

Synergism between Liquid Metal Walls, Tokamak Physics Performance, and Reactor Attractiveness

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Abstract

Liquid metal walls appear capable of allowing stable tokamak operation with increased elongation under reactor conditions. Code results from models indicate that the magnitude of improvement can be large with up to a factor of three improvement in stable beta (from 5–7% to 20–22%) at aspect ratio 4 and 3, respectively. This would enable a reduction in the size of a 1 GW advanced tokamak reactor from 5.5 m to 3.15 m. Flowing walls can stabilize resistive wall modes. Stability benefits allow operation in parameters which enable higher confinement with less extrapolation uncertainty.

Liquid metal walls have been considered in tokamaks primarily for heat flux and radiation protection, and to modify particle recycling. In addition, it is clear a priori that liquid metal walls could in principle act as a close fitting conducting shell, but the advantages of this have not been examined. Here, we describe how this can lead to higher plasma β values and improved confinement.

The stabilizing effects of the liquid metal can be either *passive* (merely due to the presence of a nearby conductor), or *active* (due to the flow of the liquid metal). The passive effects are significant because liquid metals such as lithium can be closer to a reactor plasma, as well as thicker, and thus more stabilizing. The active effects are important because they can prevent flux penetration in steady state, preventing resistive wall modes by naturally converting liquid metal kinetic energy into magnetic flux to compensate for resistive losses. It is widely recognized that resistive wall modes strongly limit performance in advanced tokamak operation, and also seriously affect RFPs and other toroidal confinement devices. We consider both passive and active effects here.

In reactor studies such as ARIES RS [1], passive stabilizing conductors are placed behind the blanket. These conductors must maintain a toroidally continuous conduction path to stabilize the vertical instability. They are placed behind the blanket because structural metals compatible with fusion are poor conductors, and a thickness to provide substantial conductivity would negatively affect tritium breeding if placed in front of the blanket. Also, the conductivity of such metals is unreliable in a high fluence reactor environment because of radiation degradation of joints and welds, jeopardizing the required toroidal continuity.

Because the stabilizing plates are located a significant distance from the plasma, which substantially reduces their stabilizing effect, tokamak reactor designs are limited to elongation κ of approximately 2 or less. It is well known that the maximum plasma current is a strong function of elongation, and thus, so is the attainable MHD beta as well as the confinement predicted by scaling laws.

Molten lithium metal can be placed close to the plasma since it does not degrade breeding (in fact it improves it). Furthermore, the conductivity of a liquid is unaffected by radiation. Liquid plasma facing designs considered by APEX have lithium much closer to the plasma. Alternatively, a liquid lithium vessel could be placed just behind a solid first wall (maintaining a toroidally continuous conduction path). Below we consider the effects of this

on κ and thus on beta.

An $n = 0$ vertical resistive stability code has been written. It solves the perturbed Grad-Shafranov equation $\Delta^* \delta \Psi = (FF')' \delta \Psi$ as an initial value code including inductive fields and resistive elements. The elliptic operator is inverted with vacuum boundary conditions, and includes the effects of external resistive coils, a resistive wall, and active feedback coils with voltages determined from the signals of sensor coils. Presently pressure is not included in the equilibrium, and the toroidal current profile FF' is taken to be a constant. The voluminous literature on vertical stability [2] shows that plasma pressure is not a major effect (and is usually stabilizing), and hollow current profiles (as expected with high bootstrap fraction operation) are expected to be more stable than a flat current profile. Thus, the results below are more pessimistic (and thus conservative) than expected from more realistic profiles.

We consider the vertical stability of a $\kappa = 3$ plasma with aspect ratio $A = 3$ and 4, with 4 cm of lithium (a typical number for thin liquid plasma facing concepts), and the liquid at a distance $b/a = 1.2$ (i.e. a distance from the plasma of 20% of the horizontal minor radius, or about 30 cm for ARIES RS). Liquid facing concepts usually have liquid closer than this, would be more stabilizing. The resistive wall time is roughly 1/2 second, and the resistive vertical instability growth time is about 1/15 second. This time scale is easily within the reach of existing vertical feedback technology (which can have response times of the order of a millisecond, or slightly less). With a standard feedback geometry with the active coil above the plasma a distance which would place it behind a 1 m shield, and a sensor coil on the outboard side (though a distance which would place it inside the shield but behind the first wall), vertical stability is achieved with feedback gain about an order of magnitude larger than in the case $\kappa = 2$, and with feedback response times ≤ 50 milliseconds. This appears to be within the range of present technology. Little effort has been spent optimizing the parameters of the feedback system, and considerable improvement might be possible.

We find the consequences of this to the attainable beta in AT modes is large. The MHD equilibrium code TOQ [3] (used routinely by the GA MHD group) has been used, to obtain high bootstrap fraction equilibria for $A = 3$ and 4. Broad pressure profiles are used which have been used by the GA group in beta optimization studies for $A = 1.4$ tokamaks. The maximum

beta for ballooning stability for $A = 4$ and 3 is:

$$\begin{array}{llll} \kappa = 2 & \beta = 5 - 7\% & \beta_N = 4.5 & S = 7.3 \\ \kappa = 3 & \beta = 20 - 22\% & \beta_N = 5.7 & S = 13.9 \end{array}$$

As can be seen, the stable beta is increased by about a factor of 3. Note β_N does not increase much, so the increased beta is mainly due to increased current. The β and β_N values for $\kappa = 2$ are quite similar to those found in the ARIES RS study ($\kappa = 1.9$, $\beta_{\max} = 5.4\%$, $\beta_{N,\max} = 4.8$). We do not have capabilities to examine $n = 1$ stability, so we estimate stability based on the shape factor $S = (I/aB)q_{\text{edge}}$. With wall stabilization, the maximum stable β_N is an increasing function of S and profile flatness $p(0)/\langle p \rangle$. If we extrapolate published results by Turnbull [4] *et al.* we infer that the much higher shape factor for $\kappa = 3$ should enable $n = 1$ stability for the modestly higher β_N value.

This has large consequences for a reactor. For a 1 GW reactor with 1 m of inboard blanket/shield and 13 T superconductors (and the same beta as ARIES RS for $\kappa = 2$):

κ	β	Major R	Mw/m ²	ρ^*	H-factor (ITER89P)
1.9	4.8%	5.5	4	1/500	1.8
3	18%	3.15	9.5	1/180	1.6

As can be seen, there is a large reduction in size and therefore mass and cost. For example, the length of superconducting wire needed is reduced by about a factor of 2.5. The wall loading is in the range considered as the nominal case for APEX design evaluations of advanced wall concepts (8 Mw/m²).

Note that the ρ^* of the $\kappa = 3$ reactor is the same as JET and JT-60. Thus, this reactor is not an extrapolation in ρ^* , but rather in geometry. Since geometry is not a fundamental physics variable, we expect that extrapolations in κ from existing machines can be made with much less uncertainty than extrapolations in ρ^* .

We now consider the effects of a flowing wall on the $n = 1$ resistive wall instability. We employ a self-consistent limit of the MHD equations to obtain an analytically solvable model of the β driven external kink mode. The model uses high A reduced MHD, simplified with flat current and pressure profiles and circular plasma cross-section. We note that independently, a similar model was investigated by Betti *et al.* with similar results.

We obtain a beta driven kink mode which requires coupling between adjacent poloidal mode numbers m for instability. The mode can be stabilized with an ideal wall. Finite resistivity and rotation are added numerically, using the analytic plasma response. As expected, with no rotation there is a resistive wall mode with $\gamma_{\text{RWM}} \sim$ the resistive wall time. For a poloidally rotating wall (which adds a current in addition to the inductively driven current of $\eta \delta j = v_0 \times \delta B = v_0 \delta B_r$), we find stabilization when the poloidal transit time for the flow to go from the top to the bottom $1/\tau_p = v_0/\pi r$ is fast enough that

$$\frac{1}{\tau_p} \gtrsim \gamma_{\text{RWM}}.$$

This result has also been found independently by Betti. Here, we note that for 4 cm Li, this corresponds to velocity levels considered by the APEX group for liquid metal walls. Note that it is not necessary for the flow to be facing the plasma, but rather the flow could be in a cavity behind a solid first wall (but close to the plasma).

This can be interpreted as an inability of the $n = 1$ flux to penetrate if the metal flows from the top to the bottom more rapidly than the growth rate, since then the metal is always being replaced by fresh metal. Alternatively, the result can be interpreted as the dephasing of a toroidal instability which requires a particular phase relationship between different poloidal harmonics. Since each m number is Doppler shifted by a different amount, there is not rotating frame where the relative phases needed for instability can be maintained.

Note that it is found that stability requires that the conducting wall be placed somewhat closer for stability than is the case for a perfectly conducting wall. This can be interpreted as being due to the fact that the mode can rotate with a frequency to remove wall stabilization for a single poloidal harmonic. Since only two of the three harmonics are wall stabilized, the stabilization is not as effective. However, in more realistic shaped equilibria, there is a much broader spectrum of m numbers required in the eigenfunction than in this circular model. Since only one among the large number of

harmonics can escape wall stabilization, we anticipate that shaped equilibria will have rotational stabilization effectiveness more nearly equivalent to that of a perfectly conducting wall.

Stabilization of resistive wall modes would lead to several benefits. Higher beta steady state equilibria could be obtained, with very hollow current profiles. Steady state operation with such profiles enables high bootstrap fractions and thus low recirculating power. Also, hollow current profiles are theoretically predicted to give $\mathbf{E} \times \mathbf{B}$ shearing rates larger than instability growth rates for conventional drift instabilities, leading to transport barriers and high confinement. Hollow current profiles are well-correlated experimentally with such good confinement. Thus, flowing liquid walls may enable the conditions needed for high steady state confinement.

We note that the codes above are being developed to handle arbitrary equilibria output from an equilibrium MHD code. We also note that flowing liquid metals can behave differently under perturbations since they can be pushed out of the way. Analysis indicates that liquids flowing at the speeds indicated above are not greatly affected by this (though a stationary liquid would be), but inclusion of this effect is also in progress.

In conclusion, calculations indicate that there is a synergism between liquid metal walls and tokamak physics performance, both in β and confinement, leading to the potential for strongly enhanced reactor attractiveness. We recommend that this synergism be pursued vigorously through cooperation between the fusion physics and the fusion engineering communities.

Acknowledgments

This work was funded by DOE.

References

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