Topics

1) Progress on codes and results on stabilization of resistive wall modes (including fast flowing liquid metals)

2) Sputtering limitations on a hot scrape off layer with Lithium

3) Progress on exhausting the plasma outside the TF coils

4) A new ultimate upper limit on energy confinement has been found which appears reachable with this concept

5) Engineering possibilities for solid walls when exhausting the plasma outside the TF coils

More Realistic Model to Examine Resistive Wall Kink Mode Stability

Recall: kink modes set the beta limit on tokamaks- the *relevant* kinks are *mainly driven by pressure*

Acceptable β => must stabilize resistive wall kinks

Up till now: analysis/code results for fast liquid metal (LM) stabilization has used *simplified models with current driven kink modes.*

Results are only qualitatively valid at best

New model: have modified ideal MHD GA code;
examine flowing LM stabilization of ***pressure driven kinks***

Presently still some simplifications:

1) circular geometry
2) only high toroidal mode numbers
3) simplified pressure profiles

Work is well on track to remove limitations 1 and 2

Despite simplifications, new model is much better

<u>Realistic features of present</u> **<u>Unrealistic feature of</u>**

Model	**current driven model**
Pressure driving term with toroidal curvature and poloidal mode coupling	No curvature No poloidal mode coupling
High n modes become up/down anti-symmetric	All modes are up/down symmetric
Kink ballooning resistive wall instabilities for n < 5-10 (like ARIES RS, ARIES AT)	Instabilities for all n
Ideal wall distance for stabilization=> constant for high n	Widely varying wall stabilization distances with n, some => 0

Results

New trends found which are not present in the current driven model:

Low- intermediate n modes can be destabilized by high enough flow

Different behavior for

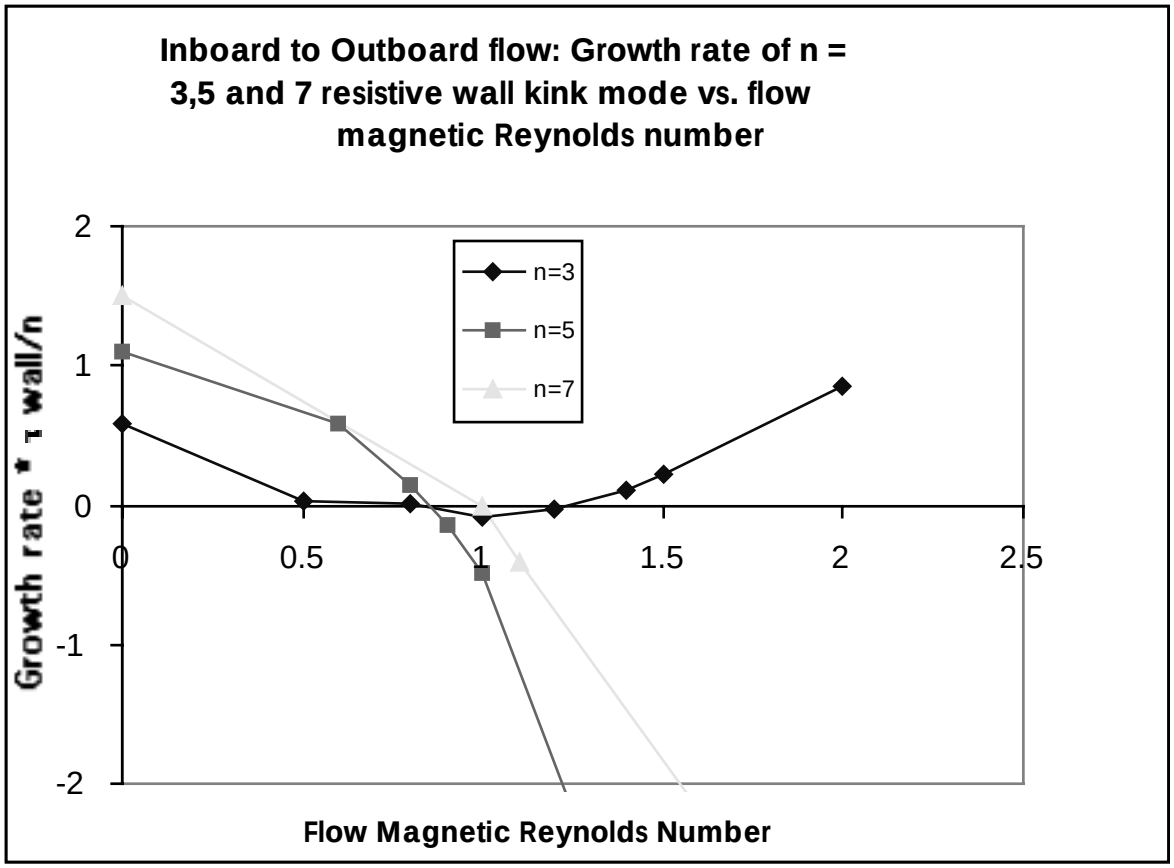
1) flow from top to bottom (standard CLIFF)
2) flow from inboard to outbord (L. Zakharov)

For standard CLIFF:

High n modes are practically impossible to stabilize

There is no velocity to stabilize high n modes without *destabilizing* low n modes

Inboard to Outboard Flow

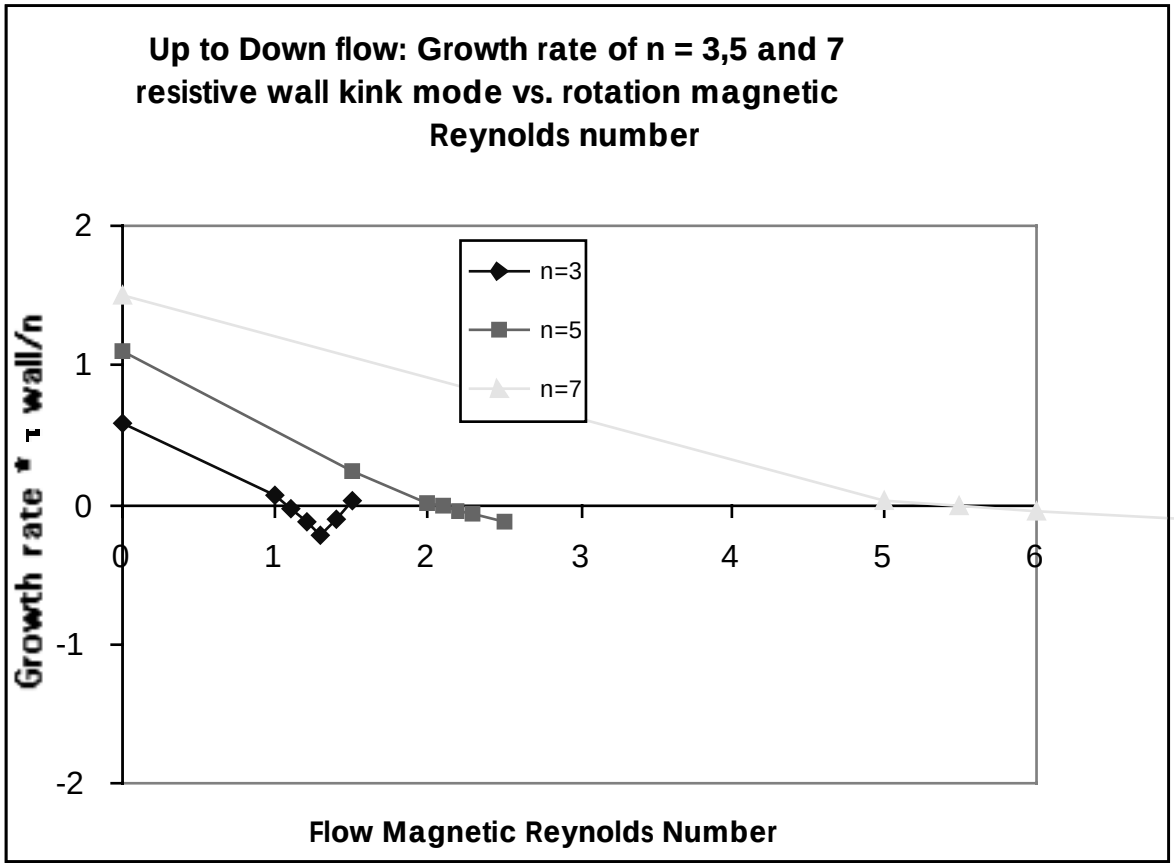


The n = 3 mode is not strongly stabilized

The n=3 mode is destabilized by large LM flow

Recall: Flow R = 1 => ~ 7 m/s for Li
Flow R = 1 => ~14 m/s for Sn

Up to Down Flow



The n=3 mode is again destabilized by large flow velocities

Stabilization of the n=5 and n=7 modes requires impractical flows

No flow simultaneously stabilizes n=3 and n=5

Future Work

Within the next ~ 3 months, modify the code to:

Remove the restriction to high n modes

Allow non-circular geometry

Examine other resistive wall kink mode stabilization schemes:

Stabilization by plasma rotation

Include novel walls (described Aug2001) to reduce the plasma rotation velocity needed for stabilization

Stabilizing effect of a hot scrape-off layer(?)

Ultimately, the code can be interfaced with WALLCODE to examine feedback stabilization

Sputtering Limitations on the Use of Flowing Liquid Lithium Plasma Facing Surfaces

It is known that liquid Li can have a sputtering coeficient greater than 1, which would probably lead to a Li “runaway”

However, the self sputtering coeficient of Li saturated with D (50% Li, 50% D) is ~ 3-4 times lower than pure Li

Recent analysis have assumed Li is saturated with D and find that sputtering is not a major issue (Brooks et. al., J. Nucl Mater., 290-293 (2001) 185-190)

However, for parameters of interest to APEX, I find that the Li probably will not be in the highly D saturated state

This could have a serious impact on the viability of Li as a PFC and previous analysis probably need to be revisited

Why is the Li Not Saturated?

There is a time limit on the exposure to a high D flux (as in a divertor or limiter) due to ***surface heating***.

This limits the total D fluence per exposure

Dispersal processes such as molecular diffusion in a liquid are probably adequate to prevent a high D concentration

Numerical Example

The maximum allowable temperature rise is probably 150 degrees (T_{melt} ~ 150 deg, 100 deg margin for heat exchanger, maximum temperature 400 deg)

Exposure of Li to 1.6 MW for .3 sec gives a surface temperature rise of 91 degrees (Moir, Nucl. Fus. 37 pg 563)

10 MW/m2 => exposure time limit of 21 msec

Following Brooks, we use a plasma temperature of 180 eV

With a sheath of 3 T, the energy per ion is (T_i + 3 T_e), plus 1 T_e for each electron.

10 MW/m^2 thus => 6.9 x 10^{18} D/cm^2/sec
Exposure time .021 sec => 1.4 x 10^{17} D/cm^2

What depth does this accumulate in?

Smallest possible distance: D stopping distance

I estimate the stopping distance is roughly 2×10^{-5} cm. Angle of incidence (in the sheath) is ~ 70 degrees => peneteration depth ~ 7×10^{-6} cm.

=> D density ~ 2×10^{22} D/cm^3

Liquid Li density ~ 4.5×10^{22} D/cm^2

⇨ D/Li ~ 1/2 at the end of exposure, and time averaged D/Li ~ 1/4, NOT 1/1

However, this neglects any D dispersal mechanisms in the Liquid Li.

Molecular Diffusion

Typical molecular diffusion coefficients in liquids are in the range 10^{-4} to 10^{-6} cm^2/sec. I do not know the value for D in Li, but I use the lowest of these numbers to estimate molecular dispersal

Over 21 msec, the diffusion distance is ~ 1.4×10^{-4} cm, so

=> D density ~ 1.0×10^{21} D/cm^3

=> Surface Ratio D/Li ~ 1/45, or ~ 2% D, 98% Li
NOT 50% D + 50% Li

Of course, even slight fluid turbulence could disperse the D much more than molecular diffusion

Nonetheless, I conclude that one should use the sputtering coefficient of Li, not LiD.

Consequences

I have written an elementary orbit code and for (what I think) are reasonable sheath parameters, and a low angle of inclination between B and the surface, I find the average angle of incidence is ~ 70 degrees

The self sputtering coeficient S_{Li} at 70 degree incidence and 500 eV is ~ 1.35, and for 720 eV, it is probably in the range ~ 2.

I understand that about 1/3 to 1/2 of the Li sputters are charged, and so will not result in self sputtering.

Nonetheless, the self sputtering coeficient of just the neutral Li appears close to 1.

Note that the "net" sputtering from D, S_D, is increased by a factor of $1/(1-S_{Li})$, due to the self sputtering of all the Li "daughters" of the original Li

S_D ~ .2-.4 in this energy range
=> even if $S_{Li} < 1$ but is close, the "net" sputtering of Li due to D is larger than 1, possibly much larger.

This issue might also affect the NSTX module, and should be examined.

In any case, this appears to put a limit on the plasma temperature in contact with a Li surface at roughly 200 eV

Progress on the Concept of Redirecting the Separatrix Flux Outside the TF Coils

Recall there are several advantages:

1) Greatly reduced surface heat flux on the first wall for a given neutron flux

2) A divertor outside the TF coils could have much greater flux expansion, and significantly easier engineering

3) Potential for increased beta (~ 2-3 times) by producing a very hot edge

4) Potential for greatly increased energy confinement time

5) Potential for direct conversion

Engineering issues include:

1) Neutron shielding of super-conducting redirection coils
2) Magnet considerations
    a) Clearance – is there enough space?
    b) Magnet structural forces
    c) Do the extra magnets cost too much?

Physics Issues:

1) To what extent do particles follow the field lines?
    a) Turbulent diffusion
    b) Particle orbits/drifts

Work is proceeding on all many of these fronts

1) Several very different geometries for the redirection coils have been examined – but none is significantly better than the original concept. Attempts at optimization continue

2) The diffusion effect has been calculated

   (1/4) Bohm diffusion (plausible from present experiments) => thickness of the plasma disk as it goes between the TF coils is ~ 1 cm.
   ⇨ plenty of vertical clearance
   ⇨ helpful for neutron shielding

   Particle orbit effects still need to be calculated

3) Analysis of the potential of the scrape-off layer plasma as a conducting shell for MHD stability

- ⇨ Reduce requirements for a metal shell for vertical stability
- ⇨ Possible stabilization of kink modes

Bringing the separatrix field lines outside the TF coils appears to improve the prospects for this, but analysis is continuing

4) Potential for increasing beta using a hot edge is under analysis. Recall that the increased beta is because the bootstrap current profile is changed by the hot edge. Further improvements may be possible using current drive in the high temperature, low density edge.

Synergisms with the ST Concept

The physics and engineering aspects of this scheme for field line redirection match nicely with the ST.

Traditional ST divertors have especially high heat loads (The small major radius of the x point => high heat loads)

It is somewhat easier to extract the separatrix field lines outside the TF coils in an ST, since the TF coils are relatively small.

The hot edge also leads to the potential for greatly increased toroidal beta which is particularly crucial for ST economics (where high power density is easily possible but recirculating power is the Achille's heal)

The hot edge would also greatly improve confinement, which is highly interesting to the physics community.

The nature of ST confinement is also well matched to attaining a high edge temperature with this scheme

WHY?

Theoretical Expectation of a Hot Edge and Improved Confinement

At low density and temperature, the scrape off layer becomes "collsionless" (mean free path >> parallel scales)

Energy is only lost by loosing particles

Separatrix Temperature is then determined by the global particle confinement of the plasma

Recall that global energy confinement is determined by

$$(N_{plasma} / \tau_E)\ T_{plasma} = \text{Net power input}$$

The separatrix temperature is similarly determined by

$$(N_{plasma} / \tau_{particle})\ T_{separatrix} = \text{Net power input}$$

If: $\tau_{particle}$ > what we expect for τ_E, then
$T_{separatrix}$ will be > what we expect for T_{plasma}

The separatrix temperature will be greater than the temperature of the bulk plasma in today's plasmas

Spherical Tokamak Results

Theoretical predictions and recent NSTX results imply that ST's are very well suited to attaining this ultimate confinement limit

Gyrokinetic calculations (Kotschenreuther et. al. IAEA 1998, and recent analysis by the NSTX team) find that velocity shear stabilization of ion scale instabilities is especially easy in ST's

Recent results from NSTX confirm this:

Ion heat transport is very low

Particle transport is very low, and roughly consistent with neoclassical results

Energy transport appears dominated by electrons

Velocity shear is high

Small scale electron modes are predicted to be unstable, and cause only electron heat transport

The Ultimate Limit of Tokamak Confinement

The ultimate limit of tokamak confinement is **<u>not</u>** the neoclassical ion energy confinement time!

In the scheme above, the ultimate limit is *the neoclassical particle confinement time*, which is longer by ~ $(m_i/m_e)^{1/2}$

Furthermore, this limit can be attained even if the electron energy transport is large and anomalous

<u>All that is required is that the particle confinement time is neoclassical</u>

Present experiments attain the condition where ion transport and particle transport are neoclassical, *as expected*

However, the electron transport in today's discharges is still anomalous, and determines the energy confinement

Attaining this limit would lead to an ignition experiment of exceptionally small size and cost

Engineering Possibilities with a Low Surface Heat Flux

A low surface heat flux might enable reactor engineering concepts with the following advantages:

1) Use of a first wall at relatively low temperature to hold a liquid blanket at much higher temperature

2) Use of nearly insulating, ablative materials to coat the first wall to protect against disruptions

Consider each:

Use of a Low Temperature First Wall With High Thermal Conversion Efficiency

Consider, for example, a steel first wall, with the usual temperature limitations (< 600 C)

If the charge particle flux is exhausted outside the TF coils, only 1-2% of the total fusion energy needs to impact the first wall (as Bremstrahling)

Thus, the first wall can be cooled to a temperature ***much*** lower than the exit temperature of the thermal working fluid.

The working fluid at the inlet temperature is used to cool the first wall

The first wall is kept relatively insulated from working fluid in the main blanket

This is then sent through the main blanket, where a much larger temperature rise will take place, with a much higher exit temperature than the first wall temperature

With flibe, the insulator might be a zone of quasi-stationary flibe itself

To eliminate fluid turbulence in the flibe insulator, this zone could be filled with a “wool” of high temperature, low density weave insulating material which is wet by the flibe-

this would insure that the flibe does not significantly move and thus acts as an insulator

Alternatively, the insulator might be a fibrous material with low thermal conductivity which is **not** wet by flibe.

<u>Numerical example: 8 MW/m^2 neutron wall loading</u>

Suppose 11 % of the neutron energy is lost per cm (this gives a factor of ten reduction in 20 cm, similar to flibe and steel)

First wall zone: 1/2 cm of steel with channels and /flibe coolant, plus 1/2 cm of insulating flibe

Total neutron energy fraction deposited in first wall + insulator = 11%

Charged particle energy deposited = 2% of neutron energy

Thermal leakage (assume 600 degree temp differential across the insulating zone) = 1.5% of neutron energy

Total energy fraction deposited in the first wall: 14.5%

Energy fraction deposited in the breeding zone = 85.5%

Ratio of temperature rise in solid wall to temperature rise in breeder = 5.9

For example, with an appropriate flow rate:

~100 degree temperature rise in the first wall
~600 degree temperature rise in the blanket flibe

Inlet temperature:	500 degree
Steel operating temperature :	500 degree to 600 degree

Flibe exit temperature : 1200 degree

This is similar to ARIES AT, but with a steel/flibe system

Importance of Keeping the Charged Particle Energy Off the First Wall

To get a large ratio of the temperature rise in the first wall to that in the blanket, it was important to keep the energy deposited in the first wall low

If a large fraction of the of the charged particle energy were deposited on the first wall, the ratio of the temperature rise in the first wall to the temperature rise in the blanket would be much less (roughly half), and the system would be significantly less attractive.

If a traditional disipative divertor were used in the main chamber, a large fraction of the charged particle energy appears as radiation which impacts the first wall

Thus, even within the temperature limitations of steel, extracting the charged particle flux outside the TF coils might enable very high thermal conversion efficiency

How to handle the divertor energy?

The remaining charged particle energy could be deposited in a high temperature/low vapor pressure liquid metal spray/divertor concept (e.g. Sn, or molten Fe/B eutectic has a melting temperture of ~ 1100 – 1200 C and low vapor pressure)

Since this is not exposed to neutrons, and there are not large heat flows in the solid components, there are a wide variety of potential refractory construction materials

The energy could be transferred to the flibe by bubbling the metal through the flibe, eliminating a high temperature heat exchanger.

Disruptions

With low surface heat loads, new first wall facing components become may become possible for disruption survival-

electrically low conductivity, ablative materials

Tiles of such materials can greatly reduce plasma halo current penetration into a conventional metal wall(reducing forces)

Rough estimate of feasibility: **How large a voltage must the insulator withstand?**

Maximum current decay rate as estimated from ITER basiis:

0.8 MA / millisecond/meter^2

5 m major radius

Faradays Law => Voltage ~ 3500 V

If this is insulated against a 3 mm tile: ~10^4 V/cm

I believe arcing in the cracks between tiles can be avoided - arcs won't happen *perpendicular* to the strong B field
Possible example: Silicon Carbide

With appropriate impurities, SiC can be tailored to have very low conductivity

During the *thermal* quench, the magnetic stored energy is deposited roughly uniformly on the surface: this is ~ 5 MJ/m^2

This would raise a 3 mm tile to ~ 600 degrees C, probably tolerable for SiC

For any localized extreme transient heat loads:

Like Graphite, SiC ablates rather than melts

Conclusions

A new more realistic model and code have been developed to examine stabilization of resistive wall kink modes

Initial results for stabilization by flowing LM are significantly less optimistic than previous models

The self sputtering of Li is likely to be an important issue for APEX applications with high plasma contact temperatures (~ 200eV or higher)

Previous analysis which came to a contrary conclusion require re-examination without assuming D saturated Li

Progress is continuing for the concept of exhausiting the plasma flux outside the TF coils

There is substantial potential for large improvements in plasma confinement and beta, leading to smaller, cheaper ignition experiments and reactors

A new , very high ultimate upper limit for confinement in a tokamak has been identified, which appears reachable within known plasma physics with this concept

This concept is particularly well matched to the ST

Engineering advantages of the low surface heat flux on the first wall might enable:

High temperature (~ 1200 C exit temperature) reactor concepts with a steel first walls and flibe

Solid first wall design options for tokamaks with much reduced disruption forces and improved thermal shock resistance