PHYSICS OPTIMIZATION OF THE ARIES-RS FUSION POWER PLANT

by
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with
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Physics Optimization of the ARIES-RS Fusion Power Plant[1] V.S. CHAN, M.S. CHU, C.M. GREENFIELD, R.J. LA HAYE, L.L. LAO, Y.R. LIN-LIU, M.A. MAHDAVI, C.C. PETTY, P.A. POLITZER, R. PRATER, H.E. ST. JOHN, G.M. STAEBLER, E.D. STAMBAUGH, A.D. TURNBULL, W.P. WEST, General Atomics, J.E. KINSEY, Lehigh University, T.K. MAU, University of California, San Diego — The 1996 ARIES-RS physics design is being revisited with the goal of further optimization in the following areas: (1) A fully-aligned bootstrap current at the plasma edge to eliminate the need for edge non-inductive current drive, (2) Refinement of the beta-limit calculation to include intermediate n ideal modes, resistive wall and non-ideal effects, (3) Use of physics-based transport model for internal transport barrier (ITB) formation, (4) Comparison of current drive and rotational flow drive using fast wave, electron cyclotron waves and negative ion beam, and (5) Further improvements in heat and particle control. Integrated modeling of the optimized scenario will be performed to study the robustness of the bootstrap alignment, ITB sustainment, and stable ramp-up path to high beta and high bootstrap fraction current operation.

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ABSTRACT

The 1996 ARIES-RS physics design is being revisited with the goal of further optimization in the following areas: (1) A fully-aligned bootstrap current at the plasma edge to eliminate the need for edge non-inductive current drive, (2) Refinement of the beta-limit calculation to include intermediate n ideal modes, resistive wall and non-ideal effects, (3) Use of physics-based transport model for internal transport barrier (ITB) formation, (4) Comparison of current drive and rotational flow drive using fast wave, electron cyclotron waves and negative ion beam, and (5) Further improvements in heat and particle control. Integrated modeling of the optimized scenario will be performed to study the robustness of the bootstrap alignment, ITB sustainment, and stable ramp-up path to high beta and high bootstrap fraction current operation

INTRODUCTION

- Significant progress in physics understanding of the reversed shear advanced tokamak regime has been made since the last ARIES-RS study completed in 1996

- New study focused on
  - Improve β-limit stability calculations to include important non-ideal effects such as resistive wall modes and neo-classical tearing modes
  - Use of physics based transport model for internal transport barrier (ITB) formation and sustainment
  - Comparison of current drive and rotational flow drive using fast wave, electron cyclotron waves and negative ion beam
  - Improved heat and particle controls
  - Integrated modeling of the optimized scenario with self-consistent current and transport profiles to study the robustness of the bootstrap alignment, ITB sustainment, and stable path to high β and high bootstrap fraction operation

SUMMARY OF KEY RESULTS

- **Stability optimization**
  - Ideal low n modes are stabilized by a conducting wall ~ 1.2 a
  - β limited by high n ideal ballooning modes near the plasma outer region
  - Rotational drive and radially localized off-axis current drive are essential for stabilization against resistive wall modes and neo-classical tearing modes
- **Transport and current drive modeling**
  - The first 13.2 MA, $\beta_N = 5.6$ design produces too much alpha heating
  - Physics-based modeling with ITB indicates a smaller device should be considered
- **Divertor heat loading**
  - High radiated fraction of the total exhausted power (> 0.5) is essential to keep the peaked inboard and outboard heat fluxes at a manageable level (< 10 MW/m^2)
  - Essential to accurately maintain the double-null magnetic balance (~ 0.5 cm)

ARIES-RS EQUILIBRIUM AND OPTIMIZATION

First quick optimization completed

- Use previous ARIES-RS 96 design as starting point
- Current profile use Miller/Lin-Liu self-consistent bootstrap current model[1]
  - $P = P_0\left(1 - \psi_n^m\right)^n$
- Fixed and free boundary equilibrium computed using ToQ and EFIT
- Scan plasma shape (elongation, triangularity, squareness, aspect ratio), pressure and current profiles, and evaluate stability using BALOO and GATO

Ongoing work and plan

- Using exact divertor shape as boundary
- H–mode pressure profiles
- Local pressure variation for optimization against ballooning modes

[1]R.L. Miller, Y.R. Lin-Liu, et al., Physics Plasmas 4 (1997) 1062

ARIES-RS STABILITY OPTIMIZATION

- Stability limited by ballooning and moderate n modes
- Low n modes are stabilized by a conducting wall ~ 1.2 a
- Current and pressure profiles are coupled due to high bootstrap fraction
- Higher κ, δ and lower aspect ratio could improve beta
- Moderate squareness improves ballooning stability
- Off-axis CD needed to improve stability against ballooning modes
- Resistive wall modes and neo-classical tearing modes are being studied

FIXED AND FREE BOUNDARY EQUILIBRIA ARE COMPUTED USING TOQ AND EFIT

```
h EFITD 129x2d 02/05/98   h   r099728.00270?55
date ran =   3-Aug-99
shot #   =       99728
t(ms,us) =     270        0
chi2(mag)=   2.729E-26
rout(cm) =      552.05
zout(cm) =       -.206
a(cm)    =      137.95
elong    =       1.814
utri,ltri=     .63      .65
indent   =        .001
V,A(m3,2)=   354.9   10.61
energy(j)=   8.973E+08
betat(%) =        6.65
betap    =        2.51
betan,In =    5.57    1.19
li,y2    =     .46    -.44
error, # =   1.510E-07  59
delstar  =   1.3E-06  1.7E-05
fpols(kA)=          .0
J0n,J1n  =     .39     .00
q1,q95   =    3.91    3.29
dsep(cm) =      -1.559
rm,rc(cm)=   585.7   569.7
zm,zc(cm)=     .05    -.01
betapd,w =    1.16     .00
betatd,w =    3.08     .00
wdia(J)  =   4.158E+08
wtor(J)  =    .000E+00
      data used:
ip(ka)   =     13154.5
bt0(t)   =       7.982
 0 flux loops
 0 magnetic probes
 1 rogow   0 fc    0 ec
scrapof(mm)   20.0
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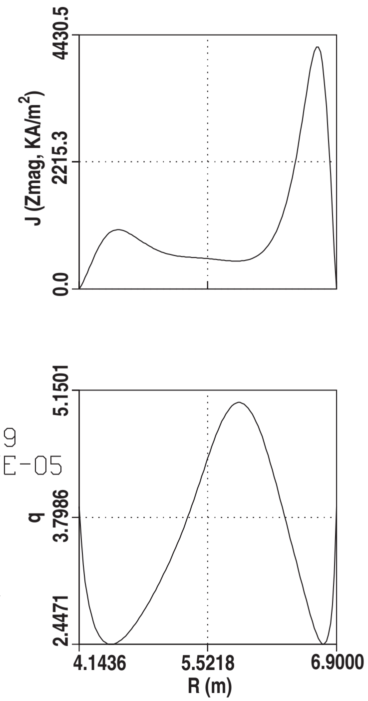


```
icp,  ivs=      0     0
kf, kp, E=     5   5   0
fpd, p, E=    .0   .0   .0
fwbp, fwq=     .0   1.0
Ze(cm)    =        .000
relax     =        .500
kcf,   kcp=      3     5
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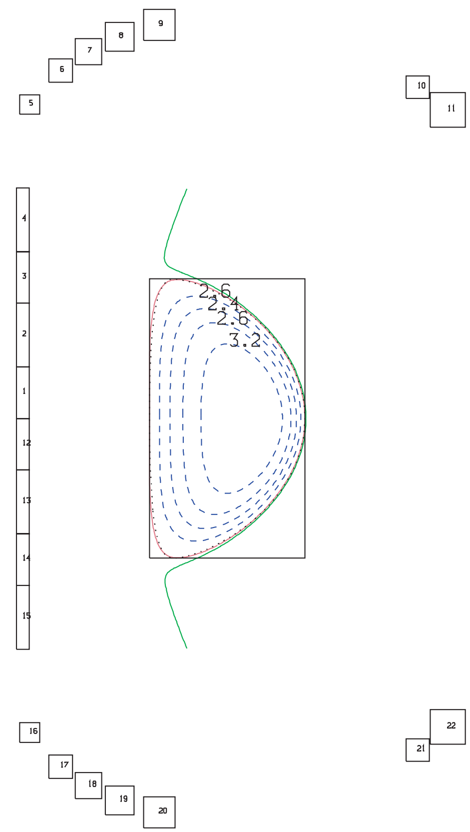
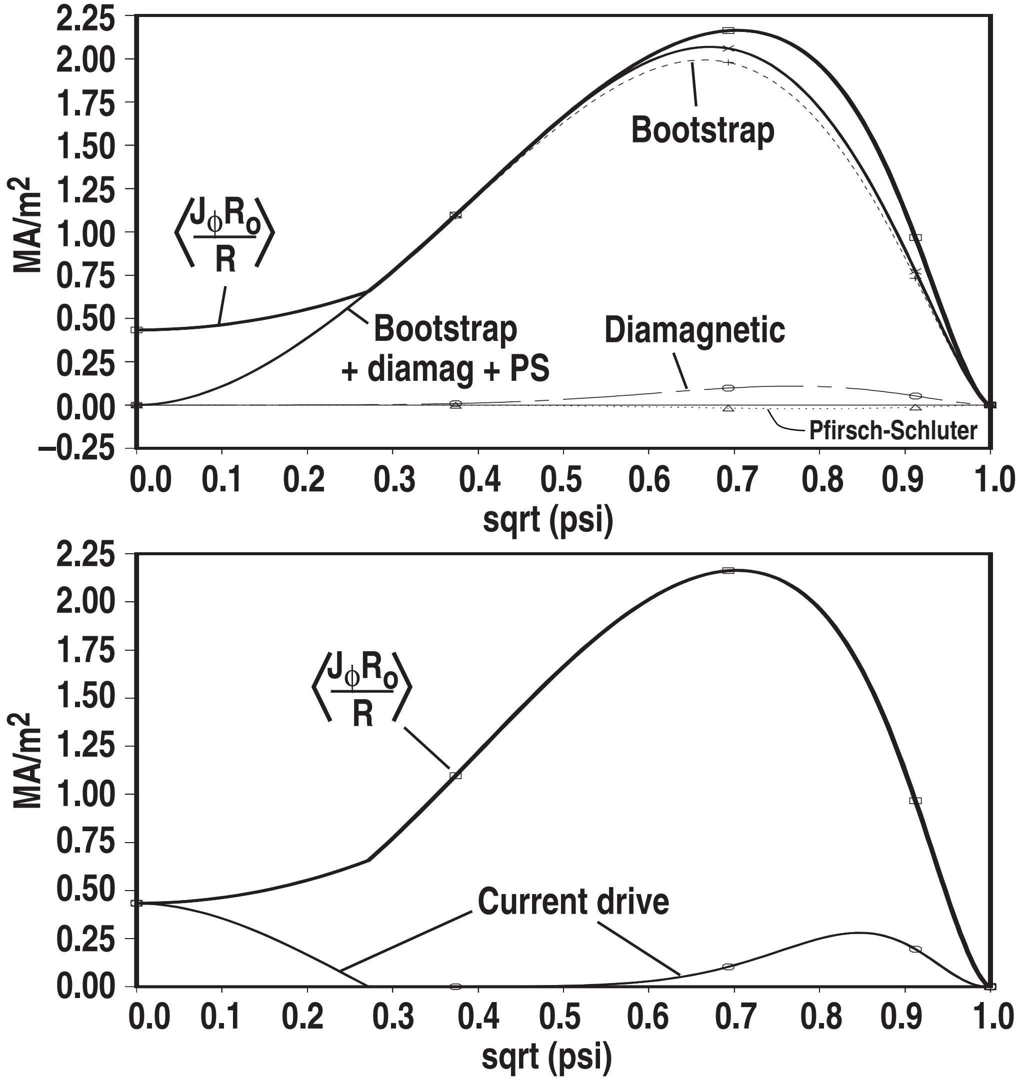


EQUILIBRIA ARE CONSTRAINED TO HAVE A HIGH BOOTSTRAP CURRENT FRACTION

- Computed using Miller/LinLiu self-consistent bootstrap current formulation based on Hirshman collisionless model

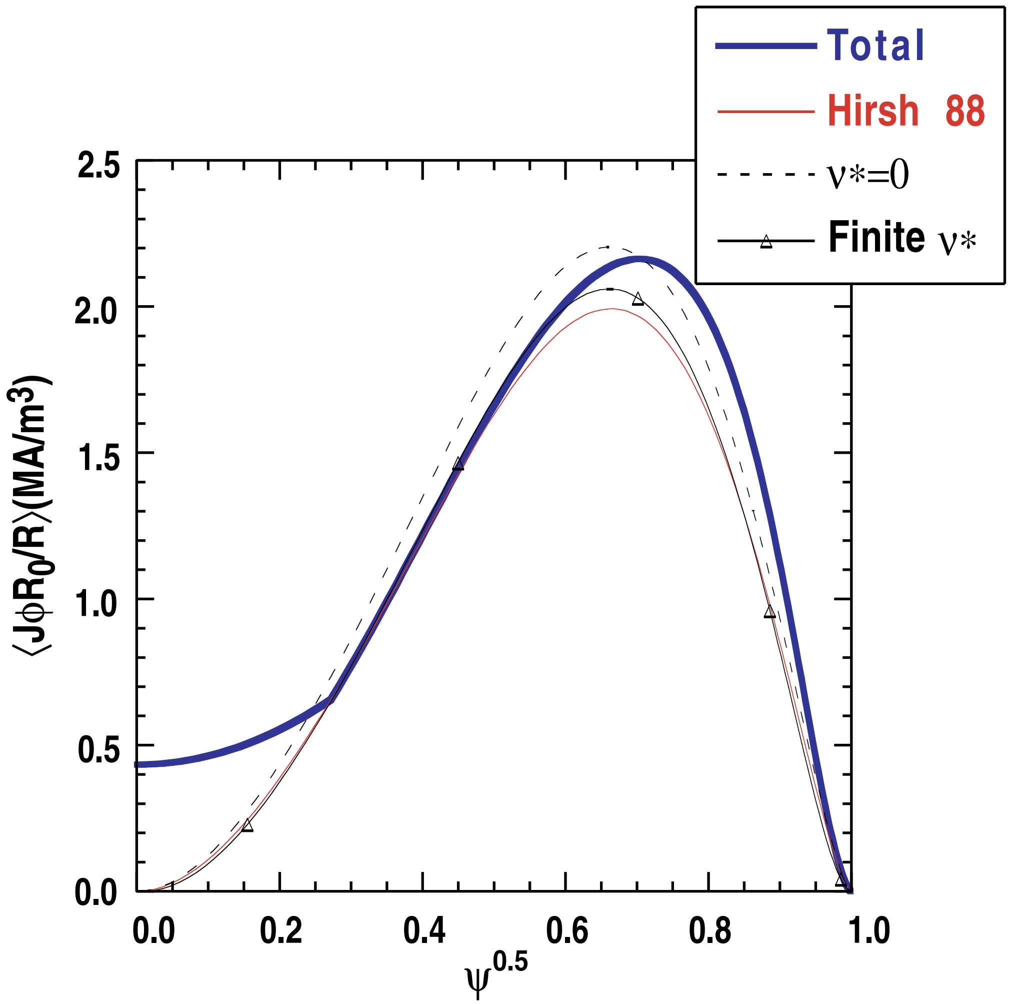
- 92% bootstrap current fraction



KINETIC CORRECTIONS REDUCE THE EFFECTS OF FINITE COLLISIONALITY IN HIRSHMAN'S COLLISIONLESS MODEL

- New analytic formulas for bootstrap current were constructed based on 3-D kinetic calculations for general tokamak geometry and arbitrary collisionality

Sauter et al., Phys. Plasma 4 (1999) 2834



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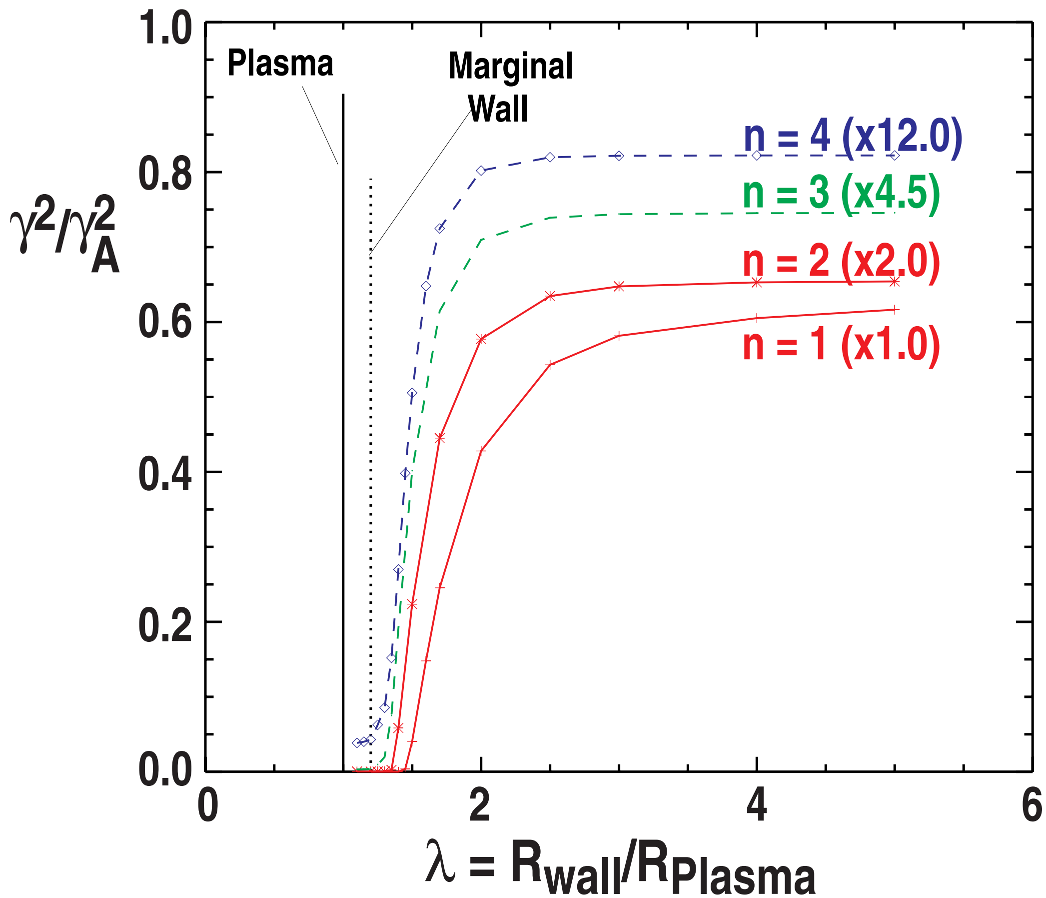
LOW *n* MODES ARE STABILIZED BY A CONDUCTING WALL

- Ideal *n* = 1-4 modes computed using GATO
- *n* = 2-5 modes are stable with a conducting wall at 1.2 a



A= 4.0, β_N = 5.3, q(0) = 2.8

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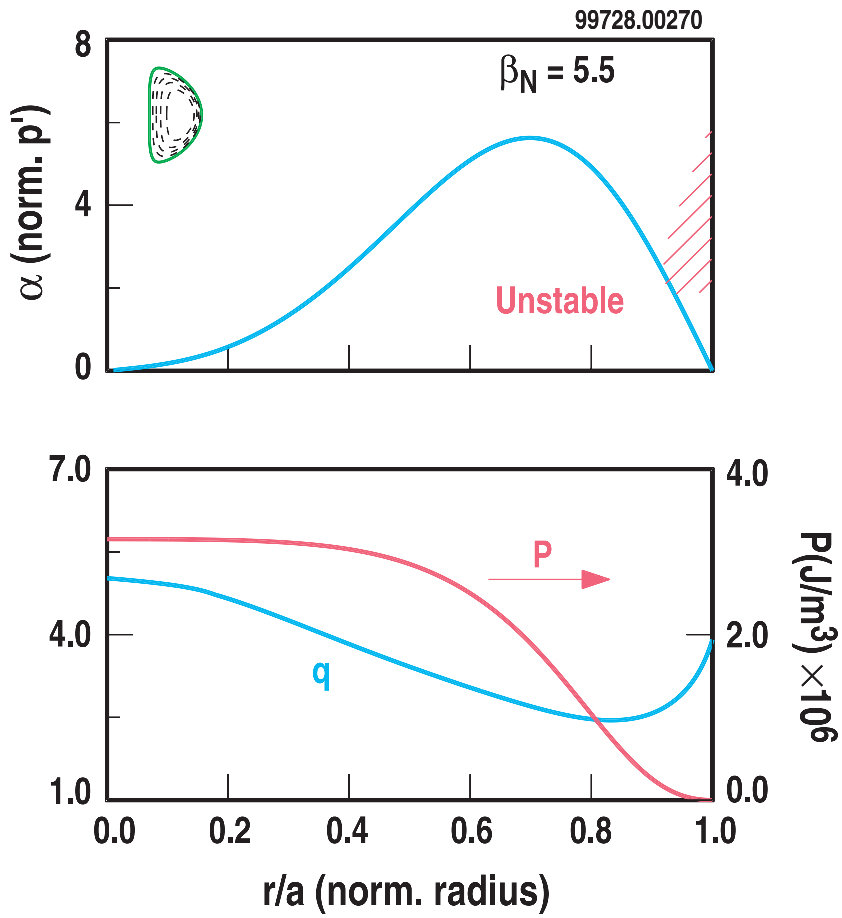
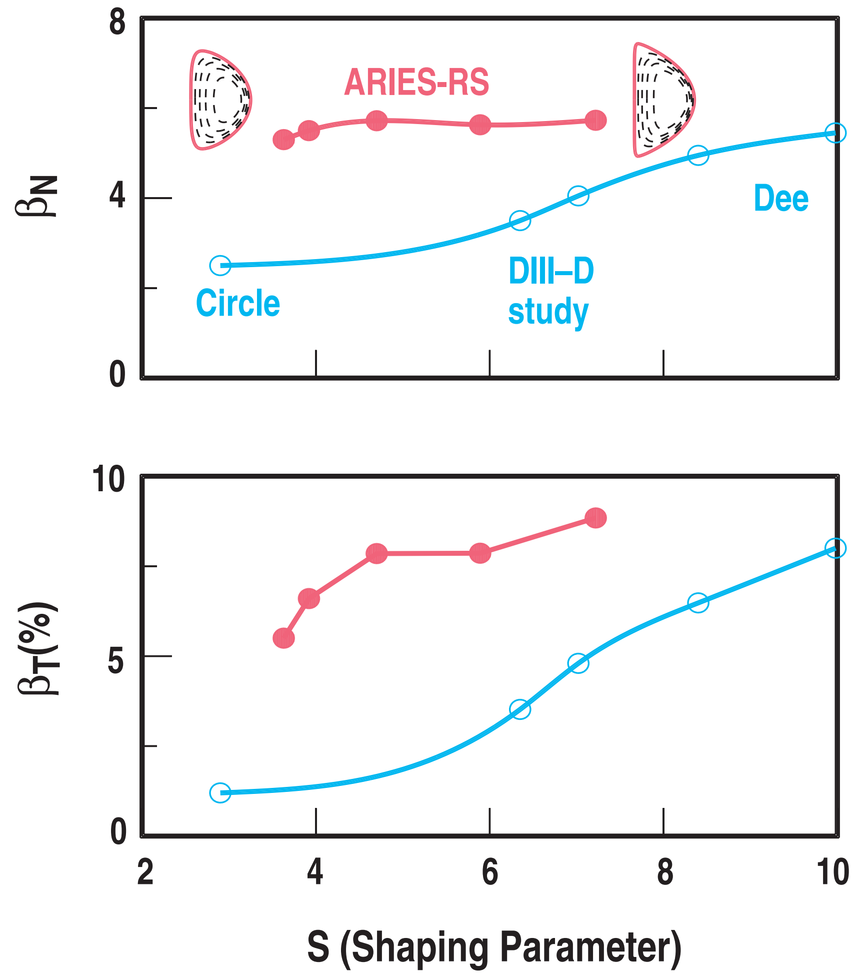
MHD STABILITY IS LIMITED BY BALLOONING MODES IN THE PLASMA OUTER REGION

- Stable to ideal *n* = 0-3 modes with a conducting wall at 1.2a (convergence study in progress)
- Higher elongation and triangurality improve both β_N and β_T
- $\kappa = 1.82$, $\delta = 0.7$, $q_{95} = 3.3$, $q_{min} = 2.4$, $\beta_T = 6.7\%$, 92% bootstrap fraction



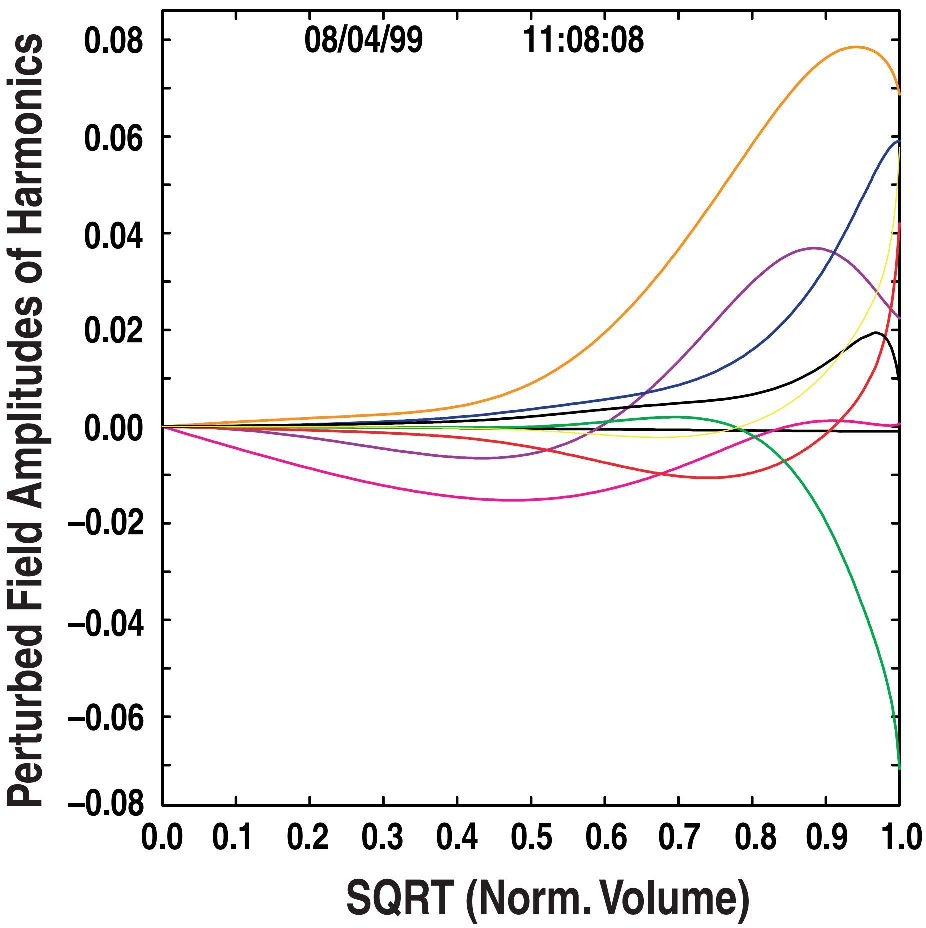
BETA INCREASES WITH SHAPING AND LOWER *A*

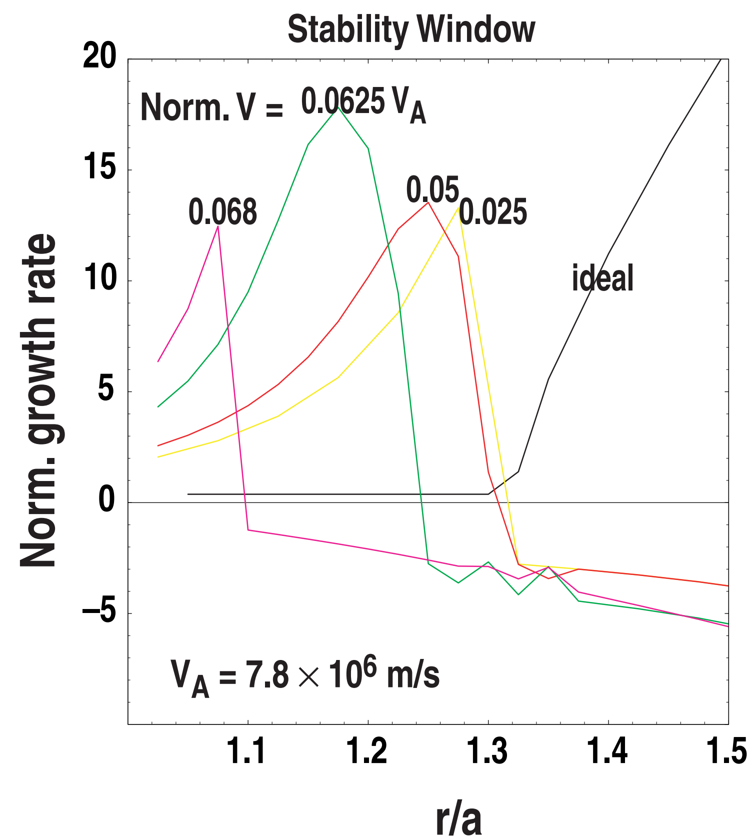
- Shaping parameter $S = I_N q_{95}$
- S increases with κ, δ and inverse aspect ratio
- DIII–D NCS study by Turnbull, et al., Nucl. Fusion 38, 1467 (1998)
- β_N varies weakly with S due to
  - High bootstrap current fraction constraint
  - Not fully optimized pressure profile, stability limited by edge ballooning



ROTATIONAL DRIVE IS ESSENTIAL FOR STABILIZATION AGAINST RESISTIVE WALL MODES

- *n* = 1 stability computed using the MARS code





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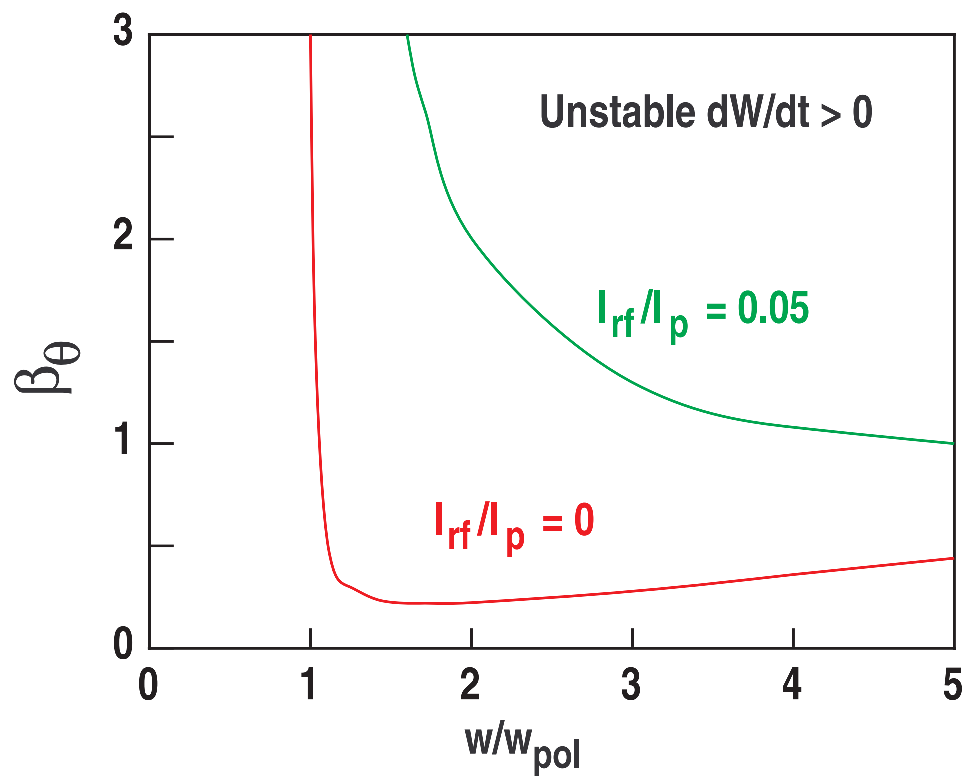
LOCALIZED OFF-AXIS CURRENT DRIVE IS ESSENTIAL FOR STABILIZATION AGAINST NEO-CLASSICAL TEARING MODES

$$\frac{\tau_R}{r^2}\frac{dw}{dt} = \Delta' + \varepsilon^{1/2}\left(L_q/L_p\right)\beta_\theta\left(\frac{1}{w} - \frac{w_{pol}^2}{w^3}\right) - \frac{8\,q^2 L_q r}{\pi^2 w^2}\left(\frac{I_{rf}}{I_p}\right)$$

$$\beta_{\theta,\,crit} \approx A_o\left(\frac{w_{pol}}{r}\right)\left[\frac{w_{seed}/w_{pol}}{1-(w_{pol}/w_{seed})^2}\right] + B_o\left(\frac{w_{pol}}{r}\right)\frac{I_{rf}}{I_p}\left[\frac{w_{seed}}{w_{pol}} - \frac{w_{pol}}{w_{seed}}\right]$$



$m/n = 5/2$

$q_0 = 2.76$, $q_{min} = 2.09$

$\Delta' r = -9.86$ ("TEAR")

$\varepsilon^{1/2} = 0.47$

$L_q/L_p = 5.0$

$w_{pol}/r = 0.02$

$\beta_\theta = 2.65$

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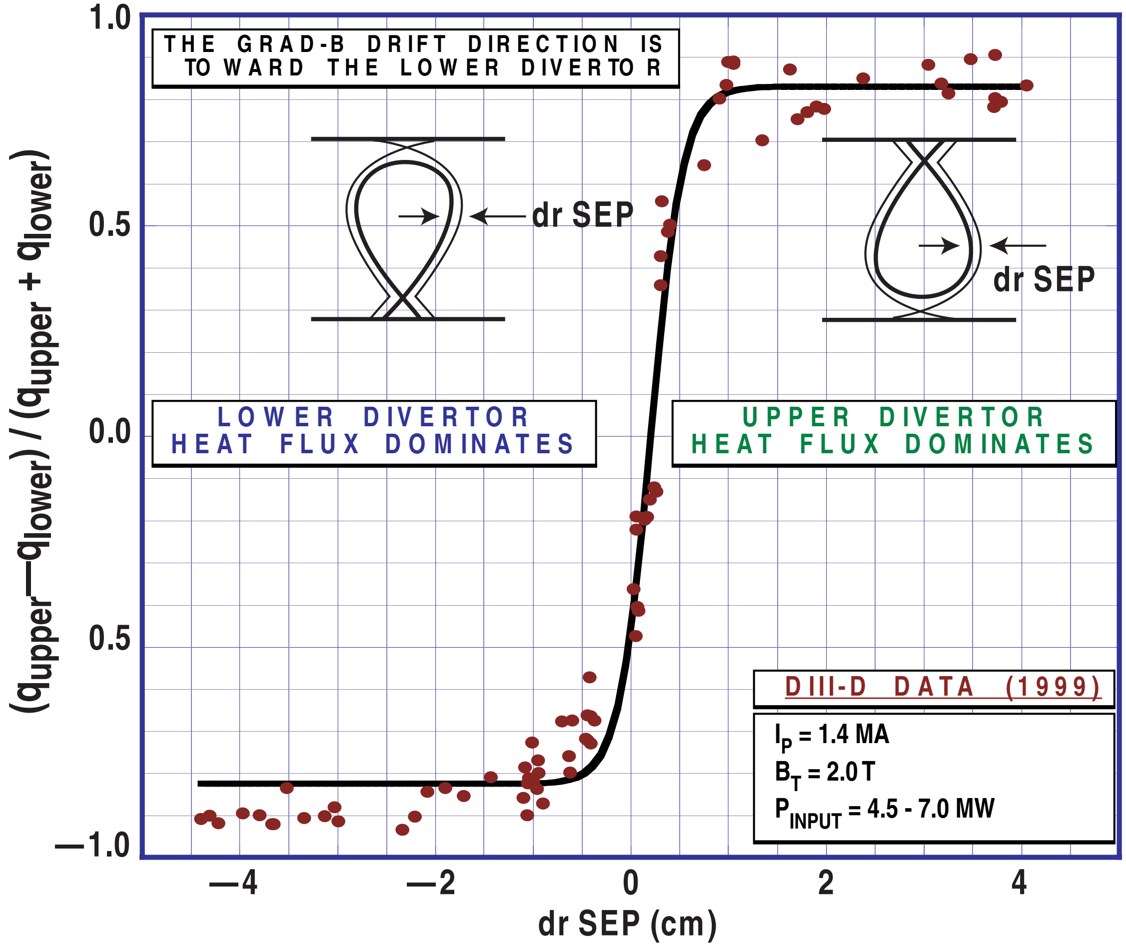
HIGH RADIATED FRACTION OF EXHAUSTED POWER IS ESSENTIAL TO KEEP PEAKED HEAT FLUXES AT MANAGEABLE LEVEL

	INBOARD LEG	OUTBOARD LEG
Power (MW)	513	513
λ_p (cm)	1.0	1.0
f_{exp}	5	5
Fraction of SOL Power Flow	0.2	0.8
α (degree)	10	10

- 18% radiated power
  - Inboard leg $Q_{DIV} = 5.2\ MW/m^2$
  - Outboard leg $Q_{DIV} = 16.7\ MW/m^2$
- 50% radiated power
  - Inboard leg $Q_{DIV} = 3.3\ MW/m^2$
  - Outboard leg $Q_{DIV} = 10.6\ MW/m^2$

ACCURATELY MAINTAINING THE DOUBLE-NULL MAGNETIC BALANCE IS ESSENTIAL FOR HEAT FLUX

- 50% radiated power and DRSEP= –0.5 cm, Q_{DIV} = 16.7 MW/m^2 in the dominant divertor



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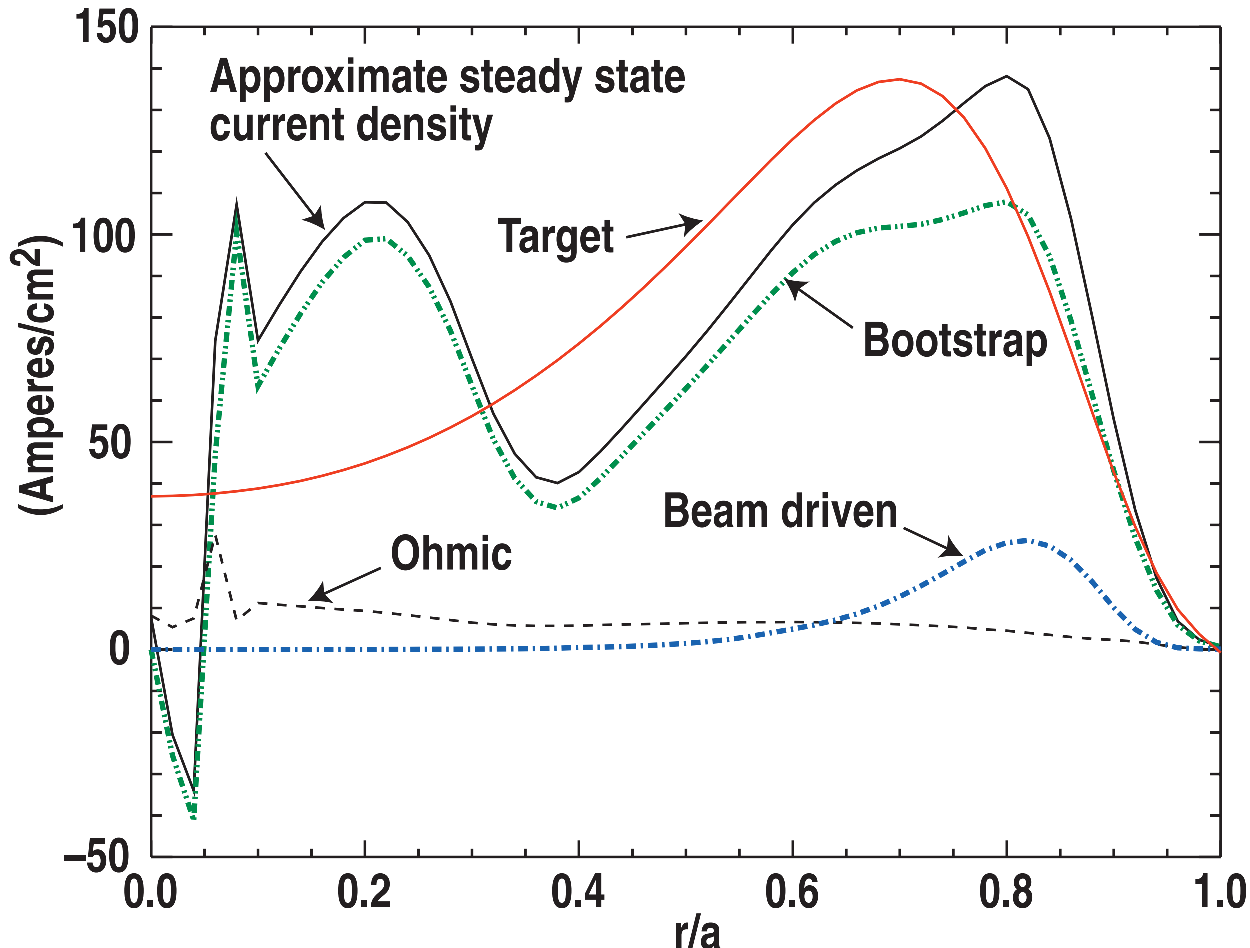
FUTURE PLAN

- Stability optimization
  - Using exact divertor shape as boundary
  - H–mode pressure and current profiles
  - Reduced size
- Transport
  - Further improve bootstrap alignment in the core consistent with ITB
  - Model high confinement scenario for smaller radius device
- Current and rotational drives
  - Optimize heating systems for current and rotational profile control

NEUTRAL BEAM/FAST WAVE CURRENT DRIVE FOR ITB CASE

- 50 MW, 250 keV neutral beam can be used to further shape the current profile
- A fast wave seed current near the magnetic axis will be required (not investigated at this time)



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ARIES-RS TRANSPORT MODELING

- Transport modeling of the ARIES-RS plasma uses a multi-code strategy

1. A bootstrap aligned MHD equilibrium is found using TOQ
2. The ONETWO transport code is run in analysis mode to compute the fusion power for the equilibrium density and temperature profiles
3. The GLF23 transport model is used (in a separate transport code) to find the steady state temperature profiles holding the density and sources fixed. The fusion power is reduced if needed to keep the pressure near the target beta
4. The GLF23 temperature profiles are transferred to ONETWO and the fusion power is recomputed. The deuterium/tritium ratio is adjusted in order to match the fusion power reduction required to match beta
5. Iteration between 3 and 4 proceeds until convergence is achieved

COMMENTS ON THE GLF23 TRANSPORT MODEL

- The GLF23 transport model uses the linear instabilities of the gyro-Landau fluid equations. These equations approximate the full gyro-kinetic theory. The transport fluxes are computed from quasilinear theory with a mixing length model for the saturated fluctuation level. The fitting parameters of the model are all fit to kinetic linear theory and to non-linear simulations of ITG-TEM turbulence. No fitting to experiment has been done. Ten wavenumbers are used for the ITG-TEM modes and ten for the ETG modes at high wavenumbers

- The GLF23 model reproduces the L–mode and H–mode profiles from the ITER database to within about 20%. This primarily tests the ITG-TEM transport

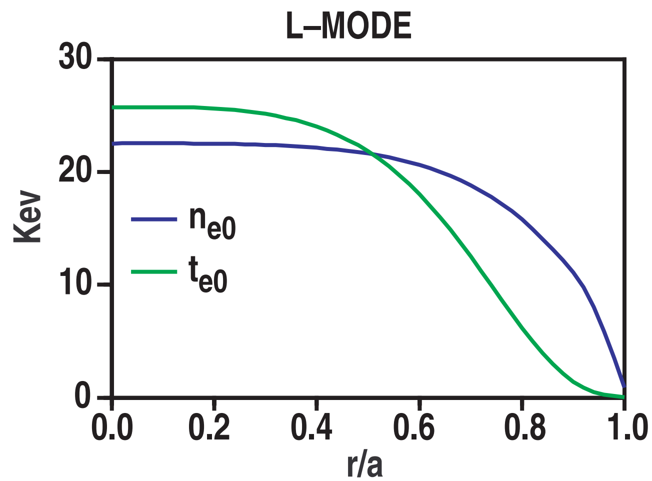
- The GLF23 model has not been compare to a large database of internal barrier discharges so the ETG mode, which determines the electron transport within the ITB, has not been extensively tested. It has been shown to be reasonable for a limited number of DIII–D discharges. The threshold level of E×B velocity shear needed to quench the ITG-TEM modes is taken from theory but has not been extensively tested in the GLF23 model

SUMMARY OF TRANSPORT RESULTS

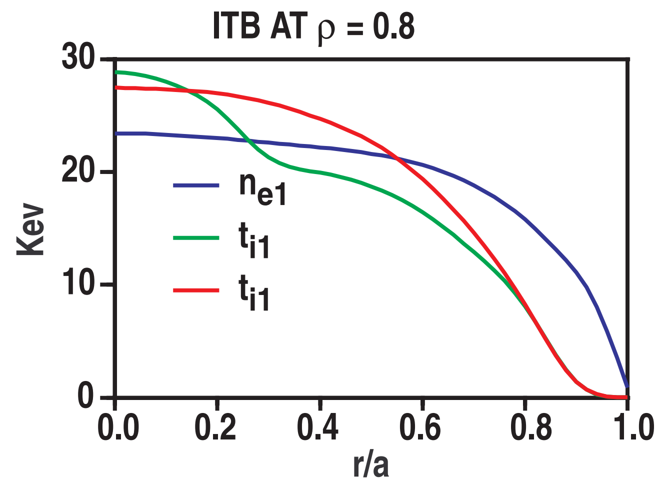
		13.2 MA Original	13.2 MA n_{eGw}	8.27 MA L	8.27 MA ITB
I_p	MA	13.15	13.15	8.27	8.27
I_{boot}	MA	10.00	8.07	6.70	7.94
I_{NBI}	MA	0.59	1.87	1.42	1.47
I_{ohm}	MA	2.55	3.2	0.147	-1.15
I_{boot}/I_p	%	76	61	81	96
n_e $10^{20}/m^3$		5.03	1.95	1.94	1.96
n_e/n_{eGw}		2.29	0.89	1.40	1.41
P_a	MW	1,713	724	434	176
τ_e	s	0.51	1.36	1.10	1.98
H_{89p}		1.54	3.0	2.84	4.11
β_N		5.54	6.49	5.36	4.87
β_p		2.51	2.93	3.75	3.40
β_T	%	6.65	7.78	4.03	3.66
Nd/Nt	%	50	50	50	90

Common parameters: B_T = 7.98 T, R = 5.52 m, a = 1.38 m, PNBI = 50 MW

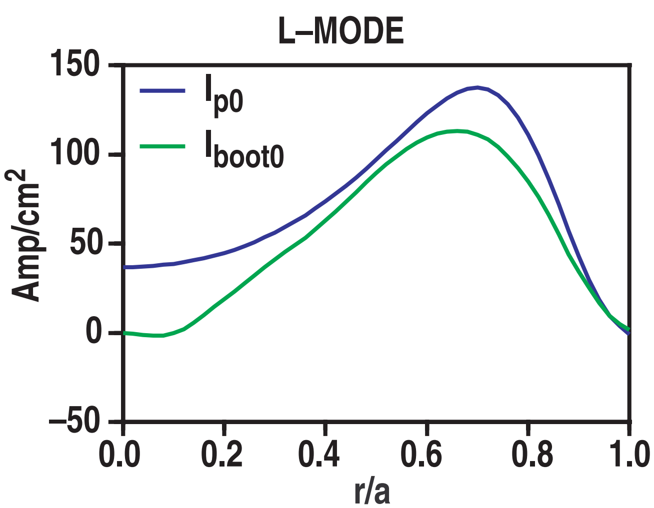
L–MODE AND ITB TEMPERATURE PROFILES



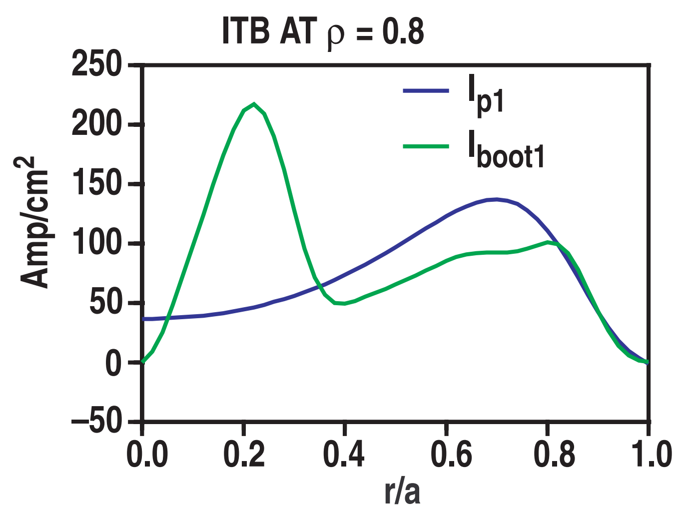
$T_i = T_e$ for the L–mode case



Transport is from GLF23 for ITB case



I_{boot} / I_p = 81% for L–mode



I_{boot} / I_p = 96% for ITB

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COMMENTS ON THE GLF23 TRANSPORT MODEL

- The large Shafranov shift and negative magnetic shear in the center of the plasma is stabilizing the ETG mode. This causes the electron temperature profile to steepen. This results in poor bootstrap alignment

- In NCS experiments with ITB's on DIII–D, the electron temperature profile is observed to be strongly flattened near the axis. The electron temperature gradient only follows the ETG mode threshold near the leading edge of the transport barrier. The cause of this flattening is not understood

- The GLF23 model predicts the energy confinement of the ITB case to be twice as good as the L–mode case. The high q in the core deteriorates the ion neoclassical energy confinement. Higher confinement should be possible at lower *q* and with a flatter *q* profile

- The deuterium/tritium ratio is unacceptably high (90%)

- The line average density is still above the Greenwald limit (n_e/n_{eGW} = 1.41)

WHERE DO WE GO FROM HERE?

- The bootstrap alignment of the TOQ equilibrium is near optimum and cannot be expected to be much improved by the self-consistent transport modeling
- It is highly desirable to find a starting equilibrium with:
  - $I_{boot}/I_p > 80\%$
  - H_{89p}~2 consistent with ONETWO calculation of the fusion power
  - n_e ~ Greenwald density
- The Greewald density limit is $I/\pi a^2$
- The TOQ equilibrium uses $T = p^{\sigma}$, $n = p^{(1-\sigma)}$, $\sigma = 0.8$ for the present L–mode case
- The bootstrap current goes up with n/T for a given pressure profile
  - $n/T \sim n^2/\beta B^2 \sim f_{GW}^2 (I/aB)^2/\beta a^2$
- Thus, at fixed β and *q* ~ I/aB it is necessary to reduce the size a to get to higher n/T

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