New Physics Studies with the FACETS Code

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Summary of Physics Studies with FACETS

- Investigate the plasma transport in plasma core including the H-mode pedestal region
  - Paleoclassical transport in the plasma edge region near the separatrix
    - Particle transport including the effect of neutral fueling
  - ETG thermal transport at the top of separatrix
  - Study of model stiffness
    - Dependence on the boundary conditions
    - Effect of plasma current evolution on the model stiffness
- Verification studies
  - Anomalous transport GLF23 and TGLF models using XPTOR and TGYRO codes
  - Neoclassical models for bootstrap current in FACETS and TRANSP
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  - Reduced model for ELMs
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  - ELM mitigation
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- ITER studies

Paleoclassical model is implemented in FACETS

$$-\langle \nabla \cdot \mathbf{Q}_e^{\rm pc} \rangle = \frac{M+1}{V'} \frac{\partial^2}{\partial \rho^2} \left(V' \frac{\eta_\parallel^{\rm nc}}{\mu_0 \bar{a}^2} \frac{3}{2} n_e T_e \right),$$

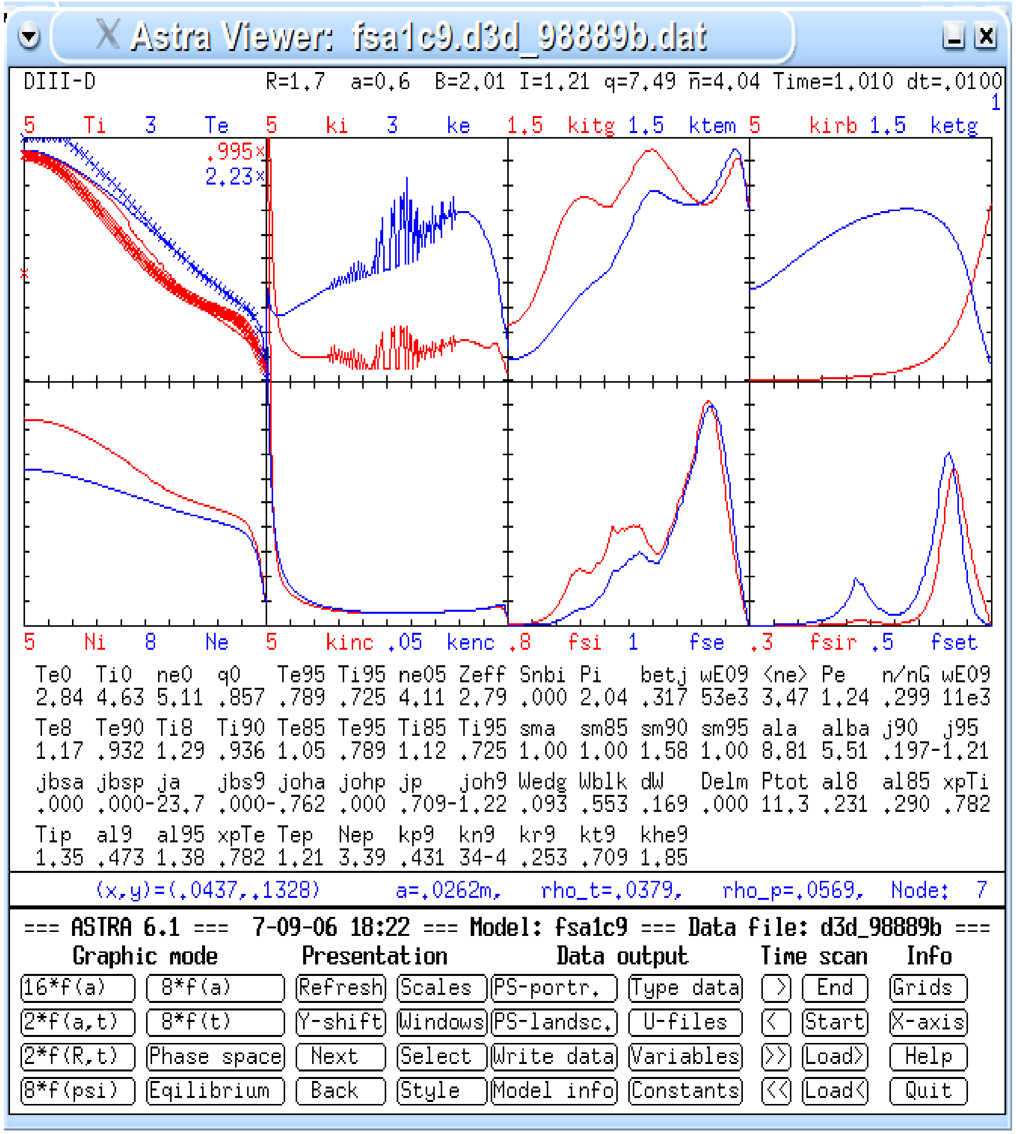
$$\chi_e^{\rm pc} \equiv \frac{3}{2}(M+1) D_\eta, \quad D_\eta \equiv \frac{\eta_\parallel^{\rm nc}}{\mu_0} \sim \frac{\eta_0}{\mu_0} \equiv \frac{1400\, Z_{\rm eff}}{T_e({\rm eV})^{3/2}},$$

$$M = \frac{\min\{\ell_{\rm max}, \lambda_e, \ell_{n\circ}\}}{\pi \bar{R}\, q} \simeq \frac{1}{\pi \bar{R}\, q} \frac{1}{1/\lambda_e + 1/\ell_{\rm max}}, \qquad \frac{1}{\bar{a}^2} \equiv \frac{\langle |\nabla \rho|^2 / R^2 \rangle}{\langle R^{-2} \rangle} \simeq \frac{1}{a^2} \frac{1+\kappa^2}{2\,\kappa^2}.$$

- **Currently, the paleoclassical model in FACETS uses simplified expression for the parallel neoclassical resistivity that should be replaced with the neoclassical resistivity computed by NCLASS**

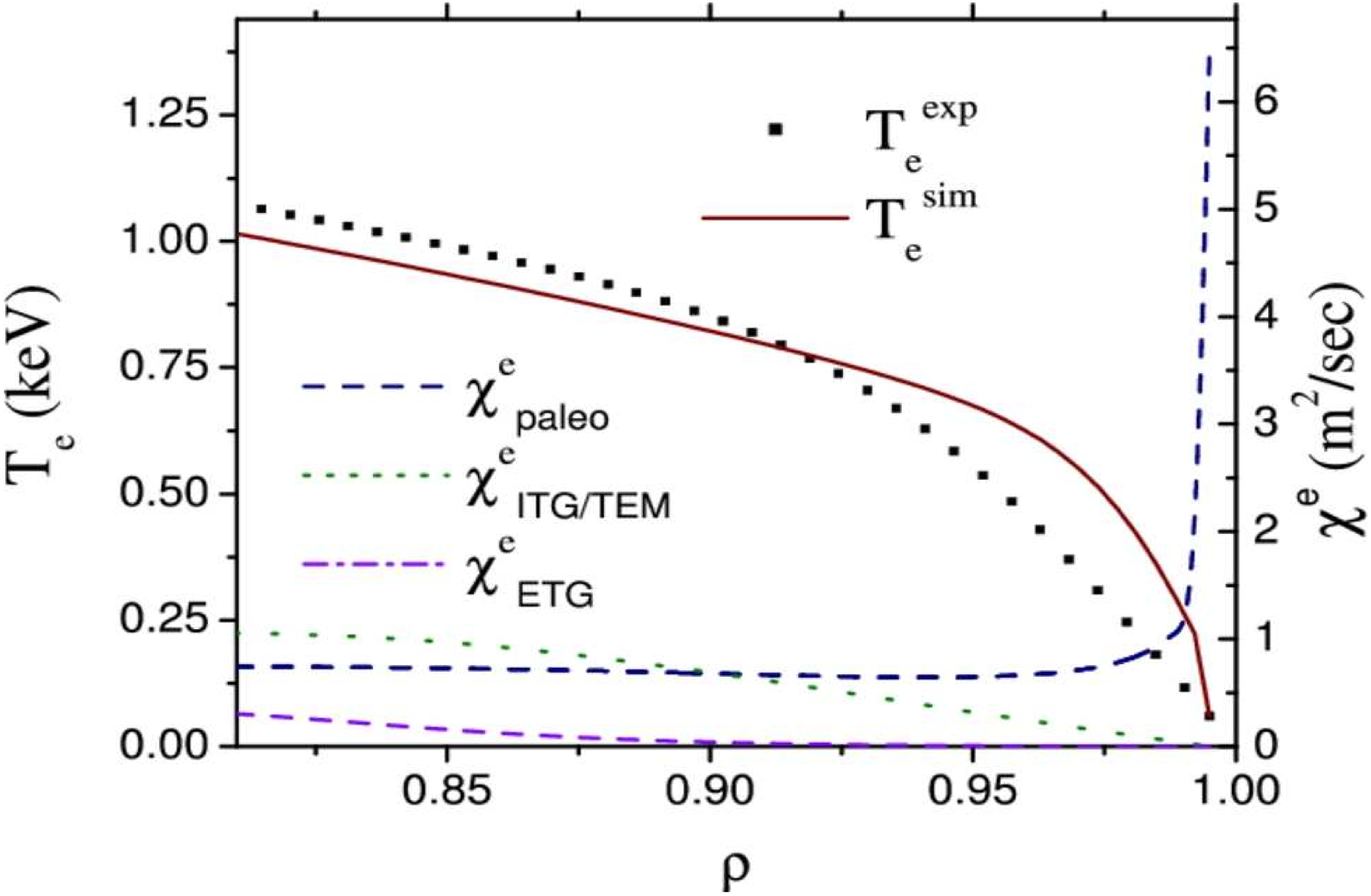
Paleoclassical model has been previously verified in the ASTRA code

- DIII-D discharges
  - **98889**
  - 77557
  - 77559
  - 99411
  - 118897
- JET discharge
  - 38285
  - 38407
  - 32745



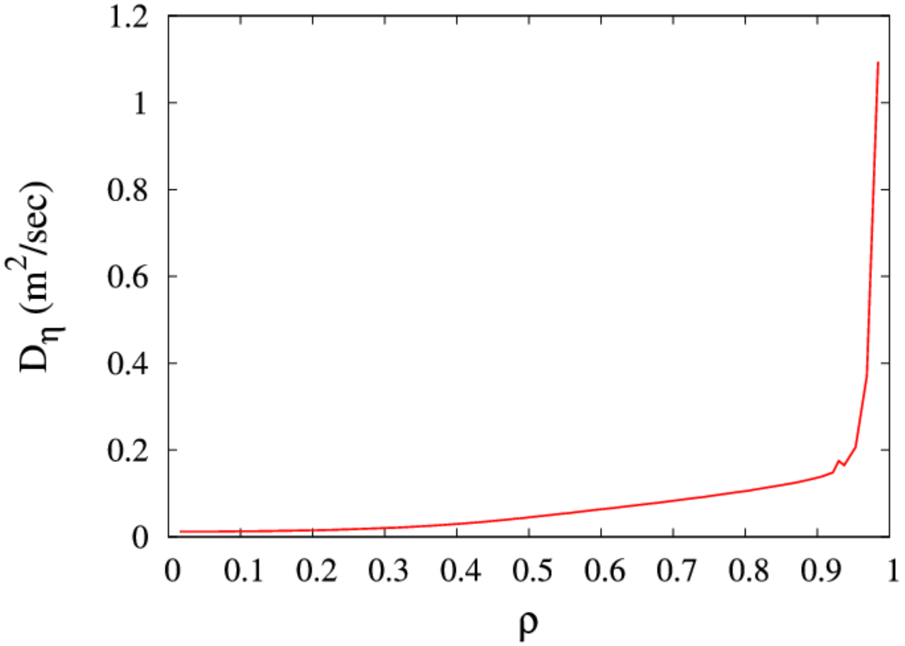
```
DIII-D              R=1,7  a=0,6  B=2,01 I=1,21 q=7,49 n̄=4,04 Time=1,010 dt=,0100

 Te0  Ti0  ne0  q0   Te95 Ti95 ne05 Zeff Snbi Pi   betj wE09 <ne> Pe   n/nG wE09
 2,84 4,63 5,11 ,857 ,789 ,725 4,11 2,79 ,000 2,04 ,317 53e3 3,47 1,24 ,299 11e3
 Te8  Te90 Ti8  Ti90 Te85 Te95 Ti85 Ti95 sma  sm85 sm90 sm95 ala  alba j90  j95
 1,17 ,932 1,29 ,936 1,05 ,789 1,12 ,725 1,00 1,00 1,58 1,00 8,81 5,51 ,197-1,21
 jbsa jbsp ja   jbs9 joha johp jp   joh9 Wedg Wblk dW   Delm Ptot al8  al85 xpTi
 ,000 ,000-23,7 ,000-,762 ,000 ,709-1,22 ,093 ,553 ,169 ,000 11,3 ,231 ,290 ,782
 Tip  al9  al95 xpTe Tep  Nep  kp9  kn9  kr9  kt9  khe9
 1,35 ,473 1,38 ,782 1,21 3,39 ,431 34-4 ,253 ,709 1,85

     (x,y)=(,0437,,1328)     a=,0262m,   rho_t=,0379,   rho_p=,0569,  Node:  7

=== ASTRA 6.1 ===  7-09-06 18:22 === Model: fsa1c9 === Data file: d3d_98889b ===
```

ASTRA simulations for DIII-D discharge 98889

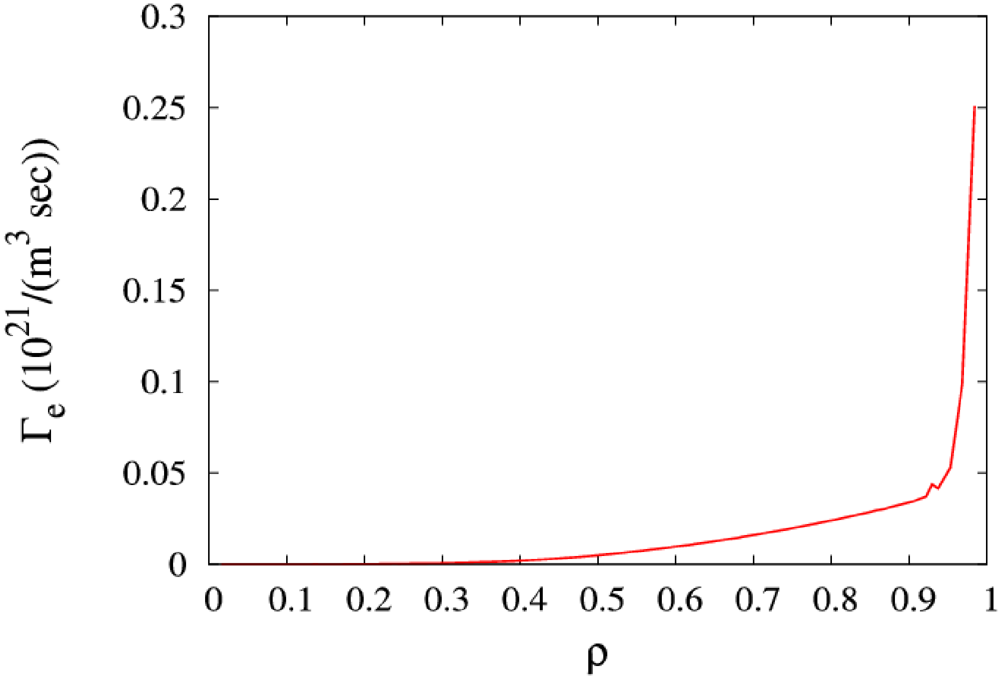


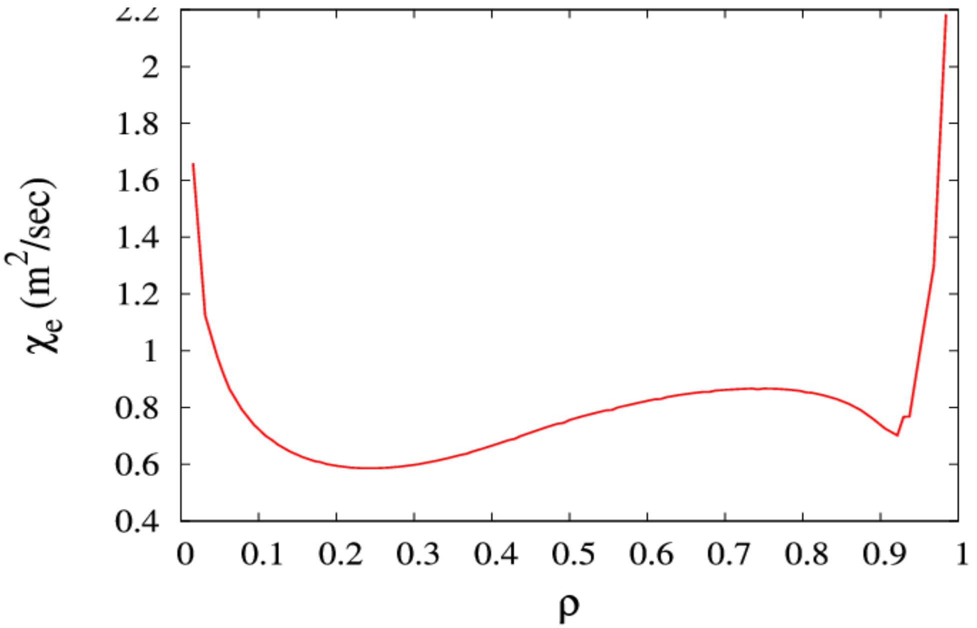
Pankin FACETS 2011

Paleoclassical model in FACETS for DIII-D discharge 98889

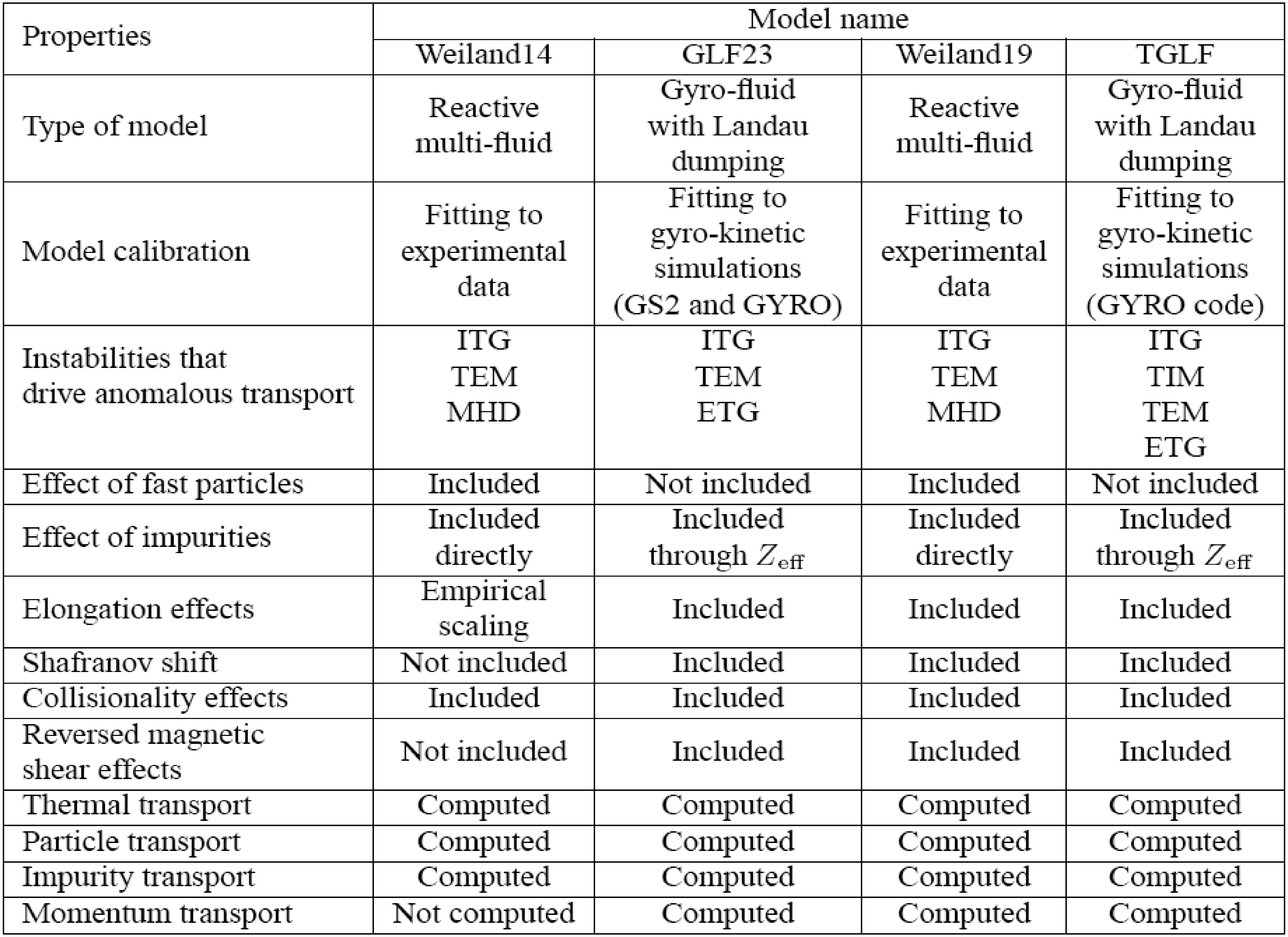


- **Both D_η and particle flux looks Γ_e very reasonable**
- **However, the effective electron thermal paleoclassical diffusivity unexpectedly increase near the magnetic axis**
    - **Definition of magnetic multiplier *M* need to be revisited**





ETG models in FACETS code



Properties	Model name			
	Weiland14	GLF23	Weiland19	TGLF
Type of model	Reactive multi-fluid	Gyro-fluid with Landau dumping	Reactive multi-fluid	Gyro-fluid with Landau dumping
Model calibration	Fitting to experimental data	Fitting to gyro-kinetic simulations (GS2 and GYRO)	Fitting to experimental data	Fitting to gyro-kinetic simulations (GYRO code)
Instabilities that drive anomalous transport	ITG TEM MHD	ITG TEM ETG	ITG TEM MHD	ITG TIM TEM ETG
Effect of fast particles	Included	Not included	Included	Not included
Effect of impurities	Included directly	Included through Z_{eff}	Included directly	Included through Z_{eff}
Elongation effects	Empirical scaling	Included	Included	Included
Shafranov shift	Not included	Included	Included	Included
Collisionality effects	Included	Included	Included	Included
Reversed magnetic shear effects	Not included	Included	Included	Included
Thermal transport	Computed	Computed	Computed	Computed
Particle transport	Computed	Computed	Computed	Computed
Impurity transport	Computed	Computed	Computed	Computed
Momentum transport	Not computed	Computed	Computed	Computed

ETG Horton Model for Electron Thermal Transport

- Developed as generalization of hydrodynamic theory for short wavelength ETG turbulence with electromagnetic effects†
- Calibrated using fast wave electron heated Tore Supra discharges with hot electrons ($T_e > 2T_i$)
- The electron thermal diffusivity is given by:

$$\chi_e^{(0)} = \begin{cases} C_e^{es} q^2 \left(\frac{R}{L_{Te}}\right)^{3/2} \left(\frac{c\rho_e}{eB_T}\right)\left[\nabla T_e - C_L \left(\frac{|s|T_e}{qR}\right)\left(1+\frac{T_e}{T_i}\right)\right], & l_{c,e}^{es} \geq \delta_e \\ C_e^{em} q^{\nu} \frac{c^2}{\omega_{pe}^2}\frac{\upsilon_e}{\left(L_{Te}R\right)^{1/2}}, & l_{c,e}^{es} < \delta_e \end{cases}$$

where q is the safety factor, δ_e is the collisionless skin depth, $C_e^{es}=C_e^{em}=0.08$, $C_L=1.88$, and $\nu \approx 0$ are semi-empirical parameters

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†W. Horton, Phys. Fluids 31, 2971 (1988); W. Horton et al, Phys. Plasmas **7**, 1494 (2000)
W. Horton et al., Comments Plasma Phys. Control. Fusion 13, 207 (1990).

Modified Horton Model for χ_e

Jenko formula introduced for $(R/L_{Te})^{cr}$ in the Horton model for $\chi_e^{(0)}$:

$$\chi_e = \begin{cases} 0, \; R/L_{Te} \le \left(R/L_{Te}\right)^{cr} \\ \chi_e^{(0)} \tanh\left(C_{th}\left(R/L_{Te} - \left(R/L_{Te}\right)^{cr}\right)\right), \; R/L_{Te} > \left(R/L_{Te}\right)^{cr} \end{cases}$$

- C_{th} is a parameter that characterizes the width of the transition region as a function of the electron temperature gradient

The threshold value for critical $(R/L_{Te})^{cr}$ is

$$\left(\frac{R}{L_{T_e}}\right)^{cr} = \max\left[(1+\tau)\left(1.33+1.91\frac{\hat{s}}{q}\right)(1-1.5\varepsilon)\left(1+0.3\varepsilon\frac{d\kappa}{d\varepsilon}\right), 0.8\frac{R}{L_n}\right]$$

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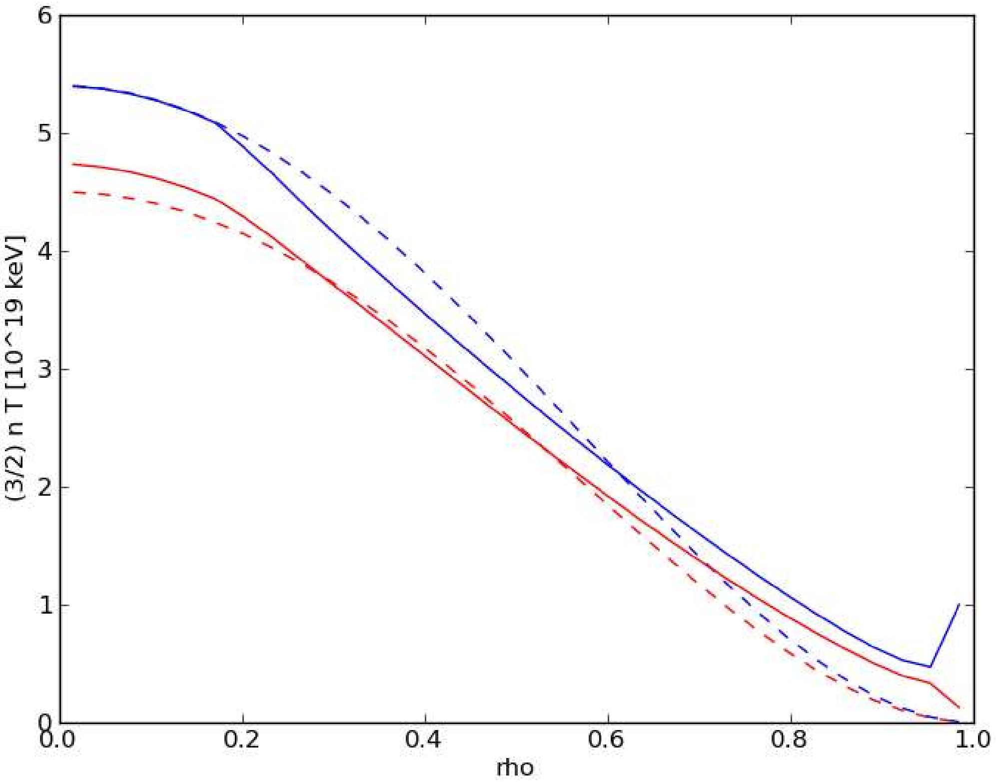
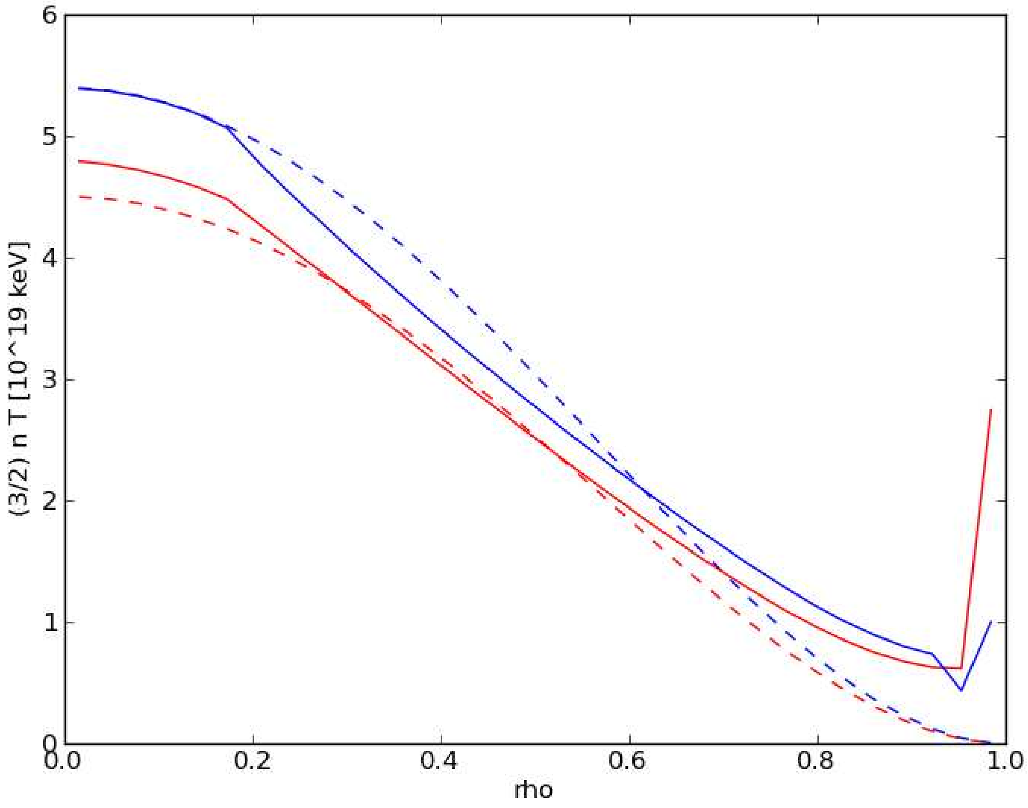
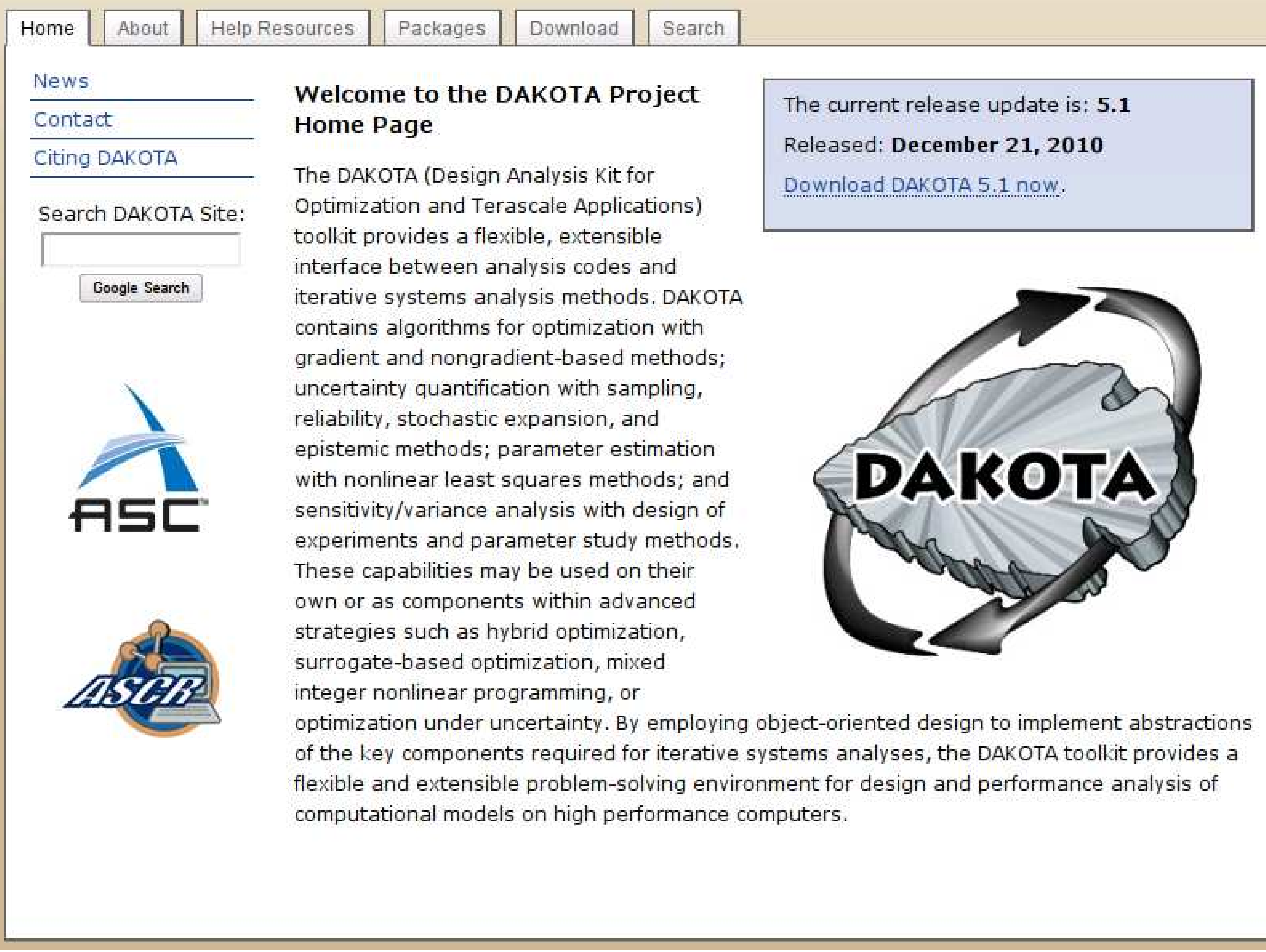
Effect of the boundary conditions – DAKOTA study

(http://dakota.sandia.gov/)

- Illustration of model stiffness







Welcome to the DAKOTA Project Home Page

The DAKOTA (Design Analysis Kit for Optimization and Terascale Applications) toolkit provides a flexible, extensible interface between analysis codes and iterative systems analysis methods. DAKOTA contains algorithms for optimization with gradient and nongradient-based methods; uncertainty quantification with sampling, reliability, stochastic expansion, and epistemic methods; parameter estimation with nonlinear least squares methods; and sensitivity/variance analysis with design of experiments and parameter study methods. These capabilities may be used on their own or as components within advanced strategies such as hybrid optimization, surrogate-based optimization, mixed integer nonlinear programming, or optimization under uncertainty. By employing object-oriented design to implement abstractions of the key components required for iterative systems analyses, the DAKOTA toolkit provides a flexible and extensible problem-solving environment for design and performance analysis of computational models on high performance computers.

The current release update is: **5.1**

Released: **December 21, 2010**

Download DAKOTA 5.1 now.

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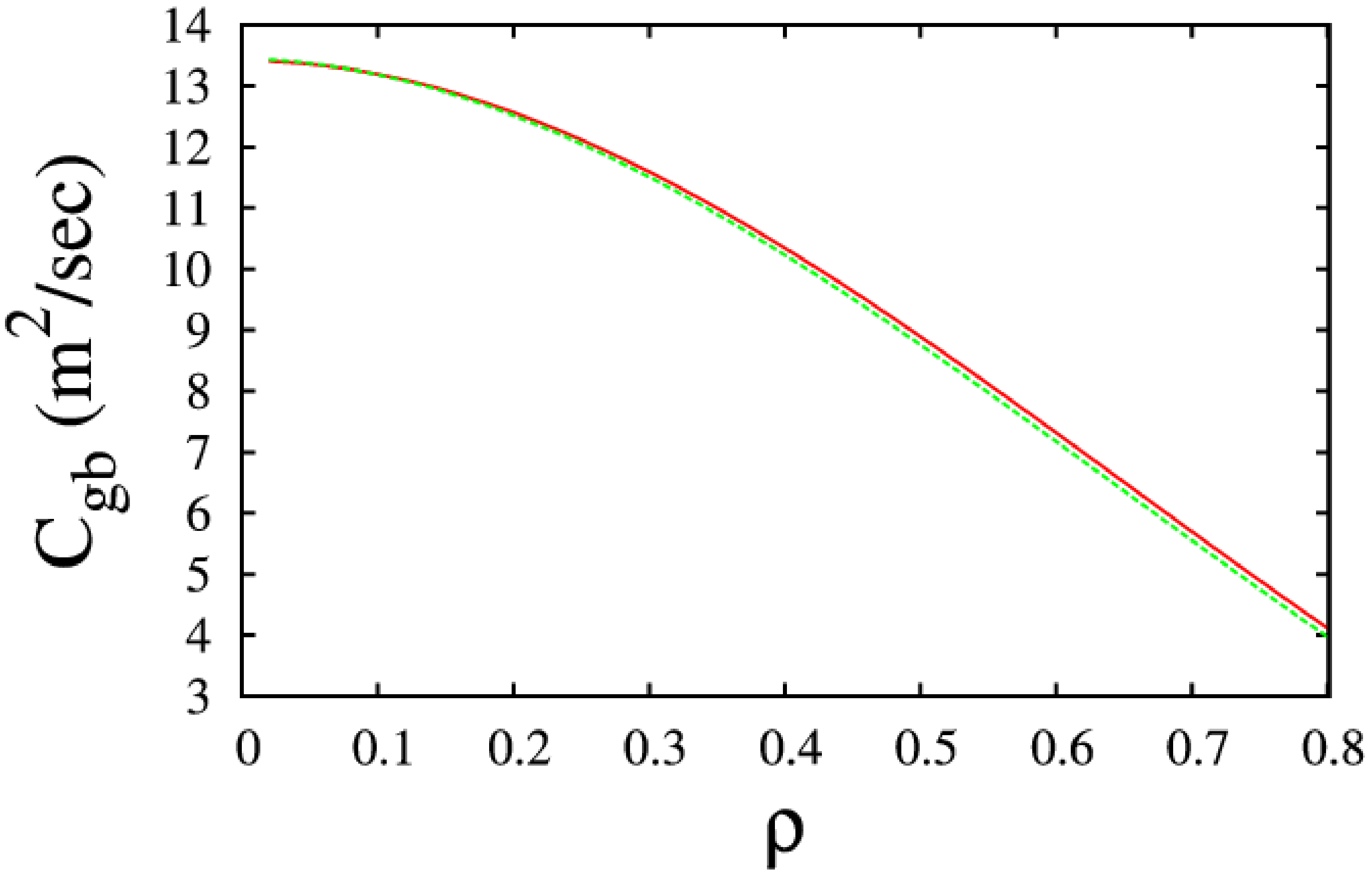
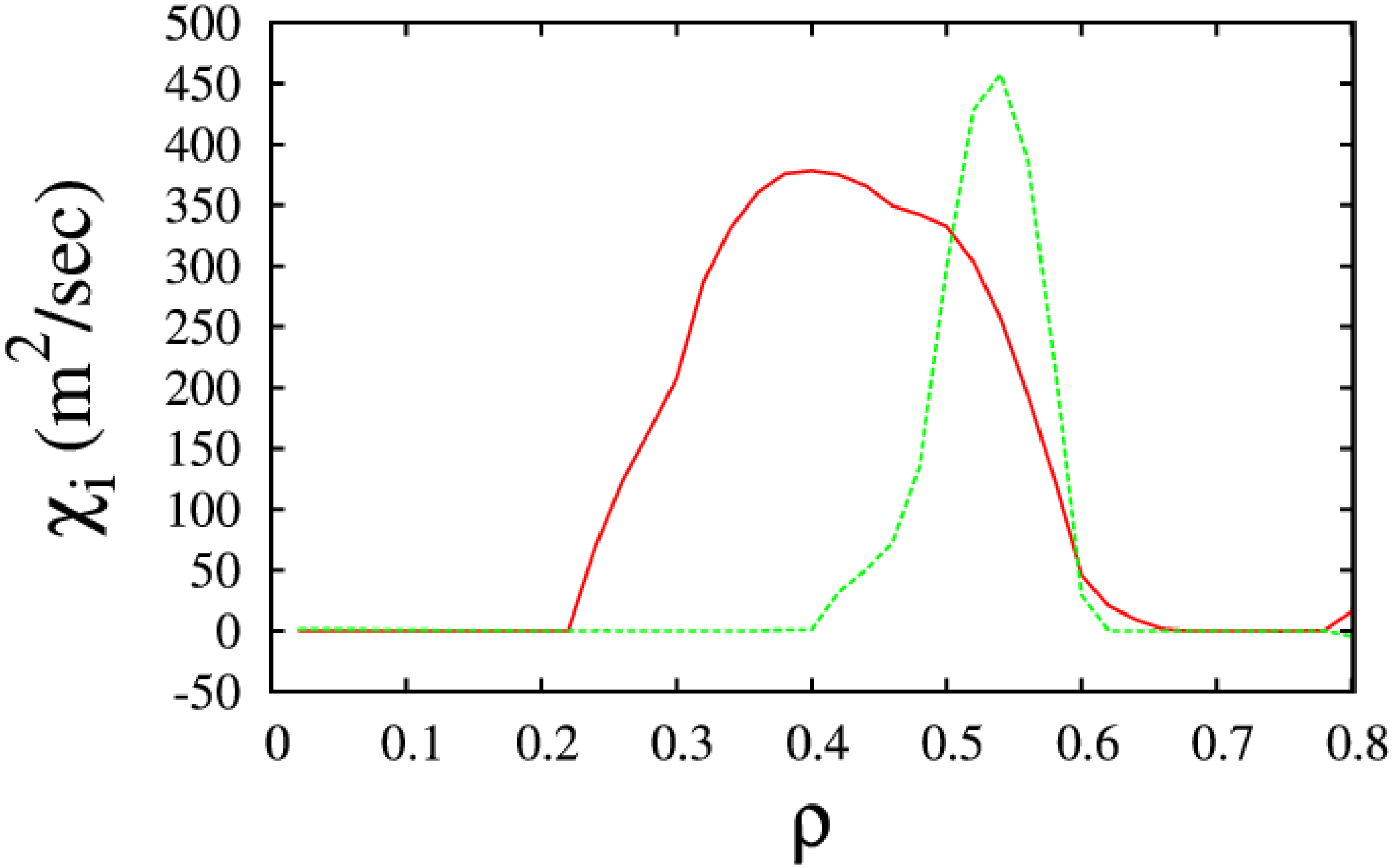
FACETS/XPTOR Verification

- Input profiles are exactly the same
- Gyro-Bohm factor is direct result of input parameters and profiles and is computed in the GLF23 interface



FACETS/XPTOR Verification

- There is still significant difference in results
- GLF23 wrapper in XPTOR is more extended comparing to the NTCC version that is being used in other codes (ASTRA, TRANSP, JETTO and others)



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Suppression of anomalous transport

- Total ion and electron thermal transport includes several major contributors

$$\chi_i = \chi_{ITG} F^i_{ITG}(s, \omega_{ExB}) + \chi^i_{RB} F^i_{RB}(s, \omega_{ExB}) + \chi^i_{KB} + \chi_{i,\mathrm{neo}}$$

$$\chi_e = \chi_{TEM} F^e_{TEM}(s, \omega_{ExB}) + \chi^e_{RB} F^e_{RB}(s, \omega_{ExB}) + \chi^e_{KB} + \chi_{ETG} + \chi_{e,\mathrm{neo}}$$

Shear suppression functions F_l^j provide the effect of flow and magnetic shear on anomalous transport

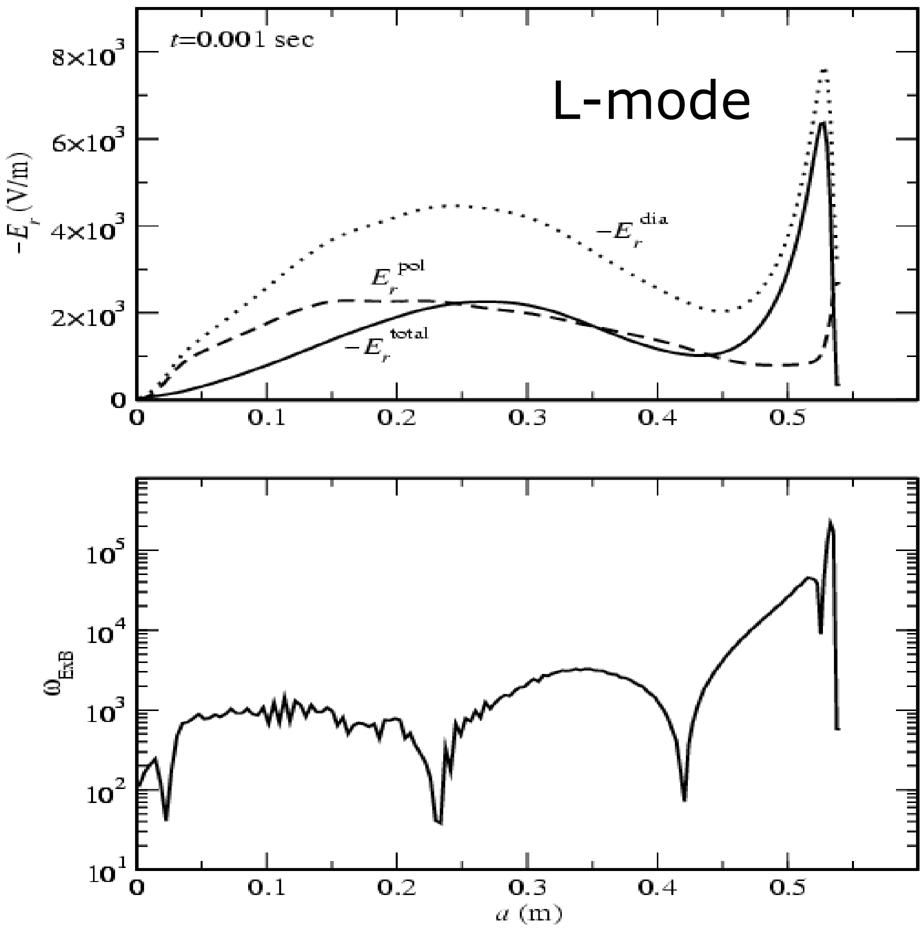
$$F_l^j(s, \omega_{ExB}) = \frac{s^{-\alpha_{lj}^{(1)}}}{1 + \alpha_{lj}^{(2)} \left(\omega_{ExB} \tau_{lj}\right)^2},$$ where $$l = \left(ITG/TEM, RB\right)$$ $$j = (ions,\ electrons)$$

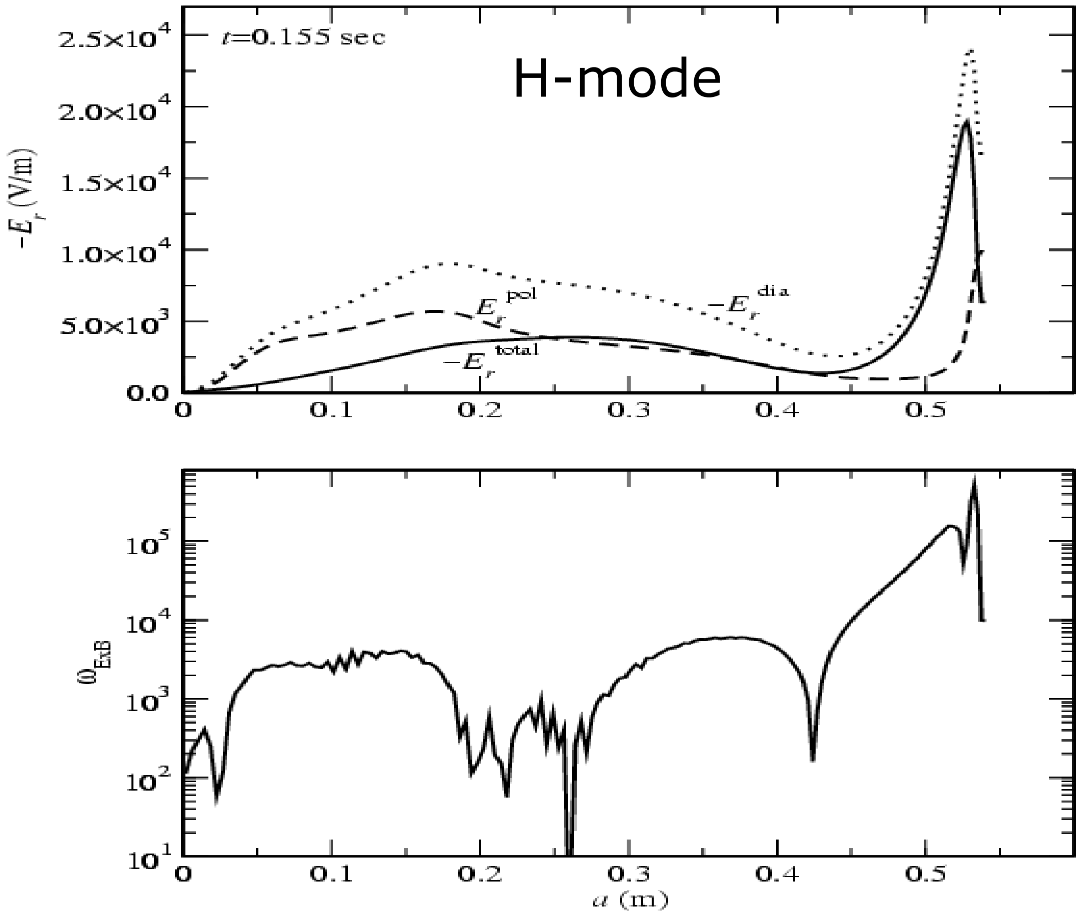
$\alpha_{lj}^{(1)}$ and $\alpha_{lj}^{(2)}$ are adjustable constants, $\chi_l^{(j)}$ is anomalous thermal diffusivity caused by (l)-mode turbulence, ω_{ExB} is flow shear ExB rate, and τ_{lj} are turbulence correlation times, which are estimated as $\tau_{lj} = L_l^2 / \chi_l^{(j)}$.

ExB flow shear rate and radial electric field

$$\omega_{ExB} = \left| \frac{RB_\theta}{B_\phi} \frac{\partial}{\partial r}\left(\frac{E_r}{RB_\theta} \right) \right|$$

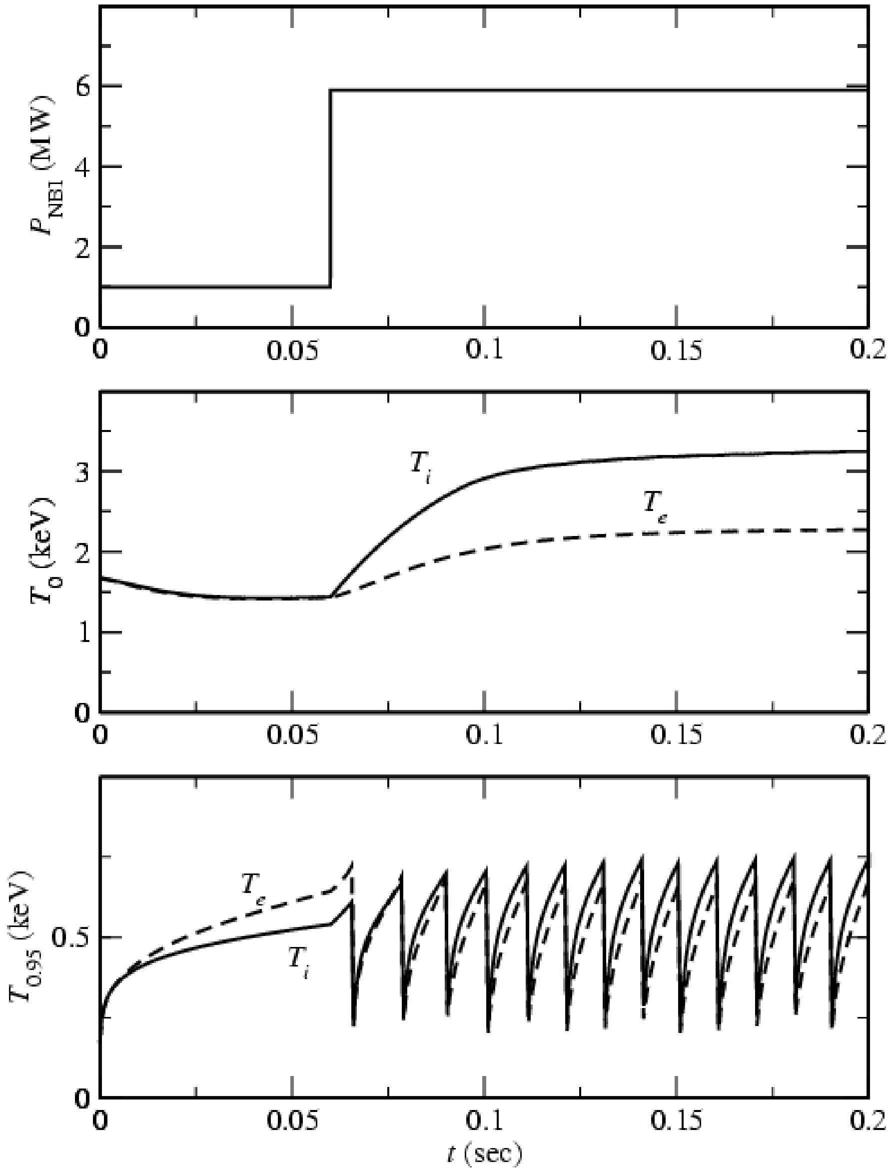
$$E_r = \frac{1}{Z_i e n_i} \frac{\partial p_i}{\partial r} - v_\theta B_\phi + v_\phi B_\theta$$





Baseline time-dependent modeling scenario

- Total neutral beam heating deposited to electrons and ions is 6 MW
- Power deposition and particle density profiles based on experimental data
- With realistic auxiliary heating, new model predicts
  - Reasonable central electron and ion temperatures
  - Spontaneous pedestal formation and triggering of ELMs

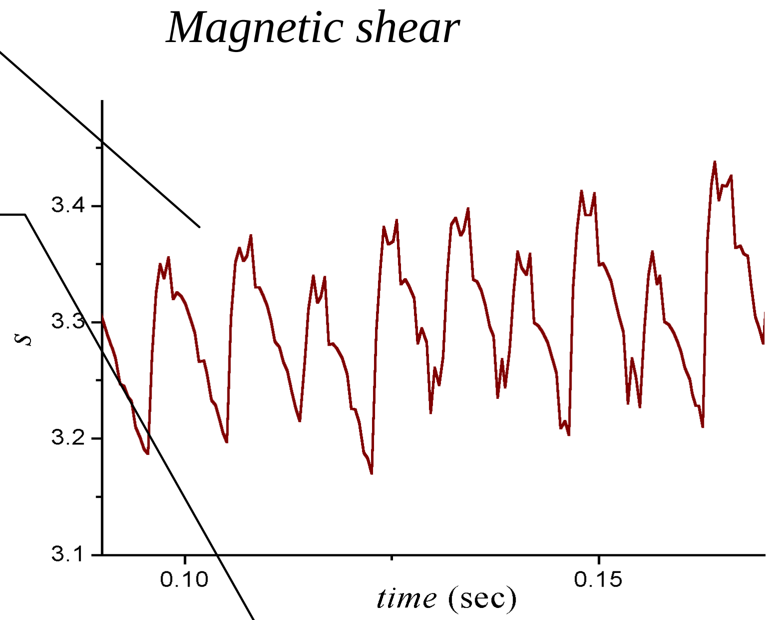


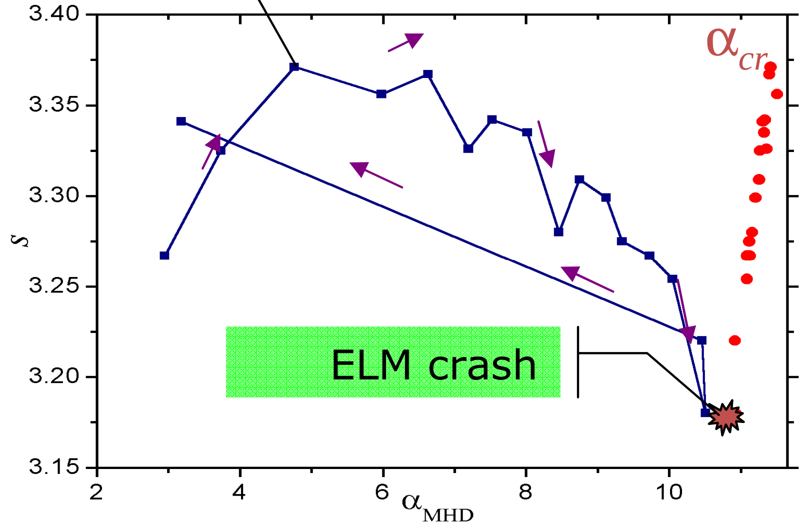
ELM crash in details

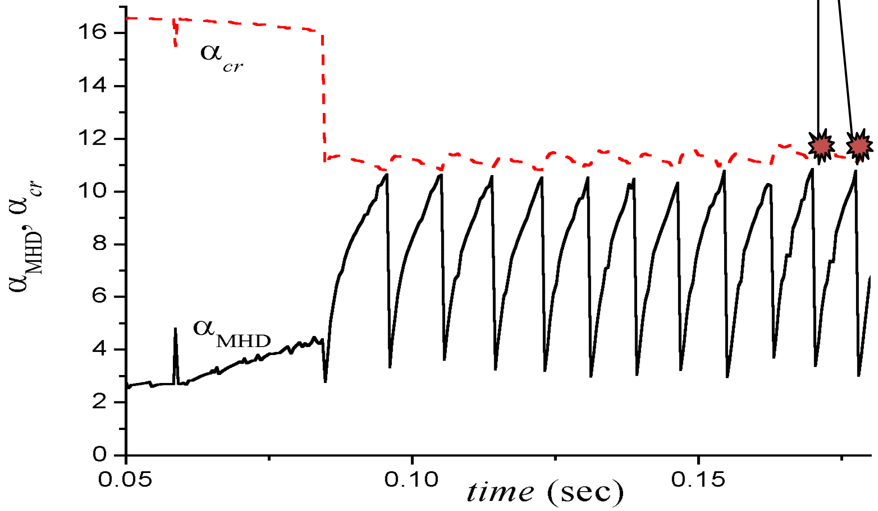
Magnetic shear evolution with time

One ELM cycle on s-α diagram

ELM crash occurs when α_{MHD} hits α_{cr}


Magnetic shear





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