MOTIVATION

Well established: Conducting shell close to the plasma improves tokamak MHD stability

APEX: *liquid* metal surrounding the plasma
1) higher vertical elongation κ possible
2) higher β
3) better confinement
4) higher bootstrap current fraction
(lower current drive)

Talk outline:

1) <u>Brief</u> tokamak MHD tutorial
2) Elongation stability analysis for Li wall (ignoring liquid nature)
3) Practicality *including* requirements for fast flowing low damping liquid
4) Synergistic solution: use one active feedback system to solve tokamak stability problem and liquid flow damping problem
5) Other liquid MHD issues
6) Issues/future directions/code development

Tokamak MHD Stability

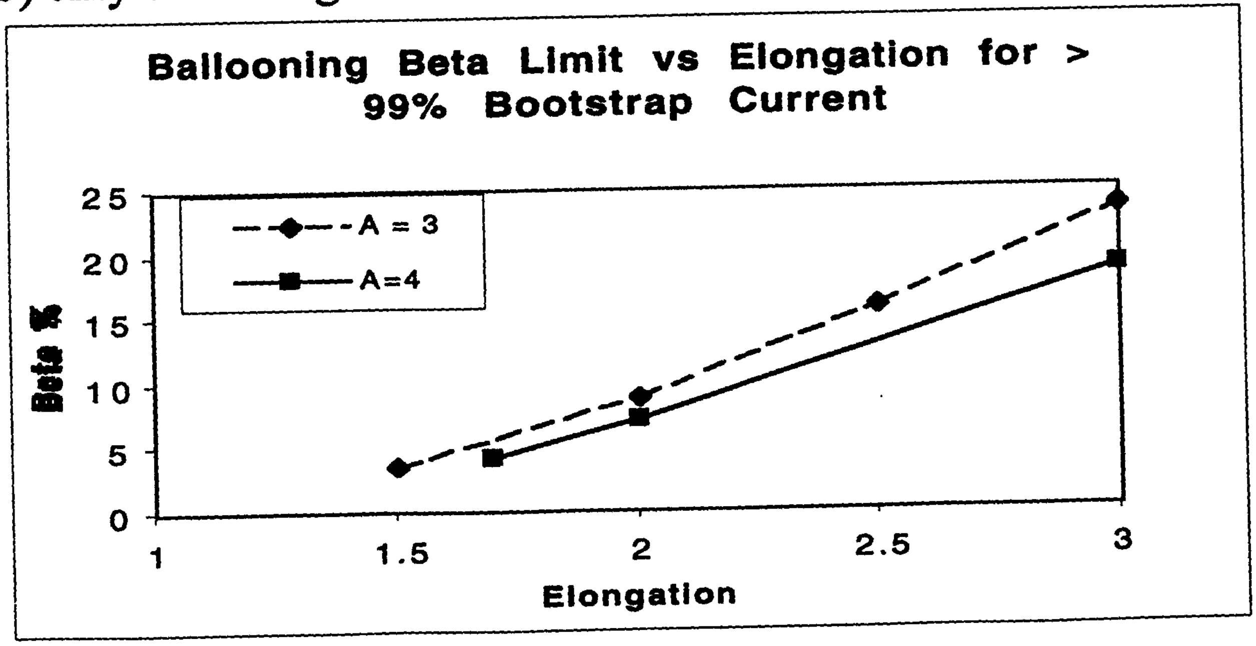
Plasma fusion power density ~ pressure^2 ~ B^4 β^2

Three plasma MHD instabilities limit plasma β:

2) kink modes -shell *strongly* stabilizing
3) ballooning modes – *unaffected* by shell
4) vertical instability - shell *strongly* stabilizing (elongation raises β limit from kink and ballooning modes- the vertical instability limits elongation)

Very close fitting *perfectly* conducting shell

5) removes kink modes & vertical instability
6) only balooning modes would limit β



Potential Reactor Impacts:

ARIES RS : $\beta = 4.8\ \%\ (A=4)$

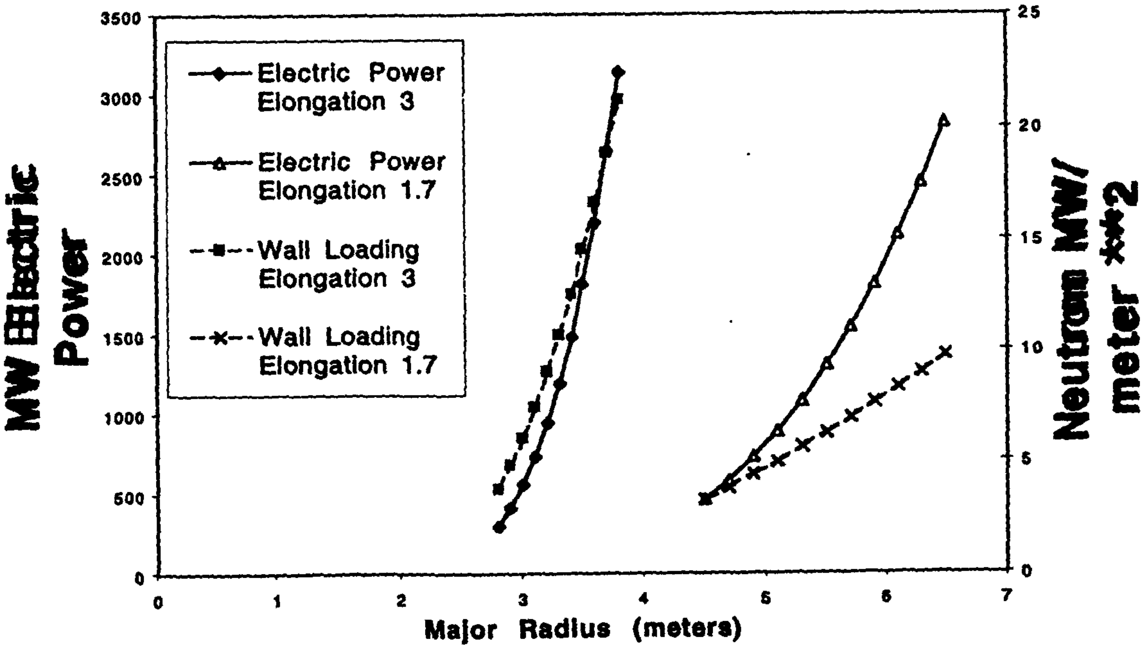
Elongation =3 : $\beta = 15.0\ \%\ (A=4)$

Most basic technological limits (as in ARIES):

1) B = 15 Tesla
2) 1.3 meter of blanket & shield between plasma inboard edge and magnets

Plasma fusion power density ~ pressure^2 ~ $B^4\ \beta^2$

Electric Power and Wall Loading for Elongation 1.7 and 3 (A=4)



Kink and Vertical Stability

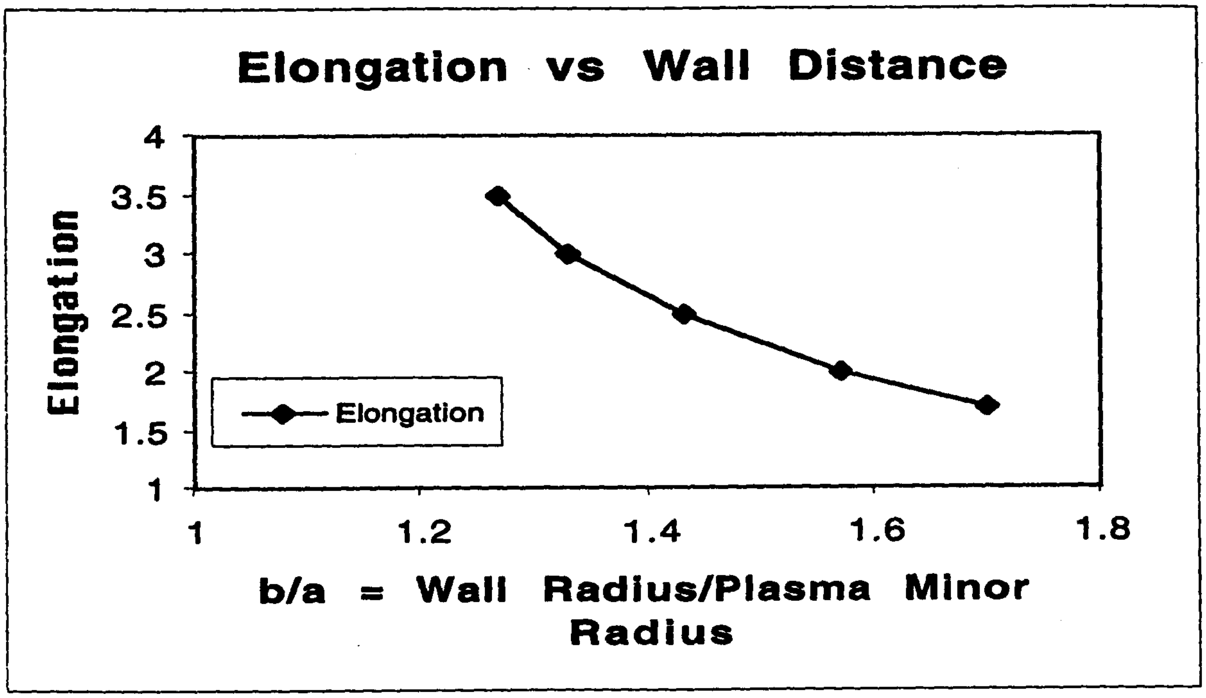
Kink β limit also improves strongly with elongation

Kink stability β limit described by β normalized to the toroidal current : $\beta_N = \beta / [I / a B]$

Elongation	β	**I /aB**	β_N
1.7	**4.8%**	**.97**	**4.83**
3.	**15%**	**2.5**	**5.99**

Higher elongation and **closer wall** increases β_N

Closer Wall also Stabilizes Vertical Instability



NOTE: another type of plasma instability ("magnetic islands") can potentially also limit plasma β . These are not considered here, but are not obviously any worse at elongation 3 than at elongation 1.7

Issues for APEX

Shell stabilizes because:
Plasma movement => inductive E
=>eddy currents in shell
=>eddy currents produce magnetic perturbation
=>eddy currents push on the plasma to oppose the instability

For vertical instability, the eddy currents are ***toroidal***
=> don't want to impede the toroidal current paths (insulating sections problematic)
=>Newton's third law implies that the plasma *pushes back* on the wall, which is an issue for a *liquid* wall which can be easily deformed

Finite Conductivity Walls

Finite conductivity shell: vertical instability and kink instability are only slowed down, not stopped

Growth rate without shell ~ 10 μsec
Growth rate with real metal ~ 10 msec

With finite resistivity, these eddy currents decay (like L/R circuit current decay)

Complete ***stability*** requires more:

Vertical Instability : *active feedback*

Kink Instabilities : *active feedback* or
plasma rotation or
liquid wall rotation

Active Feedback

For this application, technological limits => feedback time response cannot be less than 1 ms (preferably much longer for low cost)

Implication: there must be enough conduction path to slow the instabilities down to this range.

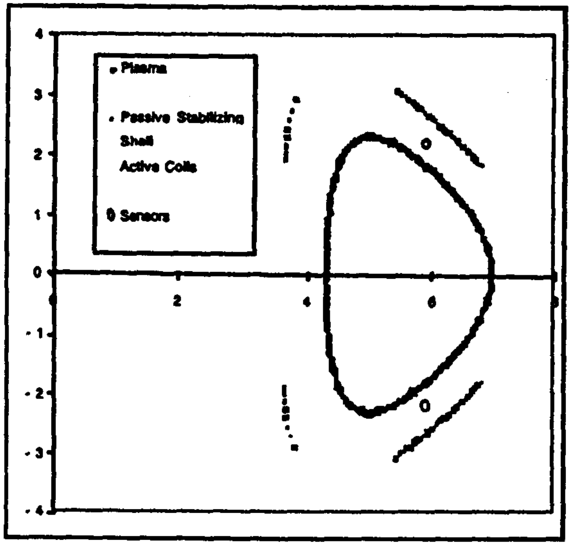
The growth rates of the resistive wall vertical instability are almost always larger than the resistive wall kink mode. It likely sets the most stringent bound so we emphasize it here.

Have written a linear vertical stability code based on the perturbed Grad-Shafronov Equation (discuss capabilities later)

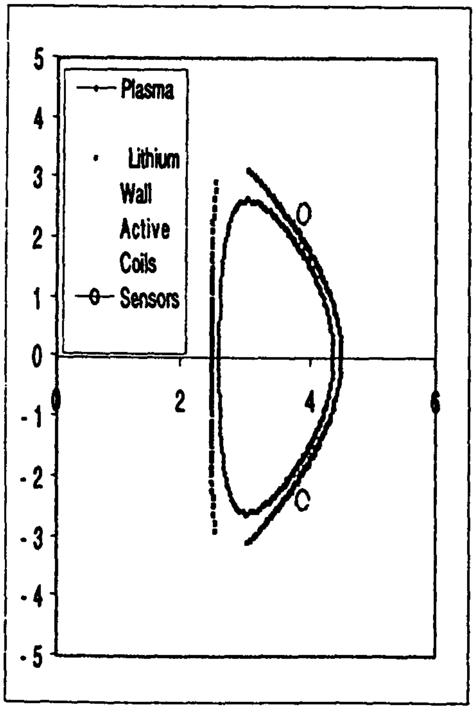
Compare Aries RS with an elongation 3 tokamak with a 2 cm lithium first wall with no insulating breaks. (Ignore liquid effects for now)

Poloidal Cross Sections

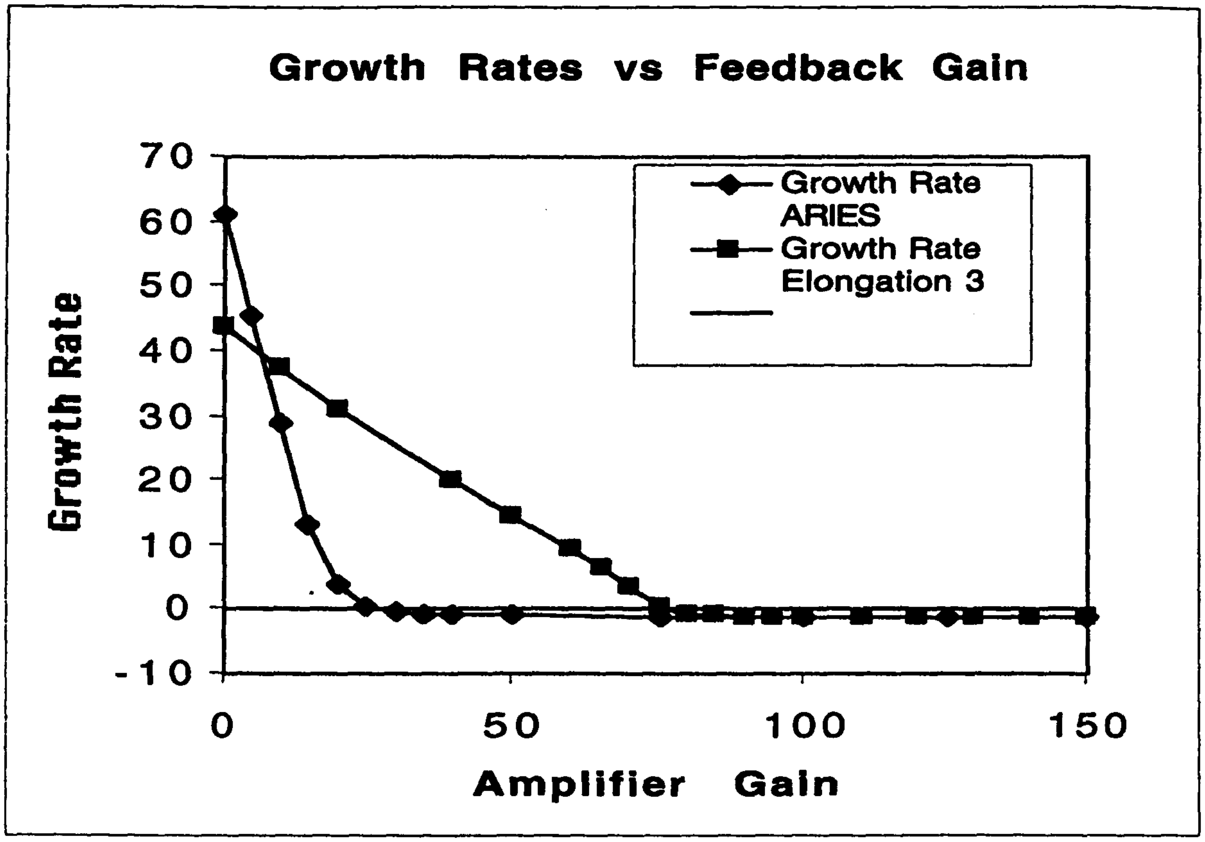
ARIES RS has a 5 cm Tungsten Conducting shell (1100 degree C) 40-60 cm away from the plasma:



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



Vertical Instability Feedback Results



The required Amplifier response time τ_g is closely related to the growth rate (at zero feedback) :

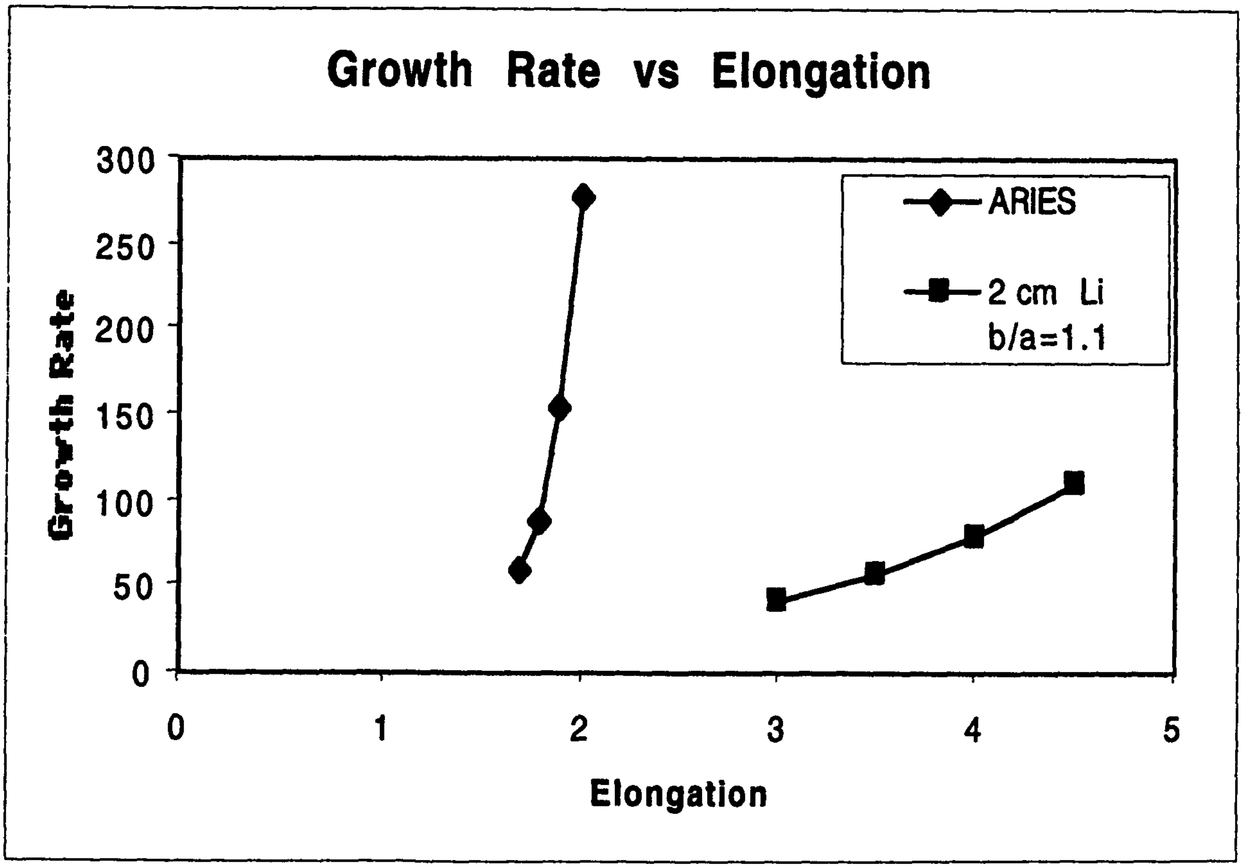
$$\tau_g \gamma \sim 0.6 - 0.7$$

The elongation 3 Li case has τ_g close to ARIES
More gain is required, which *might* translate into higher cost

Proximity to Elongation Limit

Because the conducting shell is further away for Aries, it is closer to the elongation stability limit than the elongation 3 Li case.

(Results obtained by simply stretching ARIES)



Connection: Vertical Stability Eddy Currents and Flow Damping Currents

Vertical instability is ***axisymmetric:***

7) induction electric field E_{ind} is toroidal

8) eddy currents in shell are toroidal

Damping of poloidal flow from normal B components δB :

$V \times \delta B = \eta J_{damping}$

9) $J_{damping}$ is toroidal

Damping of v: $\rho \, dv/dt = J_{damping} \times \delta B$

10) poloidal damping rate $\varpi = \delta B^2 / \rho \eta$

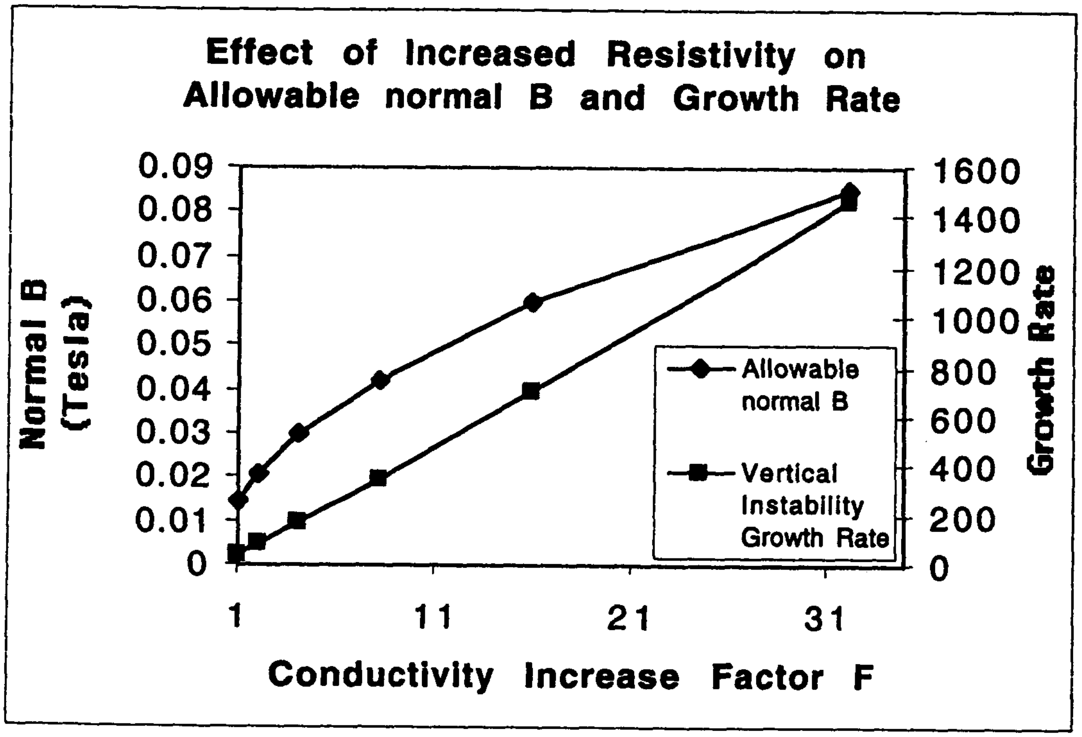
This gives a very stringent limit $\delta B < 0.015$ T

Toroidally segmented insulating breaks to impede toroidal conduction reduce $J_{damping}$, but ***also reduce*** stabilizing eddy currents

Design Window ?

For rough estimation, suppose that insulating breaks can be put in to increase the *effective* η by a factor F.

Allowable δB for damping increases by $F^{1/2}$
Vertical instability growth rate increases by F



Technological limit is $\gamma \sim 1000$, but ***cost*** of active feedback system $\sim \gamma^2$ (?) => ***at best, design window is costly***

e.g., increasing δB to .05 T (still a challenge) increases γ^2 by a factor of ~ 120

Preliminary Examination

Replacing the two active coils with 8 coils with sensors placed barely inside (~3-4 cm) the Li, the feedback system is stable up to gains about an order of magnitude higher than needed to stabilize the vertical instability.

The gain needed to stabilize the vertical instability is also reduced (by about 2).

Thus, I expect that with refinement, it is possible to devise a system which strongly reduces δB and flow damping while stabilizing the vertical instability ***without insulating breaks.***

Present Research

Presently, am working on demonstrating, optimizing and quantifying the reductions of δB possible while simultaneously stabilizing the vertical instability

Additional possibilities actively under investigation:

Feedback kink stabilization using toroidaly distinct coils: further distribute the amplifiers over different toroidal segments to both stabilize the resistive wall kink mode and reduce non- axisymmetric δB

Also: depending on geometry, wires inside a flowing liquid metal can give the signal:

1) the usual inductive E field
2) the radial magnetic perturbation δB
   (even in steady state!)
5) a linear combination of these, including E + v x B,
   which is a measure of the eddy currents in the Li

Thus, an active feedback system can reduce either δB or the eddy currents, and thus all eddy current forces (normal).

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Eddy Current Forces Perpendicular to the Surface

Though attention has focused on flow damping, MHD j x B forces can also pull the Li off the surface

E.g: $\delta B \Rightarrow J_{toroidal} = v_p \, \delta B$

J x B force opposing flow : $v_p \, \delta B^2 / \eta$

J x B force normal to surface : $v_p \, \delta B \; B_p / \eta$

The latter are larger by $B_p / \delta B$

Flow damping is important when damping rate is of order

the flow transit rate $d / v_p \Rightarrow \delta B^2 / \eta \, \rho < d / v_p$

Normal force is important when centrifugal force $\rho \, v^2 / R_c$

is exceeded $\Rightarrow \delta B \, B_p / \eta \, \rho < R_c / v_p$

Since $d \sim R_c$ but $B_p / \delta B \sim 10^2$, ***eddy currents give a roughly two order of magnitude more stringent bound on δB***

Crude estimates on the size of the eddy currents from vertical instabilities give a similar result.

The resulting bound on δB ($\delta B / B \sim 10^{-4}$) is so too stringent to be met practically =>

Magnetic restrainment (as described by Bob Wooley) will probably be needed

A crude estimate of the size of the eddy currents gives a modest and practical level for the restraining current (poloidal voltages of ~.5 V and ~ 1 MW power)

However, more work needs to be done to estimate the size of the δB and eddy currents.

Also, recall the possibility of using active feedback to reduce the total eddy currents form $E + v \times B$ instead of just δB.

Additional Fluid Issues

(In collaboration with Hal. Rappaport at the Institute for Fusion Studies)

In addition to bulk flow damping and bulk flow restraint to the surface, to what extent is the fluid different from a solid metal in it's interaction with the plasma and with δB?

Analysis is underway. Difference arise because perturbed flows can arise which modify the Ohm's law from that of a solid (i.e. the v x B term).

Preliminary results:

1) The liquid does not act like a conductor over it's entire depth, but only in a layer (around each surface)

$$\text{Depth} \sim (\omega \, \eta \, \rho \; (q \; R / B)^2 \,)^2 \quad (\omega = \text{mode frequency})$$

$$\sim 1 - 2 \text{ cm for Li and vertical instablity}$$

Inside this layer, the fluid acts more like ideal MHD where v x B cancels an inductive E.

2) The shear Alfven frequency $V_A / q R$ is of order the growth rate for the vertical instabilty *without* feedback

3) The is a possibility of interaction with surface waves.

We do not expect that 1) and 2) will qualitatively effect the results presented, but they will be have quantitative modifications.

Effect 3) is *potentially* more serious but nothing serious is obvoius at this stage.

Further analysis is in progress. Modifications of the resistive instability code for the linearized fluid response appears possible with 1-3 months effort and will begin soon.

Future Work Needed

1) Examine feedback schemes to reduce flow damping and eddy currents

2) Continue analytical investigations of fluid effects

3) Modify plasma resistive wall instability code to include linearized fluid effects for thin fluid

4) Examine feedback stabilization and flow stabilization of kink instabilites

5) Roughly estimate costs of feedback systems

6) Collaborate with MHD groups to perform plasma kink stability analysis of high elongation high bootstrap cases to verify wall stabilization is possible for $b / a \sim 1.1$

7) Modify plasma resistive wall instablity code to include more realistic geometries

8) Better define the requirements for magnetic restraint in addition to centrifugal restraint to combat eddy current

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7) Modify plasma resistive wall instablity code to include more realistic geometries

8) Better define the requirements for magnetic restraint in addition to centrifugal restraint to combat eddy current

forces to pull the liquid off the wall, and include the effects of equilibrium liquid currents in 2 above.

9) More quantitatively examine effects of insulating breaks

10) Modify plasma resistive wall code to include *nonlinear* fluid response and *thick* fluid response

Conclusions

Strong synergisms exist between the areas of

1) liquid metal walls

2) improved plasma stability at high beta

3) high power density tokamak operation

4) liquid metal / plasma MHD interaction

5) amelioration of liquid metal flow difficulties with feedback

6) high tokamak confinement and high bootstrap fraction (low or zero current drive, only stated here)

The mutual benefit to both the physics and engineering performance can potentially lead to substantially small and hopefully cheaper fusion reactors.