Progress in Modeling of ARIES ACT Plasma

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GENERAL ATOMICS

The Story

- **Systems Code identified an optimum steady state scenario:**
  - Confinement time based on assumption of steady state
- **Is this steady state consistent with equilibrium, transport, stability expected from the most up-to-date models**
- **Iteration procedure over adjustments in the scenario details is needed to refine the configuration:**
  - Achieve complete steady state and sufficient stability
- **Iteration procedure defined to:**
  - Simulate in time from initial given profiles to a final steady state
    - Obtain stationary profiles of ne, ni, Te, Ti, j, and bootstrap current
    - Use these profiles in place of initial profiles
  - Simulate LHCD and ICRF to make up the shortfall from bootstrap current
  - Check performance: confinement, β, fusion power of new configuration
    - Adjust profiles as needed to achieve desired performance
  - Iterate until steady state with desired performance is achieved
- **Aim is to use most sophisticated models for equilibrium, transport, current drive, stability currently available**

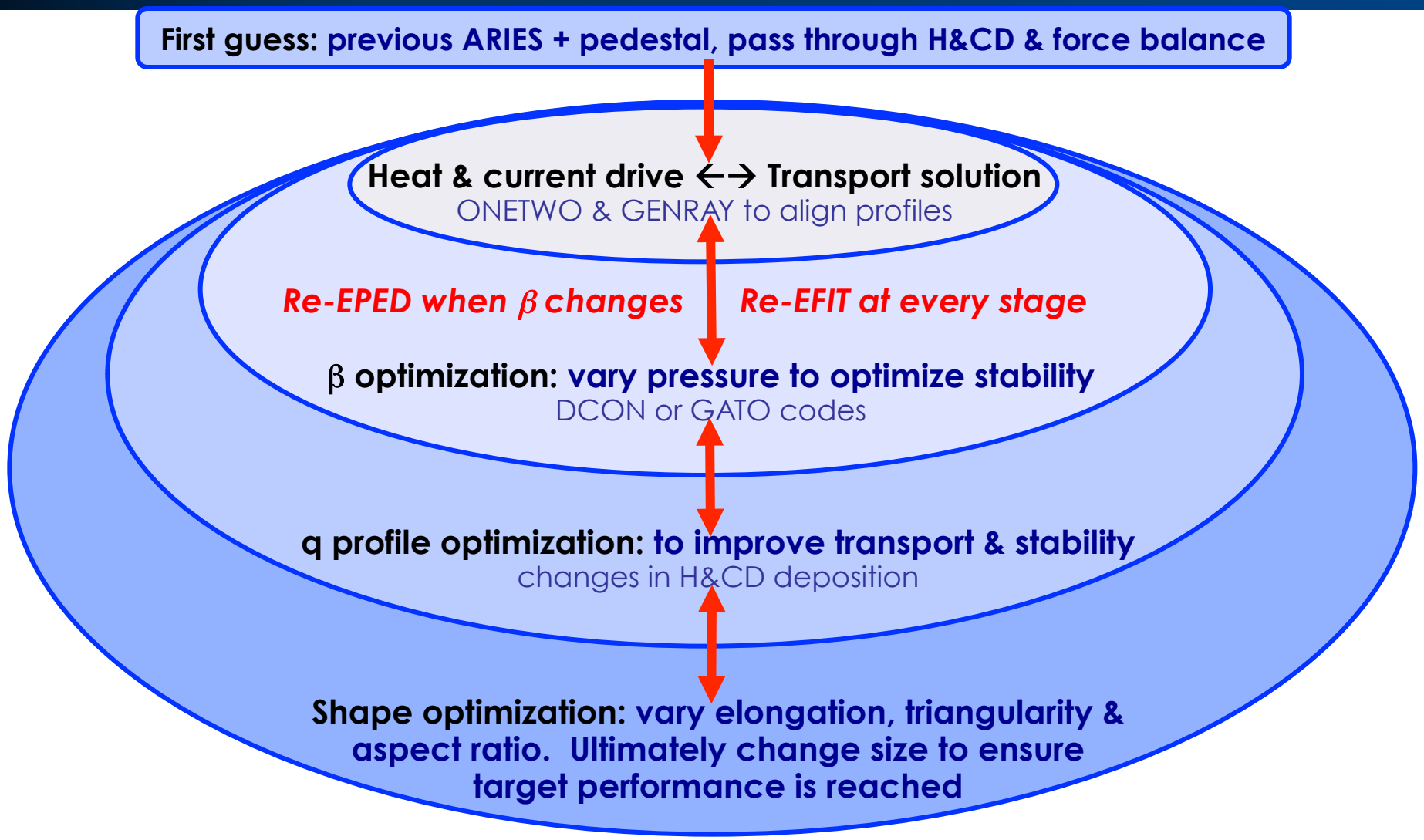
Outline: Approach, Optimization Procedure, Initial Results

- **Optimization procedure:**
  - Outline
  - New features
- **Reproduced 2006 ARIES-AT Base configuration :**
  - Reconstructed configuration with added H-mode pedestal and confirmed steady state temperatures
  - Simulated LHCD and ICRF to make up the shortfall in current density
- **Initial results from ARIES ACT I scenario:**
  - Pedestal height and width from EPED1 model sets boundary condition
  - Profiles collapse due to large energy flux in mid range
  - Increased density prevents collapse
  - Some gain from moderate density peaking
  - Current drive simulations
- **Discrepancy between Systems Code and initial simulations:**
  - There may be no steady state for these profiles or
  - Transport model may be poor for this case
- **Improved results using TGLF transport model partially resolve discrepancy**

Optimization Procedure Begins With Basic equilibrium Identified From Systems Code

- **Iteration:**
  - **Incorporate a consistent H-mode pedestal:**
    - EPED1 model to predict pedestal height and width given pedestal β
    - Re compute EFIT equilibria as needed
  - **Transport simulation to evolve initial profiles to steady state**
  - **Incorporate current drive sources to maintain configuration**
  - **Optimization for β:**
    - Check ideal stability
    - Optimize to converge to maximum stable β_N
  - **q profile optimization:**
    - Adjustment of q profile to improve stability and current drive
  - **Iterate from this as a new initial equilibrium**
- **Shape and size optimization:**
  - Elongation, triangularity and aspect ratio
  - Size adjustments as needed

Physics Overview of Optimization Logic

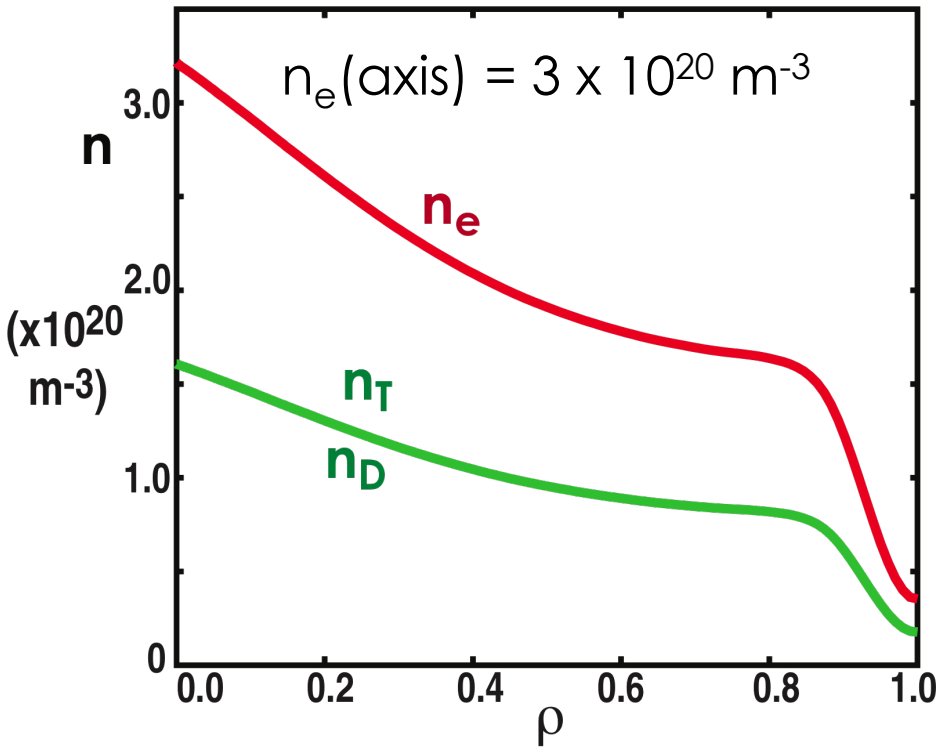


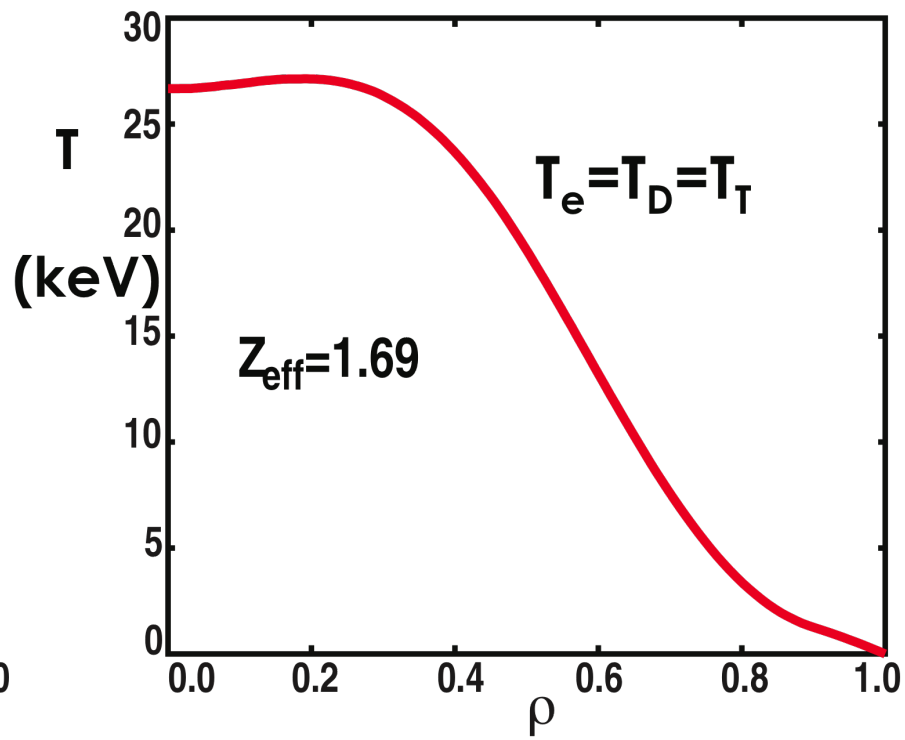
Previous 2006 Effort For ARIES-AT Repeated With Improved Tools and Understanding

- **Similar analysis was done in the past for ARIES designs but:**
  - Design points have been updated with improved Systems Code
  - Understanding of physics issues has also evolved considerably:
    - Particularly pedestal modeling and interaction with the core
- **Analysis involves:**
  - Coupled equilibrium, transport, current drive, fuelling, and stability calculations to obtain a steady state solution
  - Transport model TGLF in place of GLF23:
    - Real shaped geometry instead of GLF23 shifted circle model
  - Self consistent H-mode pedestal:
    - Realistic pedestal height and width predictions with EPED1
- **Key technical issue is that core transport is stiff:**
  - The largest leverage to improving confinement is increased pedestal height
  - Conversely, H-mode pedestal and ELM physics depends crucially on the heat and particle fluxes coming from the core

Scenario Repeated With Initial Density and Temperature Profiles From Jardin 2006 Fusion Engineering and Design

- Modified to include H-mode edge density pedestal but T_e set to be consistent with original pressure from 2006 published result

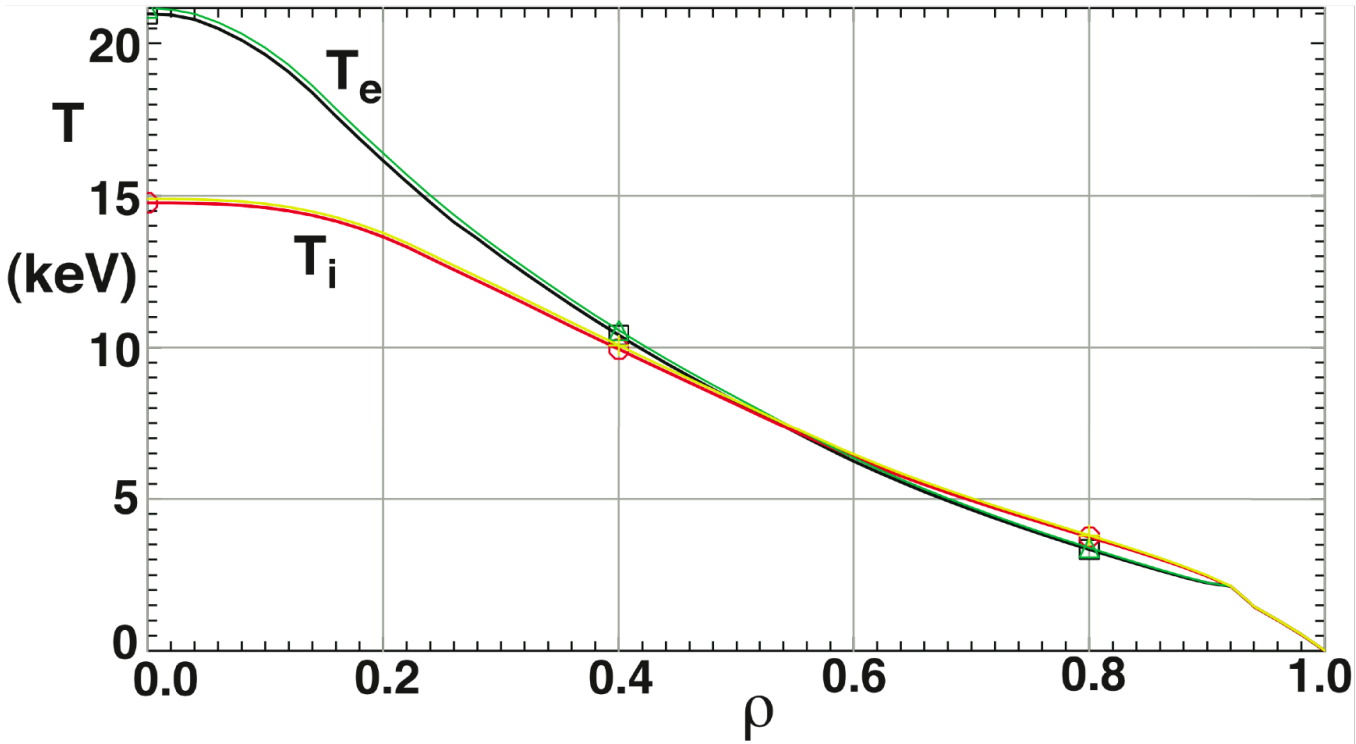




Previous Results Reproduced Using GLF23 and TGLF Transport Models With Lower Hybrid Current Drive

- **Steady state result achieved using GLF23 after one second:**
  - Fixed density and RF heating profiles
  - Shifted circle geometry assumed by the GLF23 model

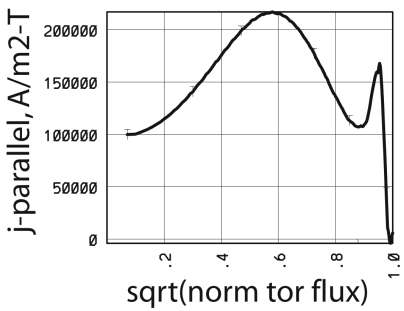
- **Steady state profiles using GLF23**

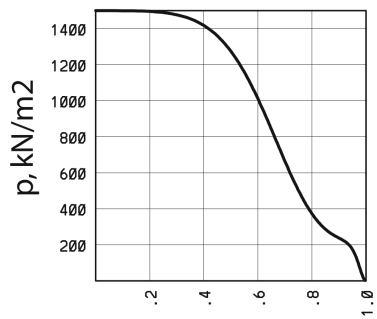


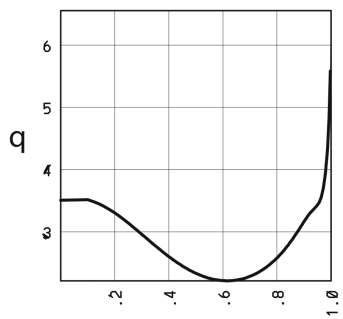
No steady state was reached using full geometry TGLF model !

Tools for Self Consistent Optimization of ARIES-AT Design Point Are in Place for ARIES ACT Study

- **Initial case set up with TSC free boundary direct equilibrium code:**
  - Equilibrium with H-mode pedestal reproduced
  - Iteration on profiles between free and fixed boundary equilibria

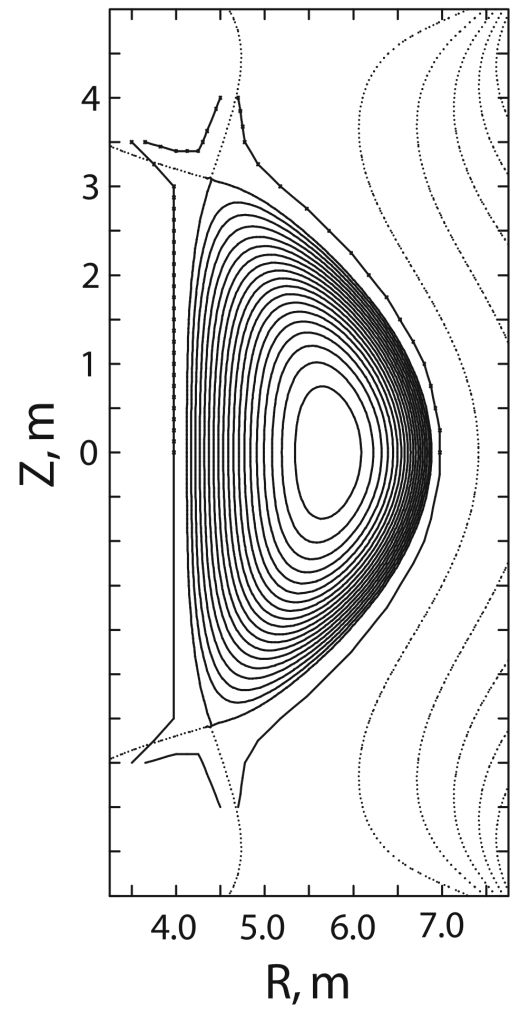






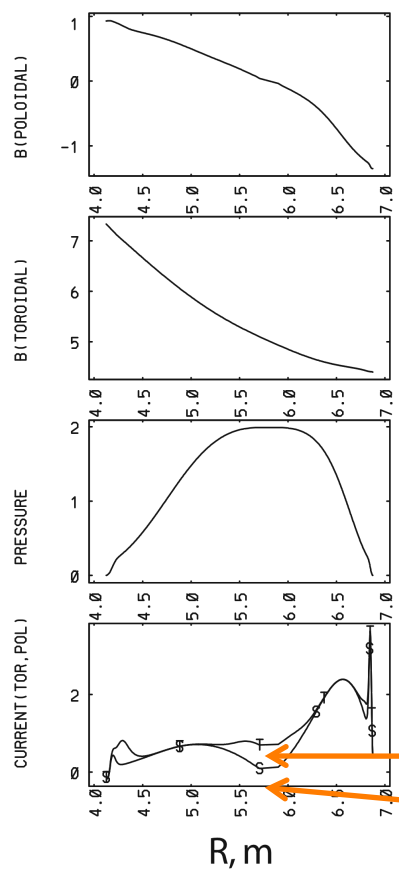
sqrt (norm tor flux)

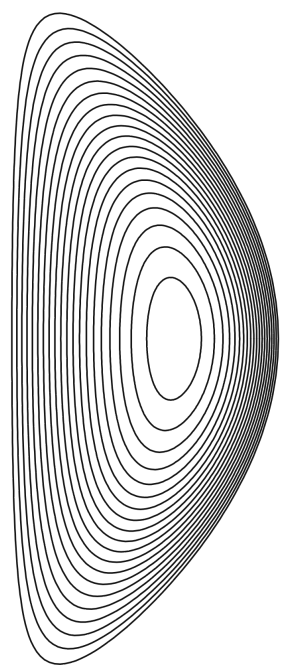
$\kappa_x = 2.21$
$\delta_x = 0.77$
$s_{o,l} = 0$
li(1) = 0.54
$\beta_N = 4.77$
$q_{95} = 3.53$



Fixed Boundary Equilibrium Recomputed from Free Boundary Equilibrium is Taken as Initial Operating Point

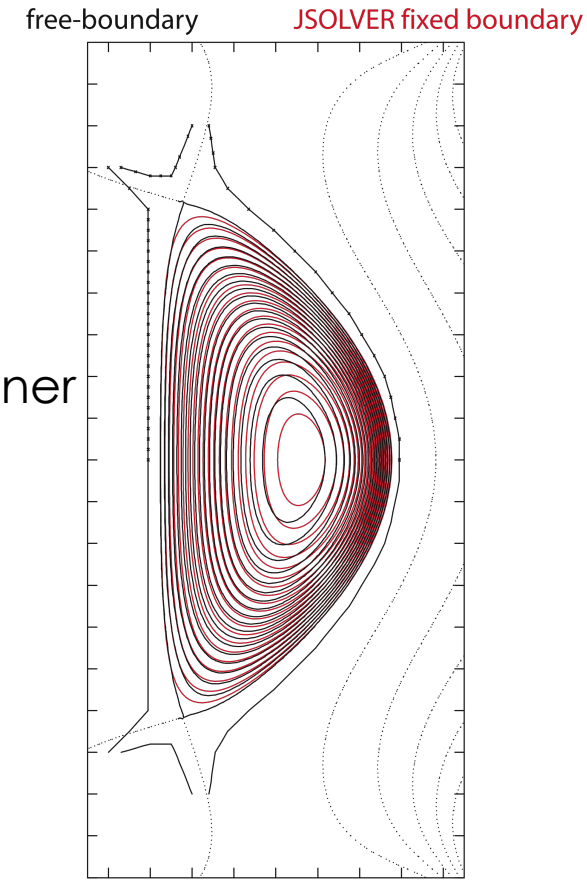
- **Fixed boundary inverse equilibrium code JSOLVER allows better freedom in matching current profile with bootstrap current**





Alignment of boundaries is good

Mismatch of inner flux surfaces is from profile differences



total $j_{toroidal}$

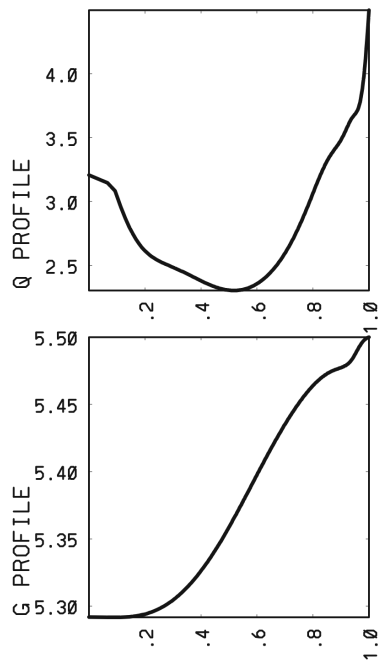
self-driven $j_{toroidal}$

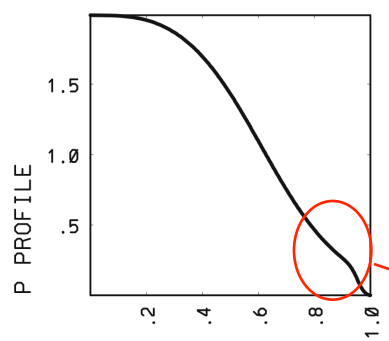
Fixed Boundary Equilibrium Preliminary Operating Point Features an Approximately Correct H-mode Pedestal

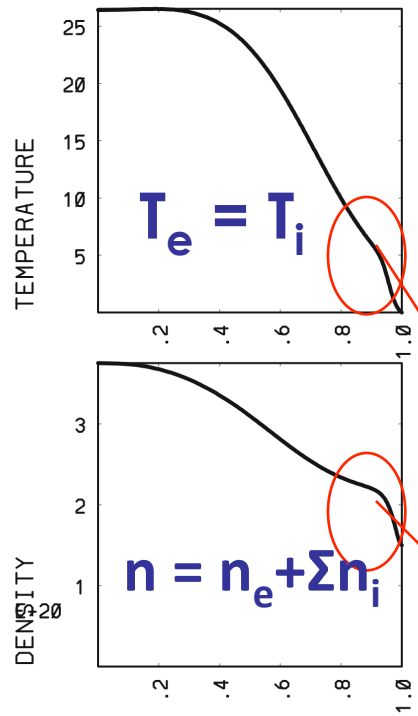
Ip = 10 MA
κ = 2.15
δ = 0.7
$s_{o,I}$ = 0

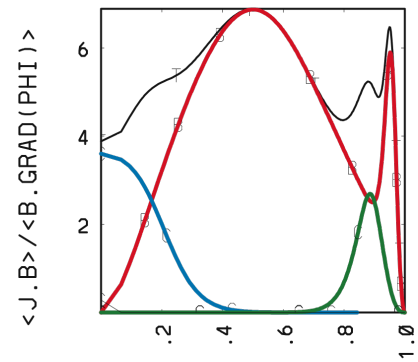
q(0) = 3.25
q_{min} = 2.3
β_N = 4.83
$\ell i(1)$ = 0.49

p(0)/<p> = 2.06
T(0)/<T> = 1.66
n(0)/<n> = 1.37
$n_e(0) = 1.97 \times 10^{20}$









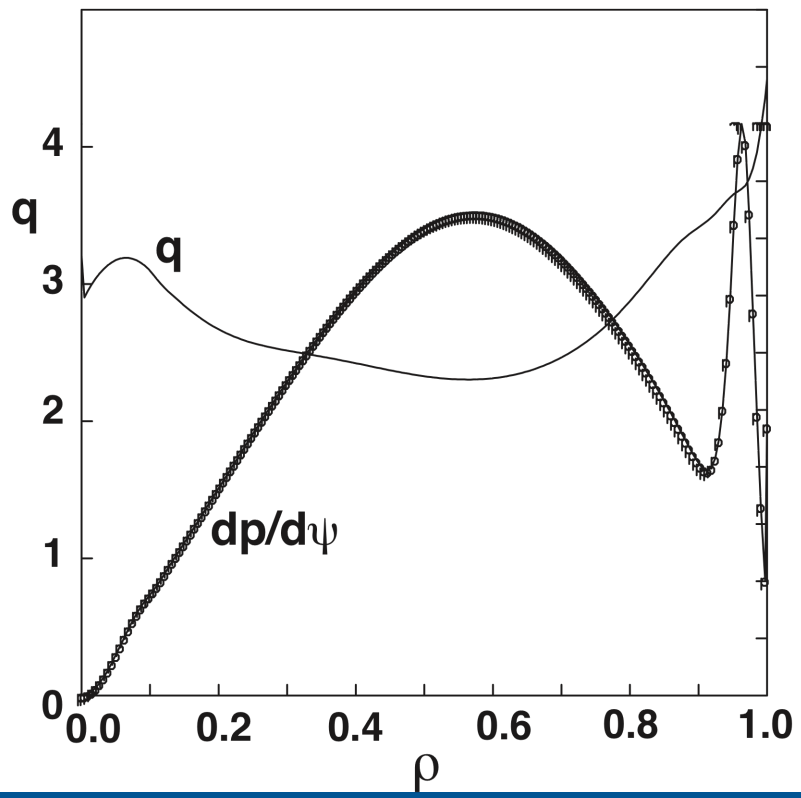
bootstrap current
IC or EC on-axis current
LH off-axis current

Pedestal in pressure, n, T
P_{ped} ~ 175 kPa,
approximately expected from EPED

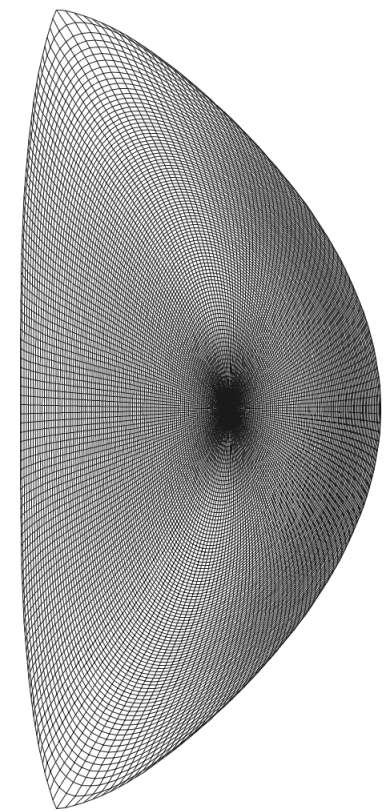
Transport Calculations Require Equilibrium From EFIT Code With Correct Pedestal as Starting Point

- **New equilibrium constructed with EFIT using:**
  - Boundary from free boundary equilibrium code and
  - Most updated profiles from fixed boundary equilibrium code
  - Pedestal consistent with EPED model

Profiles



Boundary

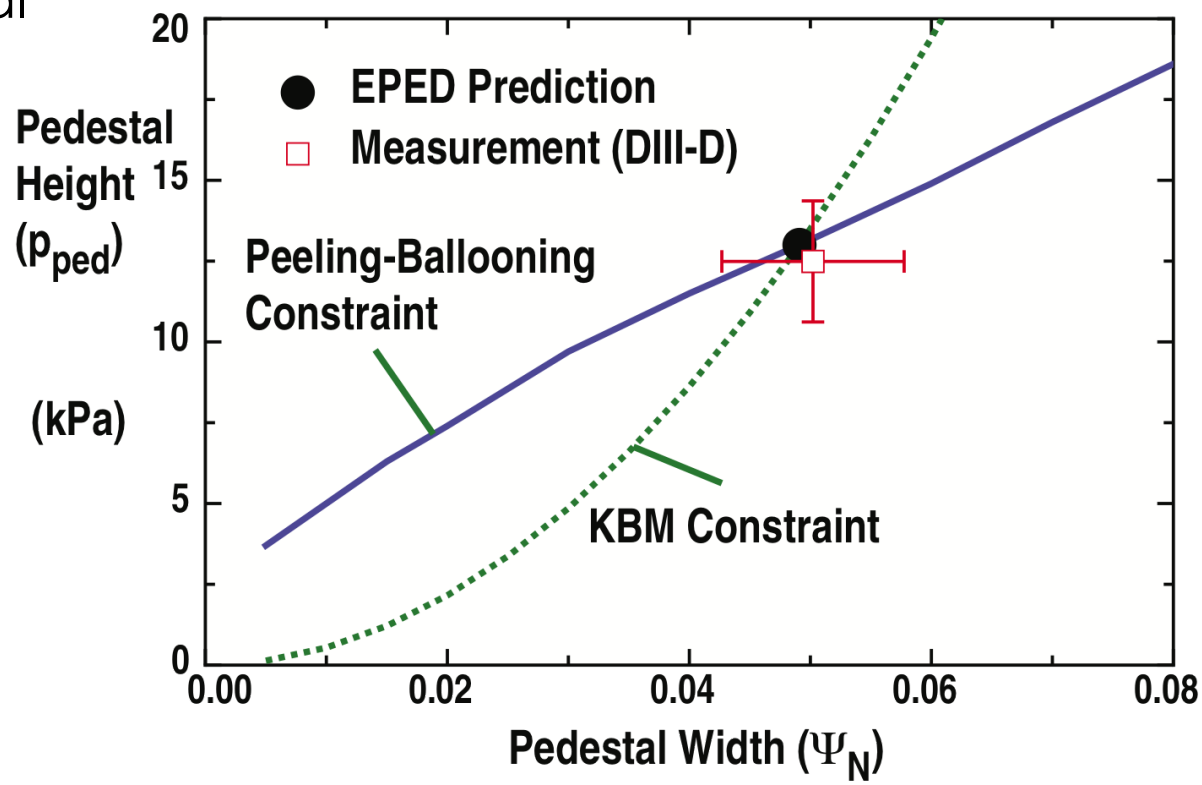


EPED1 Pedestal Model Implemented to Obtain Pedestal Poloidal Beta, β_p^{ped}

- **Transport simulations are well known to be inaccurate in and beyond the pedestal in H-mode:**
  - Require the boundary condition to be imposed at a point interior to the pedestal
  - The position for imposing this boundary condition was chosen to be at $\rho = 0.93$, which is at the top of the pedestal
- **β_p^{ped} value obtained using EPED1 stability analysis by:**
  - Constructing a population of equilibria with varying profiles and
  - Testing stability for intermediate toroidal mode number *n* ideal modes and kinetic ballooning modes
- **Optimization against both yields unique values for both height and width of the pedestal and a corresponding value for β_p^{ped}**
- **Values in the range $1.0 < \beta_p^{ped} < 1.1$ at $\rho \sim 0.9$ provide reasonable solutions**
- **The value $\beta_p^{ped} = 1$ was chosen for the simulations**

EPED1 Model Takes B_0, I_p, R, a, κ, δ, n_{ped}, and β as Input and Produces p_{ped} and W_{ped} as Output

- **Stability calculated for a series of model equilibria with varying pedestal height around n_{ped} and width:**
  - Intermediate n ideal peeling-ballooning modes (ELMs)
  - Kinetic ballooning modes
- **Different dependences of stability of these modes provides a unique intersection in the space of pedestal height and width**



- **Model successfully predicts pedestal in experiments**

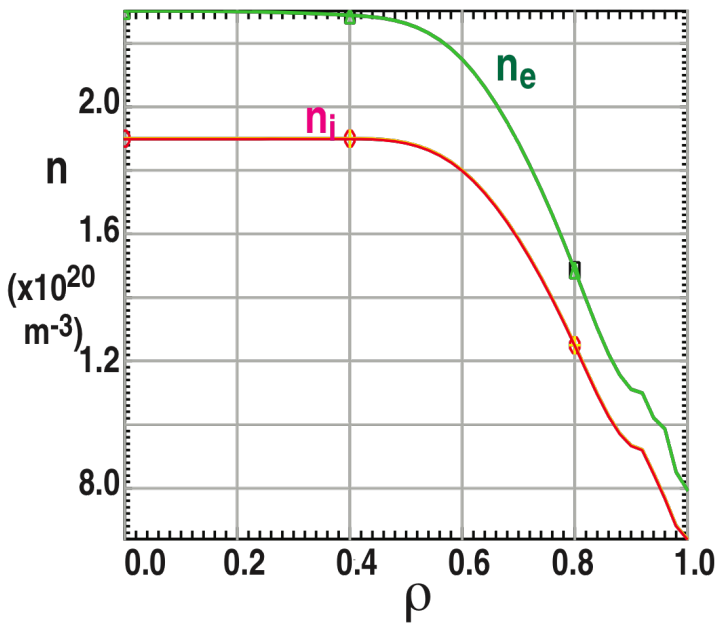
Temperature Evolution for ARIES Baseline Model Profile With Broad Density Up to Pedestal Region

- **Temperatures derived initially from equilibrium pressure and the prescribed density for the individual species:**
  - Assuming $Z_{eff} = 1.27$ and $T_e = T_i$
  - Pedestal ion density determined by value of β_p^{ped} from EPED1
- **Temperatures subsequently evolved using GLF23 transport model:**
  - Assuming no density evolution and no auxiliary heating
    - Only energy source is α particle heating
  - Temperatures held fixed at $\rho = 0.93$ as the boundary condition
  - Density is not evolved in these simulations:
    - Assumed they are maintained against diffusion by a source
- **Implemented first steps:**
  - First simulation with GLF23 found collapse of temperature profile
  - Steady state found with increased density:
    - Increase density factor 1.85 prevents core collapse
    - Edge collapse only prevented so far by imposed boundary condition

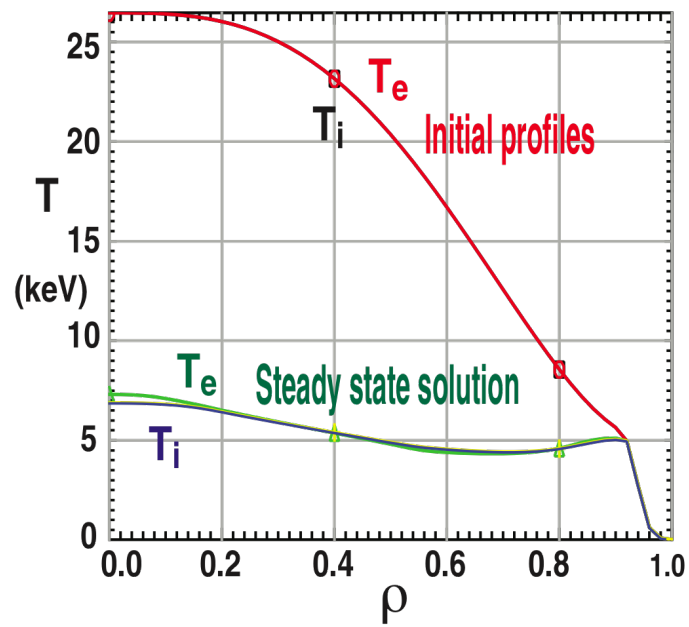
Initial Simulation Found Collapse of Temperature Profile Using Initial Baseline Flat Density Profiles

- **Profiles ultimately collapsed to boundary condition value:**
  - Essentially, fusion alpha particle heating could not be maintained against the outward heat flux

Electron and ion densities



Electron and ion temperatures



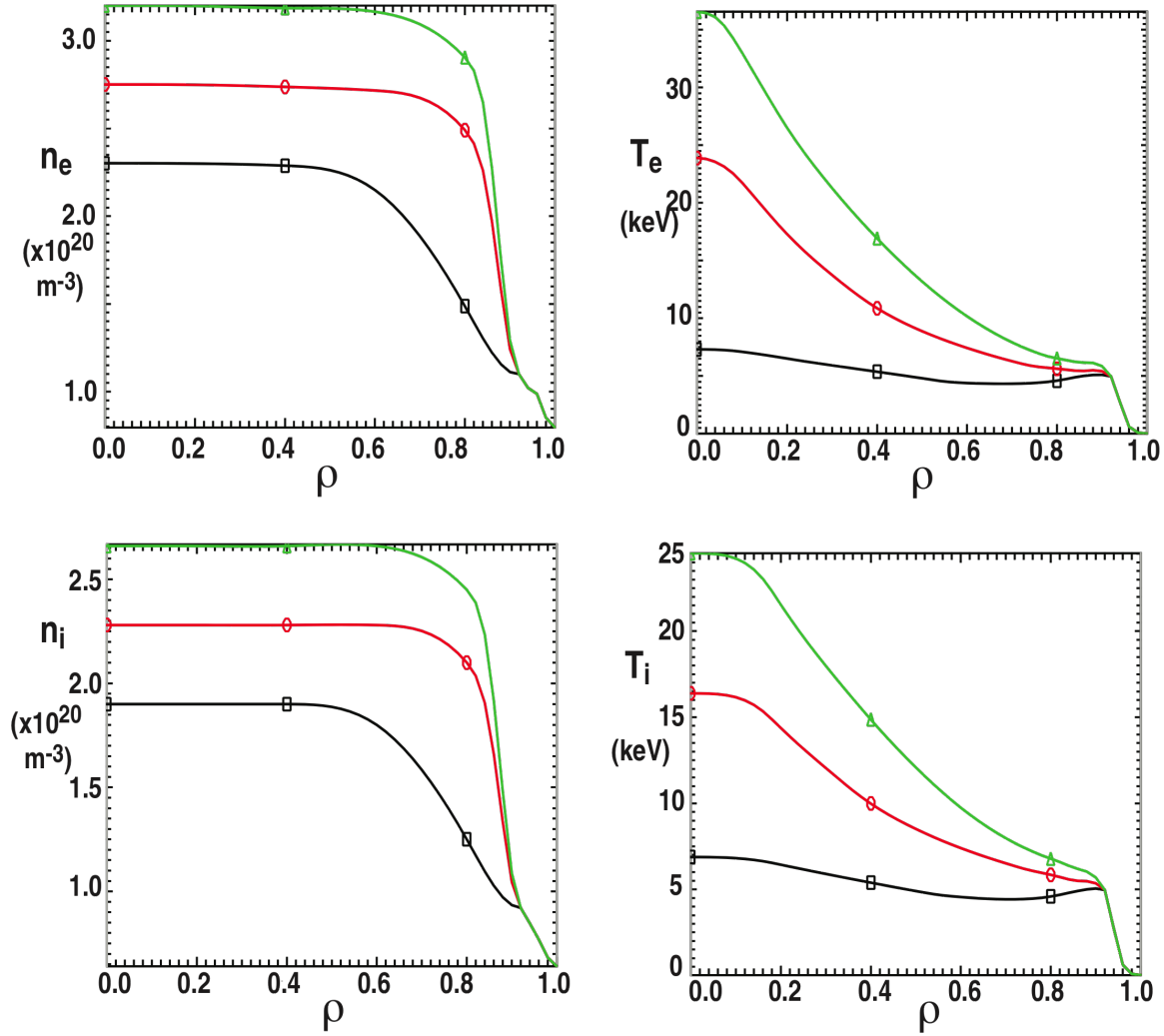
- **Two density scans were performed with varying axis values:**
  - Broad density as in the standard case, and
  - Peaked density profiles

Steady State Temperature Profiles Obtained if Density Increased by Factor 1.85 Above Systems Code Value

- **Profiles of density and temperature with three different values of the axis value:**
  - Flat density case
  - The standard case is the lowest density case of this series

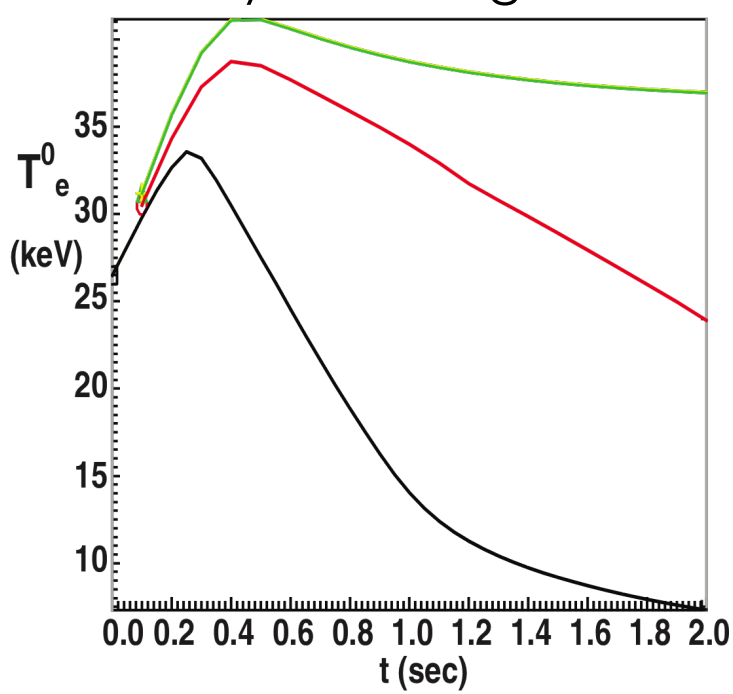
$n_e = 2.9 \times 10^{20}$

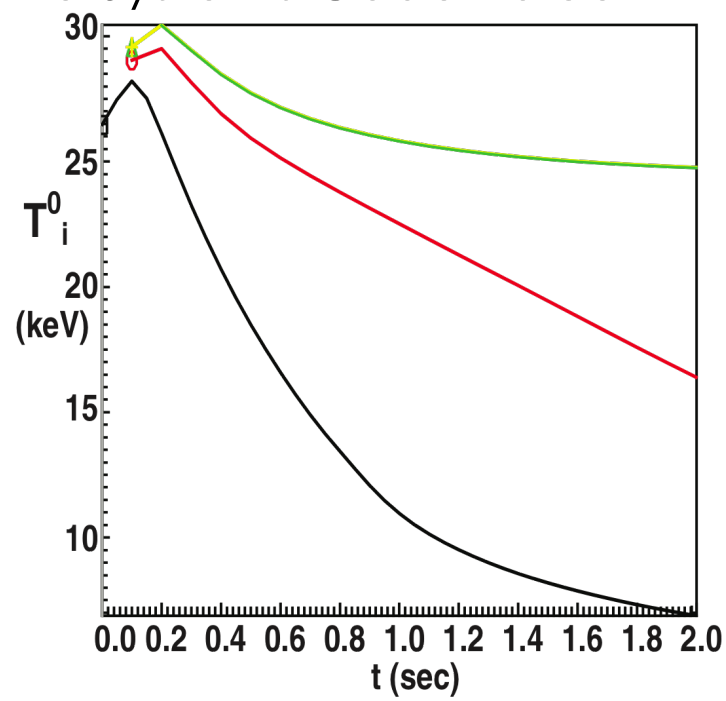
$\Rightarrow P_{DT} = 2.9$ GW



Simulations for Broad Density Show Initial T_e Barrier Formation That Subsequently Decays

- **Initial transient increase corresponds to formation of a core electron transport barrier and a weak ion transport barrier**
- **Two profiles with the lowest density eventually collapse:**
  - Highest density case appears to reach a steady state with elevated temperature and sustained fusion
  - Axis density is 80% higher than the Systems Code value



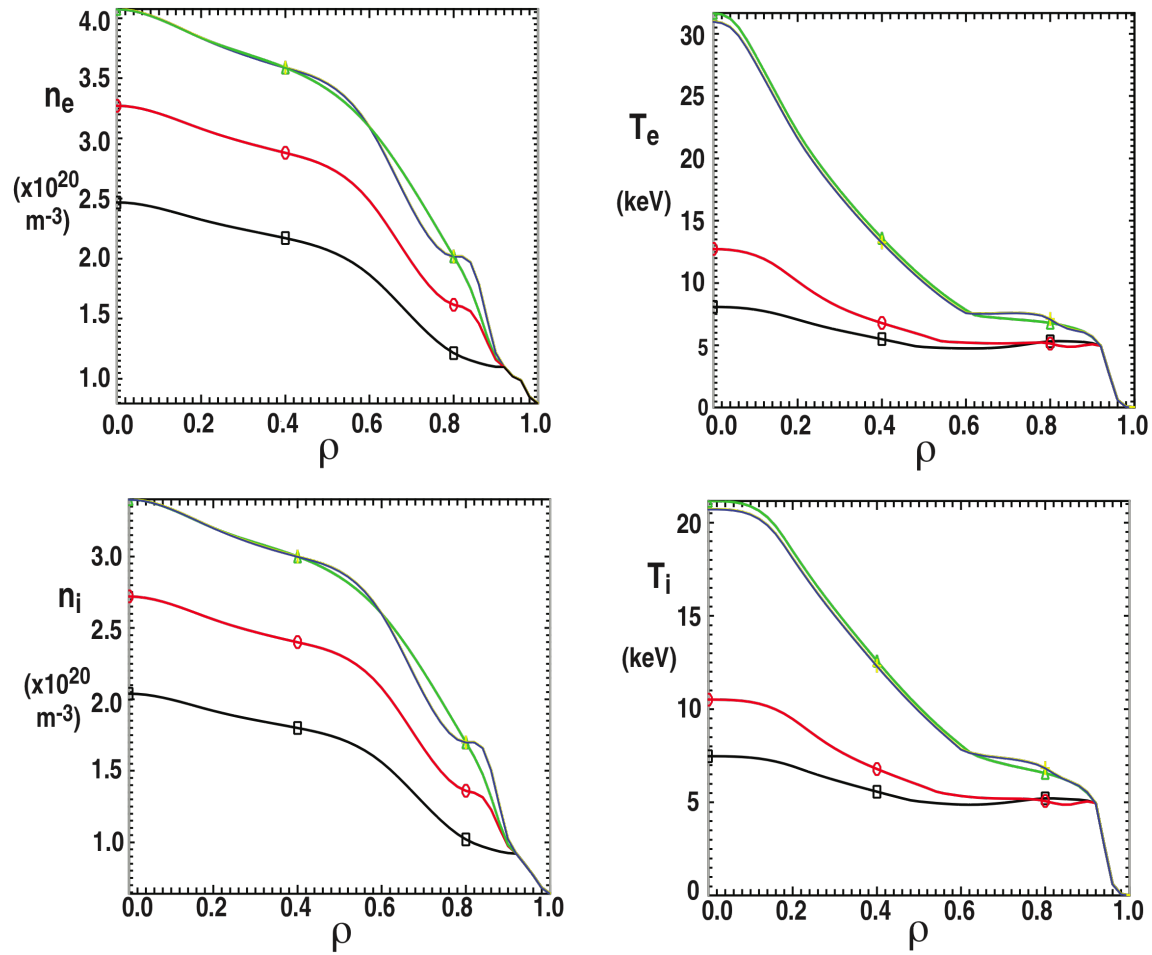


Density Peaking Typically Increases Fusion Power But the Gain for this Case is Weak

- **Fusion power is proportional to the density in the core where the ion temperatures are above the threshold for fusion:**
  - ⇒ Increasing density in the core region should increase fusion power
- **Profiles of density and temperature for the peaked density scan:**
  - Again with three values for the density on axis

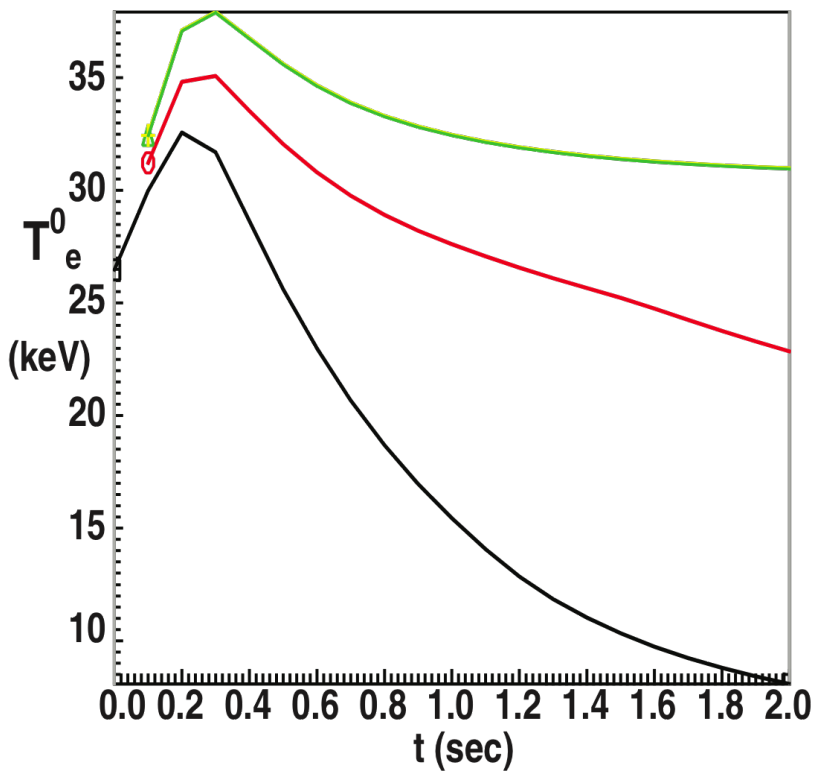
$$n_e = 3.5 \times 10^{20}$$

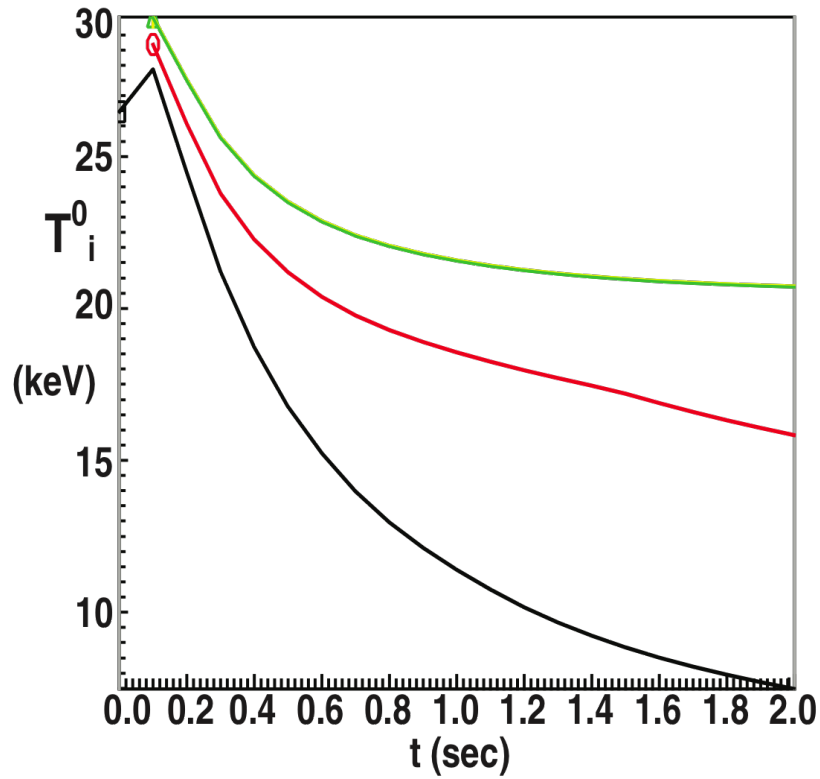
$$\Rightarrow P_{DT} = 2.75\ \text{GW}$$



Collapse for Intermediate Density Case Partially Arrested but Otherwise Little Gain From Peaking density

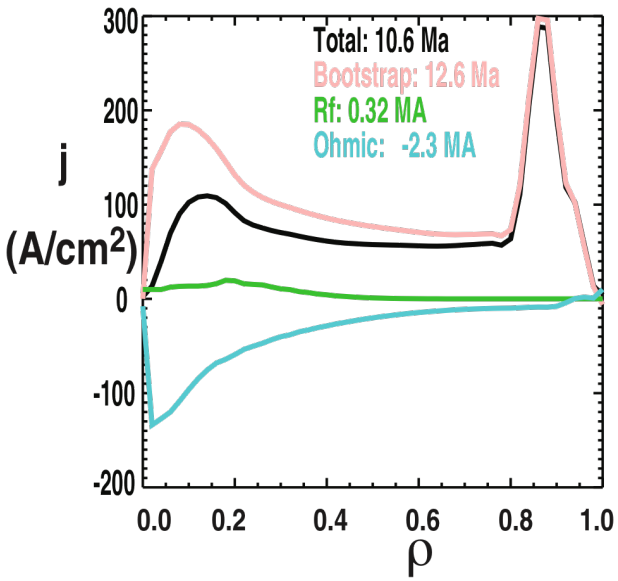
- **Simulation was not run for enough time to confirm whether a real steady state is sustained**
- **Again, a transport barrier appears transiently In the core:**
  - Somewhat weaker than for the broad density scan

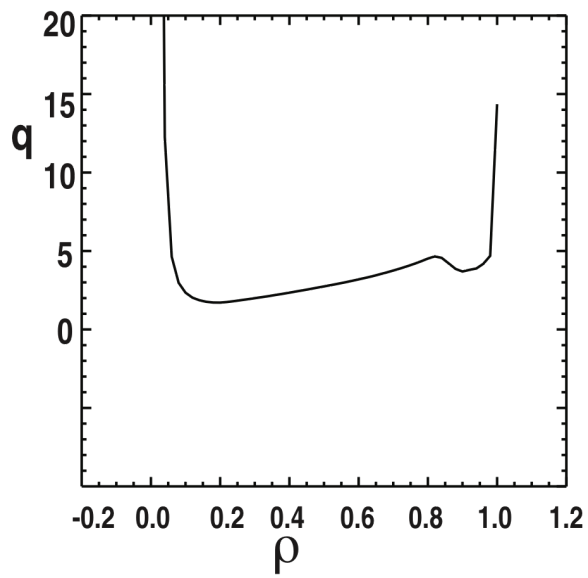


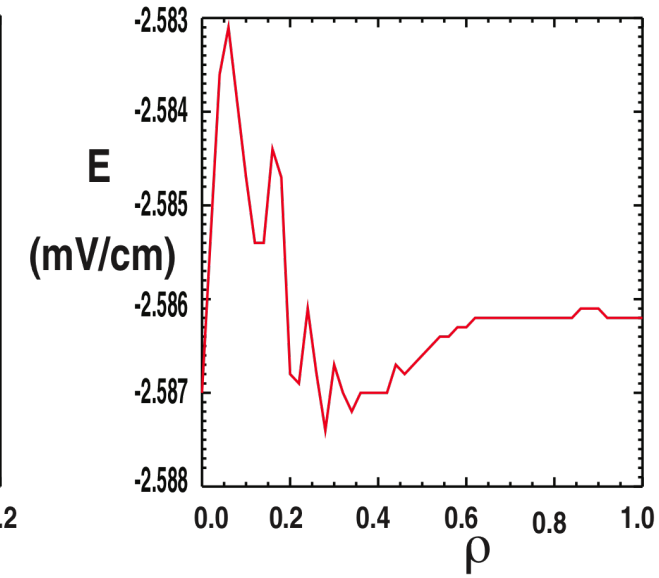


Large Bootstrap Current Density Near Pedestal Overdrives Plasma in Broad Density Scenario

- **Bootstrap in core under-drives plasma:**
  - Fast wave near the axis is not feasible to make up difference
- **Residual Ohmic current density is large and negative overall:**
  - ⇒ Not steady state



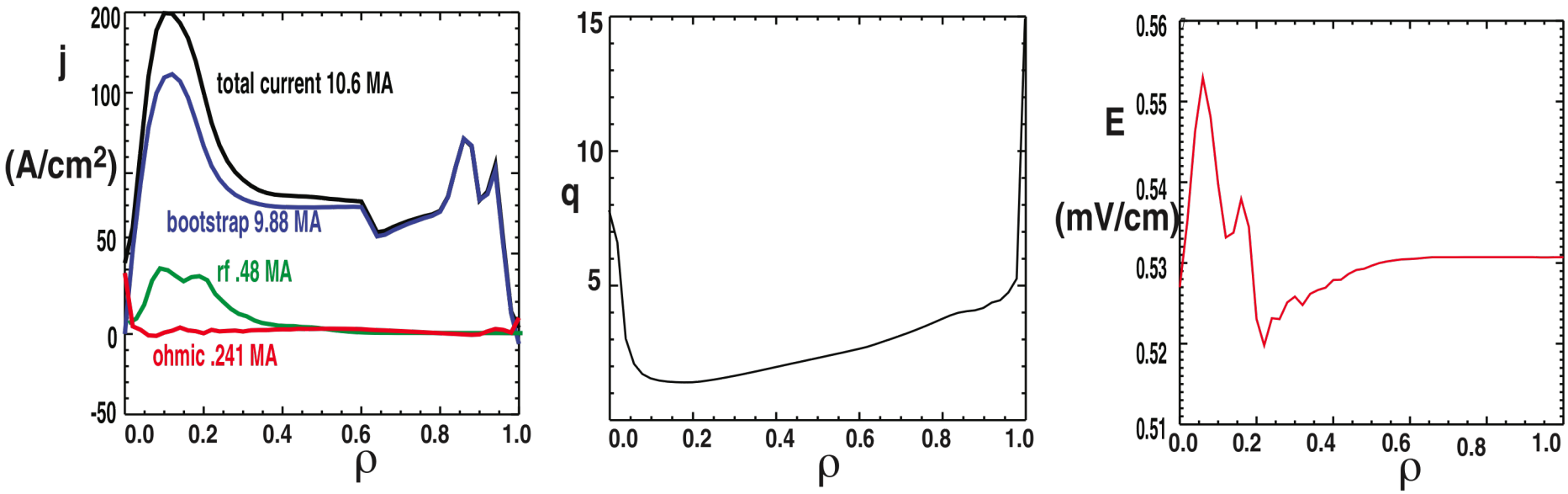




- **Density shaping near edge is needed to better align bootstrap current**

Auxiliary Current Drive Requirement in Peaked Density Scenario is Reasonable for Attaining Steady State

- **Bootstrap current density is well aligned with total current density:**
  - Need 50 A/m^2 on axis current density to drive remaining inductive current to zero
  - Requires 40 MW Fast wave

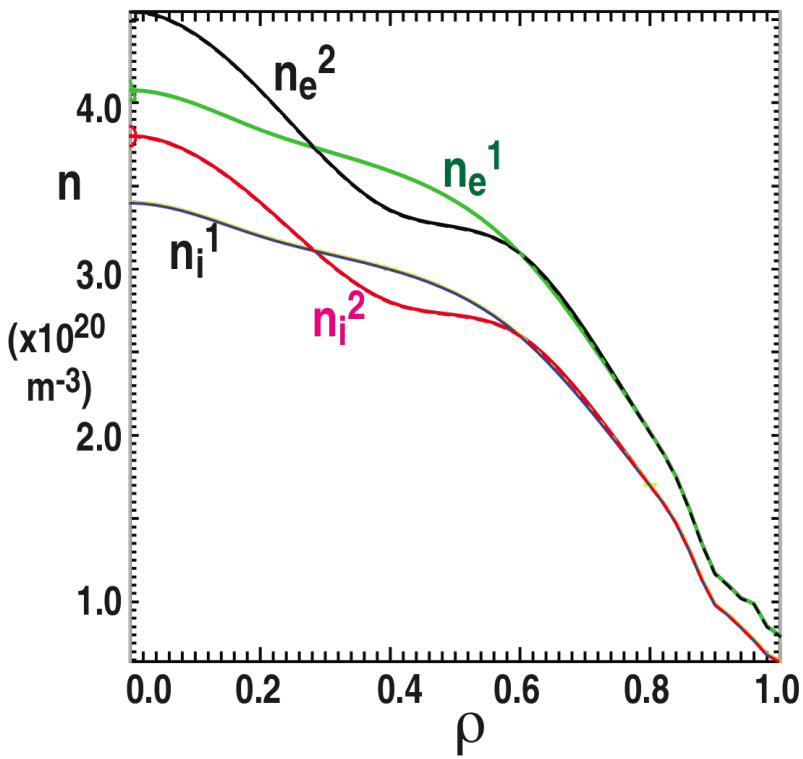


- **Residual Ohmic current in steady state is 240 kA with 0.48 MA of RF driven current from Lower Hybrid system**

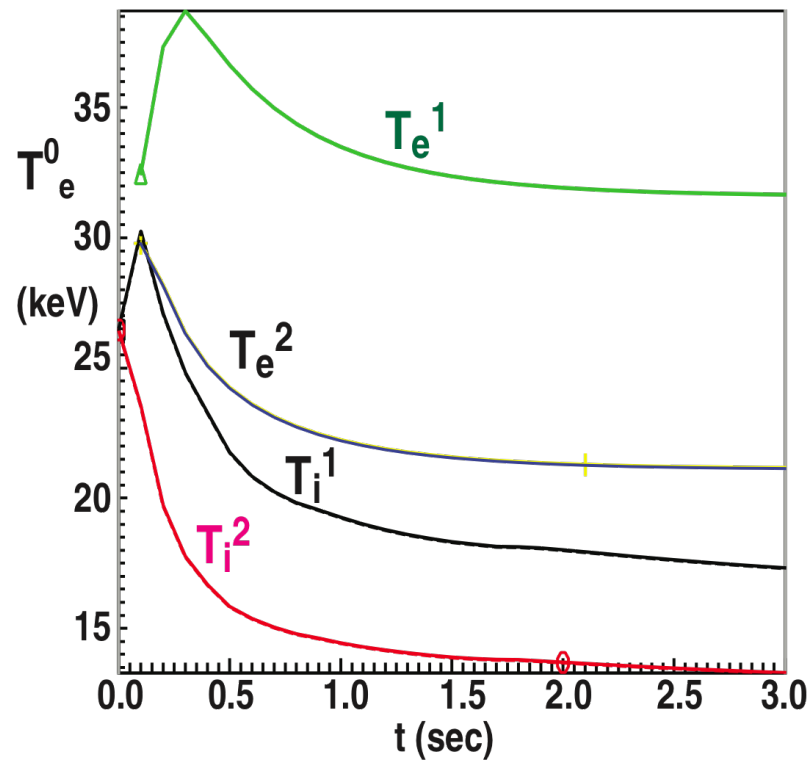
Additional Density Peaking in Core Found to Not be Beneficial as Core Temperatures Collapse

- **Additional core peaking applied to peaked density profiles with constant pedestal:**
  - ⇒ β_N increases from β_N = 3.8 to β_N = 5.0

Electron and ion densities



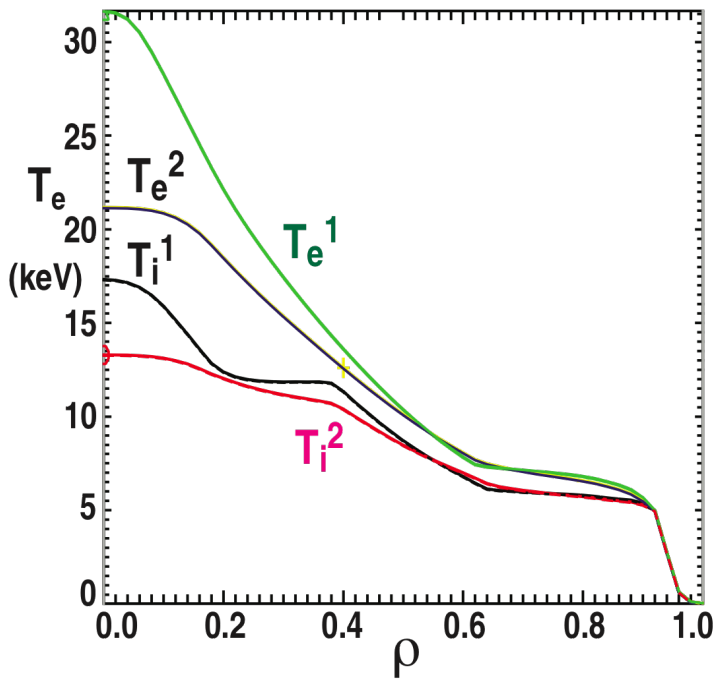
Axis temperature evolution



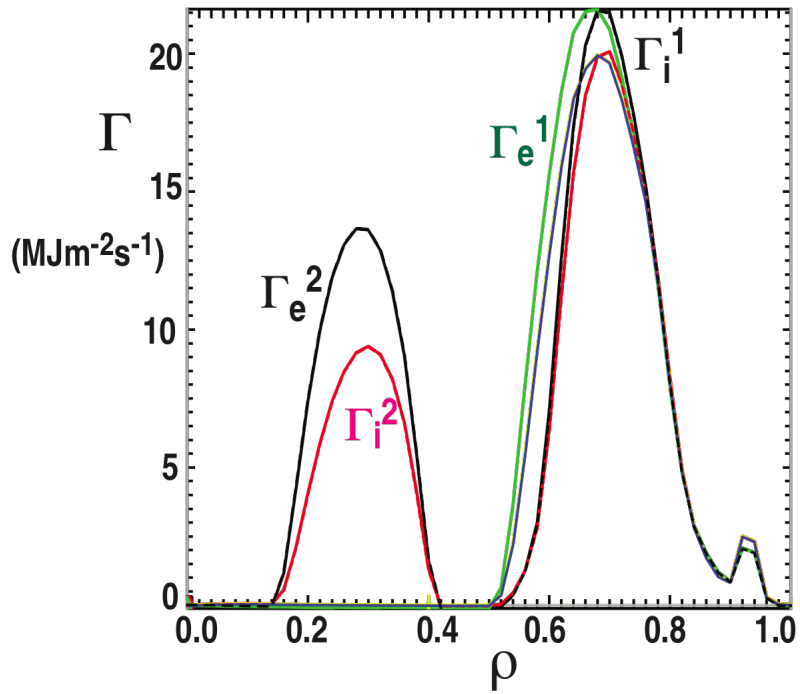
Fluxes Computed From GLF23 Show Large Energy Flow in Region of Additional Density Gradients

- **Energy fluxes show outward energy flux in outer region 0.6 < ρ < 0.9 is large In both cases**
- **Peaking causes additional energy flow over range 0.2 < ρ < 0.4**

Steady state Temperature profiles



Electron and ion energy fluxes for final 'steady state' profiles



How Can the Apparent Discrepancy Between Systems Code Scenario and These Simulations be Resolved ?

- **Systems code calculates an energy confinement time by imposing power balance from an assumed steady state:**

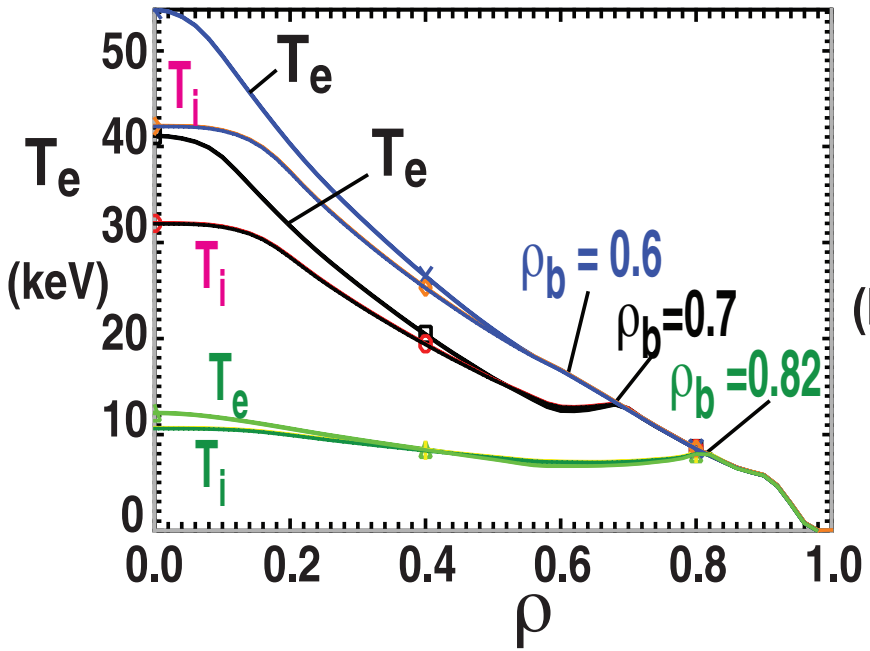
$$\tau_E = W_{th}/(P_\alpha + P_{aux} - P_{rad})$$

  - GLF23 calculations for Systems Code parameters suggest there may not be a burning plasma steady state for those parameters
- **GLF23 model is based on calculations for microinstabilities in a shifted circle cross section equilibrium :**
  - This is likely poor for the strongly shaped ARIES configuration
  - But full geometry TGLF model is generally even more pessimistic
- **Other issues with the transport modeling:**
  - Results can be sensitive to boundary condition position:
    - Model is known to be inapplicable in the pedestal
    - Where does it break down
  - Density is not evolved in present simulations:
    - Implicit particle sources and sinks can cause additional energy flows

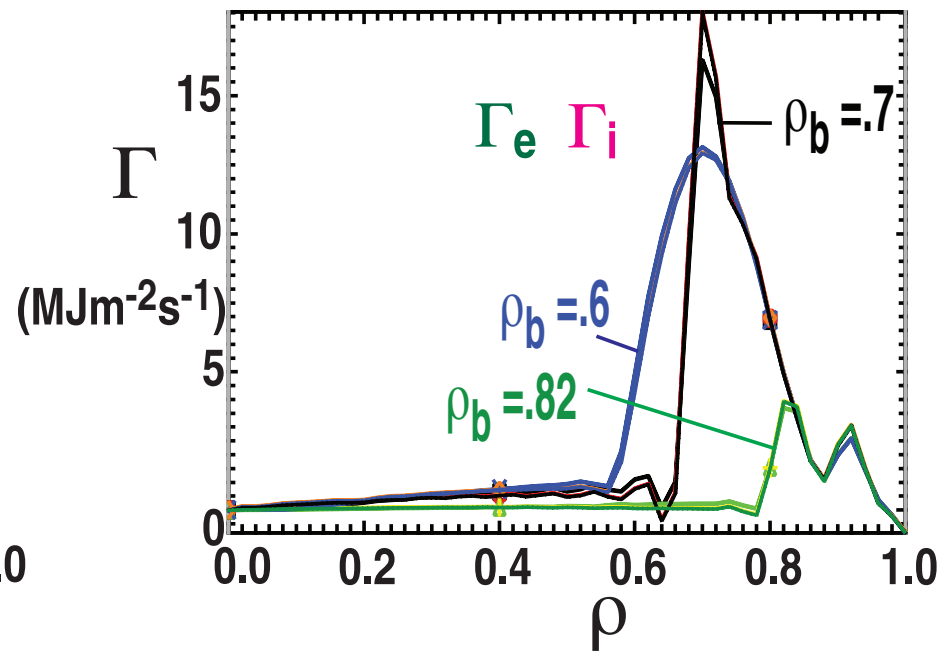
Final Result is Sensitive to Location of Pedestal Boundary Condition ρ_b

- **Simulations performed with varying boundary radius:**
  - Temperatures fixed beyond ρ_b value
  - GLF23 fluxes large outside ρ_b

Temperatures Versus ρ_b



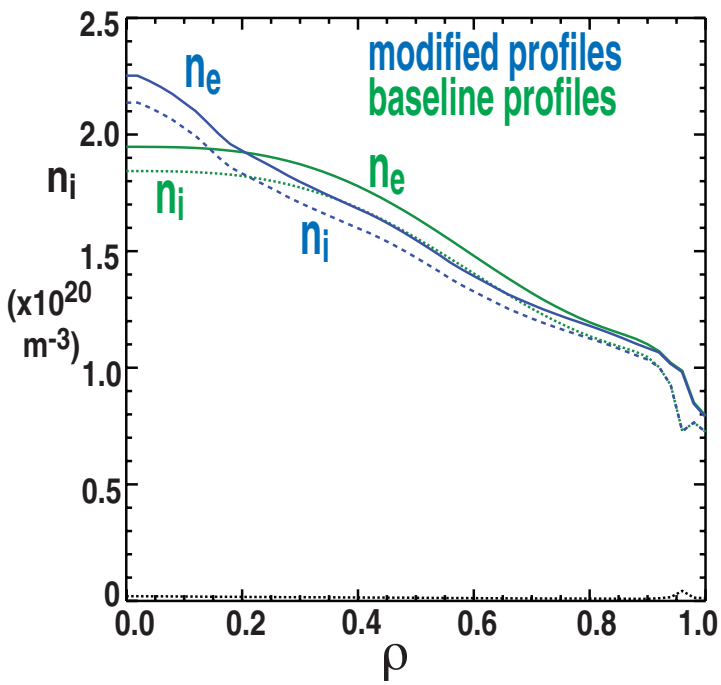
Electron and ion energy fluxes

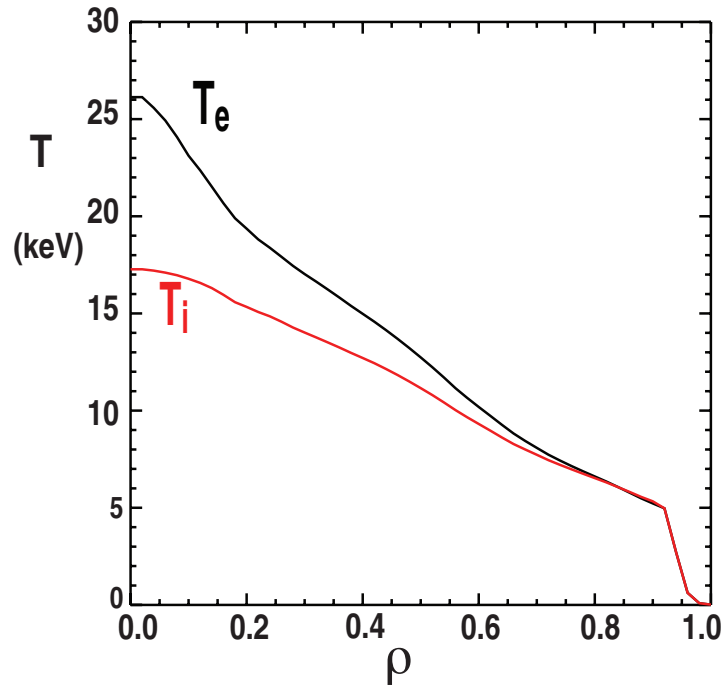


- **Final temperatures vary with ρ_b value:**
  - Boundary condition too far out results in collapse

Results with TGLF transport model are Slightly More Optimistic for Standard Density Case

- **Density profile not scaled in this case:**
  - Profile modified slightly with additional peaking to avoid collapse
  - Density evolved with temperatures for some time then fixed
    - ⇒ β_N^{ped} is no longer exactly 1.0





- **Final result with slightly peaked density profiles (n_e = 1.7 x 10^{20}):**
  - **P_{DT} = 740 MW**

Initial Simulation for ARIES ACT 1 Found Collapse of Temperature Profile Using Initial Baseline Profiles

- **Profiles collapsed below the imposed boundary condition value on first simulation**
- **Increased density by factor 1.85 prevented core collapse and yielded a steady state:**
  - Density factor has a small range for steady state solutions:
    - Factor below 1.8 leads to collapse
    - Factor above 1.9 leads to runaway core peaking
- **Peaking density yields some benefit but is not large:**
  - Benefit is mainly in current drive requirements
  - Additional core peaking results in additional core energy fluxes and more pessimistic results
- **Apparent discrepancy with Systems Code identified scenario is partly resolved:**
  - Sensitivity to boundary condition
  - TGLF is surprisingly more optimistic in this case
  - Further optimization may resolve some more differences

Backup slides

The Story

- **Aim is to use most sophisticated models for equilibrium, transport, current drive, stability currently available:**
  - TGLF transport
  - Low n ideal stability
  - ELM stability controlling of pedestal height
  - Current drive from ray tracing
- **Simulation performed for 2006 ARIES study as a check:**
  - Confirmed essential published results
  - Some minor differences
- **Simulation for newest ARIES ACT I design:**
  - Pedestal obtained from EPED1 model
  - Initial simulations with Systems Code prescribed parameters do not yield steady state
  - Steady state can be achieved over a small range of density roughly 80% higher than the prescribed value
  - Current drive requirements are reasonable

Future Plans Intend to Complete Optimization for Self Consistent Steady State Scenario

- **β optimization:**
  - Initialize with $\beta_N = 5.7$
  - Check ideal stability
  - Optimize to converge to maximum stable β_N
- **q profile optimization:**
  - Adjustment of q profile to improve stability and current drive potential
- **Shape and size optimization:**
  - Elongation, triangularity and aspect ratio
  - Size adjustments as needed
- **Aim to use IMFIT for automation of core loop of transport self consistently optimized with heating and current drive**

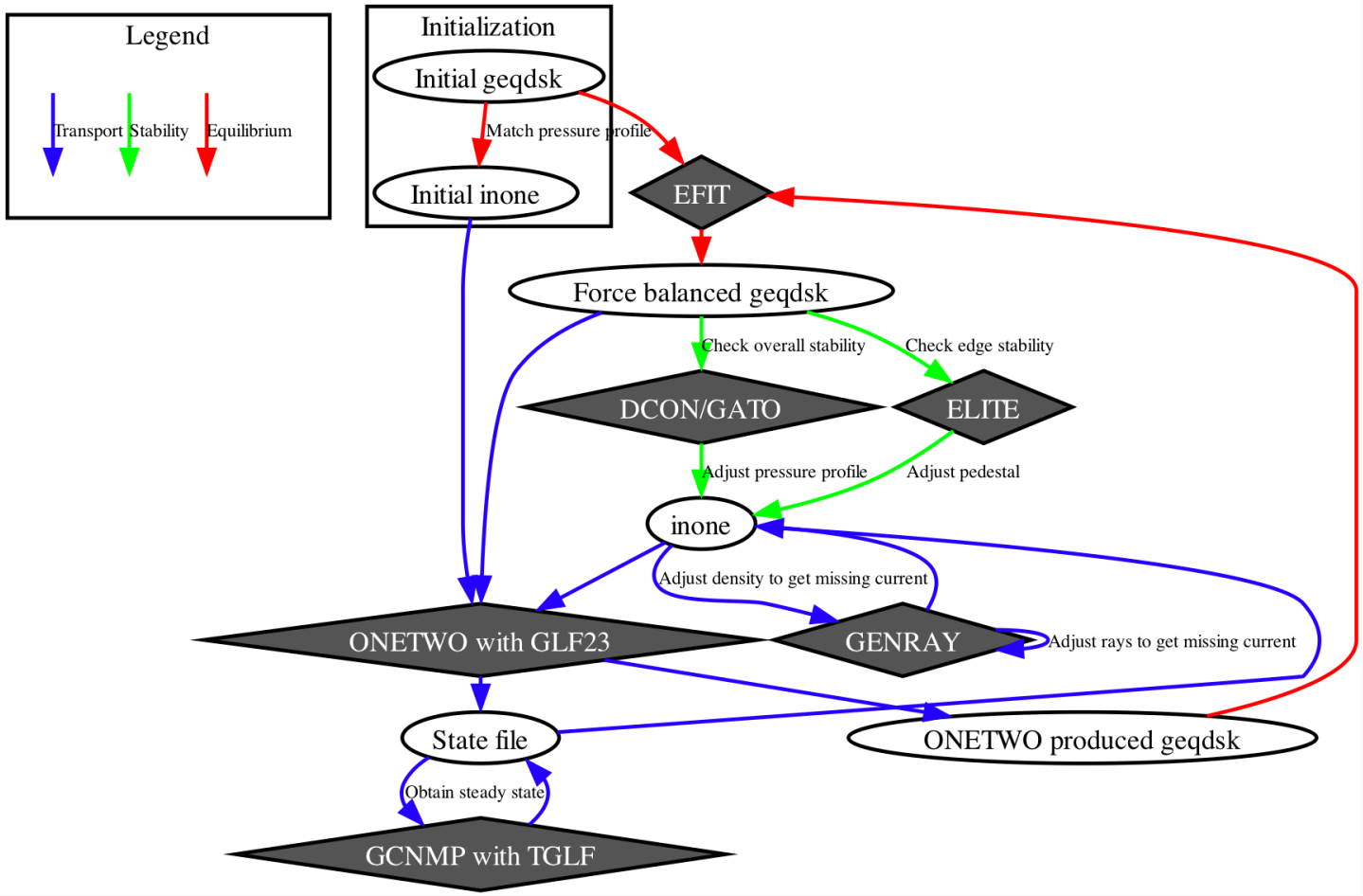
- **In the initial steps of the subsequent optimization, the GLF23 transport model will be used:**
  - Considerably faster than the more accurate TGLF model
  - Utilize TGLF once simulations are partially converged

Pessimistic TGLF Result May be Due to Full Geometry or to Other Features of the Model

- **Run one iteration to obtain individual diffusive and convective fluxes:**
  - Calculate individual fluxes and sources and compare with:
    - TGLF with shifted circle geometry
    - GLF23 (shifted circle geometry)
- **Run to steady state:**
  - If TGLF reaches steady state with shifted circle geometry then the shaping is the culprit:
    - Determine sensitivity to small tweaks in shape and profiles
  - Otherwise it may be simply higher accuracy of the TGLF model
  - May need rotational shear stabilization from neutral beams
- **TGLF and GLF23 are known to fail to predict experiments for $\rho > 0.85$ even in L-mode:**
  - Present boundary condition taken to be at pedestal ($\rho = 0.93$)
  - Option to move this boundary condition in and apply at $\rho = 0.85$:
    - Steady state was reached with boundary arbitrarily moved to $\rho = 0.82$
  - Need to properly match profiles between $\rho = 0.85$ and $\rho = 0.93$

Code Linkage Overview of Optimization Procedure

- **IMFIT code structure**



Previously Optimized ARIES Lower Hybrid Heating and Current Drive Scenarios Using CURRAY

- **Aimed to drive non-inductive off-axis current in $0.8 < \rho < 1.0$**
  - (S.C. Jardin, Fusion Engineering and design (2006))
- **Two scenarios studied with different density:**
  - 4 or 5 wave spectra of LH grills, each centered at a different $N_{//}$, were determined to have relatively broad profile

Scenario 1

$n_e(0)=2.93\times10^{20}$ m^{-3}, $T_e(0)=26.3$keV, $Z_{eff}=1.9$

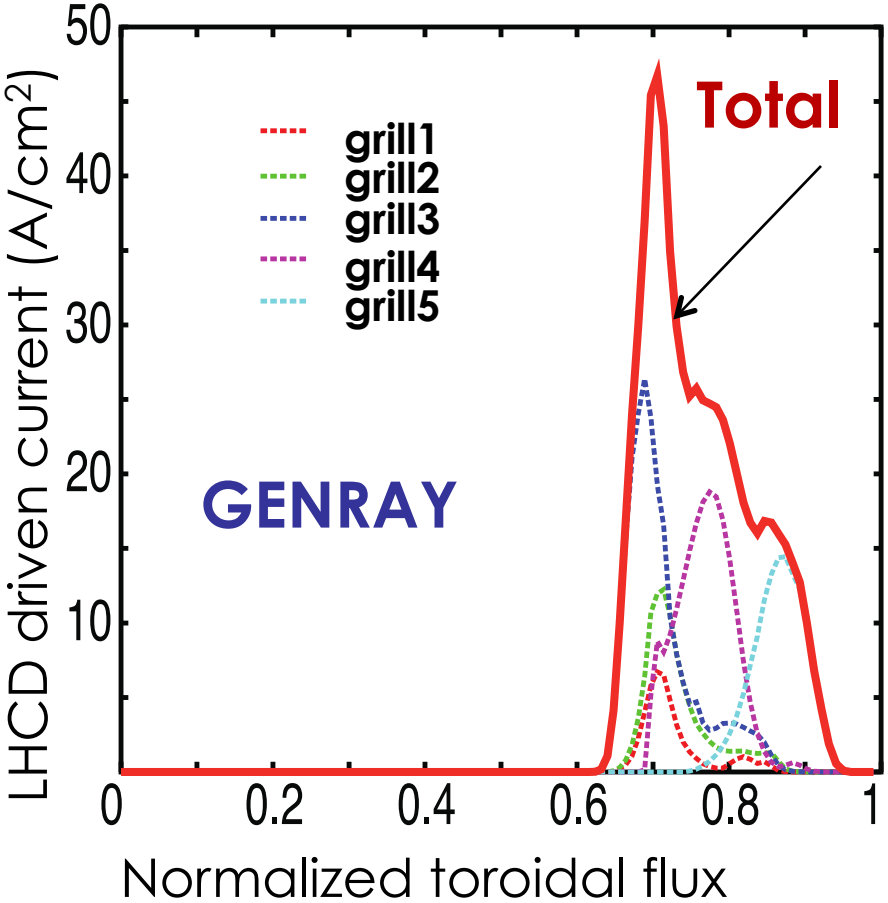
Freq (GHz)	$N_{//}$	θ	Power (37 MW)	I/P (A/W)
3.6	1.65	-90	3.06	0.053
3.6	2.0	-90	4.40	0.049
3.6	2.5	-90	8.22	0.039
3.6	3.5	-90	8.87	0.024
2.5	5.0	-90	12.39	0.013

Scenario 2

$n_e(0)=2.74\times10^{20}$ m^{-3}, $T_e(0)=28.2$ keV, $Z_{eff}=2.0$

Freq (GHz)	$N_{//}$	θ	Power (20 MW)	I/P (A/W)
4	1.7	-90	2.94	0.057
4	2.0	-90	3.24	0.052
4	2.5	-90	5.43	0.041
4	4.0	-90	8.17	0.021

For Scenario 1 GENRAY Predicts 0.63 MA Total Driven Current From Lower Hybrid System



Grill	f GHz	$N_{//}$	θ	Power (37 MW)	I/P (A/W)
1	3.6	1.65	-90	3.06	**0.013**
2	3.6	2.0	-90	4.40	**0.020**
3	3.6	2.5	-90	8.22	**0.024**
4	3.6	3.5	-90	8.87	**0.021**
5	2.5	5.0	-90	12.39	**0.010**

Driven current at higher density is much smaller

Additional Current Driven by ICCD System in Core

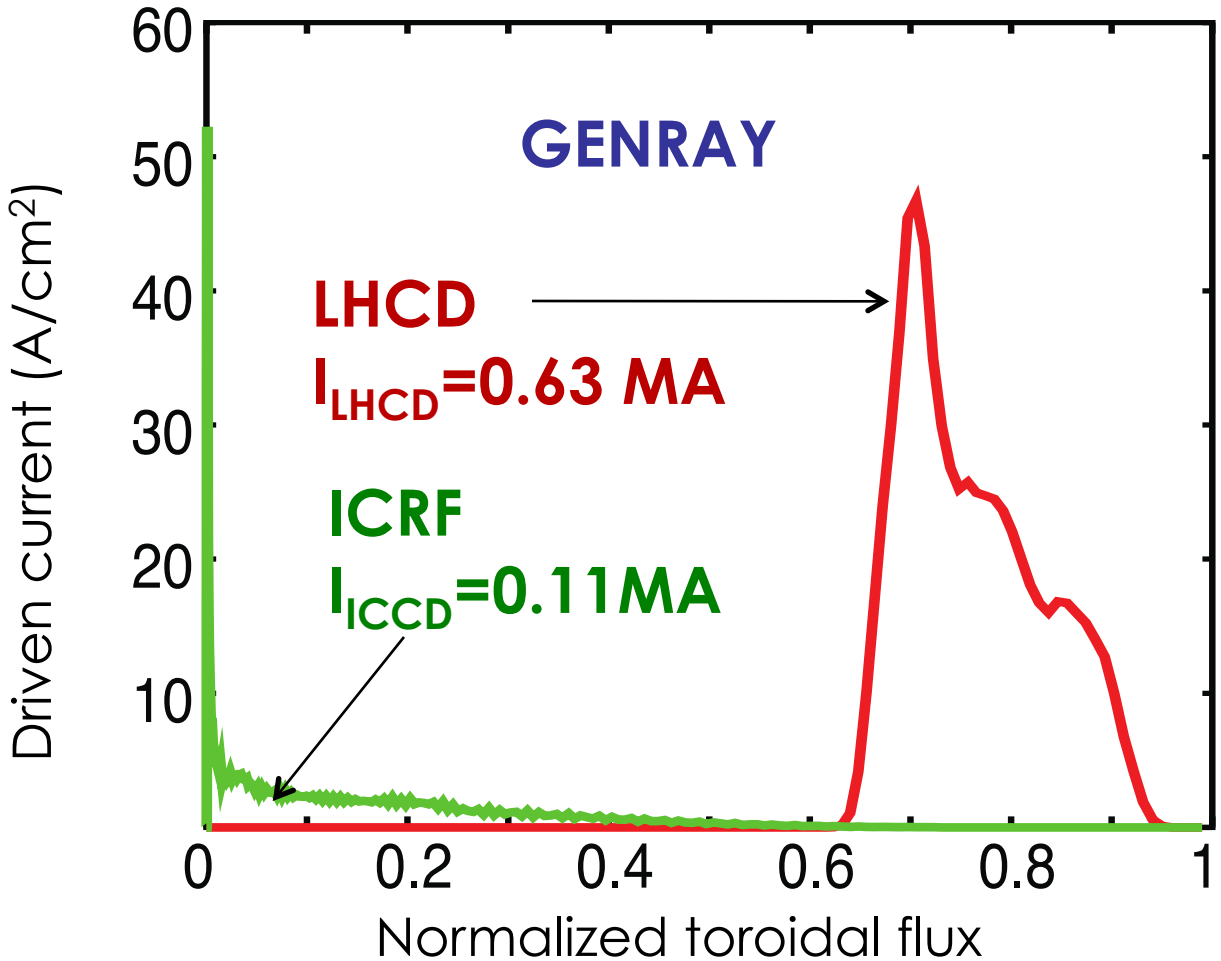
- **ICCD System:**

  f = 96 MHz

  $N_{//}$=2.0

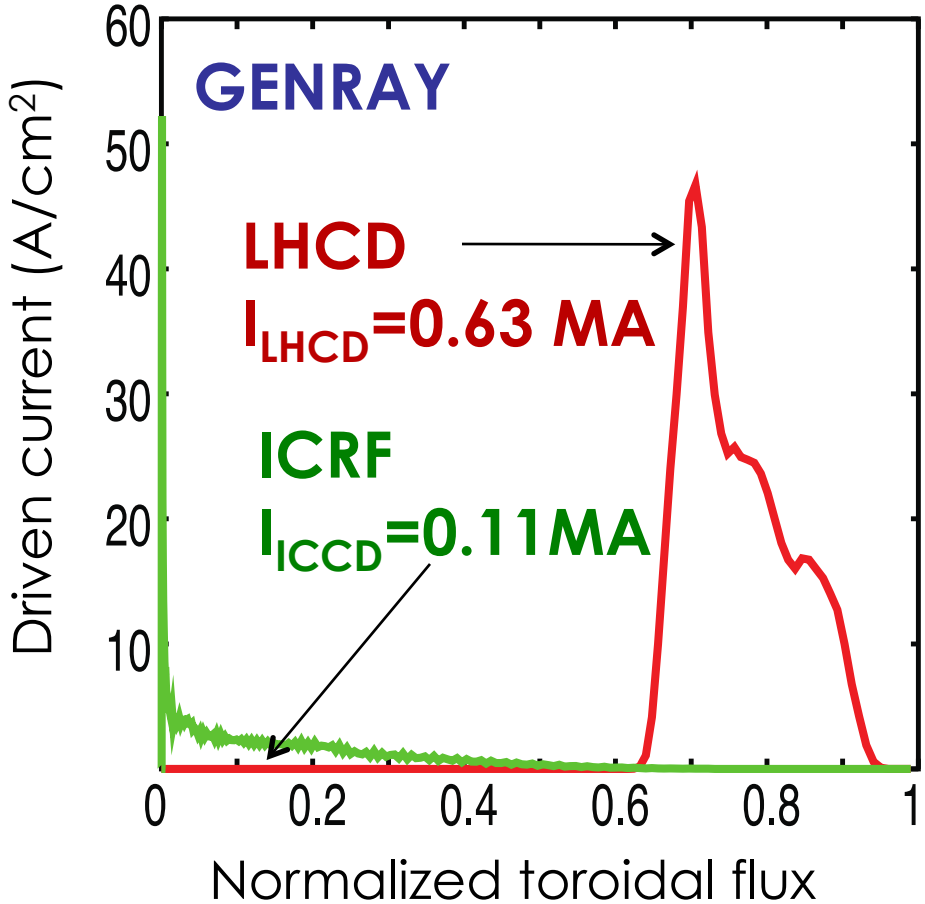
  P=4.7MW

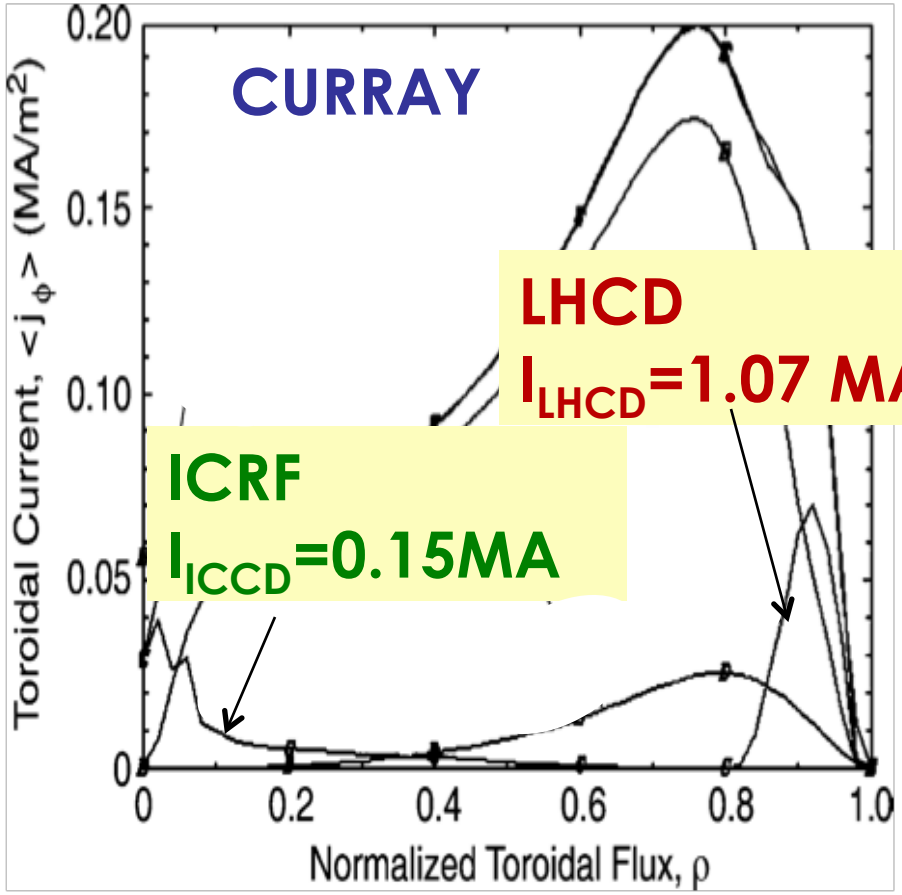
  θ = -15°



Comparison of Driven Current Profiles from GENRAY with CURRAY Results Show Lower Current Driven

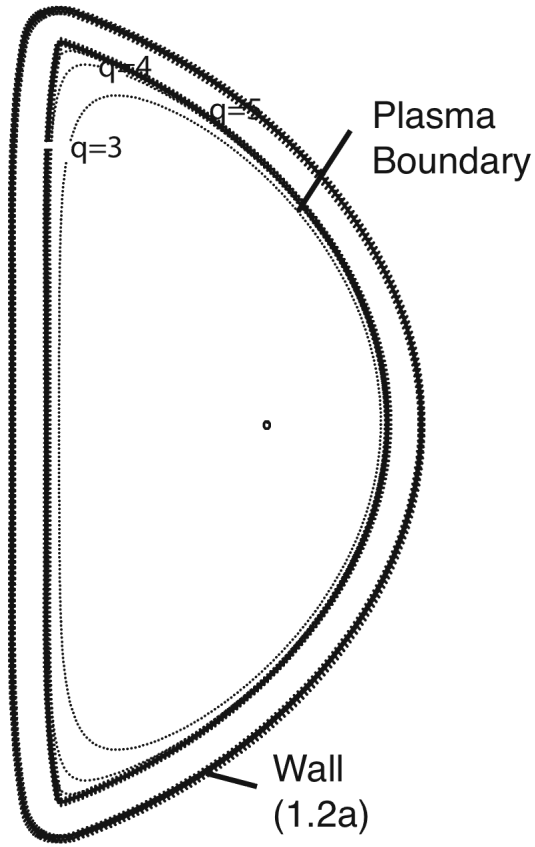
- Lower current drive found than in 2006 paper probably due to additional density pedestal in new simulation



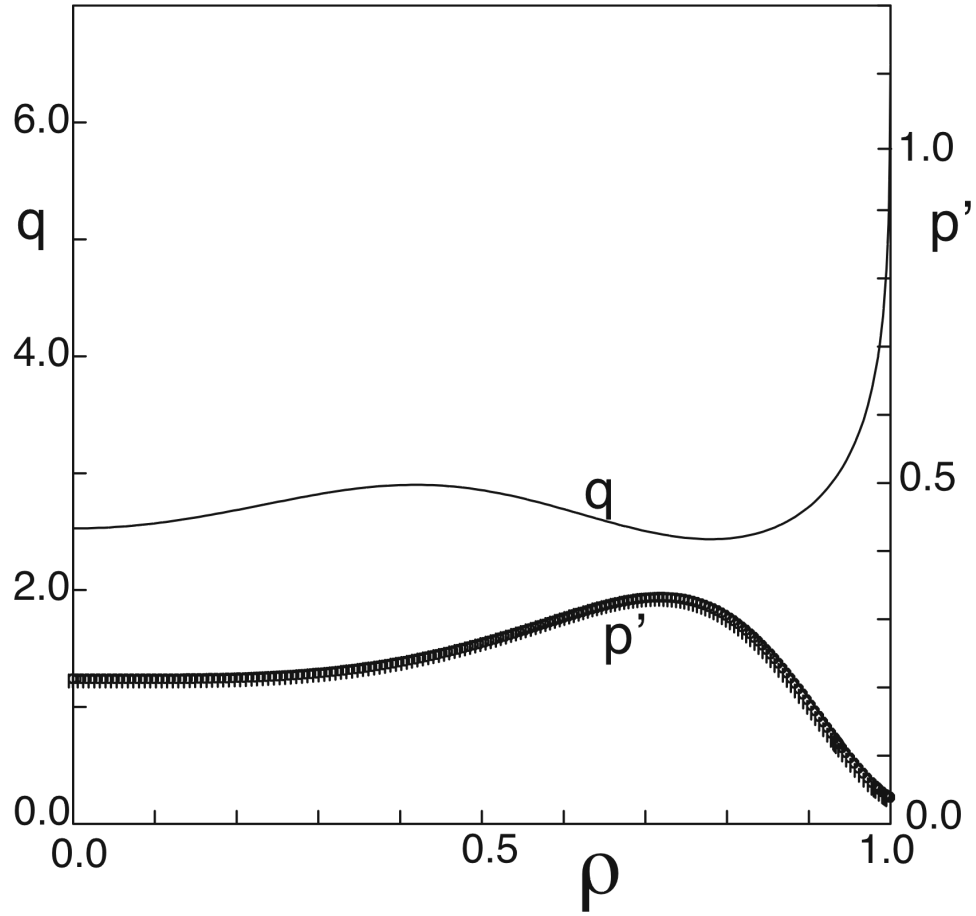


Base Line ARIES H-mode Case From 2006 Study

- **ARIES H-mode cross section:**



- **q profile:**



Detailed Configuration (JSOLVER equilibrium) Matches Systems Configuration Reasonably Well

	Systems	Detailed	ARIES-AT
R, m	5.5	5.5	5.2
I_P, MA	10.6	10.0	12.8
β_N	4.5	4.83	5.45
B_T, T	5.5	5.5	5.86
n/n_{Gr}	0.95	0.87	1.0
$n(0)/\langle n\rangle_v$	1.3	1.37	1.35
T(0), keV	26.8	26.4	31.2
$\langle T\rangle_v$, keV	16.6	15.9	15.9
I_{BS}, MA	9.54	8.35	11.65
I_{CD}, MA (on,off-axis)	1.06	1.3 (0.38, 0.95)	1.28

Preliminary Ideal MHD stability of high-n ballooning and external kink modes

Ballooning unstable on 4 out of 200 surfaces, all outside pedestal location

- **Weak instabilities, high critical-n number, should use EPED stability analysis for this region**

External kink modes (using conformal wall, unstable with no conducting wall)

Mode number	b/a to stabilize (real distance from plasma surface)
n = 1	0.46 (0.633 m)
n = 2	0.45 (0.619 m)
n = 3	0.425 (0.584 m)

Future Work will Invoke Multimode Transport Model

- **TGLF is more sophisticated than GLF23 but is much slower**
- **Multimode code claims to have the sophistication of TGLF:**
  - Density factor has a small range for steady state solutions:
  - But is claimed to be ten times faster