ISSUES FOR LIQUID METAL PLASMA FACING WALLS

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Analytic equilibrium calculation

1) axi symmetric
2) assume wall nearly follows $\vec{B}$, so $B_{normal} \equiv \delta B_r$ is small
3) assume liquid thickness << wall dimensions

Question: Can liquid metals flow fast enough?

$$\rho\, v\cdot\nabla v = j\times B - \nabla p \qquad \nabla\cdot j = 0 \qquad \nabla\cdot v = 0$$

$$E + v\times B = \eta\, j$$

$$\Rightarrow \quad \rho\, v_l \frac{\partial}{\partial l} v_l = \frac{1}{\eta} \times$$

$$-\delta B_r^2 v_l + \delta B_r B_l v_r + \frac{\partial}{\partial l} B_l \int dr \left(v_r B_l - v_l \delta B_r\right) \Big]$$

l = tangential
r = normal

$$v_r = -\int_0^r dr\; B_l \frac{\partial}{\partial l} \frac{v_l}{B_l}$$

first term on right hand side familiar

$$\rho v_\ell \frac{\partial}{\partial \ell} v_\ell = - \frac{\delta B_r^2}{\eta} v_\ell$$

$\Rightarrow$ usual MHD frictional damping

Size of other terms relative to this damping term are:

$$\sim \frac{B_\ell}{\delta B_r} \frac{w}{L} \quad \text{and} \quad \left(\frac{B_\ell}{\delta B_r} \frac{w}{L} \right)^2$$

where w = liquid depth

L = characteristic tangential length

thus, the complicated terms are negligible if liquid is thin enough: $\frac{w}{L} \ll \delta B_r / B_\ell$

Can MHD friction be made small enough?

ITER specs said plasma shape/position could be controlled to within ~ 2 % of dimensions

$$\Rightarrow \quad \frac{\delta B_r}{B_\ell} \sim 1/50 \quad \Rightarrow$$

then, the damping term gives a damping time $\tau \sim 1$ sec

so balancing friction and gravity and inertia

$$\frac{1}{\eta}\left(\frac{\delta B}{B}\right)^2 \sim \rho g \sim \rho v_\ell \frac{\partial}{\partial \ell} v_\ell$$

gives $v_t \sim 10$ m/sec, transit time ~ ½ sec for Aries RS parameters

For ARIES, complicated terms

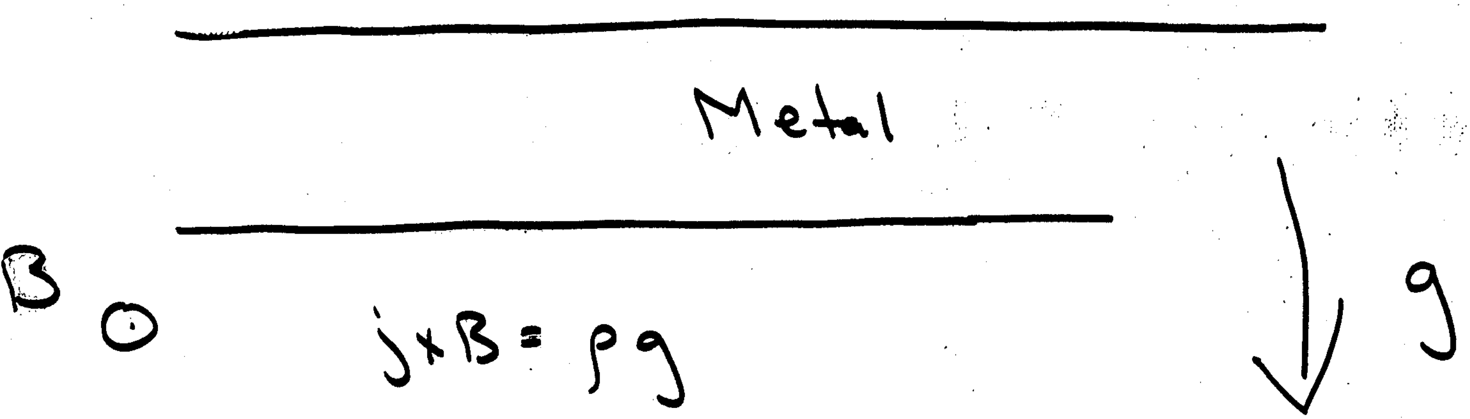
are relatively small ~~for~~

$w \lesssim 10$ cm

For thicker walls, those terms may give stronger damping

STABILITY (to gravity)

Classic problem: liquid metal supported against gravity by current



Classic result: always unstable (for (no centrifugal force)

$$\gamma^2 = g|k_x|$$

Adding surface tension:

$$\gamma^2 = g|k_x| - T_s|k_x|^3/\rho$$

For lithium with surface tension, largest γ is at

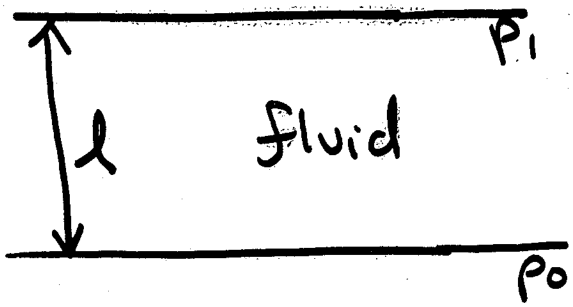
$$k_x \sim 1/2 \text{ cm}^{-1} \Rightarrow \lambda \approx 12 \text{ cm}$$

$$\gamma = 20 \text{ sec}^{-1}, \quad \tau_{growth} = \frac{1}{20} \text{ sec}$$

The magnetic field drops out of the expression for growth rate.

By understanding why this is, we are lead to find a solution which stabilizes Rayliegh-Taylor for liquid metals

First consider $B=0$ Rayleigh-Taylor case



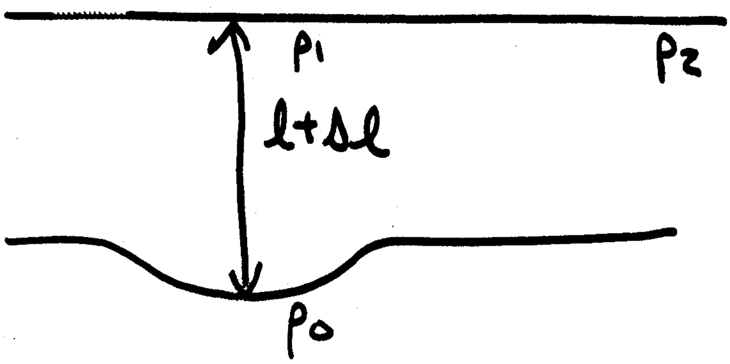
$$\nabla p = \rho g \Rightarrow$$

$$p_1 = p_0 - \int dl\, \rho g$$

$$= p_0 - l \rho g$$

gas with pressure p_0

Perturbed case



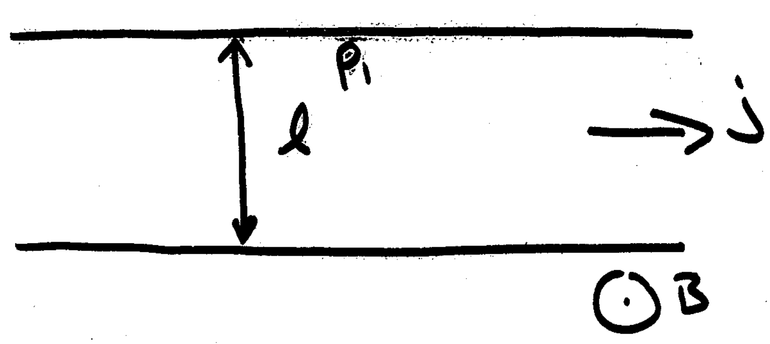
"restoring force" p_0 does not increase to compensate for the greater depth

$$p_1 = p_0 - (l+\Delta l)\rho g \qquad p_2 = p_0 - l\rho g$$

$p_1 < p_2 \Rightarrow$ fluid flows from 2 to 1

$\nabla \cdot v = 0 \Rightarrow$ bulge grows

Magnetized metal Rayliegh Taylor

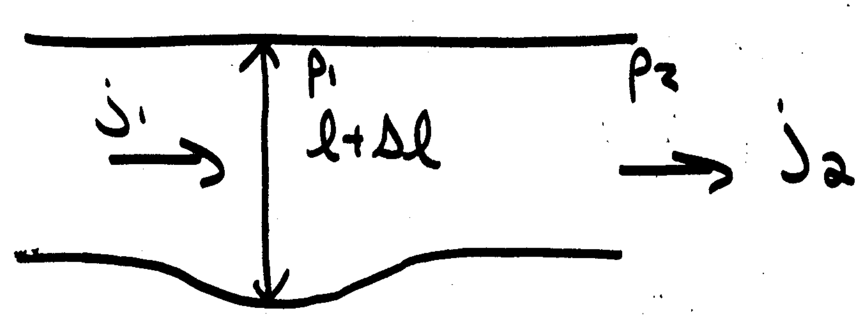


$$\nabla P = j \times B - \rho g$$

$P = 0$ vacuum

$$P_1 = \int dl\, jB - \int dl\, \rho g$$
$$= l\, jB - l\, \rho g$$

Perturb:



Crucial fact: $\nabla \cdot j = 0 \Rightarrow \int dl\, j_1 = \int dl\, j_2$

Because the $j \times B$ force is reduced in the bulge region (due to $\nabla \cdot j = 0$) the restoring force jB does not increase to compensate for the greater fluid depth

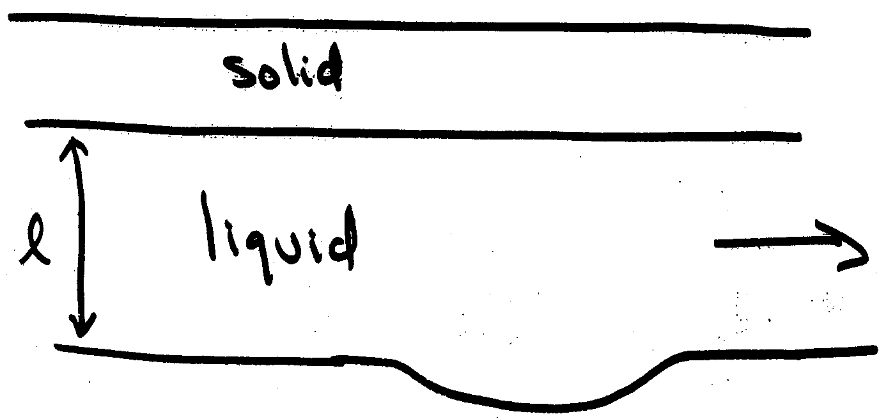
$$p_1 = \int dl\, j_1 B - \int dl\, \rho g = (l + \Delta l) j_1 B - (l + \Delta l) \rho g$$
$$= l\, j_2 B - (l + \Delta l) \rho g$$

$$p_2 = \int dl\, j_2 B - \int dl\, \rho g = l\, j_2 B - l \rho g$$

again $p_1 < p_2 \Rightarrow$ fluid flows from 2 to 1

$\nabla \cdot v \Rightarrow$ bulge grows

How to fix this? Have <u>solid</u> metal conductor carry some current



Rayliegh-Taylor is slow enough that current can redistribute resistively

Thus, current distributes itself more in the liquid in the bulge region

simple analysis shows that stability results when

$$jB \times \text{fraction of current in the solid} > \rho g$$

Note: for $\lambda \ll \ell$, rely on surface tension for

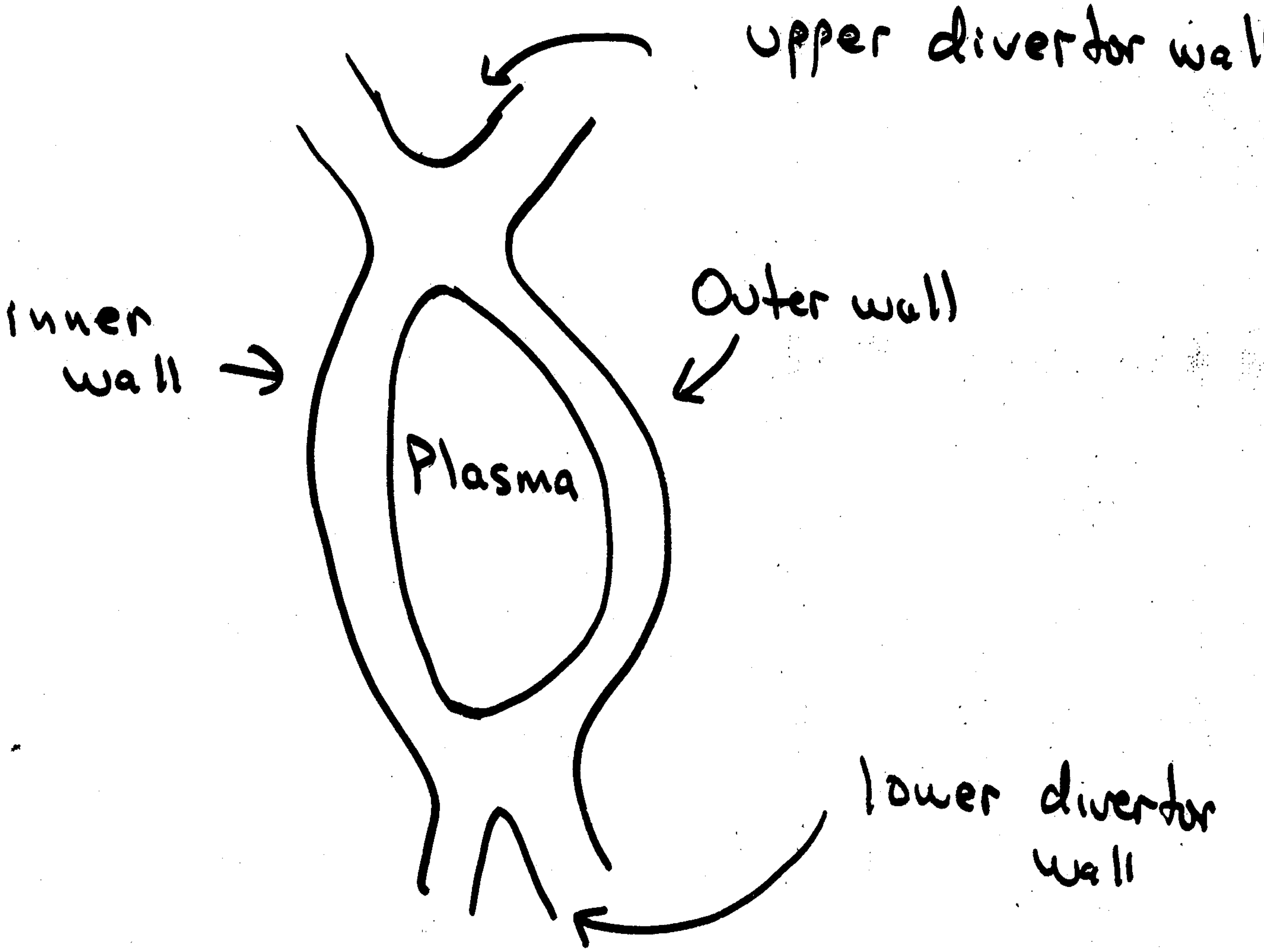
Last meeting: simplified analytical model indicating rippling mode turbulence can lower liquid surface temperature substantially

① Have not done more complete rippling mode calculation YET.

② Have MHD linear code (full resistive MHD eqns) in arbitrary geometry. Need to modify boundary conditions for free boundary. Probably could also compute equilibria. Need programming help

③ Have done simplified analytic equilibrium calculation indicating that at least thin liquid walls ($\lesssim 10$ cm) can flow fast enough

liquid surface
Tokamak



liquid metal ~ 2cm thick, held in place by $j \times B$, (Bob Wooley) stabilized by metal backing

This may be the only way to get liquid to conform to all the walls

Conclusions

1) Simplified analytical models and physical pictures are encouraging for liquid metal facing

- rippling mode to lower surface temperature
- large flow rates possible
- idea for gravitational stability

2) WHAT IS REALLY NEEDED TO GO FURTHER: MHD CODE RUNS

Have an MHD code: full MHD equs, arbitrary geometry, variable grid spacing, semi-implicit (large time step), T3E

(4) Have done analytic stability calculation of gravitational instability (Rayliegh - Taylor) including surface tension

(5) Am devising a way to cure the Rayliegh - Taylor instability, and at the same time provide a flow startup scheme

(6) Am devising concept with thin liquid facing and easily replacable solid blanket components (no welds, very low solid stress) possibly with replacement while reactor is running (like CANDU)

New Concept:

Liquid walls with some

small "non-structural" components

WHICH ARE REPLACEABLE WITH

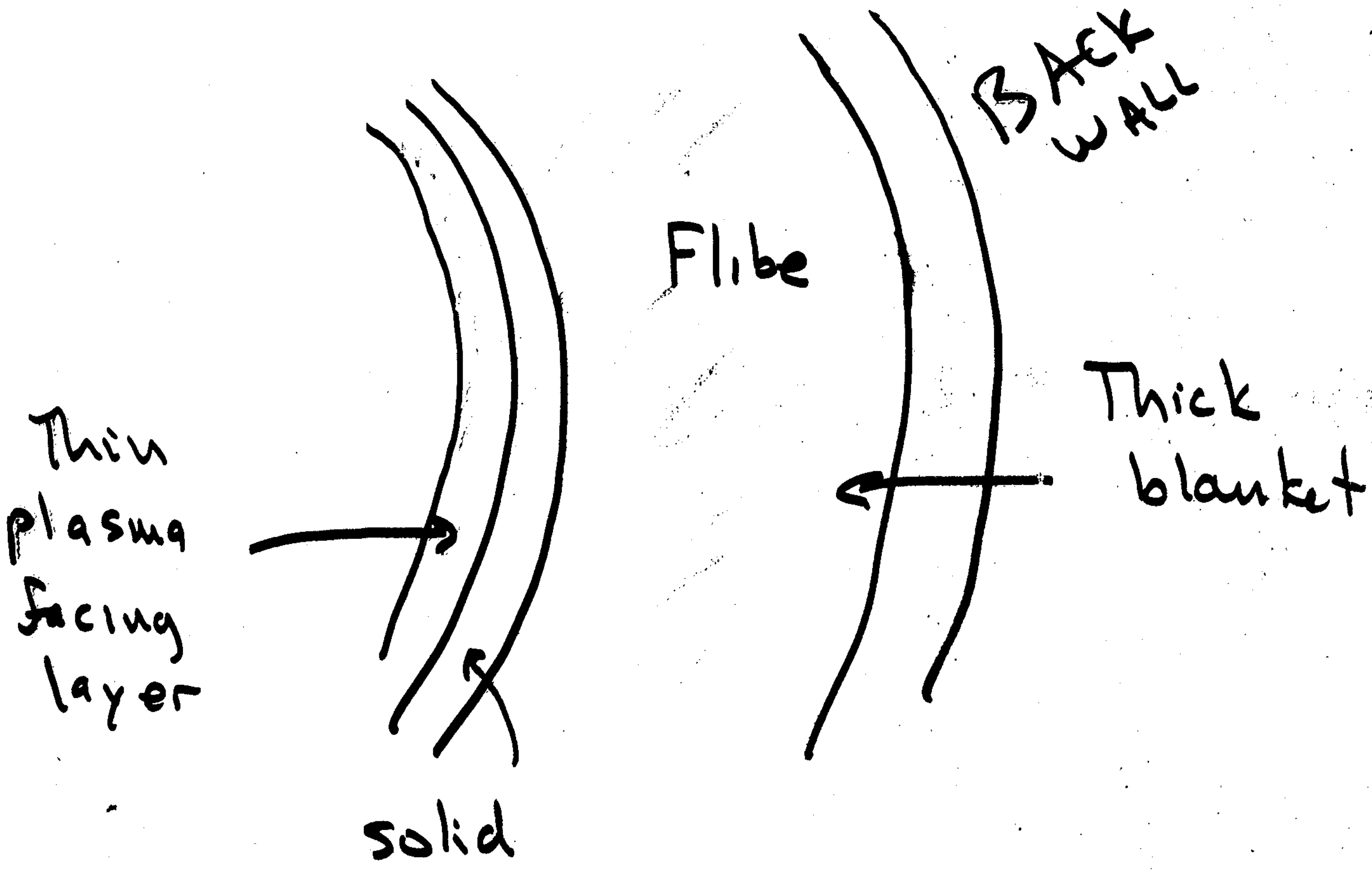
THE REACTOR IN OPERATION

Similar to CANDU reactor - which is

refueled while operating

FLIBE VERSION:

thin liquid facing



suppose the "solid" wall were made up of small squares, each connected to the back wall by say a thin rod

If the squares were small, couldn't they be replaced with reactor operating?

If each square is small:

* little mixing bettween cooler plasma facing layer and hotter bulk blanket

Suppose the solid were a non-conductor like silicon - carbide

* low loads make use of SiC possible

* No disruption forces in either Flibe or SiC

* SiC is cheap - could you just throw it away? inexpensively re-melt, re-cast and recycle?

Recommend-

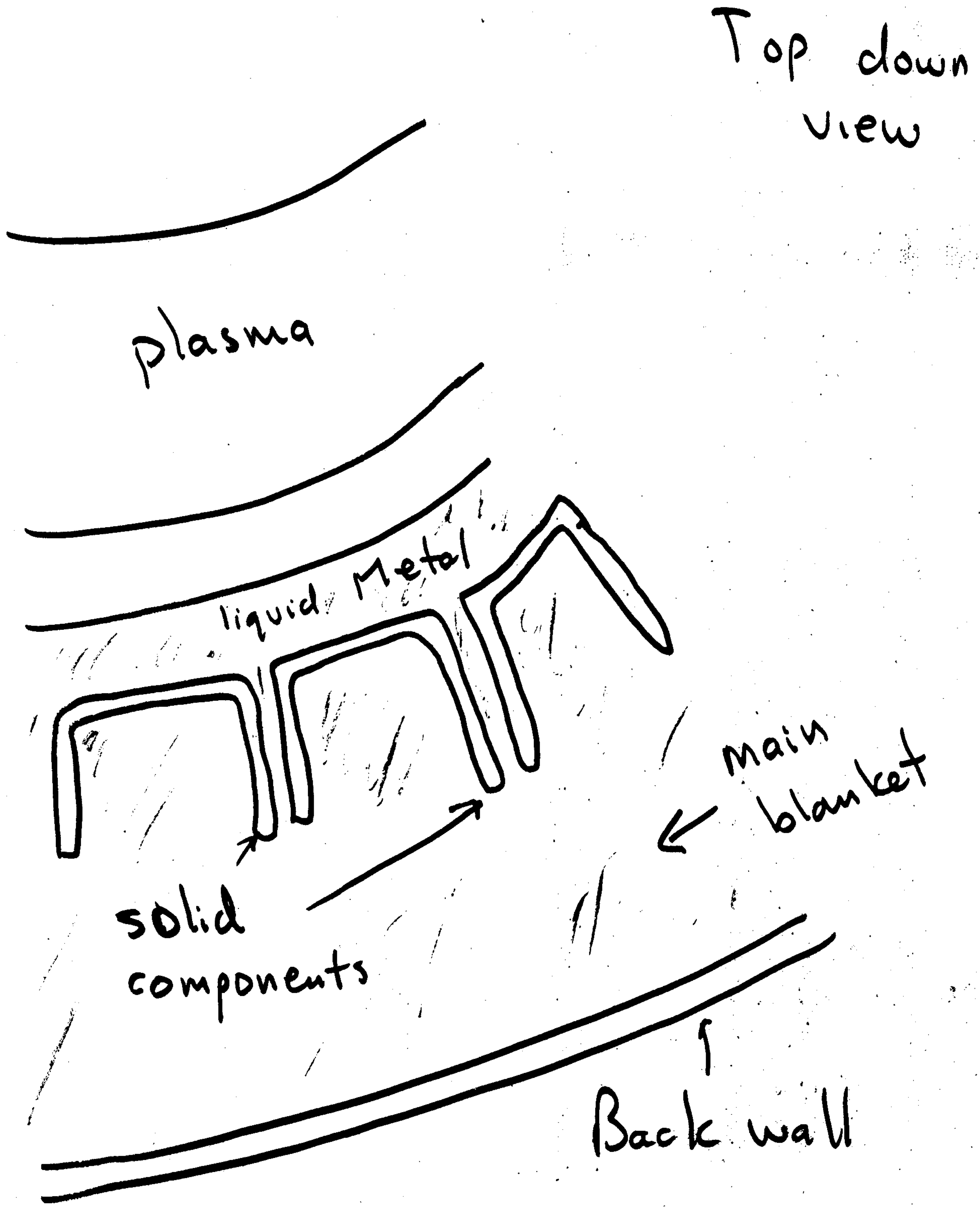
do a dynamic fluid simulation

of a section of a wall with a
small square being removed slowly.

Is it possible to do this
without splashing or disturbing
the plasma facing flow overly

seriously?

Easily replaceable solid wall



Flow through the cracks in the solid first wall components is <u>very</u> slow: $v_{crack} \sim E/B$

$\ll 1$ mm/sec

If vapor pressure is a problem, the liquid facing the plasma could be at a low temp (e.g. < 300°C) while most of the energy is deposited in the much hotter main blanket

(extra complexity: two power conversion systems?