# REACTOR PROSPECTS

# of the

# BELT PINCH


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## INTRODUCTION

It is well known that high elongation enables high I/aB

Inductive belt pinch experiments indicate:

high I/a B => high $\beta$ is possible

Theoretical results of Turnbull et. al. :

high ballooning limit for high elongation cases ($\kappa \sim 6$) with indentation
( “ellipsoidal shell” tokamak )

*However:*

For a *reactor*, cannot simply specify a high current: current is essentially whatever the bootstrap effect provides

**Here we examine high bootstrap fraction (>99%) belt pinches**

Use equilibrium code TOQ developed by General Atomic MHD group for high bootstrap ST s (B. Miller, A. Turnbull, Lin Liu et.al. )

Pick a somewhat broad pressure profile $p(\psi)$ and vary $\kappa$ and A

We examine : Ballooning stability

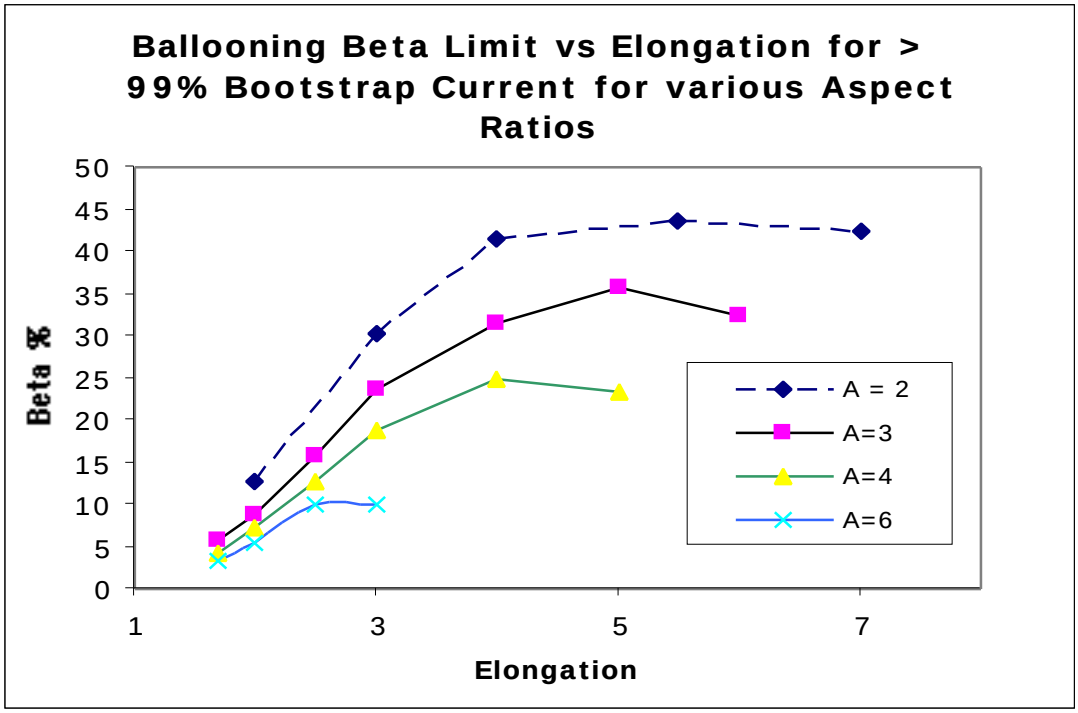
Reactor power density

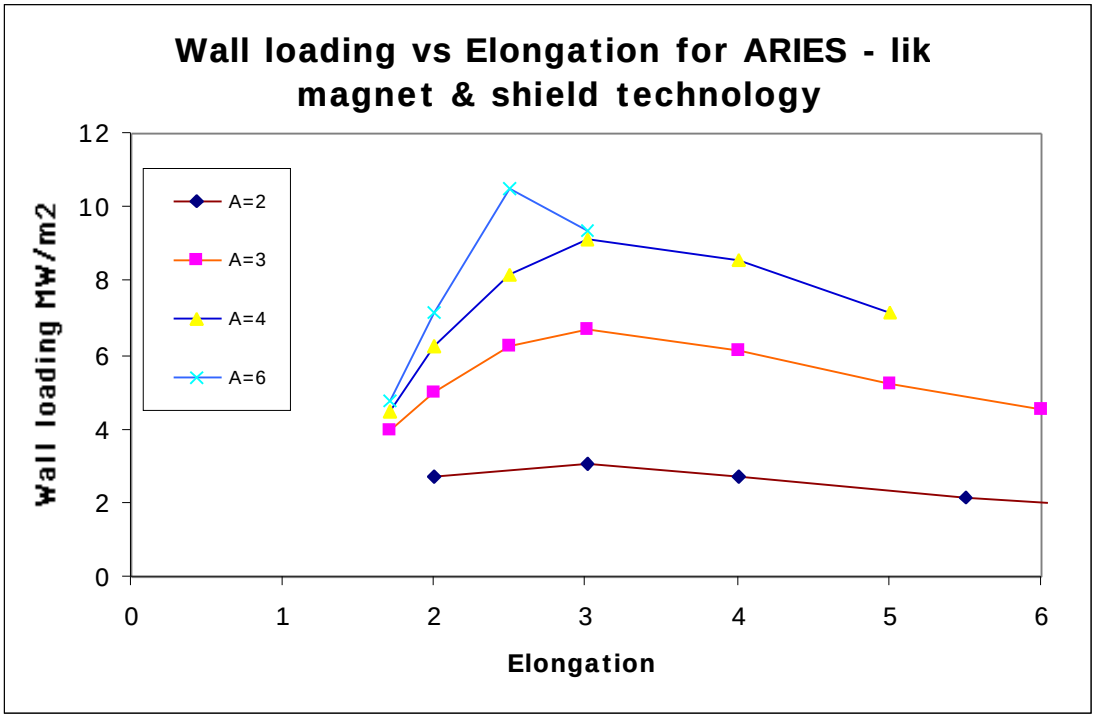
Vertical stability (resistive wall)

Kink stability (hand waving)

Bootstrap driven Islands

Microinstability / E x B turbulence suppression


Ballooning Beta Limit vs Elongation for > 99% Bootstrap Current for various Aspect Ratios
Beta %
50
45
40
35
30
25
20
15
10
5
0
1
3
5
7
Elongation
A = 2
A=3
A=4
A=6


Wall loading vs Elongation for ARIES - lik magnet & shield technology
Wall loading MW/m2
12
10
8
6
4
2
0
0
1
2
3
4
5
6
Elongation
A=2
A=3
A=4
A=6

# REACTOR POWER DENSITY
# (WALL LOADING)

Wall loading is a reasonably good measure of cost, if the wall technology can handle the flux

(cost ~ surface area ~ 1/ wall loading)

The Advanced Power Extraction group is examining various technologies to handle high fluxes

To evaluate how high the wall loading could be in a belt pinch, , we use an ARIES RS like model:

- Inboard blanket + shield => 130 cm between the inner plasma and the superconducting coil
- 15 T at the superconducting coil
- beta = 80% MHD limit (ballooning here)

# Kink Stability (?)

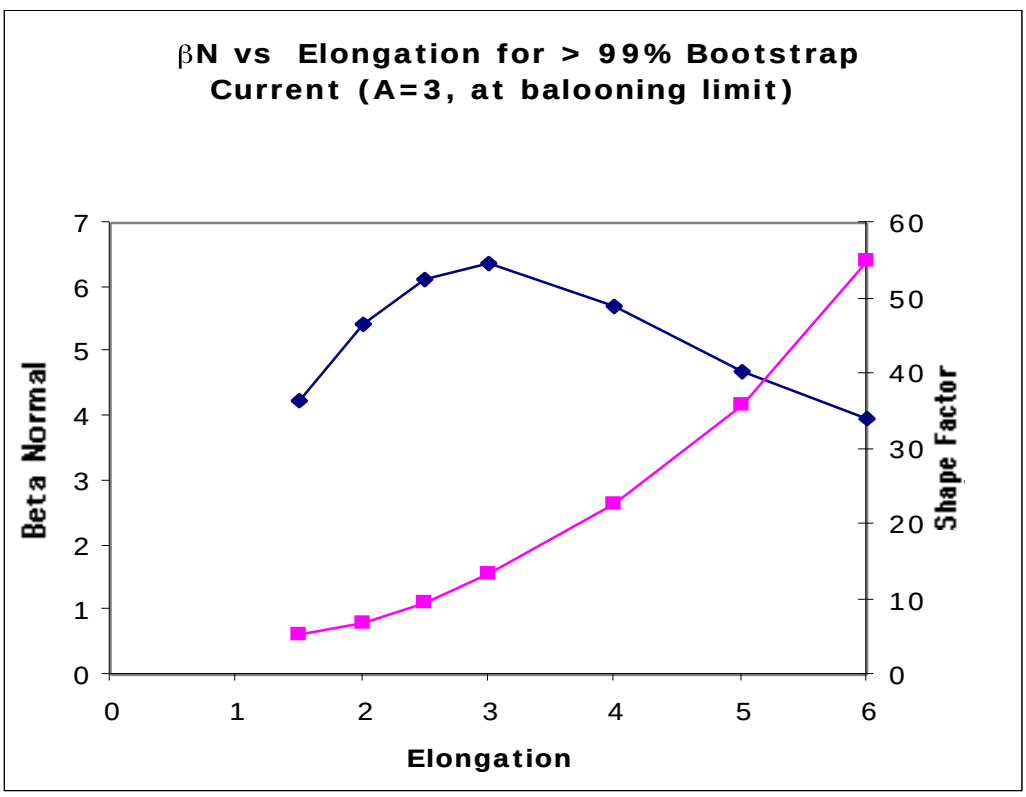
Turnbull finds that the $\beta_N$ kink stability criterion with a wall is strongly modified by the shape, and this can roughly be maesured by the "shape factor" S= (I/aB) $q_{edge}$

He examined elongations up to 2 with shape factors up to about 10, and found the (n=1) kink stable $\beta_N$ for S=10 to be ~ 5.3 for a wall distance b/a=1.5

In addition, decreasing b/a to 1.25 could double $\beta_N$

Higher elongation slightly increases $\beta_N$ but can very strongly increase S

Thus, it appears reasonable to expect kink stability with a wall



# Pessimistic Beta Limit Case

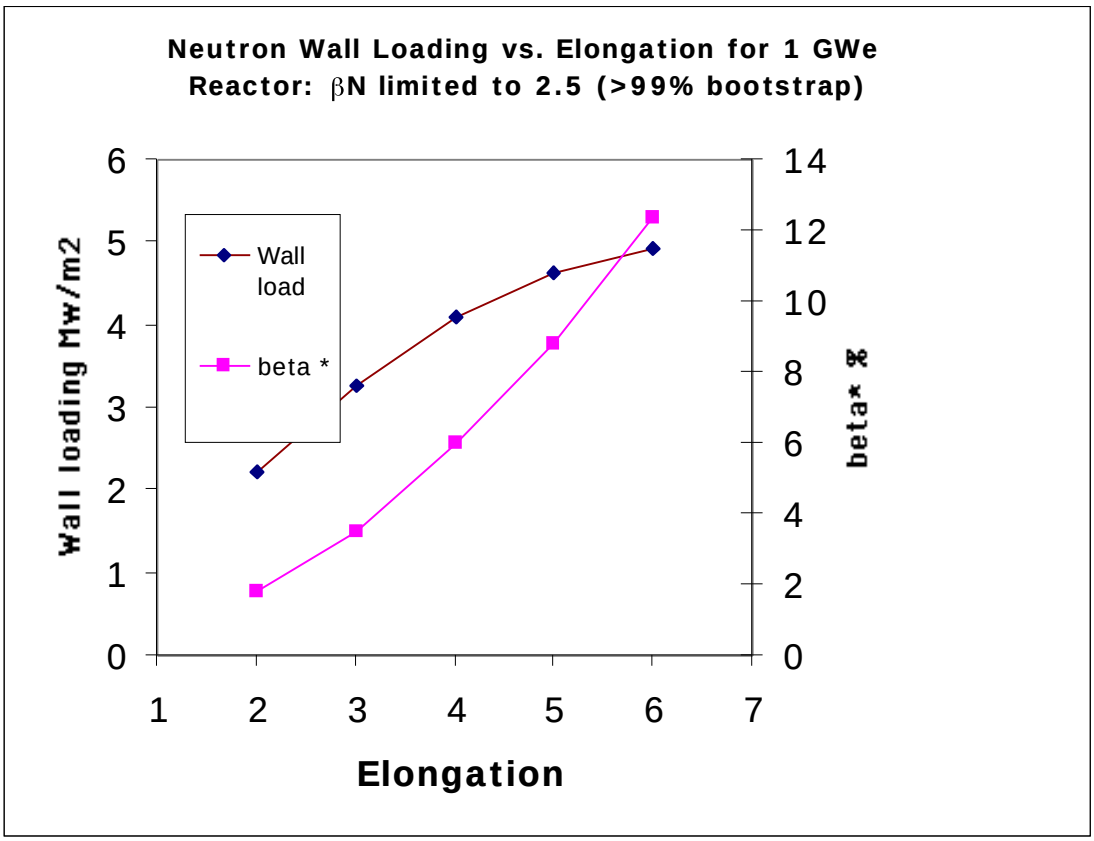
*Suppose* $\beta_N$ is limited to 2.5

(due to resistive wall kink modes, bootstrap Islands, etc.)

For a $\kappa$ ~ 1.7-2 reactor this is a "disaster" : for 99% bootstrap, $\beta$ ~ 2% & wall load drops by a factor of 2

But $\beta_N$ = 2.5 for a high k belt pinch is about the same as $\beta_N$ = 4.2 for ARIES with elongation ~ 1.7-2

Thus high elongation is "insurance" against a low $\beta_N$ limit



# Vertical Stability

Have developed n = 0 linear resistive wall stability code based on perturbed Grad Shafranov equation:

$$\Delta^* \psi = A(\psi) + p(\psi) R^2$$

$$\Delta^* \delta\psi = A'(\psi)\, \delta\psi + \delta\psi\, p'(\psi) R^2 + \delta A + \delta p\, R^2$$

Vacuum boundary conditions, includes arbitrary inductively responding axisymmetric loops outside the plasma

Many closely spaced loops (with appropriate conductivity) approximate a solid wall

Selected wires can be driven with an additional external voltage determined from sensor loops (feedback)

Code for arbitrary A, p is almost complete

For now, use flat current profile (Solvev equilibrium)

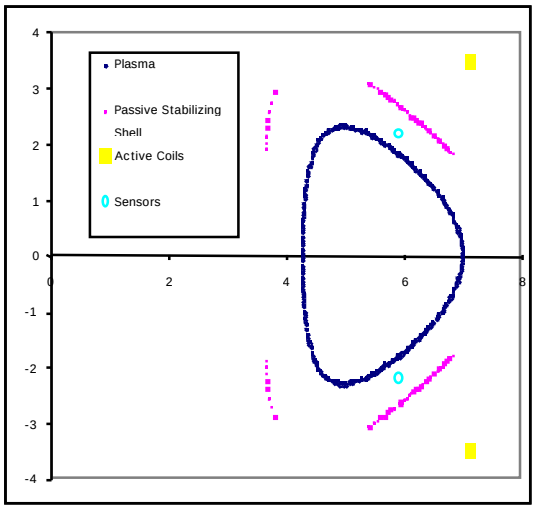
This is *pessimistic* compared to a high bootstrap fraction case :

It is well described in the literature that n=0 instability is reduced by reducing $l_i$ the internal inductance (current peakedness)

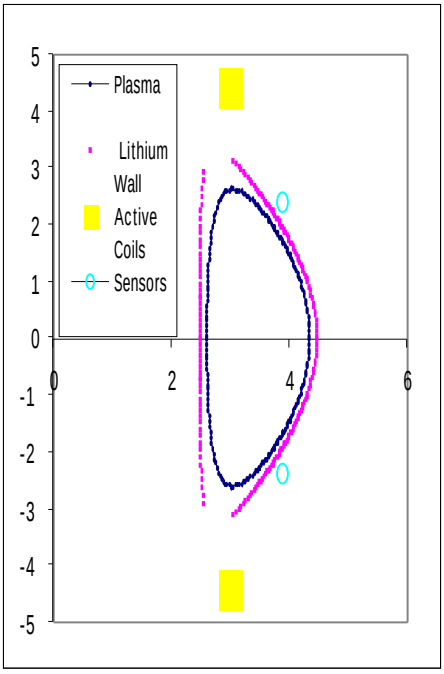
Flat current profile has *higher* $l_i$ than high bootstrap cases by roughly a factor of 1.6, so *the flat current results are pessimistic*

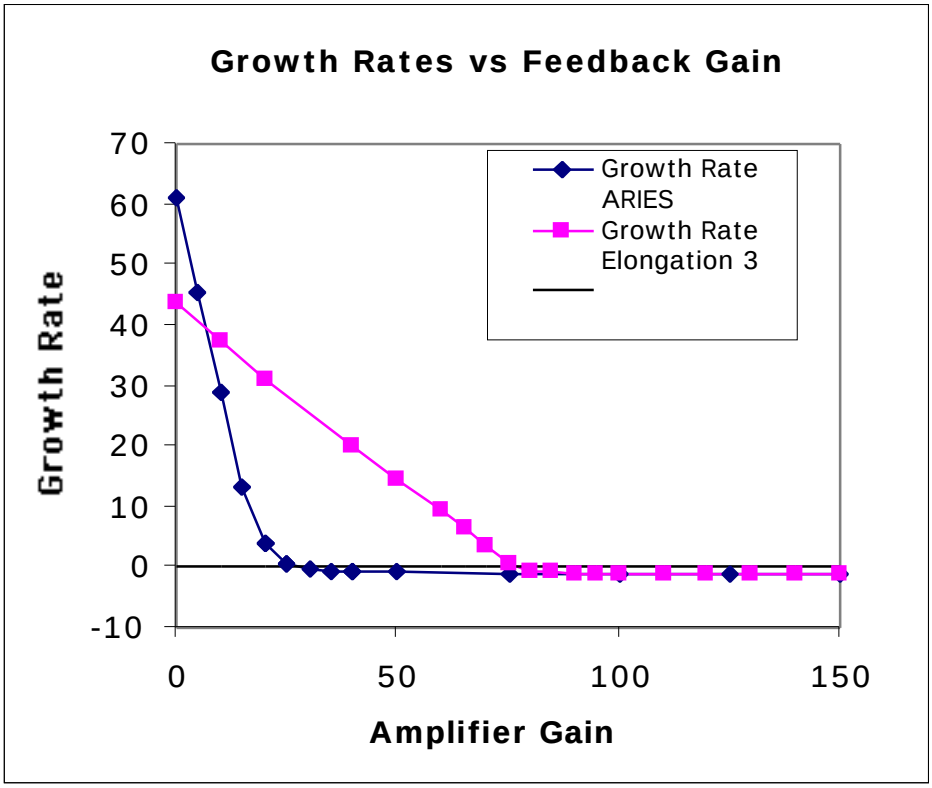
# Poloidal Cross Sections

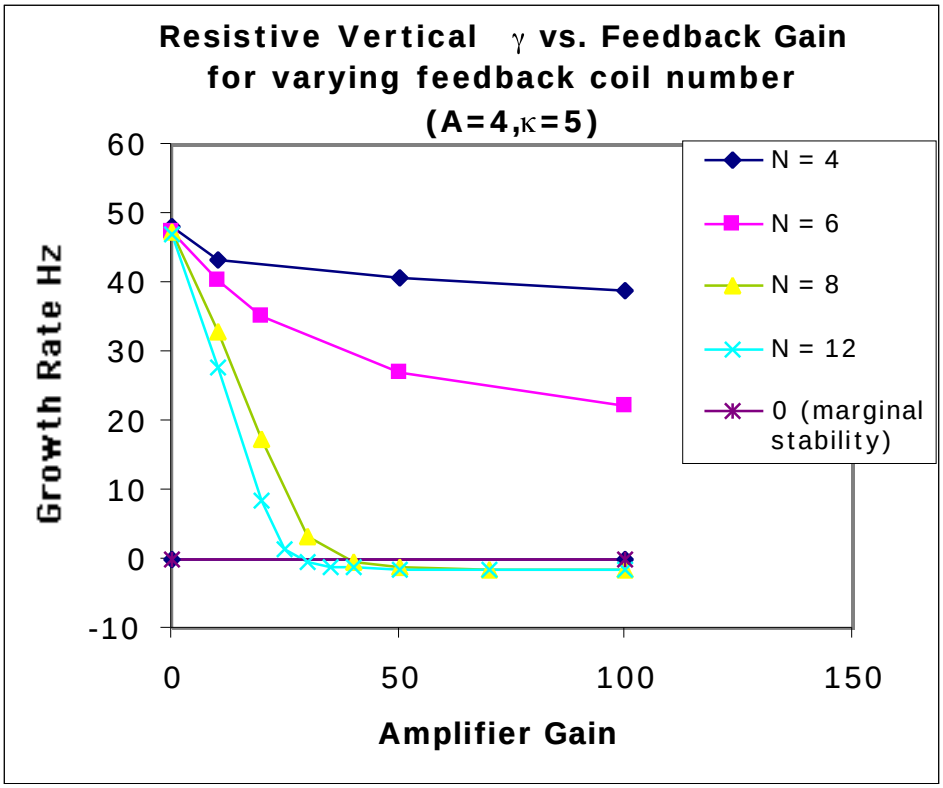
ARIES RS has a 5 cm Tungsten Conducting shell (1100 degree C) 40-60 cm away from the plasma:




Elongation 3 Li case: Li 10 cm from plasma edge, 2 cm thick (400 degree C)




Growth Rates vs Feedback Gain
Growth Rate
Amplifier Gain
70
60
50
40
30
20
10
0
-10
0
50
100
150
Growth Rate ARIES
Growth Rate Elongation 3


Resistive Vertical γ vs. Feedback Gain
for varying feedback coil number
(A=4,κ=5)
Growth Rate Hz
Amplifier Gain
60
50
40
30
20
10
0
-10
0
50
100
150
N = 4
N = 6
N = 8
N = 12
0 (marginal stability)

# Bootstrap Current Driven Magnetic Islands

Thin island stability is dominated by sum of 2 pressure driving effects:

1) Bootstrap Current Drive

2) MHD average curvature (Glasser, Greene & Johnson)

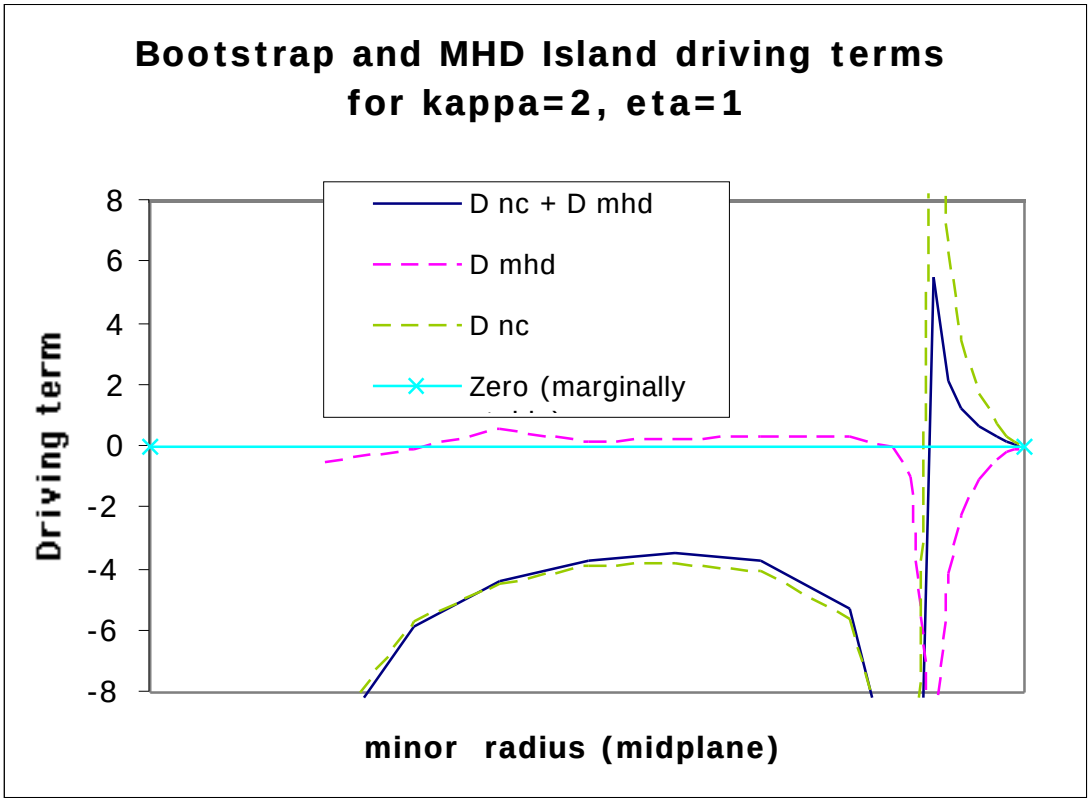
Can evaluate these terms from TOQ (include recent Hegna effect)

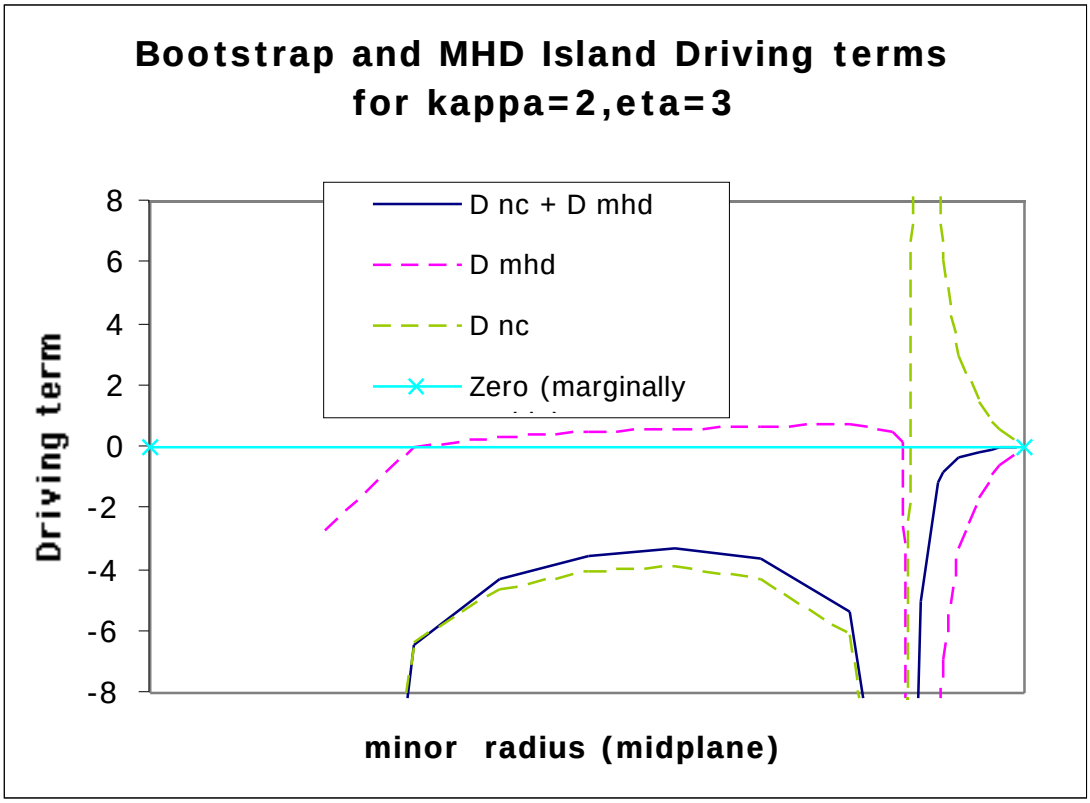
***Find:***

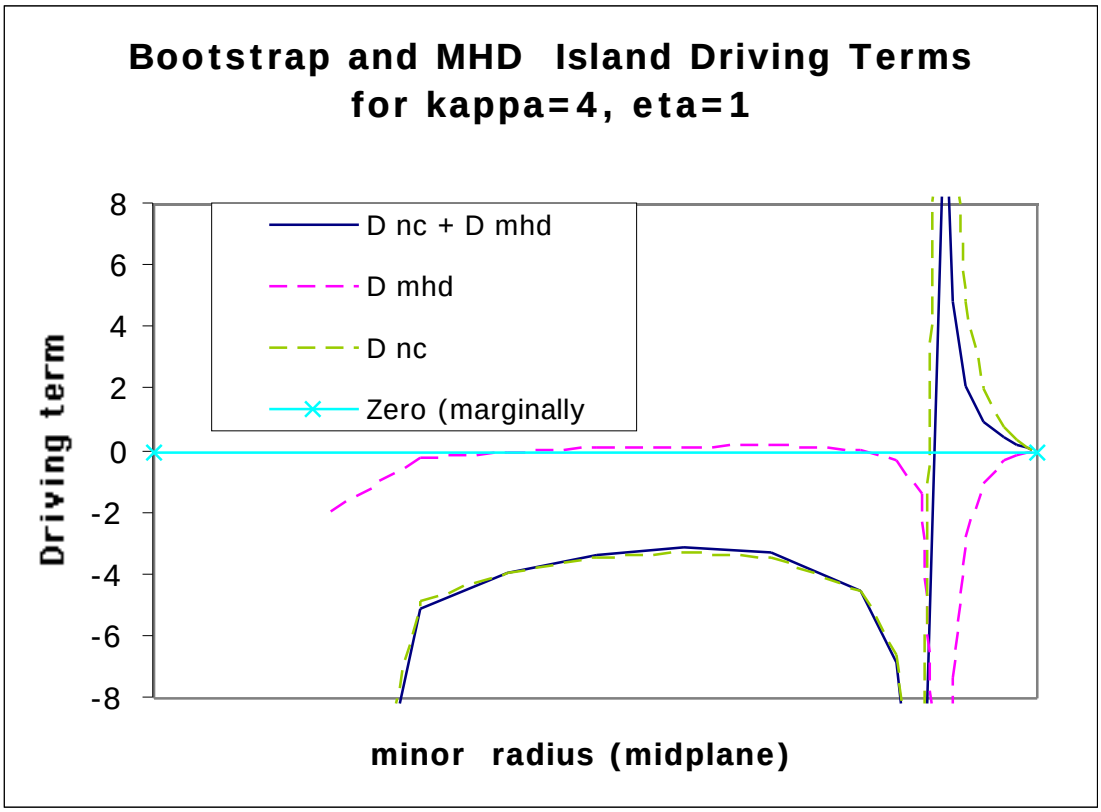
for high bootstrap fraction cases, the MHD term is more competitive than for less hollow current profiles (possible effect of Shafranov shift or magnetic shear?)

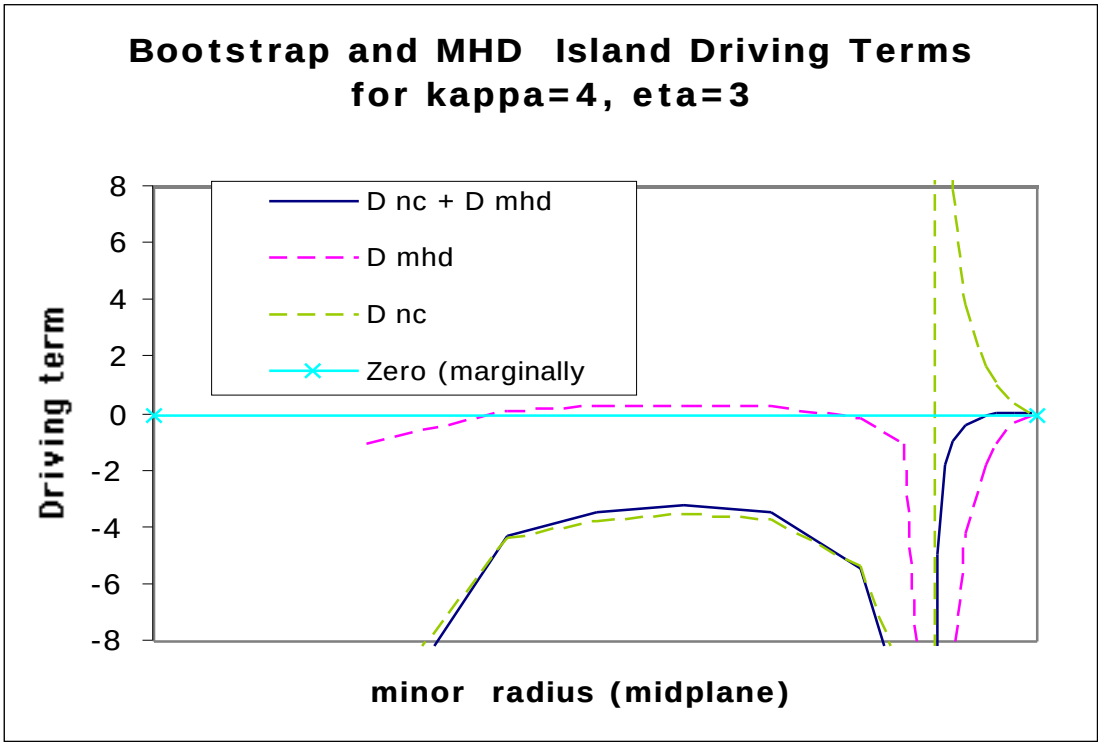
***Is actual stability possible?***

**Yes**, with either *indentation* or *higher* $\eta$ ( = d ln T / d ln n )


Bootstrap and MHD Island driving terms
for kappa=2, eta=1
D nc + D mhd
D mhd
D nc
Zero (marginally
Driving term
8
6
4
2
0
-2
-4
-6
-8
minor radius (midplane)


Bootstrap and MHD Island Driving terms
for kappa=2,eta=3
D nc + D mhd
D mhd
D nc
Zero (marginally
Driving term
8
6
4
2
0
-2
-4
-6
-8
minor radius (midplane)


Bootstrap and MHD Island Driving Terms
for kappa=4, eta=1
8
6
4
2
0
-2
-4
-6
-8
Driving term
D nc + D mhd
D mhd
D nc
Zero (marginally
minor radius (midplane)


Bootstrap and MHD Island Driving Terms
for kappa=4, eta=3
8
6
4
2
0
-2
-4
-6
-8
Driving term
D nc + D mhd
D mhd
D nc
Zero (marginally
minor radius (midplane)

# Microinstability Results

Linear comprehensive gyrokinetic stability analysis have been performed on $\kappa$ scans of the numerical equilibria from TOQ

Code gs2: developed originally by M. Kotschenreuther
parallelized by Q.P. Liu & W. Dorland
nonlinear terms added by W. Dorland

Linear version used by G. A. and PPPL to analyze experimental data

***SUMMARY:***

Elongation reduces growth rates ~ $1 / \kappa$

The instabilities shift to longer wavelength, so $D_{mixing}$ is not much affected.

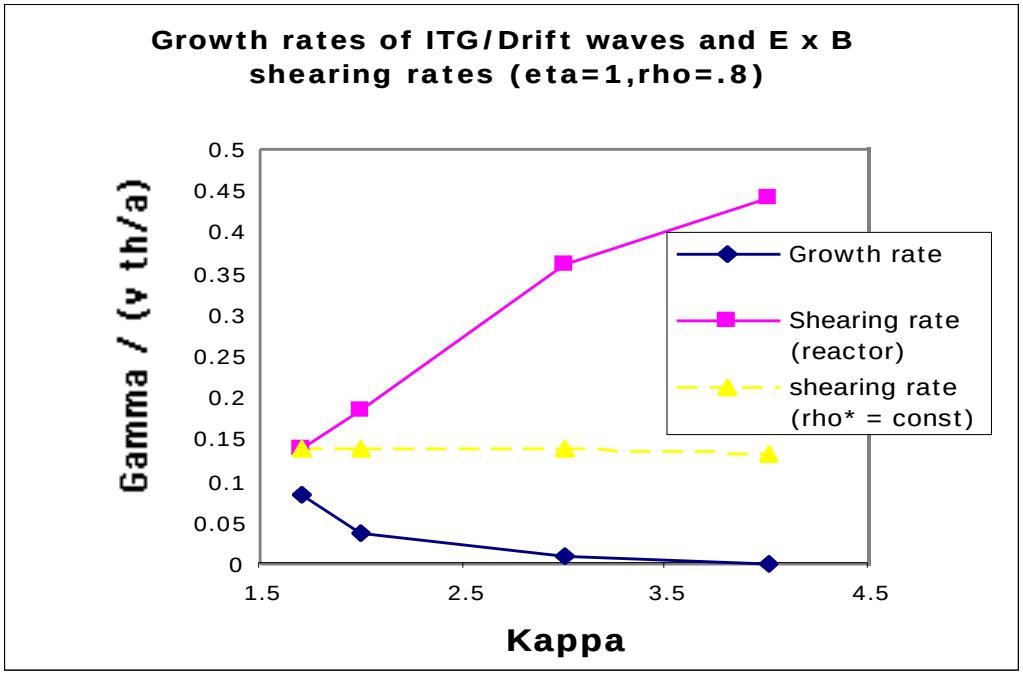
Velocity shear is increases by ~ $\kappa$, since:

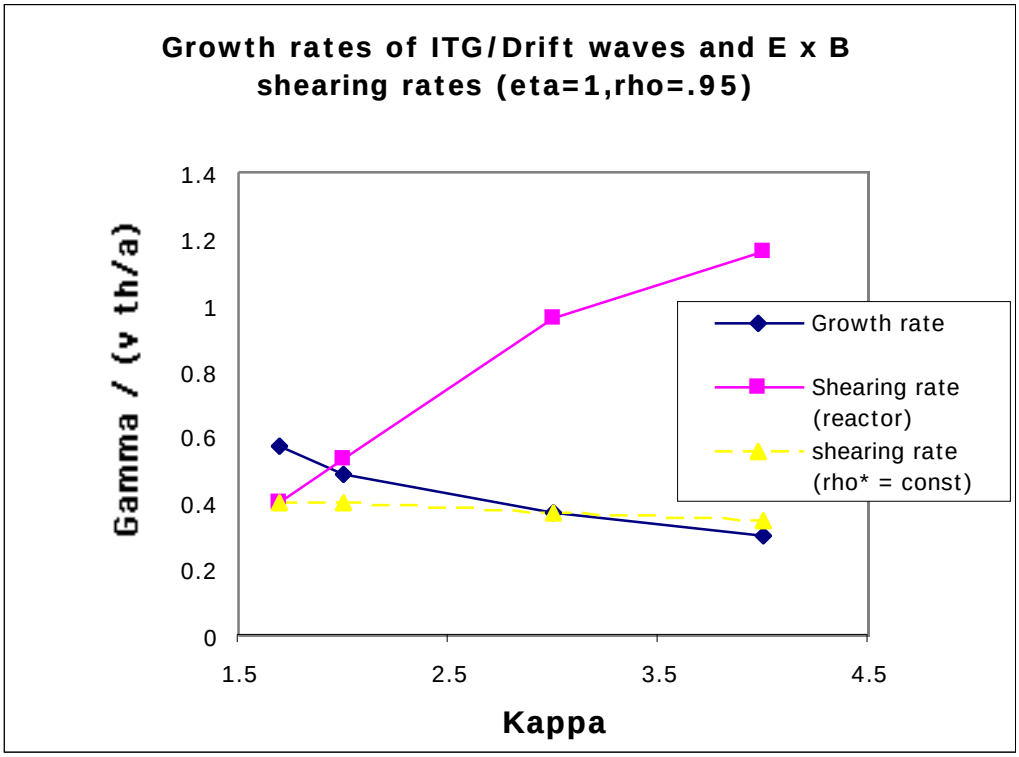
Driven velocity shear is increased because $B_{pol}$ is increased (see Hahm-Burrel formula)

Diamagnetic velocity shear is increased because $\rho^* = \rho / a$ is decreased (higher b => lower B, smaller a)

Thus, prospects for turbulence suppression are greatly improved.

For equilibria just below the balooning beta limit with 99% bootstrap:


Growth rates of ITG/Drift waves and E x B shearing rates (eta=1,rho=.8)
Gamma / (v th/a)
0.5
0.45
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
1.5
2.5
3.5
4.5
Kappa
Growth rate
Shearing rate (reactor)
shearing rate (rho* = const)


Growth rates of ITG/Drift waves and E x B shearing rates (eta=1,rho=.95)
Gamma / (v th/a)
1.4
1.2
1
0.8
0.6
0.4
0.2
0
1.5
2.5
3.5
4.5
Kappa
Growth rate
Shearing rate (reactor)
shearing rate (rho* = const)