Resistive Wall Instabilities in Tokamaks

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Introduction

Tokamak Power density is limited by plasma ideal MHD instabilities

High power density and high wall load requires high β

This requires a conducting shell around the plasma to stabilize MHD instabilities

(E.G., ARIES RS and AT use these)

Ideal MHD codes assume an *infinitely* conducting wall

But due to *finite* resistivity, ideal MHD instabilities are not stopped by a metal shell, but are only greatly slowed down.

The residual ***resistive wall instability*** still has an unacceptable growth rate and ultimately leads to a disruption unless it is linearly stabilized

Stabilization techniques for these instabilities are the major topic of this talk

Resistive Wall Instabilities and Stabilization methods

A conducting shell allows higher β both directly and indirectly.

Indirectly:

It enables higher elongation κ

Higher κ than present tokamaks and ARIES potentially
=> ***much*** higher β
=> higher wall loading

A shell stabilizes the ***vertical instability*** which limits elongation

Directly:

It stabilizes the ***kink mode*** which limits beta

There are 3 potential ways to stabilize resistive wall modes

1) Plasma rotation: assumed by ARIES for kink stability but impractical for vertical instability

2) Conducting wall rotation (possible with liquid metals)

3) Feedback: proven method for vertical stability and under investigation for kink stability

Talk Topics

1) Progress on using PPPL MHD codes to evaluate the ideal MHD stability of highly elongated, high bootstrap fraction, *high* β plasmas

2) Progress on code development to examine stabilization methods for resistive wall MHD modes

3) Use of the code in it's present state and with the existing literature to give an initial assessment of the three resistive wall stabilization schemes

4) Comments on the relative merits of β optimization methods: Higher kappa and plasma pressure profile tailoring

5) Feedback schemes to reduce the normal component of **B** and thus greatly reduce liquid metal flow damping

6) Note that the use of flowing liquid metals as sensors may be able to overcome known serious limitations of magnetic feedback techniques for *steady state* operation

7) Vertical instability presentation tomorrow

Ideal MHD Kink Stability

Even for an infinitely conducting wall there is a minimum wall distance for MHD kink stability. The criterion is usually quoted for a conforming wall d away, and d is expressible fraction of the minor radius.

Past experience:

ARIES RS: $\kappa = 2$ d/a=0.3 => d ~ 40 cm

More recently, the ARIES AT design has obtained higher β by using both higher κ and pressure profile optimization (assuming profile optimization is possible).

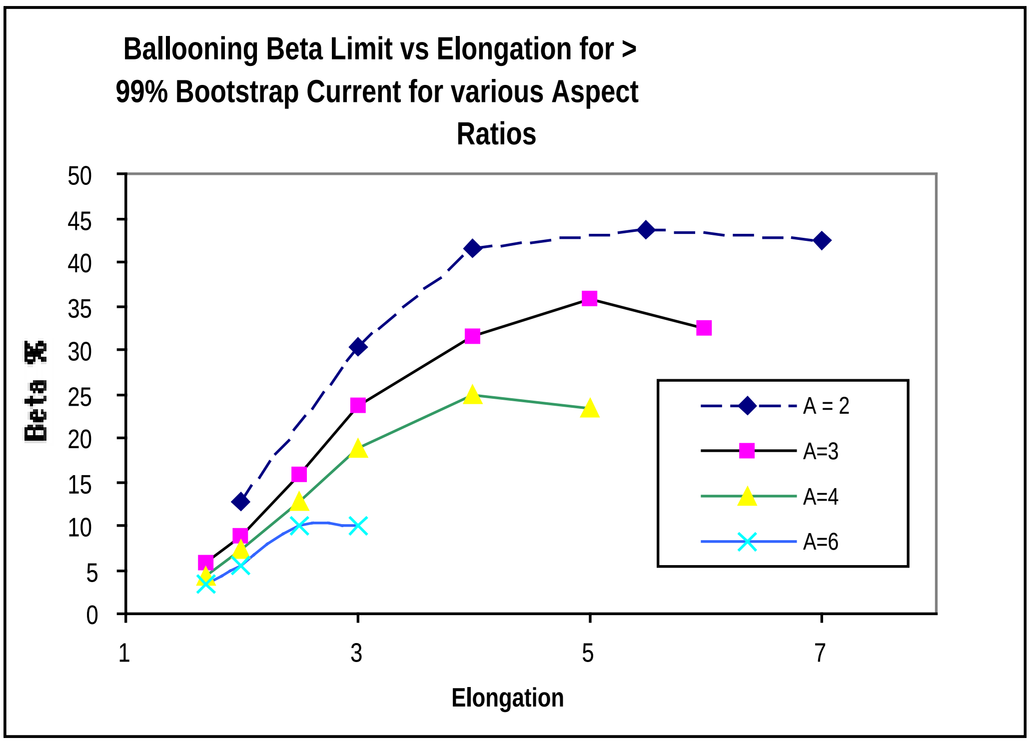
ASIES AT: $\kappa = 2.2$ d/a=0.2 => d ~ 27 cm

(Courtesy of C. Kessel)

Very High κ

High β is being investigated as part of APEX to increase wall loading

Assuming kink modes can be stabilized by a sufficiently close wall, β is limited by ballooning modes. This limit is greatly improved by increasing κ



QUESTION: AT HIGH κ, HOW CLOSE DOES THE WALL HAVE TO BE TO STABILIZE KINK MODES?Kink Stability Progr

Recent High κ Kink Progress

(with help from J. Menard and J. Manickam of PPPL)

Using PPPL code JSOLVER, a high bootstrap fraction high k equilibria has been created for:

4) Easy comparison with GA codes TOQ and BALOO I have used up to now

5) Kink stability analysis using PEST

Case has: ***κ = 3, β= 14.4%***

But: has *non-optimal current drive profile* => ballooning stable β is about 30% lower than possible

Nonetheless, the case demonstrates the β advantage of higher k: with this current drive profiles:

β for κ = 3 is ~ 2 time β for κ = 2

These are *challenging* and *novel* equilibria; cross checking TOQ and JSOLVER shows their equilibria are acceptably close

Kink Stability:

Stability to n = 1,2, and 3 modes requires a conducting shell at d/a = 0.24; this is quite similar to AREIS RS and ARIES AT

This initial results are encouraging: the higher β possible with high k does not exacerbate the kink problem

Progress on Resistive Wall Code Development

The vertical instability code WALLMODE has been modified to perform calculation of resistive wall kink modes

(Recall that WALLMODE can describe arbitrary (axi-symmetric) wall shapes and feedback coil positions)

At present this neglects some terms small by $1/A^2$ but these terms can be included (not serious for ARIES-like cases $A \sim 4$)

A prescription has been developed to utilize information from an ideal MHD instability code to obtain the plasma response (Alan Boozer has independently developed a very similar formalism).

WALLMODE has been modified to run in terms of that formalism

A procedure has been devised to obtain the information from the Princeton MHD code PEST with no coding in PEST

A postprocessor to turn information from PEST into information usable by WALLMODE is about 75% coded

WALLMODE has been modified to include a simple model of moving walls ($E + v \times B = \eta j$) (but recently found a bug)

WALLCODE has been modified to perform simulations of feedback stabilization of *both kink modes and vertical instabilities*

The basic methodology used by PPPL and the ARIES team to evaluate the feedback power requirements for the vertical instability has been implemented in WALLCODE. *This power calculation is crucial in determining the required location, conductivity and thickness of the shell*

Benchmarks with ARIES RS and AT cases for the vertical instability have been *successful*

Pending completion of the porting of realistic MHD equilibrium information from PEST, model MHD equilibria have been developed which can be used in WALLCODE *now*. These are chosen to approximate as many characteristics of the actual equilibria as possible.

Analysis of wall mode stabilization with these model equilibria are given here

Resistive Wall Mode Control

The PPPL codes assume an infinitely conducting wall.

Due to finite resistivity, resistive wall modes arise and must be controlled to avoid a disruption

Three methods for this are known in the community:

1) Plasma rotation

2) Wall rotation (practical only with a liquid metal)

3) Magnetic feedback

Note: 1 and 2 are related by name only: the physics of stabilization by plasma rotation and wall rotation is quite different

We are developing the code WALLCODE to examine 2 and 3 above

We assess 1 from the existing literature

Stabilization of Resistive Wall Kinks by Plasma Rotation

Assumed by ARIES RS

Based on theoretical calculations.

Requires plasma rotation $\omega \sim .075\ v_A/R$ => $v_{tor}/v_i \sim .67$

This is a very high rotation level which is only observed in strongly neutral beam heated tokamaks

Neutral beam power required to drive this rotation was not included in ARIES RS – we estimate it here

Experimental experience is that high rotation speeds do not stop the resistive wall kink but only delays the final major disruption

In the theory, the plasma dissipation which leads to rotational stabilization is treated by a heuristic fluid approximation – not according to first principles. Thus the calculations are not as certain as ideal MHD

Beam Power Estimate

Simple (almost tautological) zero D arguments give:

$v_{tor}/v_i \sim 3\,(\tau_\Pi / \tau_E) \cos\theta\ (T_{avg} / E_b)^{1/2} / (1 + P_\alpha / P_b)$

$\tau_\Pi =$ Global momentum confinement time

$\tau_E =$ Global energy confinement time

$\cos\theta$ = Angle between beam and toroidal direction

$T_{avg} =$ Average Plasma Temperature ~ 18 kev

$E_b =$ Beam energy (50-1000 kev)

$P_\alpha =$ Alpha heating power (~ 430 MW for ARIES)

$P_b =$ Beam power

The best case is very low energy beams: take 50 kev (& $\cos\theta = 1$)

A very optimistic estimate of (τ_Π / τ_E) is 1 since the beams are deposited close to the edge where the momentum diffuses out much more rapidly than the centrally deposited energy

Beam power: ~ 250 MW

Beams are about 50% efficient so electrical input ~ 500 MW: an unacceptable re-circulating power by a margin which exceeds the uncertainty in the calculation

RF is observed to be less efficient at driving rotation than beams

Model Equilibria

The model equilibria has been examined for an ARIES AT like case:

κ = 2.2 , A =4 , R_{major}=5.5 , B_t=5.7 , triangularity = .5

The model equilibria has only current gradients but it's parameters have been adjusted to mimic several features of the actual case:

For n = 1 and 2, it requires a wall at d/a =0.28 and 0.25, similar to the ARIES cases – *thus, the strength of the wall interaction is comparable to the ARIES cases*

The elongation gives very strong coupling of poloidal harmonics, as is well known to be true for ARIES –like cases (and which has been neglected in prevoius analytical treatments)

Resistive Wall Kink Stabilization by Flowing Liquid Metal

Liquid metal flow has been included by including the Lorentz term in Ohm's Law: $E + v \times B = \eta j$

The velocity V is taken to be a constant along the surface

Self-consistent flow evolution is neglected

However, the geometry of the real case is treated

Analytical calculaltions by H. Rappaport and M. Kotschenreuther which include the self consistent liquid evolution indicate that for thin flows the treatment above is essentially correct (< ~ 5 cm for Li, 2-3 time this for Sn – Li)

WALLCODE was used to obtain flow velocity requirements and thicknesses to stabilize n = 1 kink modes for the previously described equilibria

Unfortunately, a bug was discovered recently; I suspect that the qualitative conclusions are still valid; thus I will give a rough outline of the results

Summary of Flow Stabilization of Kink Modes

Flow stabilization with Li or Sn-Li is possible for flows > 10-25 m/s and thickness > 2-4 cm. Faster and thicker is better

The fast flow must be close to the plasma surface (d/a~0.05 - 0.1)

There is a substantial stationary conducting surface behind the fast flow a distance 15-30 cm away.

All conductors must have poloidal and toroidal current continuity

The thickness and conductivity of this additional surface determines whether the flow velocity and thickness requirement falls into the higher or lower velocity/thickness range: ~ 20 cm Li is needed for the low range, and ~ 4 cm gives the high range

A CLIFF configuration was examined with a hole for the divertors and with streams on inboard and outboard sides going down. This was ~ 20% less effective than a rotational pattern with one side flowing up and the other flowing down

For Sn-Li, it *might* be possible to reduce the velocity further by increasing the thickness of the fast stream

Feedback Control of Kink Instabilities

Kink control requires non axi-symmetric coils

To allow easy maintenance, toroidally connected loops can be avoided by the following scheme:

Each blanket segment has it's own set of feedback coils and leads for those coils (N blanket segments, N~ 20-24)

By proper phasing of the currents, feedback signals with toroidal mode numbers n up to N/4 ~ 5-6 could be simulated

Since there are no toroidally connected loops, numerous individual coils could be located poloidally around the plasma

WALLMODE has been used to examine feedback stabilization of this case for the flat current equilibria

Feedback Stabilization of Kink Modes

The relative power for fixed noise for different feedback coil distances and mode numbers is given below

Instability mode Number	Distance from Plasma	Power (arb unit)
N=1	0.06 m	0.3
N=1	0.30 m	1.8
N=1	0.65 m	2.6
N=1	1.30 m	13.
N=2	0.06 m	0.2
N=2	0.30 m	1.7
N=2	0.65 m	4.6
N=3	1.30 m	50

Note that as mode number increases, the feedback power increases much more strongly with distance. This is sensible since the higher mode numbers have higher harmonic magnetic perturbations which decay mode rapidly in space.

Note that the ARIES AT design requires wall stabilization of modes with N up to 7. To stabilize such modes it is quite likely that the coils cannot be placed behind the shield

The absolute feedback power cannot be determined without additional assumptions about the amplitude of the noise in the sensor loops

This subject is controversial even for much better studied vertical instability. It is possible to blindly apply the PPPL/ARIES vertical feedback rules to the kink feedback problem to obtain an absolute power, but the meaningfulness of this is questionable.

For a first wall made 2 cm of steel, the absolute rms power for a 1 cm rms plasma displacement (the PPPL/ARIES rules):

Instability mode Number	Distance from Plasma	Power (MVA)
N=1	0.06 m	2.4
N=1	0.30 m	6.3
N=1	0.65 m	9.7
N=1	1.30 m	21
N=2	0.06 m	2.6
N=2	0.30 m	3.1
N=2	0.65 m	18
N=3	1.30 m	97

Note that most of the power (> 90%) is reactive for the .65 and 1.3 m cases and could *in principle* be recaptured in an energy storage buffer. Most of the power is resistive for the .0 - .3 m case

Feasibility of Close (~.06 - .3 m) Active Feedback Loop

The feedback "loops" for the .06 and .3 m case were taken to be a single turn of 1 cm thick steel

For the 0.06 m case there was no steel in passive shell in the first wall- the feedback loops *were* the passive shell (2cm thickness)

The typical voltages in a single turn steel coil were on the order of 0.5 V for the 0.06 m case and 1-2 V for the .3 m case. (I ~ several KA)

With such low voltages, coils might be wrapped as bands around the outside of the blanket modules and insulated with SiC.

If the voltages could be kept in the 1 V range, the coils might be submerged in FLIBE without electrolysis

Electrically acceptable systems using traditional fusion materials would enhance the prospects for such systems.

A significant issue is appropriate very low impedance power supplies

Comments on Relative Merits of beta optimization Methods

Higher elongation has conducting shell requirements and feedback requirements. These have deterred reactor designers from pushing kappa in the past.

Profile tailoring can also give modest beta increases, seemingly without the engineering difficulties of elongation

However, it should be recognized that profile tailoring has it's own set of drawbacks:

1) There is no credible theoretical model or experimental evidence that transport barriers can be easily controlled with a small amount of current drive or other inexpensive external measure. These large physics uncertainties can easily be overlooked in engineering studies

2) Ii is impossible to calculate the requirements of profile tailoring given out present level of understanding, whereas it is quite possible to calculate the requirements of increased elongation

Feedback Reduction of Normal Magnetic Perturbations

A feedback system with a large number of independent active coils (such as discussed in the kink feedback system) can also be used to give very precise flux surface shape control.

Model calculations with WALLCODE indicate that the rms normal **B** can be reduced by a factor of 20 or more

The rotation damping of fast flowing liquid metals can therefore be reduced by a factor of 20^2 =400 or more.

This can greatly improve the prospects for fast flowing free suface flows.

Liquid Metal Sensors as a Cure for Fatal Feedback Difficulties

In MFE, magnetic feedback schemes based on inductive pickup loops cannot function for long times

Sufficiently slowly growing perturbations are swamped by noise or amplifier offset bias. Thus, in the long time limit these perturbations are not appropriately damped

With present technology the timescale for this is ~ 10^3 seconds
Reactors must have pulse lengths ~ 10^7 seconds

However, flowing liqiud metals produce a voltage which is proportional to **B** normal, ***not a time derivative***. Thus it is not subject to the limitations above

This sensor signal could be produced merely from liquid metal flowing in several pipes with electrodes.

A practical system might incorporate loops for fast signal detection and liquid metal sensors (with low pass filtering) for slow signals

This could render feedback systems such as the ones described above practical for steady state operation.
WALLCODE is being modified to examine such schemes

Summary

1) Substantial progress has been made in developing codes to investigate stabilization of resistive wall MHD modes, which will be required for tokamaks with high wall loading

2) Initial results find that kink stability of high elongation cases is similar to conventional elongations, despite much higher beta

3) Analysis indicates that plasma rotational stabilization of resistive wall modes requires unacceptable beam power

4) Coding to use PEST output to analyze resistive wall modes is mostly complete. Model equilibria have been used for some investigations now

5) Coding corrections need to be implemented to justify preliminary favorable results for kink stabilization using flowing liquid metals

6) Feedback stabilization of kink modes is also possible. The power levels needed are hard to predict, but estimates appear acceptable for high n modes only if the active coils are not behind the shield

7) Electrically acceptable feedback designs for close active coils have very low voltage requirmets; steel or Vanadium can be employed for the conductor and possibly SiC for the insulator. This ability to use these material could enhance the prospect for such schemes

8) Initial results indicate feedback schemes can reduce the magnetic pertubations causing damping in fast flowing liquid metals, reducing damping by over two orders of magnitude

9) Flowing liquid metals used as sensors may overcome the time limitations of present magnetic feedback schemes, enabling steady state operation. WALLCODE will be used to investigate this

Future Work

1) Complete the link between WALLCODE and the PPPL codes so that resistive wall modes with feedback and /or rotating walls can be examined for realistic equilibria

2)Try to flesh out reactor compatible kink feedback schemes, including:

3) coil placement
4) coil driving (low impedance?)
5) liquid metal sensors
6) coil materials and compatible insulation

7) Implement more realistic treatments of liquid metal dynamics into WALLCODE