The Belt Pinch and Liquid Metal Walls

M. Kotschenreuther , J. Manickam 2), J. Menard 2), H. Rappaport, Linjin Zheng, B. Dorland 3) , R. Miller 4), A. Turnbull 4)

1) Institute for Fusion Studies, The University of Texas, Austin, TX 78712, U.S.A.
2) Princeton Plasma Physics Laboratory, Princeton, NJ 08543
3) Institute for Plasma Research, University of Maryland, College Park, MD 20742-3511
4) General Atomics, P.O. Box 85608, San Diego, CA 92186-9784

Abstract: MHD stability of highly elongated tokamaks (termed a belt pinch) are considered for high bootstrap fraction cases. By employing high triangularity or indentation, and invoking wall stabilization, and β can be increased by a factor of roughly 3 by increasing κ from 2 to 4. Axisymmetric stability up to $\kappa = 4$ tolerable by employing a shell which conforms more closely to the boundary than in present experiments. Engineering difficulties with a close fitting shell in a reactor environment may be overcome by employing a liquid lithium alloy shell. Rapid metal flows can lead to potentially deleterious plasma shifts and damping of the flow.

Several authors have found that kink stability, as measured by β_N, decreases for $\kappa > 2$ [1,2]. We have used the MHD stability code PEST [3] together with the equilibrium code JSOLVER [4] to investigate kink stability. Unlike previous investigations, we examine high bootstrap fraction profiles with greater than 99% pressure driven current.. The plasma shape is parameterized by κ and δ [4]. We have also considered indented cases; the boundary shape is specified bending a purely elliptical plasma inward along a constant radius to produce the desired indentation Δ.. A wall is assumed at b/a = 1.3. The results can roughly be summarized by stating that with sufficient triangularity cases with $\kappa = 3$ have stable β values twice as high as similar cases for $\kappa = 2$. If there is sufficient triangularity, cases with $\kappa = 4$ have three time higher stable β. Cases with $\kappa = 4$ are very challenging numerically and it has only been possible to examine stability up to mode numbers n = 5.

In the following, we have required that modes with n = 5 be stable without a wall. This is a plausible restriction, since the use of wall stabilization implies that resistive wall kink modes must be stabilized. In a reactor environment, plasma rotation is not a viable stabilization method because the required rotation velocity is too high. Feedback stabilization is under examination for low n modes. The unstable eigenfunctions for the high n cases extend far into the plasma, indicating that they are not edge localized modes, but rather would have serious consequences. Thus they would require feedback stabilization. Practical considerations probably will restrict the number of n modes which can be stabilized. Thus, we have determined the stable beta values for cases where modes with n =3 and above are stable without a wall, and thus would not require feedback. For triangularity = .71, resulting stable β^* for κ = 2,3 and 4 is 4.4%, 7.2% and 8%, respectively, and is 10% for a case with indentation = .5 and κ = 4. Requiring (with no wall) for modes with n =5, the stable β^* for κ = 2,3 and 4 is 6.6%, 10.5% and 14%, respectively, and is also 14% for the indented case with κ = 4. Raising triangularity even slightly greatly improves the high elongation cases; for indentation .78, the stable beta values for for κ = 2 and 3 are 6.7 % and 13%, respectively. For κ = 4, the stable β^* increases to 22%.

At high elongation, axi-symmetric instabilities require stabilization by a passive shell, and an active feedback system. For active stabilization to be feasible the resistive growth rate cannot be too large. An initial value code has been written to examine resistive wall axi-symmetric instabilities. Since the resistive wall evolution is slow compared to the Alfven time, the perturbed Grad-Shafranov equation is used; for the stability calculation, we linearize in the perturbed flux, starting from a full numerical equilibrium from the code TOQ. The plasma, wall and external coils are broken into 1000 - 2000 finite elements, so that all plasma deformations, wall responses and feedback effects can be described accurately. Convergence in the number of elements was checked routinely in the following calculations.

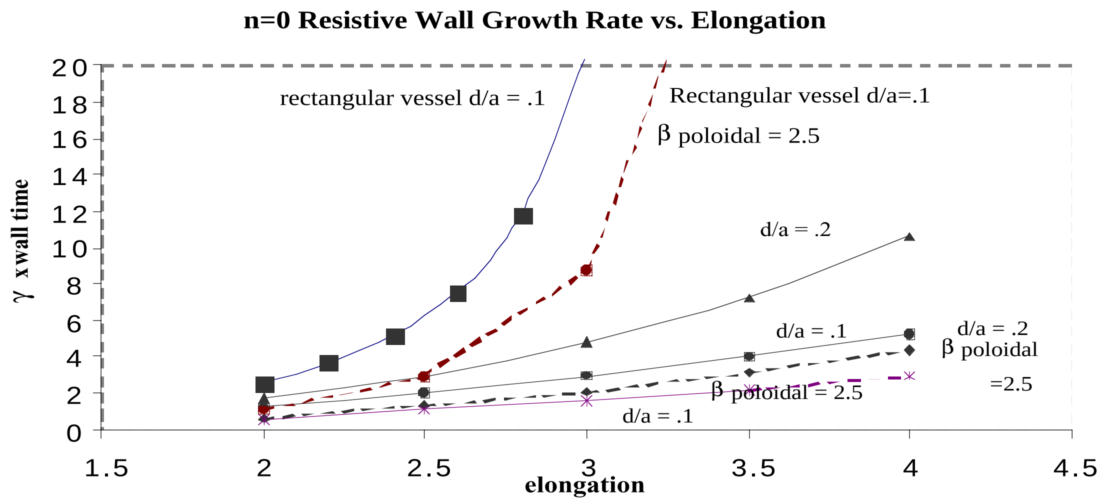


Fig. 1: Normalized growth rate vs. plasma elongation (triangularity .7) for conformal and rectangular shells. The minimum distance from the plasma is.1 a on each side of the rectangular shell, and as indicated for th e conformal shells. The plasma l_I = .7, and β_p = 0, or β_p = 2..5 if indicated.

Growth rates normalized to the shell L/R decay time (for anti-symmetric decay) are shown in figure 1, for conformal shells and a rectangular shell, for a plasma with δ = .7. The tokamak facilities DIII-D and TDV, which have explored high elongation, have vacuum vessels which can be regarded as roughly rectangular, for highly triangular plasmas. As can be seen, a close conforming shell enables much higher elongation without high growth rates, as compared to a "close" rectangular shell. Also note that advanced tokamak operation (β_p ~ 2.5) further enables high elongation.

For a conducting shell corresponding to 2 cm of lithium with reactor dimensions, τ_{wall} ~ .1 sec, so the growth rates low enough to be stabilized. We have found positions for sensor and active loops which give stabilization, for two or more sensor and active coils located at the top of the vessel, (and two at the bottom). The active coils are located 1.3 meters away from the plasma, far enough to be behind the shield. Stability is sensitive to the size of the hole in the shell which is needed for a divertor; hole widths ~ .7 are acceptable for d = .7, but not much beyond this. Indented cases have much lower wall growth rates, and less sensitivity to the divertor hole.

In a reactor environment, there are serious engineering difficulties in designing a solid conducting shell close to the first wall. Even a few cm of material can seriously degrade the tritium breeding ratio, and mechanical stress from neutron heating and embrittlement can lead to low reliability. In reactor design studies such as ARIES RS [8], the conducting shell is placed partially or completely behind the blanket, limiting the elongation and beta. Liquid lithium alloys used as a conductor can *conceptually* solve these problems. Several liquids have breeding ratios greater than one, and are not subject to mechanical stress concerns.

Here we will limit ourselves to the question of whether a liquid conductor in a magnetic field can act as a stabilizing shell. We consider a thin shell of fluid with finite conductivity, so E + v x B = μ j. The fluid could either have solid walls on both sides (i.e., be in channels just behind the first wall) or have a free surface facing the plasma. We use low aspect ratio reduced MHD to describe the liquid, and consider the coupling of the liquid to plasma MHD perturbations. In response to an external time varying magnetic field of frequency ω, the liquid attempts to respond by flowing with the inductive E x B velocity. Note that in such a case the eddy currents (which tend to stabilize the plasma) which would arise in a solid wall would not be produced, since E would be balanced by v x B in the case of a liquid, rather than of μ j as in a solid. However, the liquid cannot flow into the wall, which results in a boundary layer of width $(\omega\rho\mu/B^2) / k_{||}$ (where $k_{||}$ is the parallel wave number, and all quantities are in MKS units). Within this layer, v x B cannot cancel E, so eddy currents are produced as in a solid. A shell of fluid which is thinner than this behaves as a solid. In the case of the vertical instability, ω is several tens of Hz, and $k_{||}$ for the lowest Fourier Harmonic is ~ q R. For lithium, this width is ~ 10 cm. For Li alloys (which are denser) this width is thicker. Thus, even for the higher harmonics in the system, a 2 cm liquid layer should behave as a solid shell. We expect that other mechanical obstructions to the flow (such as channels) reinforce this conclusion. Space does not permit a discussion of other effects such as rapid liquid flow, and ways to reduce the flow damping and plasma shifting to low levels in fast flows to acceptable levels.

References

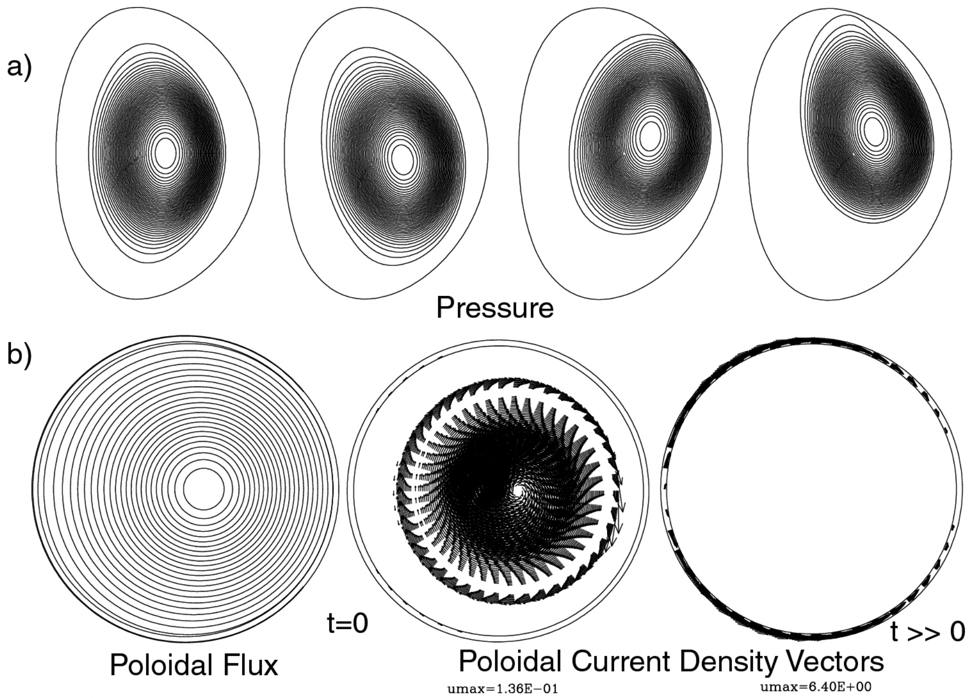
[1] A.D. Turnbull, et. al, Nuclear Fusion, **28** (1988) 1379.
[2] M.W. Phillips, et. al., Nuclear Fusion, **28**, (1988) 1499.
[3] R. Grimm, et. al., J. Comput. Phys. **49** (1983) 94.
[4] J. Delucia, et. al., J. Comput. Phys. **37** (1980) 183
[5] R. L. Miller, et. al., Phys. Plasmas **4** (1997) 1062
[7] R.L. Miller and J.W. Van Dam, Nuclear Fusion **27** (1987) 2101
[8] F. Najmabadi et. al., Fusion Eng. and Design, **38** (1997) 3

II. Effects of Liquid Metal Walls on Equilibrium and Stability

A.Y. AYDEMIR, Institute for Fusion Studies

For a flowing liquid metal wall to be effective in controlling MHD instabilities, the flow needs to satisfy two essential requirements. The first is an equilibrium condition: In steady state, the flow has to be of the form $\mathbf{u} = F(\psi)\,\mathbf{B}/\rho + R^2\Omega(\psi)\nabla\zeta$ where $F(\psi)$ and $\Omega(\psi)$ are arbitrary flux functions[1], and ζ is the toroidal angle. The flow is within flux surfaces. It is also easily seen that **u** can be purely toroidal but cannot be purely poloidal.

The second is a stability requirement: For the liquid metal wall to respond as a ``perfect'' conductor to MHD instabilities, the flow has to satisfy $\Omega_R / \Omega_W > 1$, where Ω_R is an effective rotation frequency for the liquid wall, and $\Omega_W = 2\pi / \tau_W$, and τ_W is the resistive wall time on which the resistive wall modes are expected to grow. Satisfying the equilibrium and stability conditions simultaneously is a nontrivial task that does not seem to have received adequate attention. Violating the equilibrium condition while trying to satisfy the stability requirement will drive very large currents in the liquid metal, since the flow will drag along any ``frozen-in'' ambient equilibrium field (poloidal or toroidal). Consequences of violating the equilibrium condition are graphically demonstrated in the figure below. The pressure contours in an elongated, n=0 unstable equilibrium, depict the induced rotation in the plasma when the liquid starts rotating poloidally (but not within flux surfaces) with $\Omega_R / \Omega_W = 0.2$, due to induced co-rotating toroidal currents in the liquid. Even when a poloidal flow is almost entirely within flux surfaces, it leads to large poloidal currents in the liquid wall, $J_p \geq 10\ J_{eq}$ for $\Omega_R / \Omega_W \cong 1$ due to dragging of the toroidal field. These currents would be expected to interfere and stop the flow.



[1] E. Hameiri, Phys. Fluids **26**, 230 (1983).