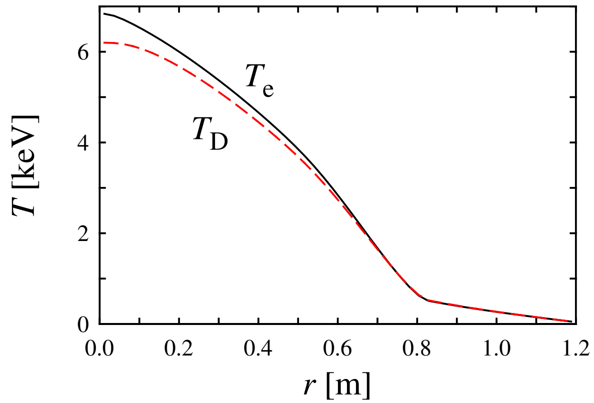


- **Various improved core confinement modes have been reproduced**
  - **High-β_p mode**
  - **PEP (Pellet Enhanced Performance) mode**
  - **LHEP (Lower Hybrid Enhanced Performance) mode**
  - **Negative Magnetic Shear mode**

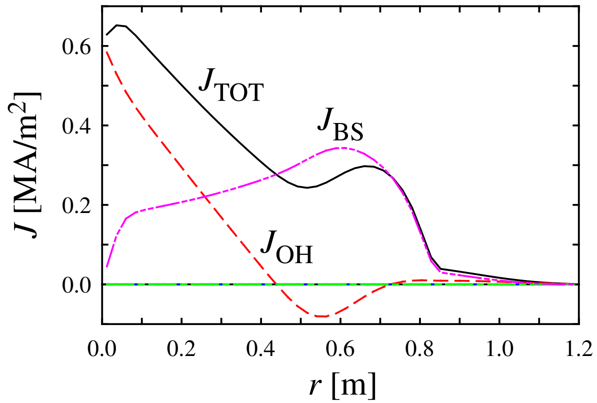
High β_p mode

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

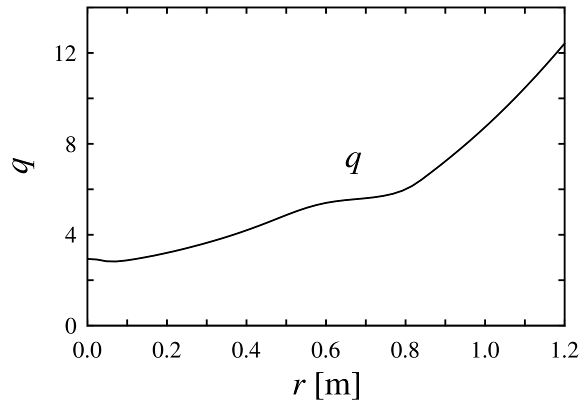
Temperater profile



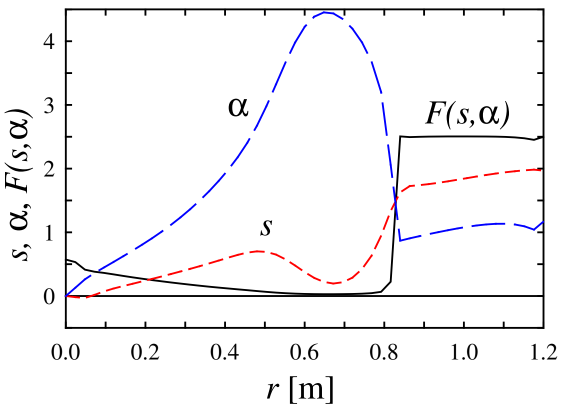
Current profile



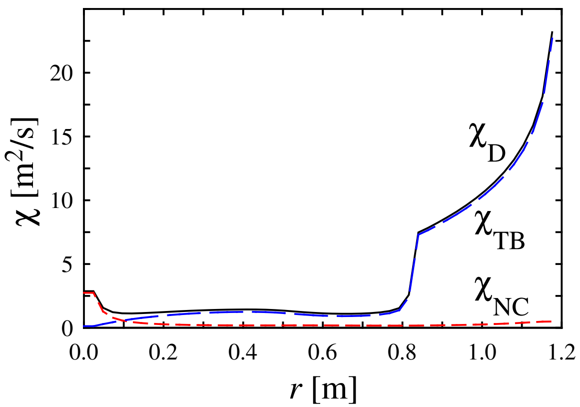
Safety factor



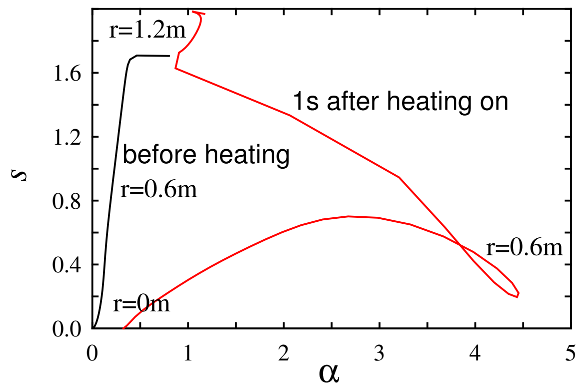
Shear and pressure



Thermal diffusivity

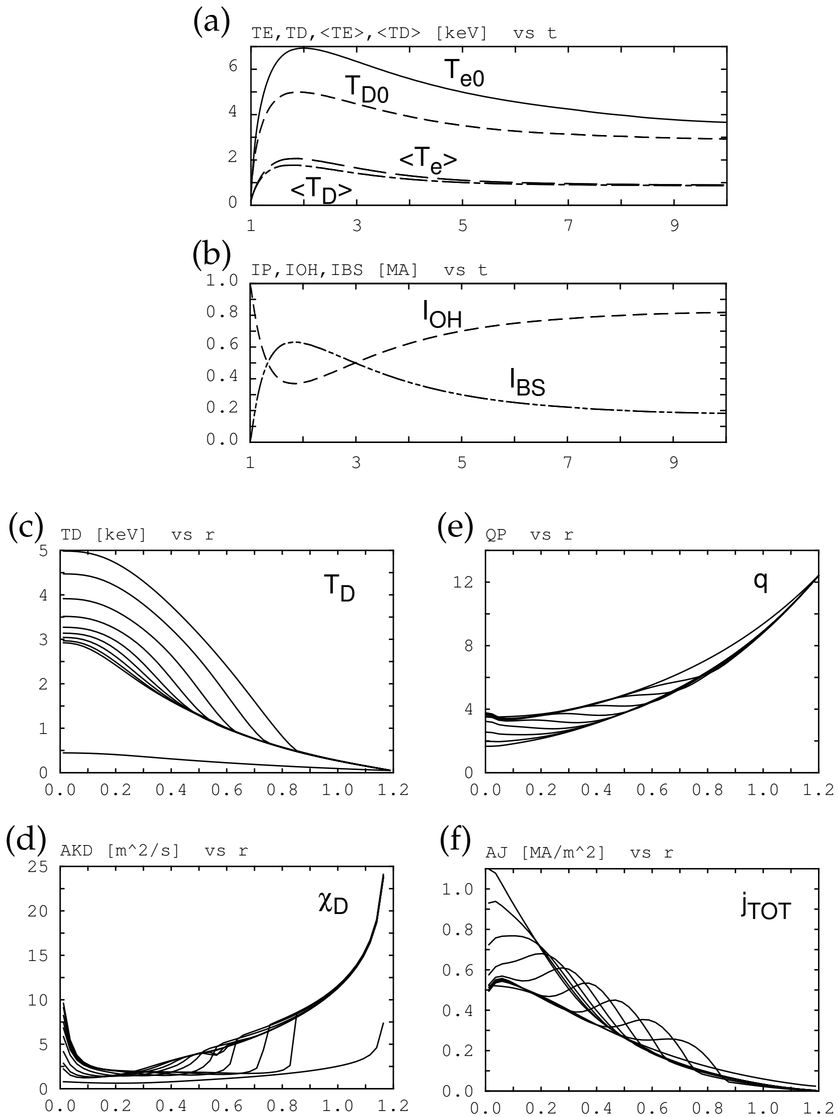


$s - \alpha$ diagram

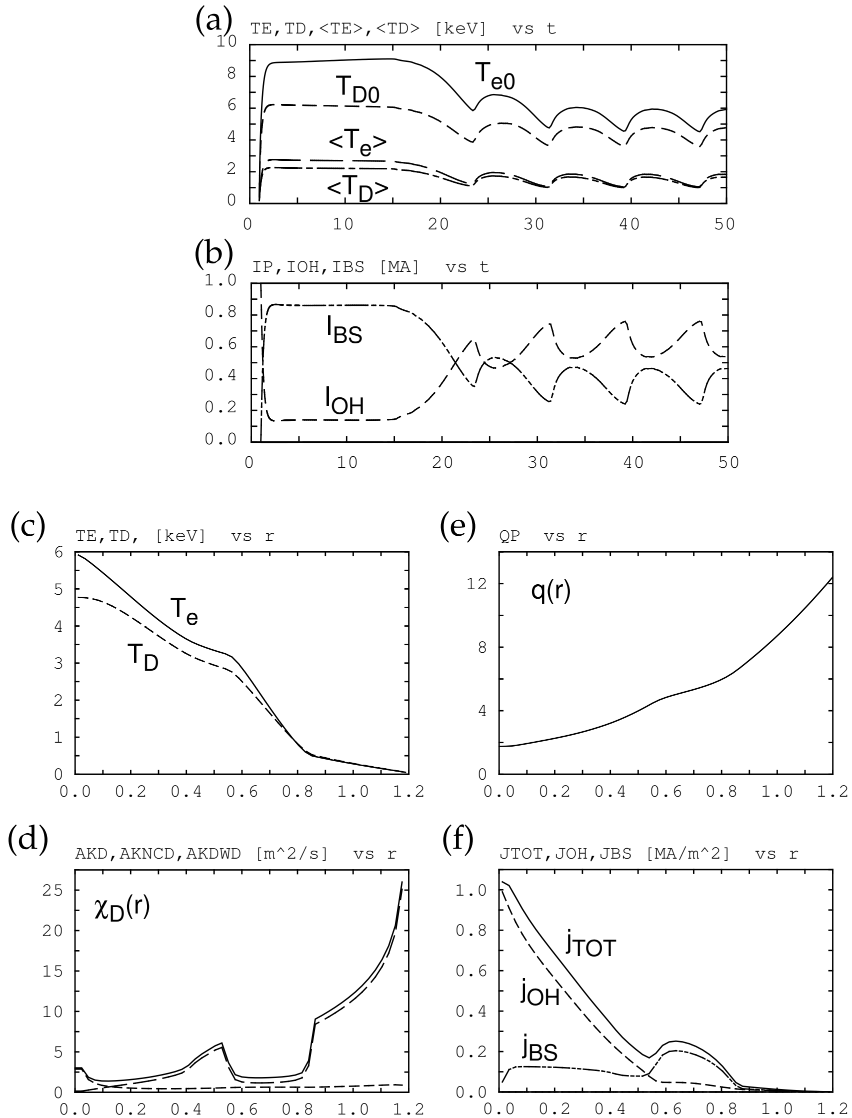


Time Evolution of High β_p mode

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



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



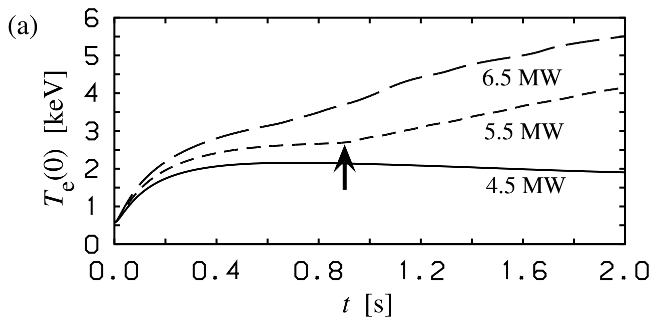
Effect of $E \times B$ Rotation Shear

- **Reduction of transport** **due to small s and large α:** $F(s, \alpha, \kappa)$

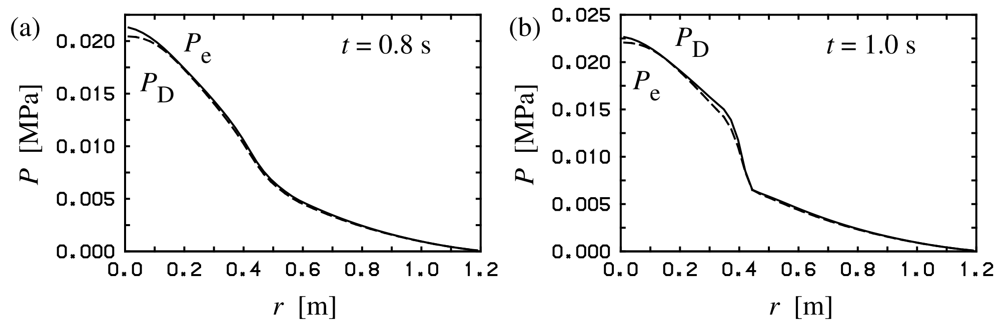
  $\Longrightarrow$ **Rapid increase of rotation shear:** $1/[1 + G(s, \alpha)\omega_{E1}^2]$

  $\Longrightarrow$ **Transition to enhanced ITB**

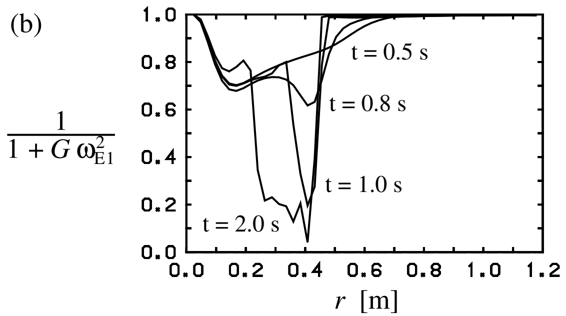
Time evolution of $T_e(0)$



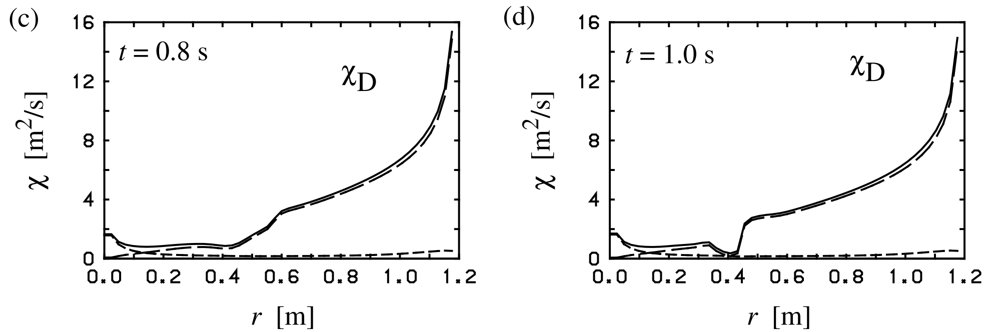
Pressure Profile Before and After Transition



Rapid Change of Rotation Shear



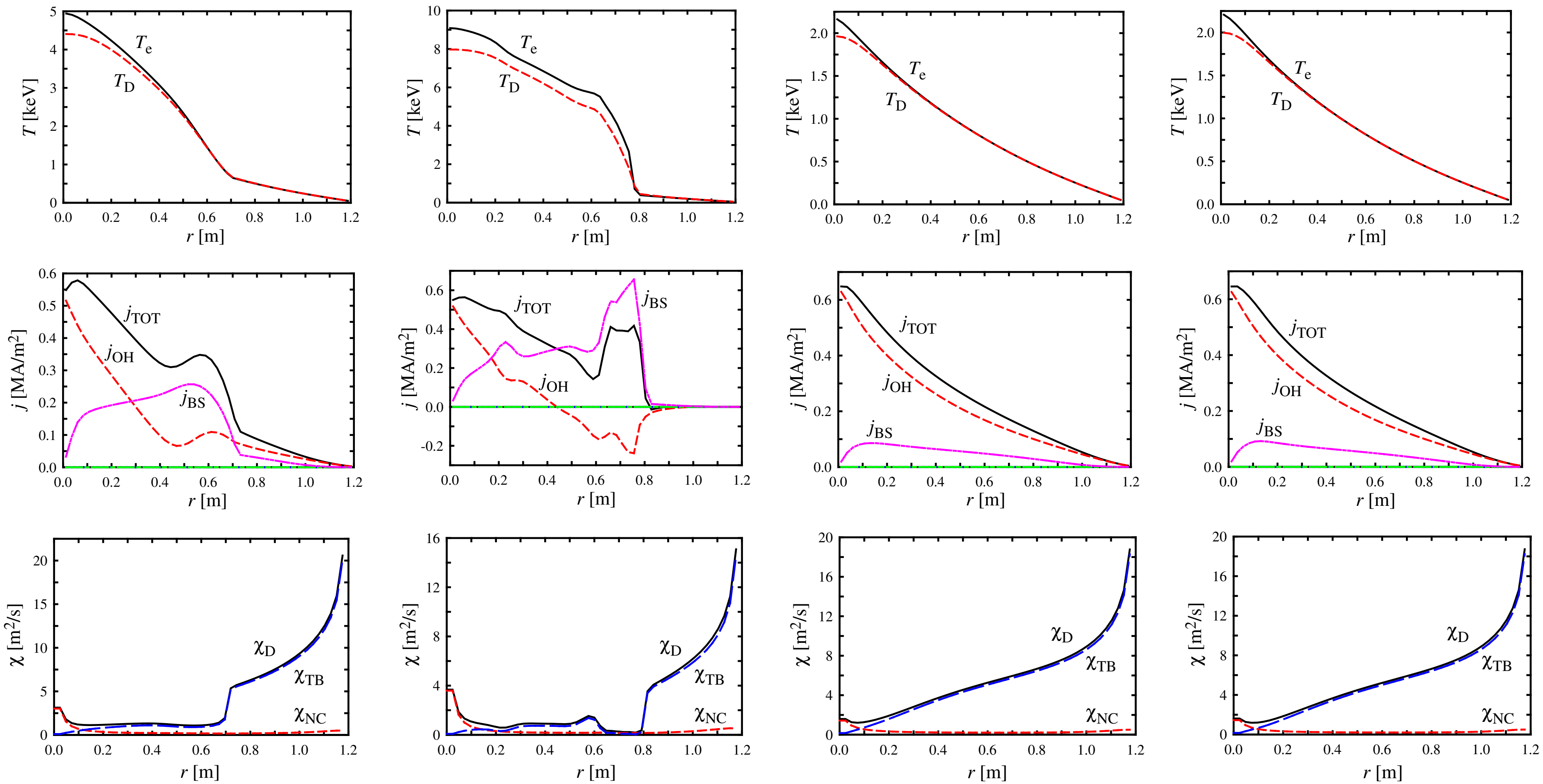
Thermal Diffusivity Before and After Transition



Shape of Transport Barrier

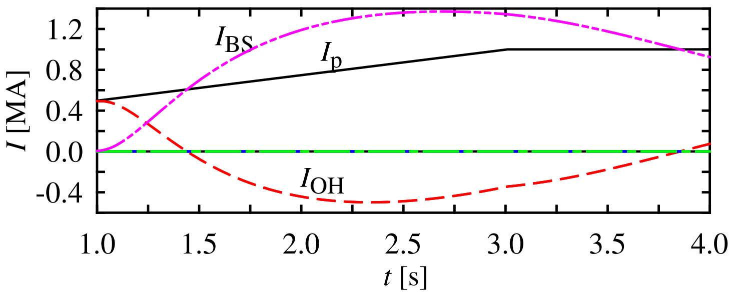
- **Dependence on the model**

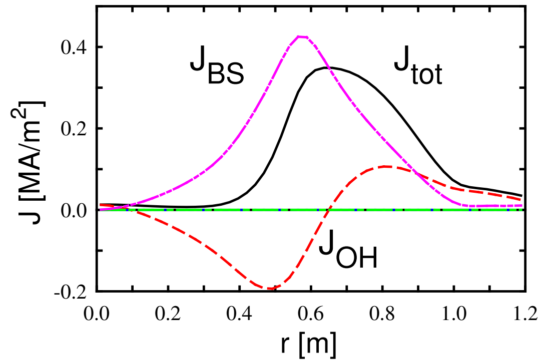
$F(s,\alpha)$ | $F(s,\alpha)/(1+G\omega_E^2)$ | $F(s)$ | $F(s)/(1+G\omega_E^2)$

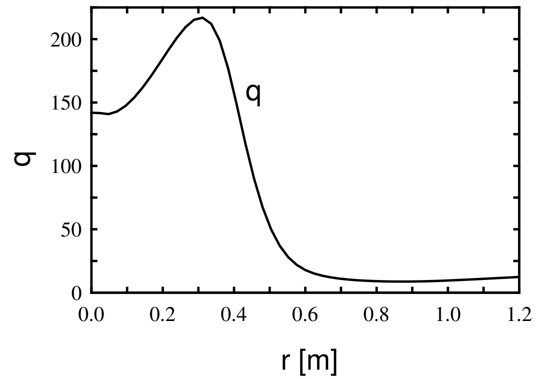


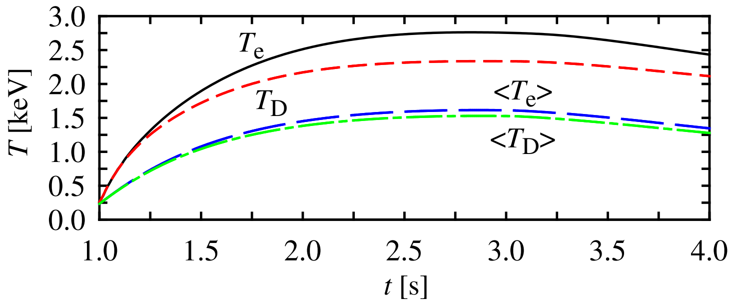
Simulation of Current Hole

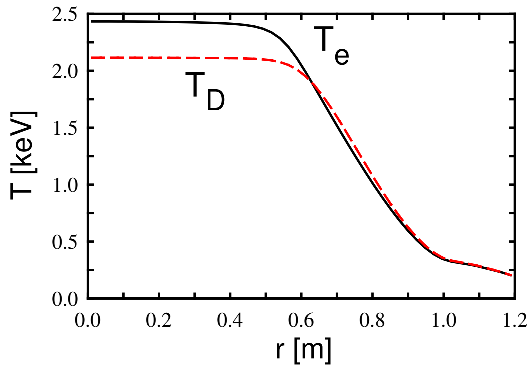
- **Current ramp up:** $I_p = 0.5 \longrightarrow 1.0\,\mathrm{MA}$
- **Moderate heating:** $P_H = 5\,\mathrm{MW}$
- **Current hole is formed.**
- **The formation is sensitive to the edge temperature.**

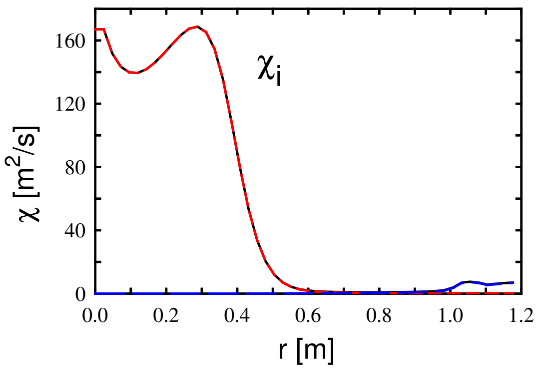












Modeling of ETB Formation

- 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

Transport Model

- **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**

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

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

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

Transport Model (1)

- **Neoclassical transport**
  - **Viscosity force arises when plasma rotates in the poloidal direction.**
  - **Banana-Plateau regime**

$$F^{\mathrm{NC}}_{s\theta} = -\sqrt{\pi} q^2 n_s m_s \frac{v_{\mathrm{T}s}}{qR} \frac{\nu^*_s}{1+\nu^*_s} u_{s\theta}$$

$$\nu^*_{\mathrm{s}} \equiv \frac{\nu_s qR}{\epsilon^{3/2} v_{\mathrm{T}s}}$$

- **This poloidal viscosity force induces**
  - **Neoclassical radial diffusion**
  - **Neoclassical resistivity**
  - **Bootstrap current**
  - **Ware pinch**

Transport Model (2)

- **Turbulent Diffusion**
  - **Poloidal momentum exchange between electron and ion through the turbulent electric field**
  - **Ambipolar flux (electron flux = ion flux)**

$$F_{\mathrm{i}\theta}^{\mathrm{W}} = - F_{\mathrm{e}\theta}^{\mathrm{W}}$$

$$= - ZeB_\phi n_\mathrm{i} D_\mathrm{i} \left[-\frac{1}{n_\mathrm{i}} \frac{dn_\mathrm{i}}{dr} + \frac{Ze}{T_\mathrm{i}} E_r - \langle \frac{\omega}{m} \rangle \frac{ZeB_\phi}{T_\mathrm{i}} - \left(\frac{\mu_\mathrm{i}}{D_\mathrm{i}} - \frac{1}{2} \right) \frac{1}{T_\mathrm{i}} \frac{dT_\mathrm{i}}{dr} \right]$$

- **Perpendicular viscosity**
  - **Non-ambipolar flux (electron flux ≠ ion flux):** $\mu_\mathrm{s} =$ **constant** $\times D$
- **Diffusion coefficient (proportional to $|E|^2$)**
  - **Current-diffusive ballooning mode turbulence model**

Modeling of Scrape-Off Layer Plasma

- **Particle, momentum and heat losses along the field line**
  - **Decay time**

$$\nu_\mathrm{L} = \begin{cases} 0 & (0 < r < a) \\ \dfrac{C_\mathrm{s}}{2\pi r R\{1 + \log[1 + 0.05/(r-a)]\}} & (a < r < b) \end{cases}$$

  - **Electron source term**

$$S_\mathrm{e} = n_0 \langle \sigma_\mathrm{ion} v \rangle n_\mathrm{e} - \nu_\mathrm{L}(n_\mathrm{e} - n_\mathrm{e,div})$$

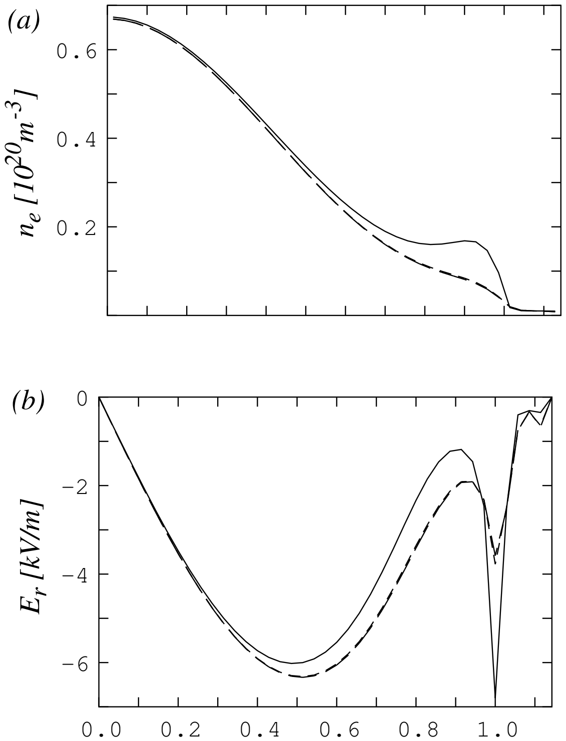
- **Recycling from divertor**
  - **Recycling rate:** $\gamma_0 = 0.8$
  - **Neutral source**

$$S_0 = \frac{\gamma_0}{Z_\mathrm{i}} \nu_\mathrm{L}(n_\mathrm{e} - n_\mathrm{e,div}) - \frac{1}{Z_\mathrm{i}} n_0 \langle \sigma_\mathrm{ion} v \rangle n_\mathrm{e} + \frac{P_\mathrm{b}}{E_\mathrm{b}}$$

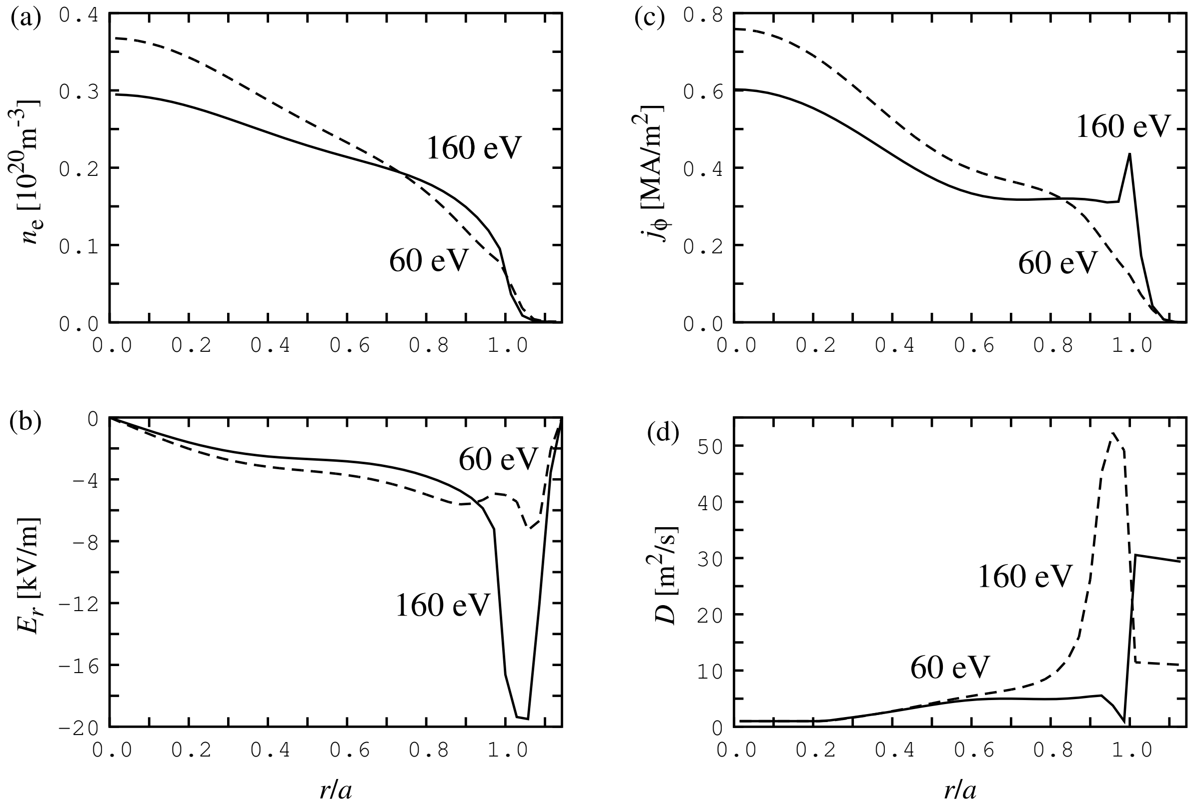
- **Gas puff from wall**

Typical Profiles

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

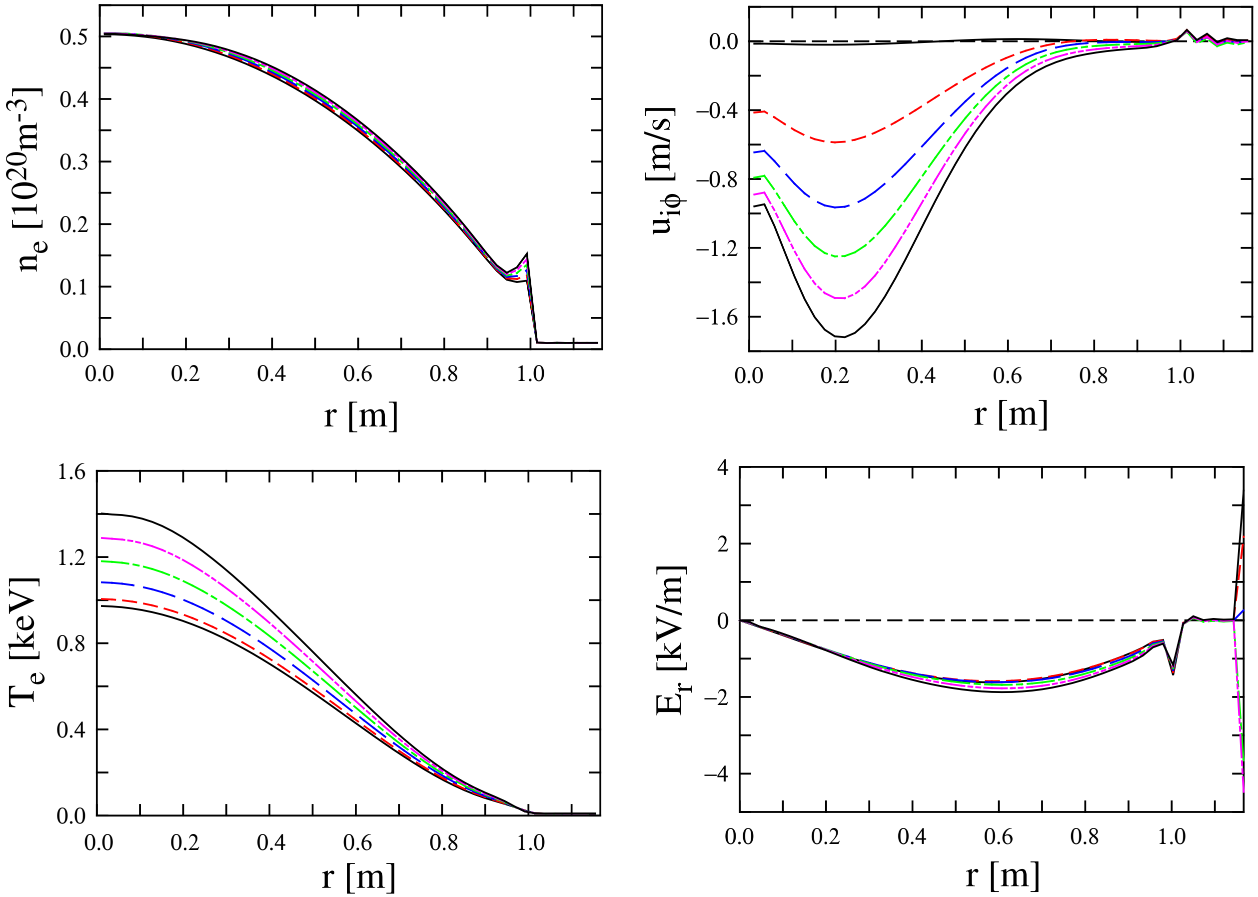


Edge Temperature Dependence



Transport Modeling in Helical Plasma

- **Neoclassical toroidal viscosity**
- **Negative magnetic shear**
- **Preliminary Result**
  - **NBI heating** ($P = 5\,\mathrm{MW}$) **: Order of magnitude slower rotation**



Summary

- **Viable transport models reproduce nonlinear relation between flux and gradient, L-mode confinement time scaling, radial profiles and its time evolution, fluctuation behavior and transport barrier formation.**

- **Turbulence transport model driven by current diffusive ballooning mode satisfies most of these conditions and reproduces various kinds of improved confinement mode associated with ITB formation.**

- **ETB formation in H-mode was studied by using surface-averaged fluid equations in both core and SOL plasmas. The change of transport mechanism across the separatrix generates the radial electric field at the edge and suppress the transport.**

- **In toroidal helical plasmas, neoclassical toroidal viscosity impedes toroidal rotation and affects the transport. Preliminary result was presented.**

- **Further improvement in modeling of barrier formation is required:**

  Time evolution, Parameter dependence and Collapse