Progress on Optimization Results for Steady-State Plasma Solutions

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Previous Progress Through January 2012: Profiles Collapsed Using GLF23 Transport Model

- **GLF23 Model predicted collapse of standard ARIES ACT1B scenario:**
  - EPED1 pedestal model incorporated in profiles consistent with model for peeling-ballooning stability
  - Collapse could only be avoided with an increase in density by a factor 80%
    - Collapse apparently due to large transport flux in outer part
    - Transport resulted in edge collapse to boundary condition value which then propagated inward
  - Collapse appears to be a feature of alpha-heated scenarios
- **TGLF model with real geometry was much more optimistic:**
  - Collapse avoided with small peaking of density:
  - Appears to better represent the transport in the strongly shaped outer region
  - Issue with TGLF is it is extremely slow compared to GLF23
- **Proposed to implement Multi-Mode model:**
  - Claimed to be as high fidelity as TGLF but an order of magnitude faster

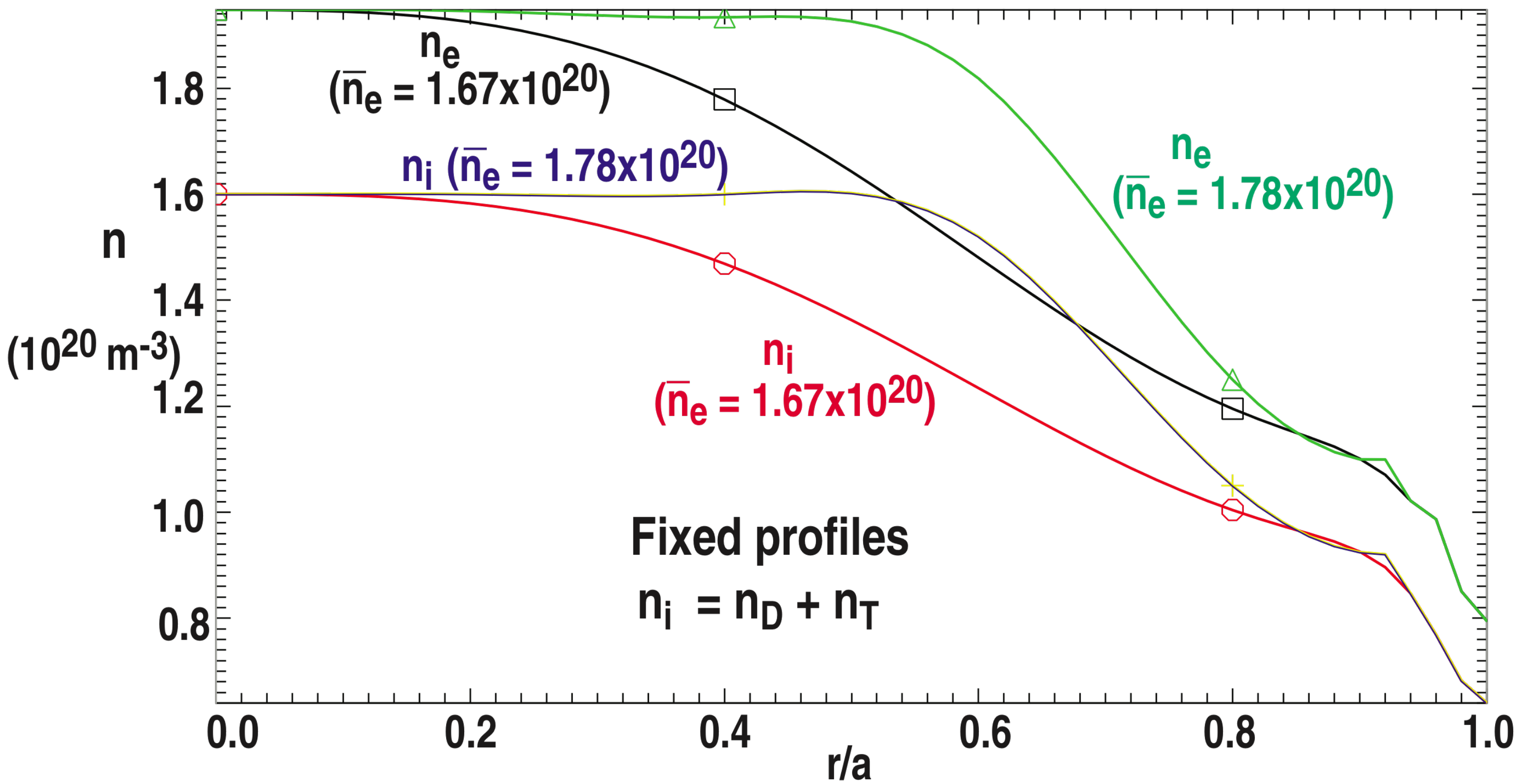
Progress Made in Implementing Planned Self Consistent Simulation for ARIES-AT Baseline

- **Implemented Multi-Mode Gyrofluid transport Model:**
  - Ten times slower than GLF23 but ten times faster than TGLF
- **Main Result:**
  - Successful simulation of ARIES base case to steady state
    - No collapse
  - Two cases considered with different density:
    - For $n_e = 1.67 \times 10^{20}$ m^{-3} $P_{DT} =$ 1.1 GW and $Q_{DT} = 28.7$
    - For $n_e = 1.78 \times 10^{20}$ m^{-3} $P_{DT} =$ 1.5 GW and $Q_{DT} = 39.7$
  - Major issue with considerable evolution of q profile:
    - Axis temperature overheats causing large on-axis current density despite small residual steady-state electric field
    - q_0 drops well below unity and is probably unstable
    - Requires large RF current drive on axis to maintain $q_0 > 1$
- **Future plans:**
  - Eliminate overheating of axis temperatures and excess axis current density
  - Evolve to steady state
  - Iterate using steady state as new starting equilibrium

Two Cases Considered With Different Line Averaged Density Obtained by Varying Broadness

- **Axis density kept fixed at standard density value but line averaged value is varied:**

$$\bar{n}_e = 1.67 \times 10^{20}\ m^{-3} \quad \text{and} \quad \bar{n}_e = 1.78 \times 10^{20}\ m^{-3}$$



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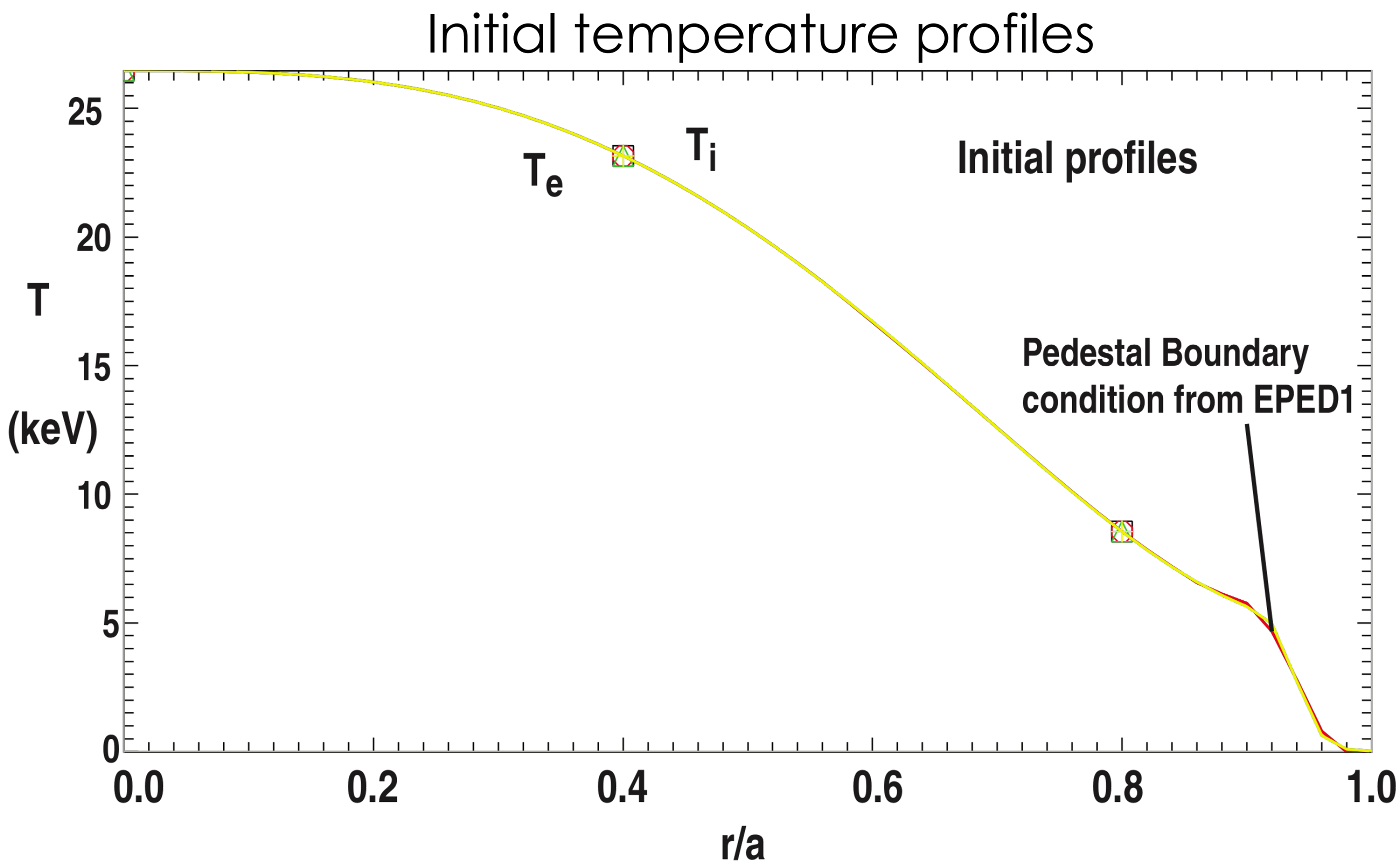
Electron and Ion Species Temperatures Evolved According to Multi-Mode Species Transport Coefficients

- Profiles initialized with $T_e = T_i$ and species evolved separately to steady state with Multi-Mode model

- Density profiles fixed in time in these simulations



Multi-Mode Theory-based Anomalous Transport Model Predicts Temperature, Density and Rotation Profiles

- **ONETWO transport code evolves temperatures and densities for each individual species s under heat and particle diffusion and sources:**

$$\frac{\partial(n_s T_s)}{\partial t} = \nabla\cdot\left(D_s^1 n_s \nabla T_s\right) + \nabla\cdot\left(\nu_s^1 n_s T_s\right) + S_s^1$$

$$\frac{\partial n_s}{\partial t} = \nabla\cdot\left(D_s^2 n_s\right) + \nabla\cdot\left(\nu_s^2 n_s\right) + S_s^2$$

- **Multi-mode calculates particle diffusion, $D^{1,2}$, heat convection $\nu^{1,2}$, and sources $S^{1,2}$ from:**
  - Weiland model for ITG, TEM, and MHD modes:

    J. Weiland, Plasma Physics. Institute of Physics Publishing, 2000
  - Drift-resistive-inertial ballooning modes (DRIBM):

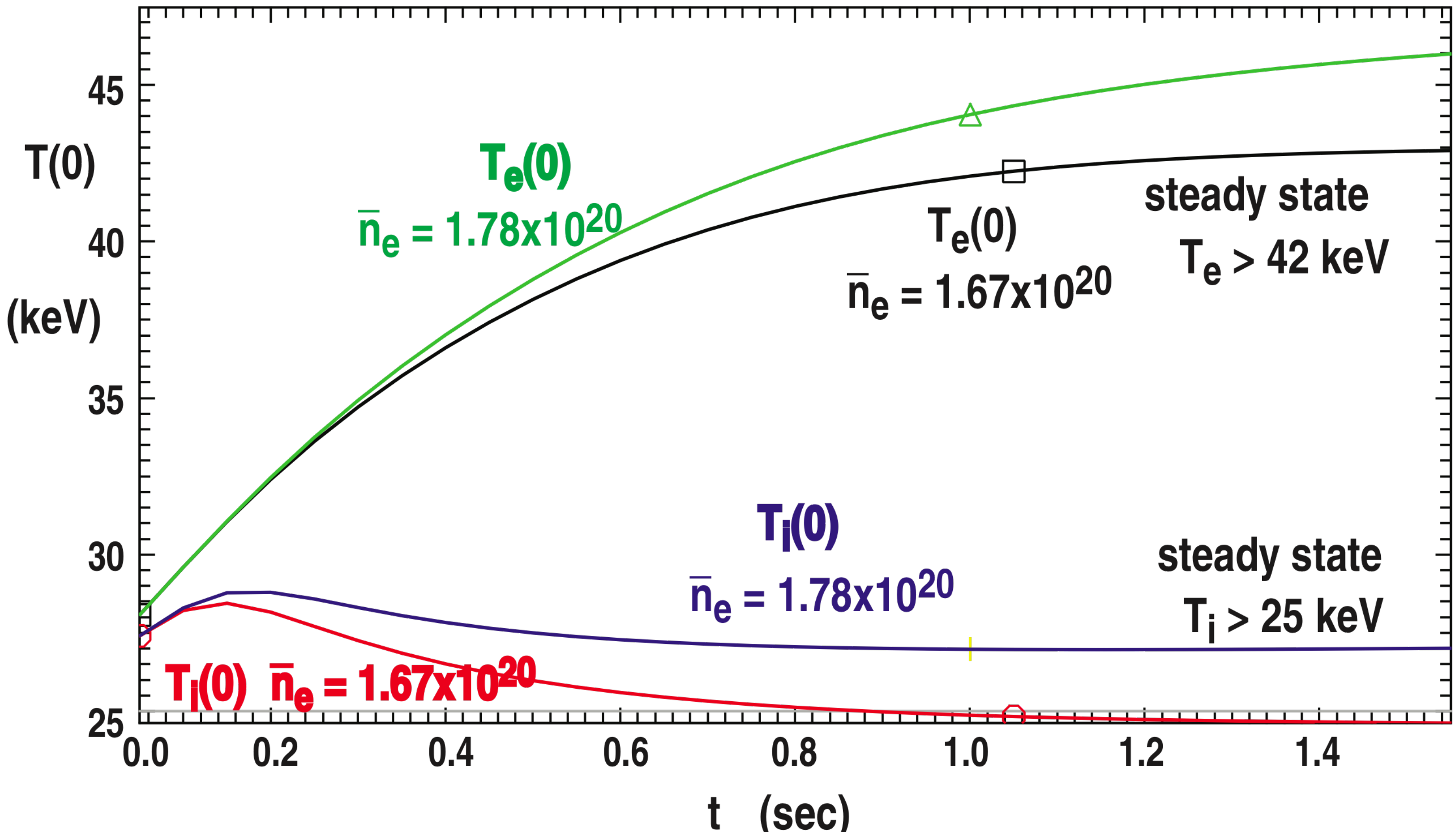
    *T. Rafiq, et al., Physics of Plasmas, **17** 082511, 2010*
  - Horton model for short wavelength ETG anomalous transport with threshold obtained from Jenko threshold:

    W. Horton, et al.,, Physics of Plasmas, vol. 7, no. 5, pp. 1494–1510, 2000

    *F. Jenko, et al. Physics of Plasmas, **8**, 4096–4104, 2001*

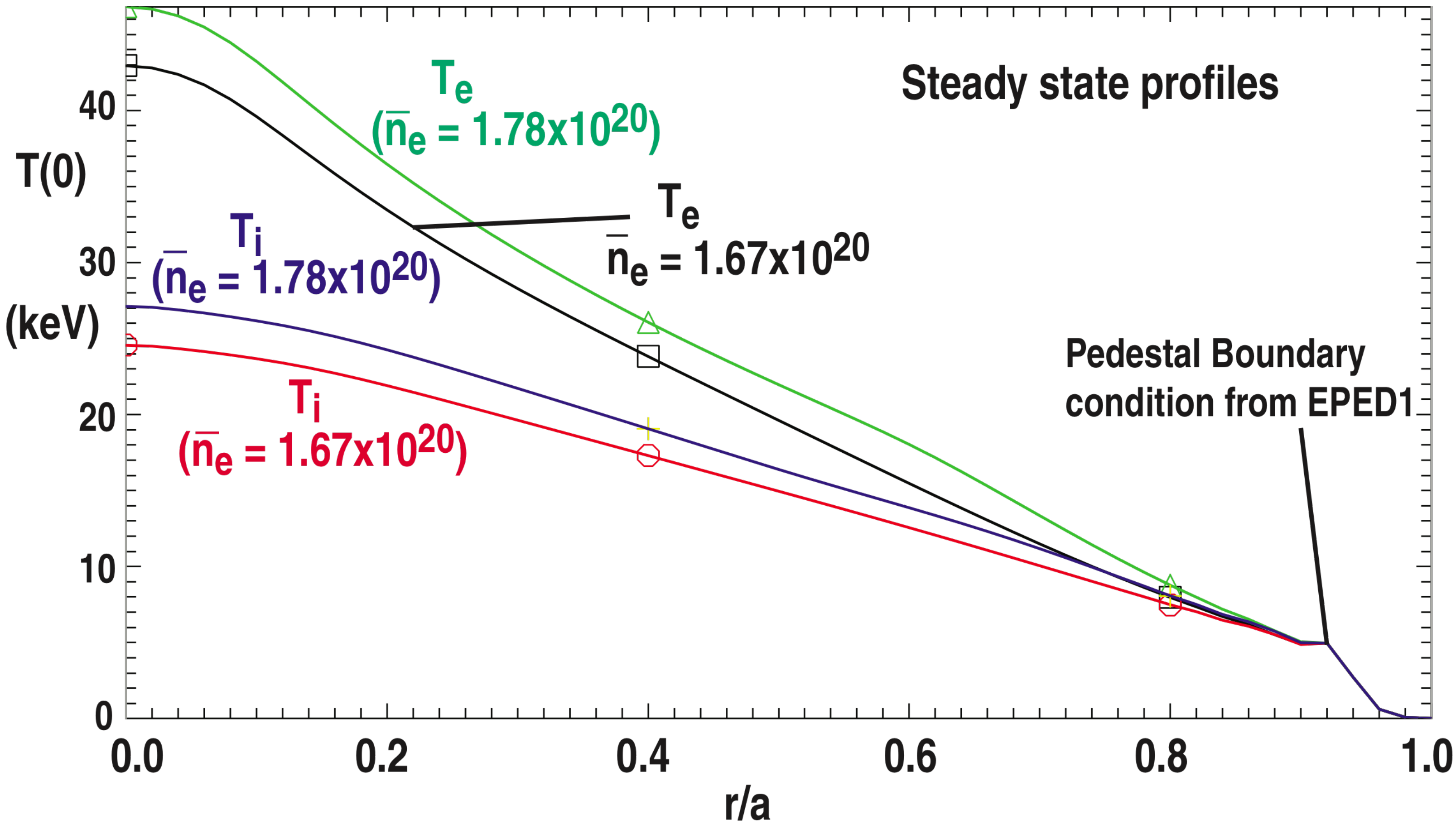
Temperatures Evolved to Steady State for Both Density Cases Without Collapse

- **Both cases overheat core electron temperature:**
  - High T_e leads to other issues



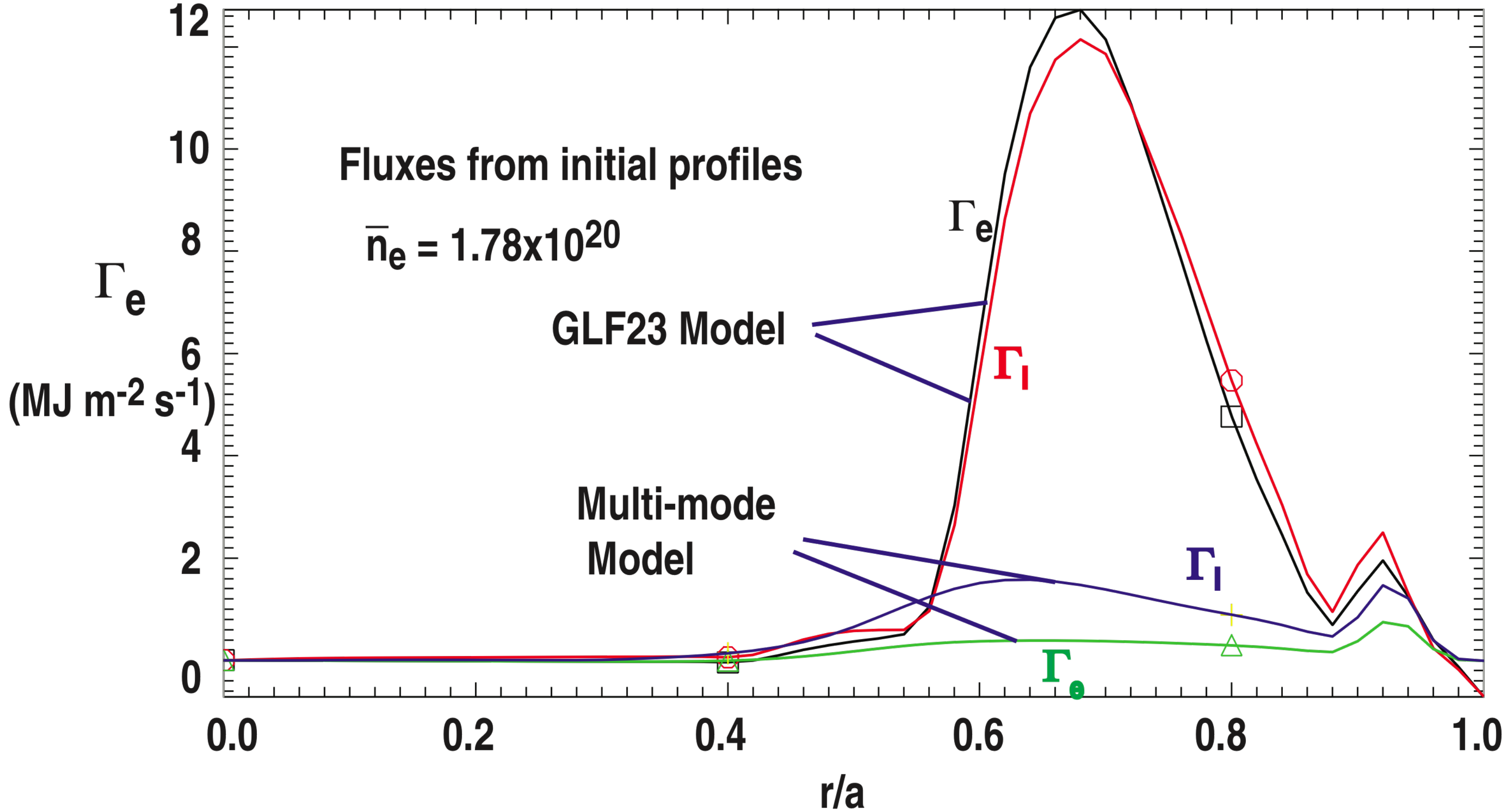
Steady State Electron Temperatures Above 40 keV While Profile Integrity Maintained to Edge Boundary Condition

- **Slight mismatch at edge boundary condition:**
  - Can probably be eliminated on further iterations



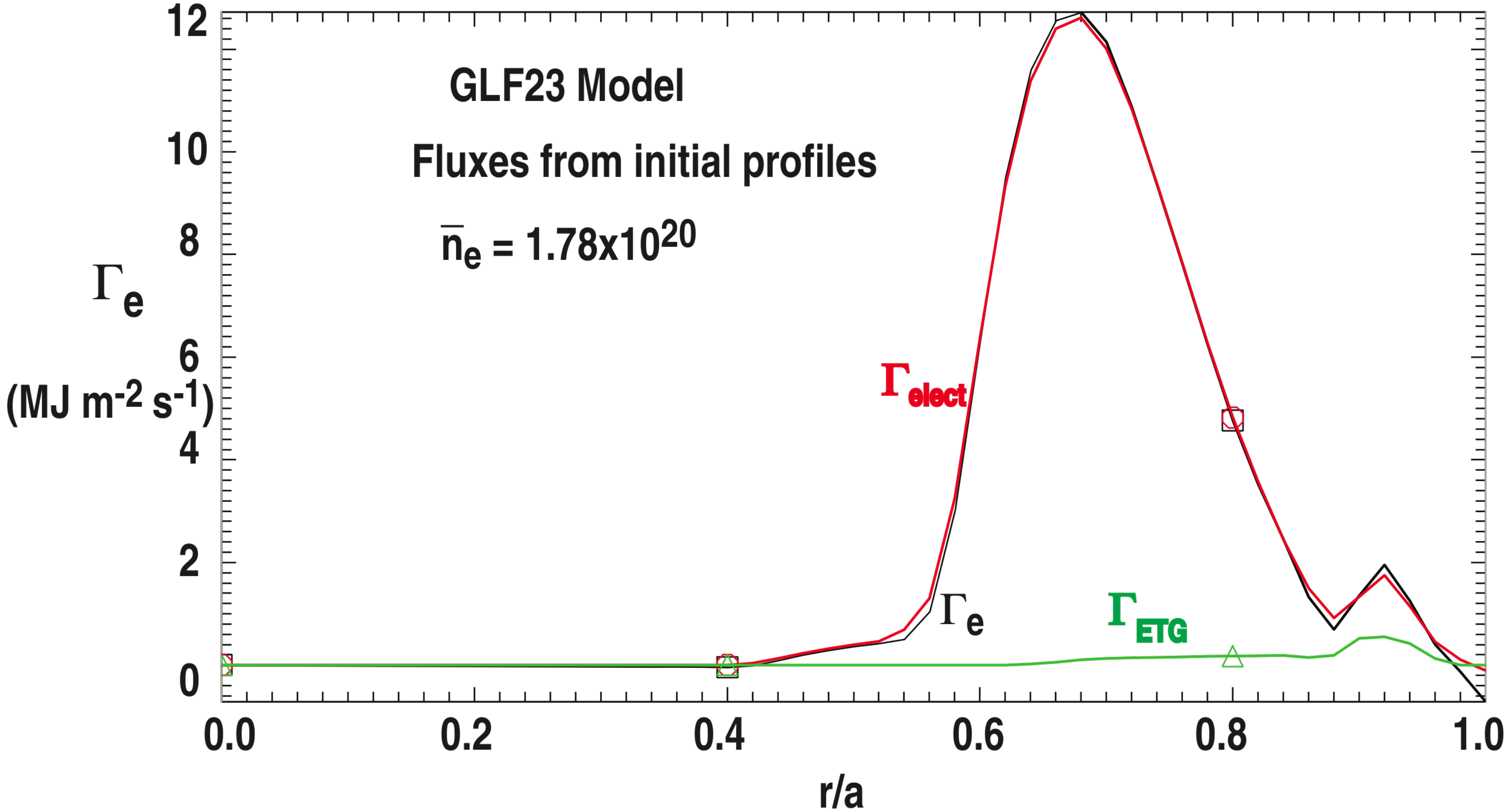
Comparison of Steady State Fluxes With GLF23 Shows Multi-Mode Has Much Reduced Flux in Outer Region

- **Both species fluxes outside r/a = 0.6 are reduced by almost an order of magnitude**



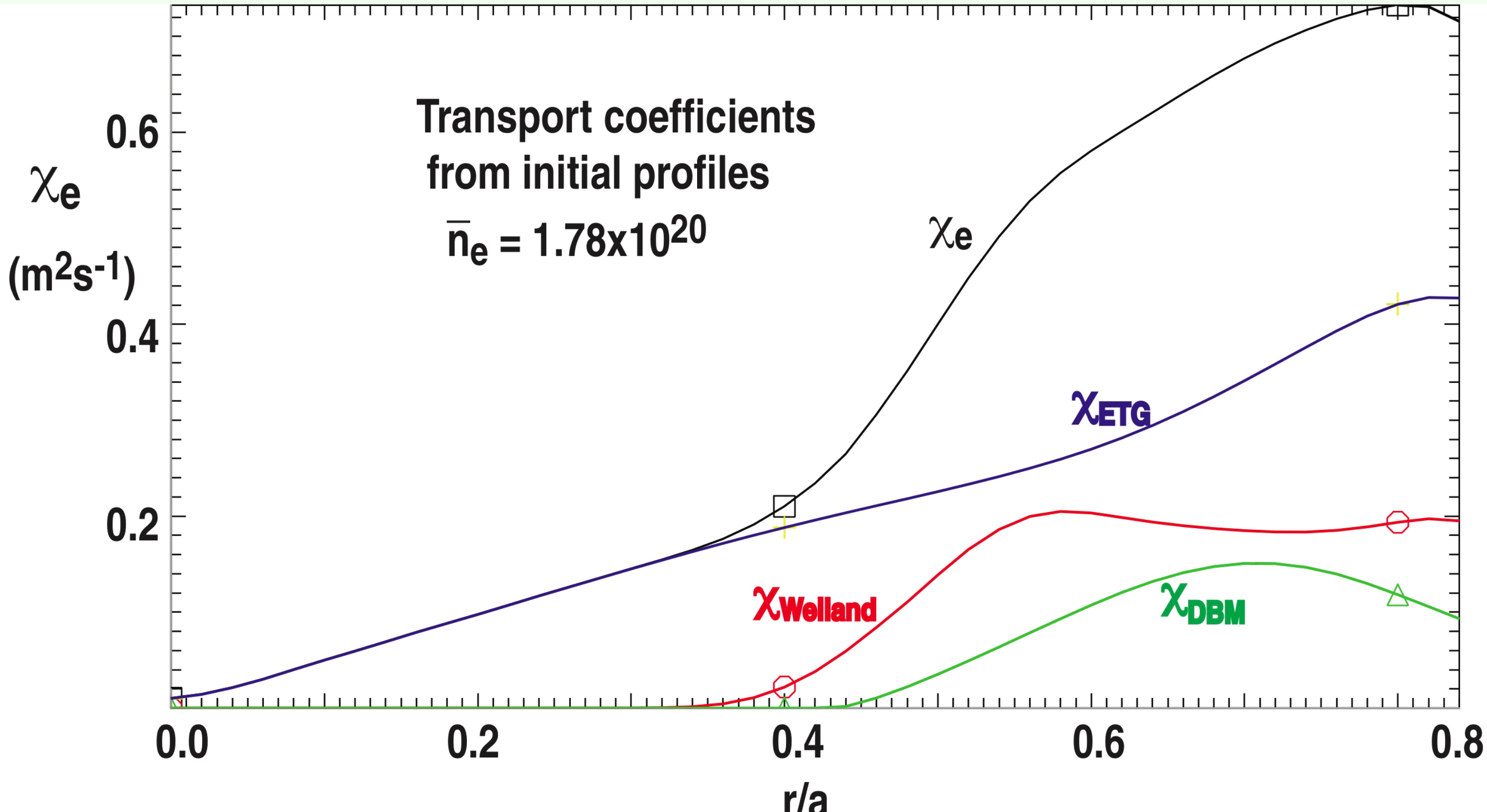
Electron Transport in GLF23 Simulations Showed Apparently Large Trapped Electron Mode Contribution

- **TEM is believed to be dominant non-ETG contribution:**
  - GLF23 does not further isolate individual contributions



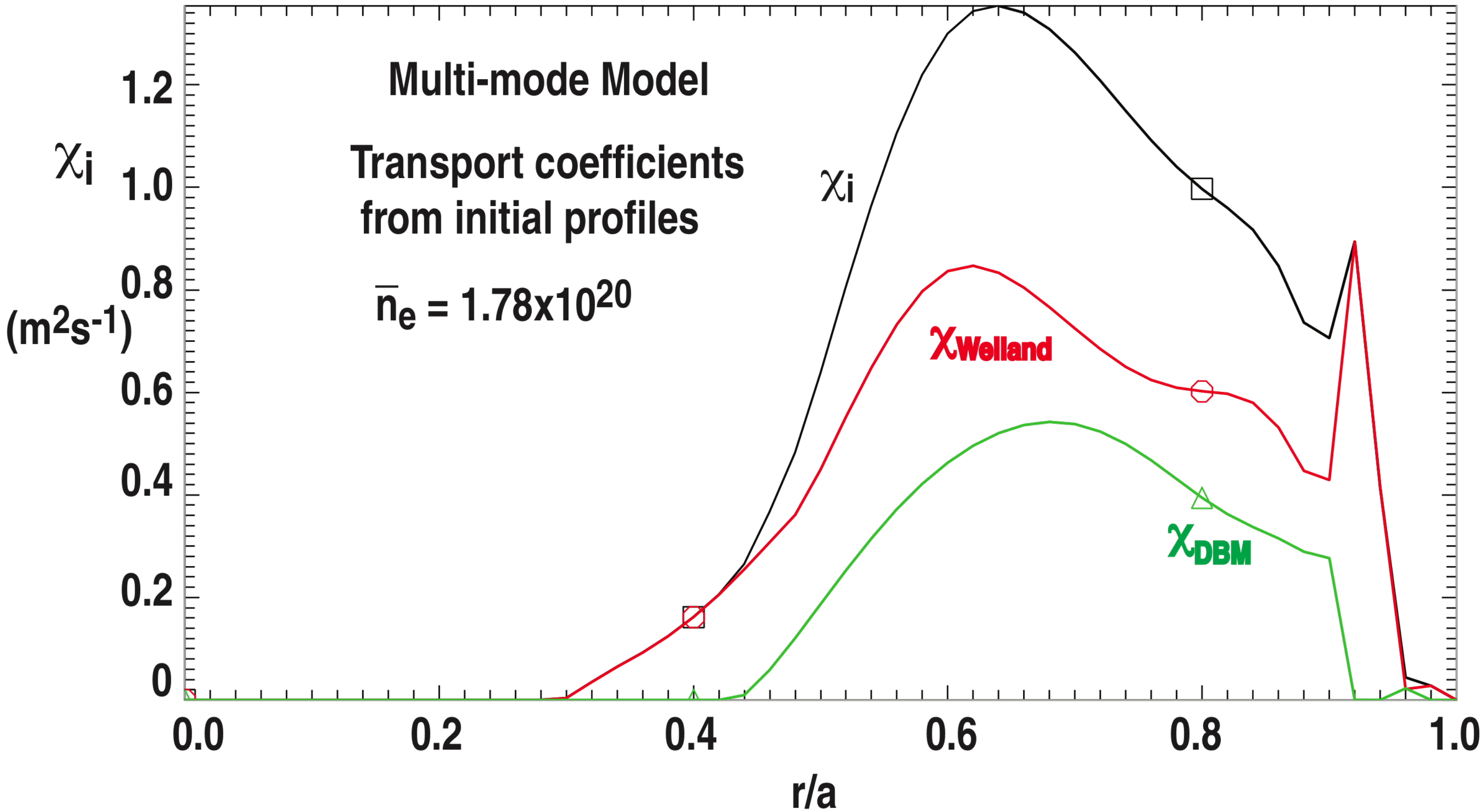
Diagnosis of Transport Shows ETG as Dominant Electron Transport Mechanism in Multi-Mode Model

- **Trapped electron mode contribution is smaller than but comparable to ETG transport:**
  - Included in Weiland electron transport model



Diagnosis of Ion Transport Shows ITG Modes Contained in Weiland Model is Largest Contribution

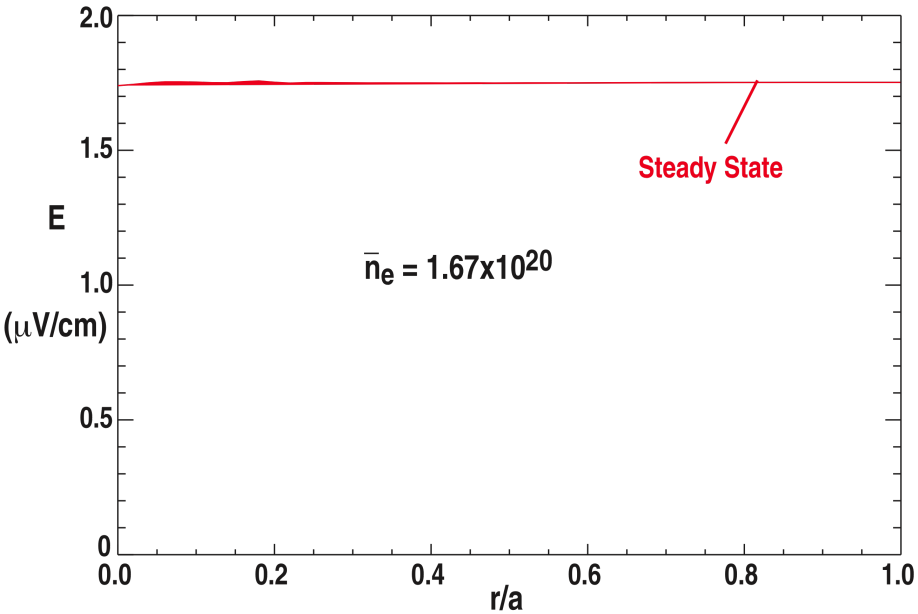
- **Drift ballooning modes are also significant:**
  - These are not included in GLF23 or TGLF

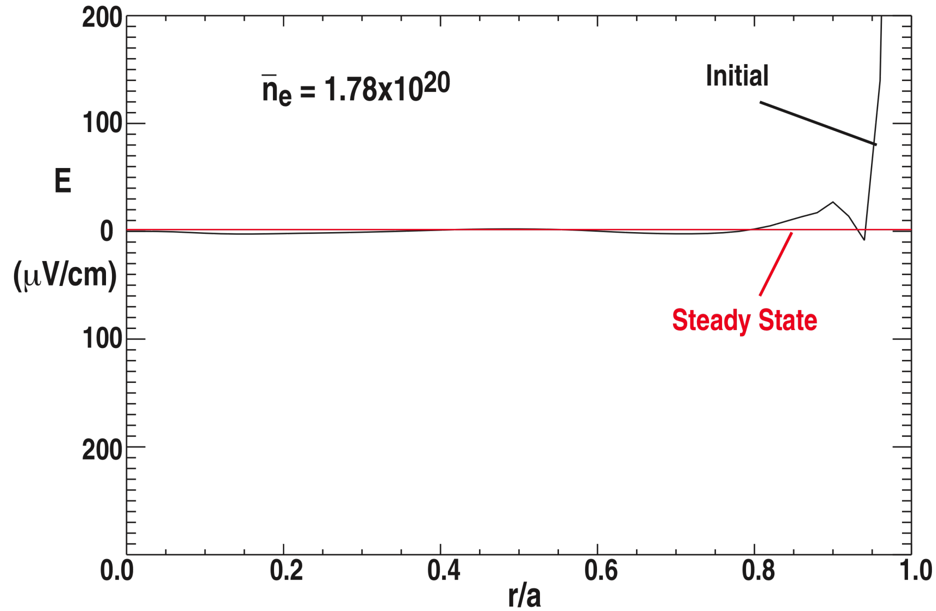


Evolution to Steady State with Small Residual Electric Field (~ μV)

- **Flat electric field profile indicates steady state:**

$$\partial B / \partial t = \nabla \times E \qquad \partial \psi / \partial t = rE_{\phi} + V_{loop}$$



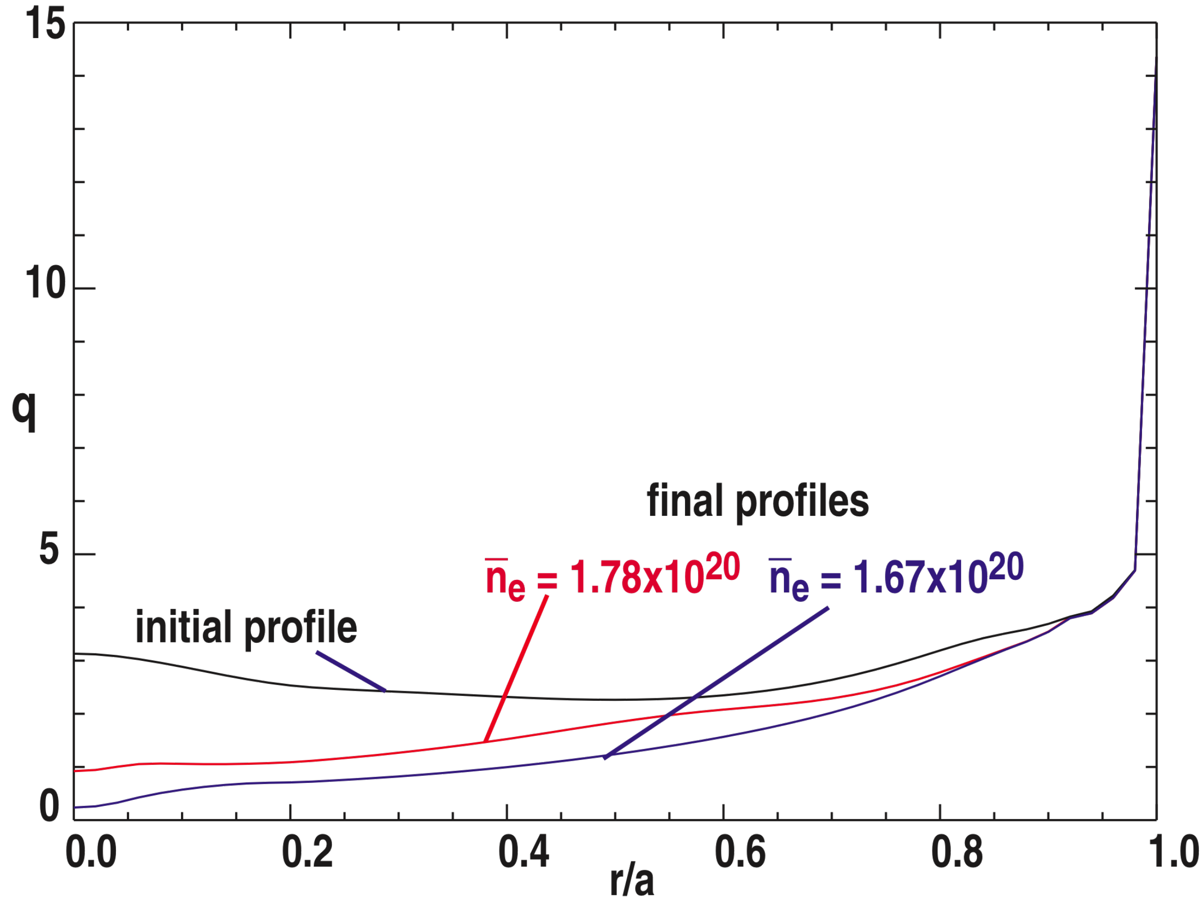


Safety Factor on Axis Evolves to a Value Below Unity Even With Small Residual Electric Field

- **Likely to be unstable to internal kink modes:**
  - Expected sawtoothing discharge

- **High axis T_e implies local current density can be large:**

$$j \sim E_0/\eta \sim E_0 T_e^{3/2}$$



Current Density Requires Further Iteration to Remove Residual Ohmic Contribution With Moderate RF Power

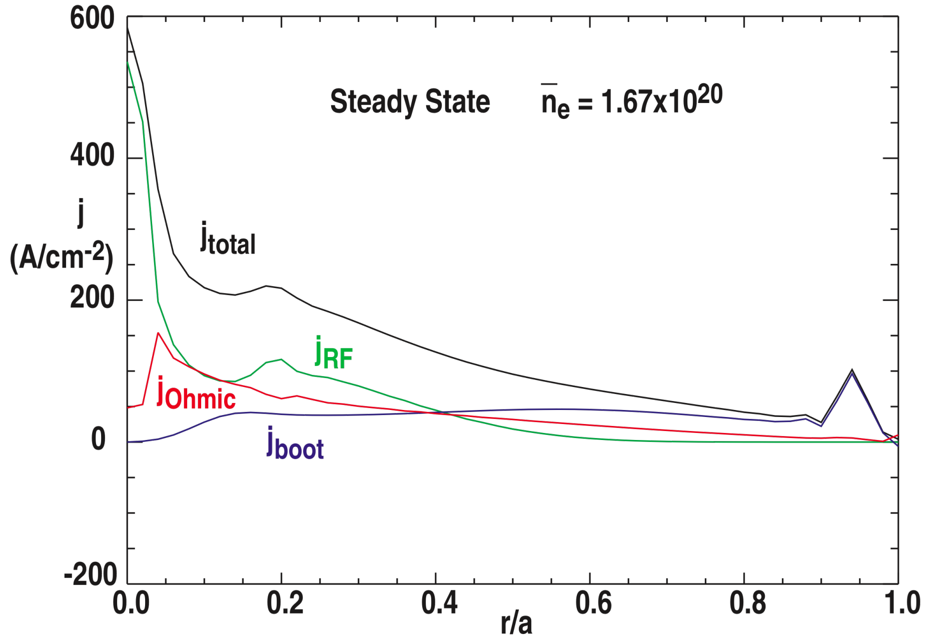
- Large local axis RF driven current is required to eliminate Ohmic axis current density:

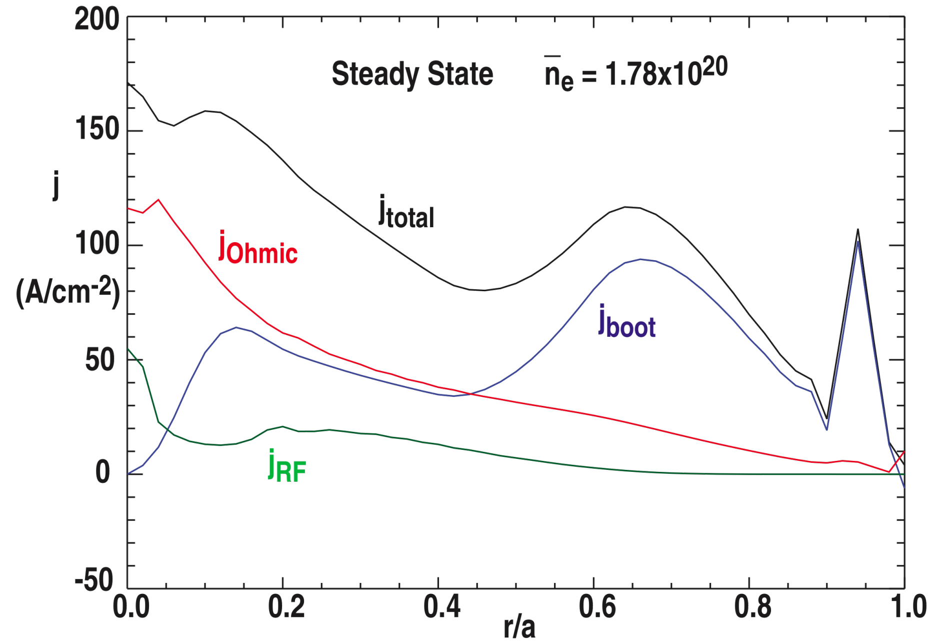
$\bar{n}_e = 1.67\times10^{20}\ m^{-3}$ $\quad I_{RF} = 2.6MA$

$I_{Boot} = 4.9MA$ $\quad I_{Ohm} = 3.1MA$

$\bar{n}_e = 1.78\times10^{20}\ m^{-3}$ $\quad I_{RF} = 2.5MA$

$I_{Boot} = 6.6MA$ $\quad I_{Ohm} = 1.4MA$





Multi-Mode Transport Package Implemented in ONETWO Code

- **First iteration finds reasonable steady state solutions:**
  - Ten times faster than TGLF model
  - Profile collapse found with GLF23 is avoided

Future Steps

- **Benchmark solution with previous successful TGLF simulation**
- **Eliminate axis overheating and excess axis current density:**
  - May or may not be a bug in implementation of Multi-mode model
  - May resort to pellet fuelling to maintain axis density and simultaneously suppress overheating in the core
- **Evolve to steady state:**
  - GENRAY calculation of current drive needed to maintain profiles
- **Iterate using steady state as new starting equilibrium:**
  - Transport coefficients are based on initial equilibrium
  - Need to be updated to reflect quite different steady state profiles
  - Then evolved to new steady state
  - Further iteration may be necessary

Backup Slides

Summary Data: $n_e = 1.67 \times 10^{20}\ m^{-3}$

Minor radius a (cm):	139.9	b/a:	2.29
Nominal Rmajor (cm):	550.0	R at geom. cent. (cm):	548.2
R at mag. axis (cm):	580.1	Z at mag. axis (cm):	0.0
Volume (cm**3):	4.22E+08	Pol. circum. (cm):	1519.0
surface area (cm**2):	4.90E+06	cross. sect area:	1.28E+05

Bt (G):	5.54E+04	Ip (A):	1.06E+07
Bt at Rgeom (G):	5.56E+04	r(q = 1)/a:	0.40
Line-avg den (1/cm**3):	1.85E+14	Tau-particle-dt (s):	2.000

profiles	ucenter	uedge	ucen/uav
elec. den. (1/cm**3):	1.96E+14	7.95E+13	1.38
elec. temp. (keV):	42.94	0.02	2.89
ion temp. (keV):	24.55	0.02	2.16
current (A/cm**2):	584.16	3.92	6.73
Zeff:	1.27	1.44	0.97
q:	0.24	14.36	
q* at edge:		4.29	
ang. speed (1/sec):	9.00E+01	1.00E+00	1.86E+00

Summary Data: $n_e = 1.67 \times 10^{20}\ m^{-3}$

	exper.	code	
Surface voltage :	0.00	0.01	Volts
Average voltage :	0.00	0.00	Volts
Ohmic power:	0.00E+00	1.86E+04	Watts
Beam power-torus:	0.00E+00	0.00E+00	Watts
Neutron rate D(D,N):	0.00E+00	1.14E+18	#/s

Computed quantities

Beam power elec. (W):	0.00E+00	ke at a/2 (1/cm-s):	1.08E+18
Beam power ions (W):	0.00E+00	ki at a/2 (1/cm-s):	2.57E+18
Beam power cx loss (W):	0.00E+00	ki/kineo at a/2:	98.77
Shinethrough (%):	0.00	chi electrons at a/2:	6.59E+03
RF power absorbed:	3.83E+07	chi ions at a/2:	1.73E+04
Radiated power (W):	6.67E+07	r*/a: Te = (Te(0)+Te(a))/2	0.46
Brems prim ions (W):	2.26E+07	Brems imp ions :	4.39E+07
Poloidal B field (G):	8.77E+03	Beta-poloidal:	2.400
beam torque (nt-m)	0.00E+00	total torque (nt-m):	-3.05E-03
stored ang mtm (kg*m2/s):	4.39E-01	momt inertia (kg*m**2):	7.15E-03
kinetic energy of rotation (j) :	2.00E+01		

Summary Data: $n_e = 1.67 \times 10^{20}\ m^{-3}$

	electrons	ions	thermal	total
Stored Energy (J)	2.451E+08	1.667E+08	4.117E+08	4.684E+08
dE/dt (W):	6.596E+03	-1.192E-06	6.596E+03	6.596E+03
Input power (W):	1.819E+08		2.568E+08	2.568E+08
Energy conf. time (s):	1.3471		1.6033	1.8239

H(89p) = 2.61 H(89pm) = 3.03 H_ITER98y2 = 1.26 H_Petty = 0.80

Beta-toroidal	volume-avg	center
electrons:	3.147E-02	1.097E-01
ions:	2.140E-02	5.583E-02
beam:	0.000E+00	0.000E+00
alphas:	7.274E-03	4.345E-02
total:	6.014E-02	2.090E-01

Normalized beta 4.413E+00

total power input (W) = 3.831E+07 time = 1.0000E+06

Itot = 1.06E+07 Iohm = 3.08E+06 Iboot = 4.89E+06 Ibeam = 0.00E+00 Irf = 2.63E+06

genray	cd,amps	qe ,watts	qi, watts
	2.632E+06	3.804E+07	2.548E+05

QDD = 0.03 QDT = 28.67 QTT = 0.05

P DD = 1.2772E+06 P DT = 1.0986E+09 P TT = 2.0263E+06 W

D(D,n) = 1.1365E+18 D(T,n) = 3.8966E+20 T(T,2n) = 1.1194E+18 #/sec

paux (MW) = 3.83E+01 palpha = 2.18E+02 prad = 6.67E+01 Ptransport = 1.90E+02

Summary Data: $n_e = 1.78 \times 10^{20}\ m^{-3}$

Minor radius a (cm):	139.9	b/a:	2.29
Nominal Rmajor (cm):	550.0	R at geom. cent. (cm):	548.2
R at mag. axis (cm):	580.1	Z at mag. axis (cm):	0.0
Volume (cm**3):	4.22E+08	Pol. circum. (cm):	1519.0
surface area (cm**2):	4.90E+06	cross. sect area:	1.28E+05

Bt (G):	5.54E+04	Ip (A):	1.06E+07
Bt at Rgeom (G):	5.56E+04	r(q = 1)/a:	0.07
Line-avg den (1/cm**3):	1.90E+14	Tau-particle-dt (s):	2.000

profiles	ucenter	uedge	ucen/uav
elec. den. (1/cm**3):	1.97E+14	7.95E+13	1.27
elec. temp. (keV):	47.48	0.02	2.85
ion temp. (keV):	27.24	0.02	2.17
current (A/cm**2):	239.33	3.91	2.76
Zeff:	1.28	1.44	0.98
q:	0.59	14.36	
q* at edge:		4.29	
ang. speed (1/sec):	9.00E+01	1.00E+00	1.86E+00

Summary Data: $n_e = 1.78 \times 10^{20}\ m^{-3}$

	exper.	code	
Surface voltage :	0.00	0.00	Volts
Average voltage :	0.00	0.00	Volts
Ohmic power:	0.00E+00	2.83E+03	Watts
Beam power-torus:	0.00E+00	0.00E+00	Watts
Neutron rate D(D,N):	0.00E+00	1.63E+18	#/s

computed quantities

Beam power elec. (W):	0.00E+00	ke at a/2 (1/cm-s):	1.34E+18
Beam power ions (W):	0.00E+00	ki at a/2 (1/cm-s):	2.84E+18
Beam power cx loss (W):	0.00E+00	ki/kineo at a/2:	49.26
Shinethrough (%):	0.00	chi electrons at a/2:	6.96E+03
RF power absorbed:	3.86E+07	chi ions at a/2:	1.62E+04
Radiated power (W):	7.35E+07	r*/a: Te = (Te(0)+Te(a))/2	0.46
Brems prim ions (W):	2.90E+07	Brems imp ions :	4.43E+07
Poloidal B field (G):	8.77E+03	Beta-poloidal:	2.987
beam torque (nt-m)	0.00E+00	total torque (nt-m):	-3.35E-03
stored ang mtm (kg*m2/s):	4.87E-01	momt inertia (kg*m**2):	7.84E-03
kinetic energy of rotation (j) :	2.20E+01		

Summary Data: $n_e = 1.78 \times 10^{20}\ m^{-3}$

	electrons	ions	thermal	total
Stored Energy (J)	3.017E+08	2.021E+08	5.038E+08	5.829E+08
dE/dt (W):	1.263E+04	-3.576E-06	1.263E+04	1.263E+04
Input power (W):	2.350E+08		3.435E+08	3.435E+08
Energy conf. time (s):	1.2838		1.4666	1.6969

H(89p) = 2.80 H(89pm) = 3.15 H_ITER98y2 = 1.37 H_Petty = 0.83

Beta-toroidal	volume-avg	center
electrons:	3.873E-02	1.220E-01
ions:	2.595E-02	6.194E-02
beam:	0.000E+00	0.000E+00
alphas:	1.016E-02	5.235E-02
total:	7.484E-02	2.363E-01
Normalized beta	5.491E+00	

total power input (W) = 3.862E+07 time = 1.0000E+06

Itot = 1.06E+07 Iohm = 1.46E+06 Iboot = 6.61E+06 Ibeam = 0.00E+00 Irf = 2.53E+06

	cd,amps	qe ,watts	qi, watts
genray	2.534E+06	3.847E+07	1.493E+05

QDD = 0.05 QDT = 39.69 QTT = 0.07

P DD = 1.8286E+06 P DT = 1.5331E+09 P TT = 2.8514E+06 W

D(D,n) = 1.6310E+18 D(T,n) = 5.4373E+20 T(T,2n) = 1.5751E+18 #/sec

paux (MW) = 3.86E+01 palpha = 3.05E+02 prad = 7.35E+01 Ptransport = 2.70E+02