APEX Task B Summary for FY01

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1. Task B: Liquid wall-Bulk Plasma Interactions

1.1 Introduction

The main goal of APEX Common Task B is to support the major APEX task areas. In FY01, this effort focused on Task I: Options and Issues for Implementing Flowing Liquid Wall in NSTX, Task II: Experiments and Modeling with Liquid Walls, and Task V: Conducting Shell Deployment for Liquid Wall Concept.

1.2 Support of Task I

1.2.1 Characterization of NSTX Operating Conditions

As part of the effort to develop a liquid lithium module for NSTX, magnetic field distributions for NSTX plasmas were contributed to a database that is accessible by APEX and ALPS designers for scoping studies. This information is also available for an Alcator C-Mod discharge. Details regarding access to the database were described in memoranda by M. Ulrickson of Sandia National Laboratories.[1]

The poloidal field distribution in and near the plasma for NSTX and Alcator C-Mod in the database were computed based on the EQDISK file information from the machines. The EQDISK files were generated using the EFIT equilibrium reconstruction code.[2] The poloidal field was then be decomposed into vertical and radial fields according to the vector potential. In addition, field gradients are also computed.

For NSTX, the two cases presently available are for a low beta, lower single null plasma and high beta (23%) discharge. In the latter, the plasma is limited on the inner wall, i. e., the center stack, but there is an X-point not far from the last closed flux surface. Additional cases will be added, so that the design of a liquid surface module can consider a range of operating points to assure the module is suitable.

1.2.2 Identification of Key Issues for NSTX Liquid Lithium Module

The issues related to the implementation of a liquid lithium module in NSTX, including the relative merits of divertor and limiter concepts, were identified. These were described in a summary of the Applications of Liquid-plasma Interactions Science and Technology (ALIST) Working Group Meeting held May 5-7, 2001.[3]

The focus for ALIST is particle control rather than power handling. A tokamak issue relevant to NSTX is whether or not the two phenomena be separated. The conclusion was that both divertor and limiter concepts need to be pursued for NSTX and Alcator C-Mod. It was noted that wall coatings are already in their baseline programs, and do not need to be specifically included in ALIST activities. The need to inventory materials in these machines for compatibility with Li was also identified.

Concerning the consideration of specific module types, the need to develop concepts for bottom troughs, jets (including jets flowing along wires and jets angled to give a toroidal component to the flow), flow over a plate, the soaker hose, and the neutral catching Li film was identified. The following general questions that might be useful for future discussions were suggested: modules versus toroidally continuous flow; jets or streams versus flow over a plate; and, batch handling rather than continuous flow. With regard to batch handling, it was felt that, if heat removal were possible with batch handling, the simplifications (e.g., avoid continuous fluid flow or at least entrance and exit flows) might be a significant advantage. The group recommended that ALIST be in touch with NSTX and C-MOD to identify the issues associated with the implementation for any schemes we suggest.

A more complete description of the issues is provided in the ALIST meeting summary. Their resolution is a key element in the development of an R&D plan for liquid lithium implementation on either NSTX or Alcator C-Mod.

1.3 Support of Task II

1.3.1 Liquid Metal Experimental Facility

Support for the liquid metal MHD facility at UCLA (MTOR) was also included in Task B. Initial exploratory experiments have begun, and plans are already being made for upgrading the device for higher field operation.

Two documents record the Task B work on MTOR in FY01. The first described a calculation of the inductance of the MTOR toroidal field (TF) coil set by R. Woolley of PPPL.[4] The inductance parameter, L, is defined in terms of total magnetic energy and per-turn current, as

$$L = \frac{2E}{{I_{turn}}^2} \tag{1}$$

Total magnetic energy is calculated as the volume integral over all space:

$$E = \iiint \frac{B^2}{2\mu_0} dV \tag{2}$$

where B is the local magnetic field at each location in Teslas, dV is an infinitesimal element of volume, and μ_0 is the permeability of free space. Although MTOR has 24 discrete TF coils, the MTOR facility is approximately axisymmetric. Because of this, the coil set was modeled as a spatially continous toroidal shell with a circular cross-section and a constant nonzero coil winding thickness.

Under this assumption, the estimated inductance is 0.074 henries. The estimated stored magnetic energy at 1800 amps per turn is as follows.

$$\begin{aligned} E(1.8kA) &= \frac{1}{2}(0.074039)(I_{turn} = 1800)^2 \\ &= 119,943 \approx 120 \text{ kilojoules} \end{aligned} \tag{3}$$

This inductance estimate, when combined with the rated coil resistance of R=(24)(.00723)=0.1735 ohms, implies a time constant, for the current in a shorted coil system to decay to (1/e) of its initial value, of L/R=0.074/0.1735 = 0.4265 seconds.

The second was a description of a proposed grounding and ground fault detection system by R. Ramakrishnan and R. Woolley of PPPL.[5] This is shown in Fig. 1.

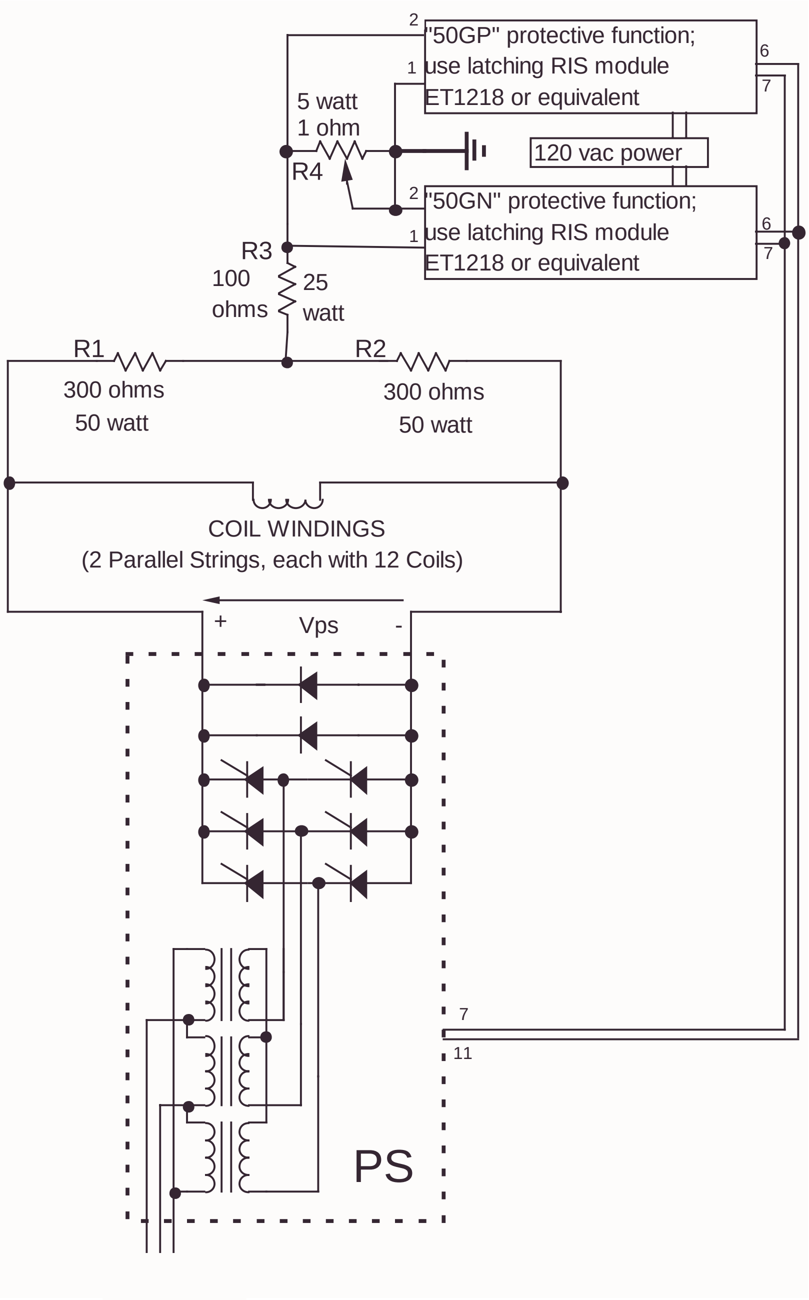


Fig. 1.3-1: Grounding and Ground Fault System for MTOR

Fig. 1.3-1 depicts the twenty-four coils as a single inductor, even though the coil windings are electrically connected in two parallel strings, with each string including 12 coils connected in series. The scheme includes ground circuit resistors R1, R2, R3, and R4. Because R1 and R2 have identical resistance values, the ground connected to R4 effectively biases the midpoint of the coil system to ground potential. During normal powered operation without any ground fault, currents flowing in resistors R1 and R2 are equal, so the ground fault current flowing through resistors R3 and R4 remains zero. If a coil system ground fault connection develops at some location different from the coil system's midpoint, however, then currents through R1 and R2 become unequal during powered operation, so a ground fault current then flows in resistors R3 and R4.

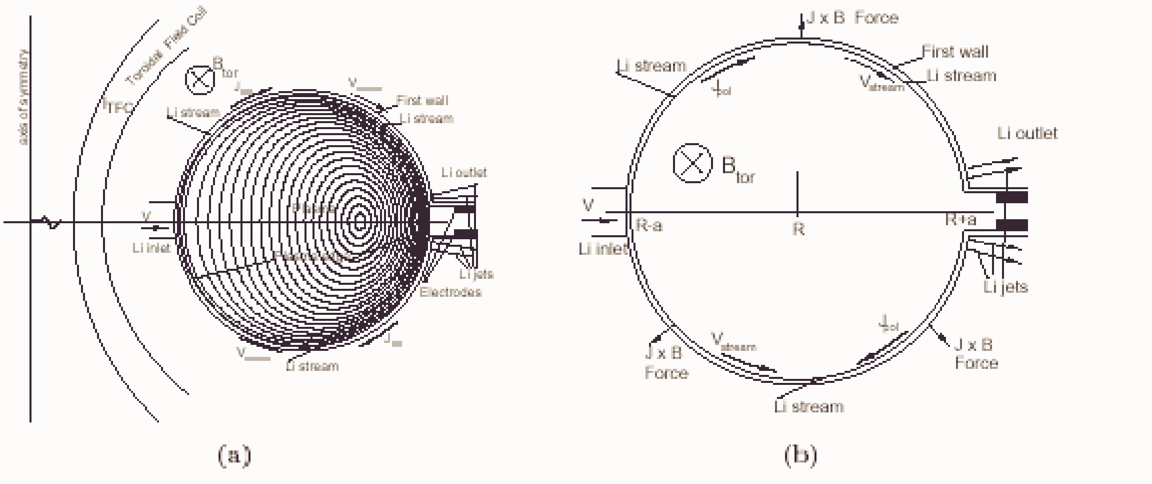
The grounding system recommended by Ramakrishnan and Woolley is not intended to provide personnel protection when people are working, hands-on, on the unpowered system. Indeed, its impedance to ground is too high. During such work, low impedance ground connections should be firmly connected to system conductors, and either power supply operation must be utterly defeated or the supply disconnected.

1.4 Task V: Conducting Shell Deployment for Liquid Wall Concept

1.4.1 Magnetic Propulsion/Resistive Wall Mode Stabilization

Theoretical results were also obtained and published on the stabilization of tokamak plasmas by lithium streams in FY01. They were summarized in a report by L. Zakharov of PPPL.[6] The stabilization theory of free-boundary magnetohydrodynamic instabilities in tokamaks by liquid lithium streams driven by magnetic propulsion was formulated. While the conventional, wall-locked, resistive wall mode can be well suppressed by the flow, a new, stream-locked mode determines the limits of the flow stabilization.

The flow stabilization uses a mechanism of magnetic propulsion for driving fast lithium streams along the plasma facing surface of the tokamak vacuum chamber (Fig.1.4-1a). The metal is maintained at the first-wall surface by the ***JxB*** electromagnetic force (Fig.1.4-1b), where ***J*** is the poloidal current driven through the liquid metal by an external power source, and ***B*** is the tokamak magnetic field. The magnetic pressure, created in the fluid, is nonuniform along the lithium layer. The fluid is propelled from the high-field side of the tokamak to the low-field side in the form of two streams along the top and bottom halves of the vacuum chamber.



(a) (b)

Fig.1.4-1: (a) Cross section of the tokamak with lithium streams (inlet and outlet are both schematic). (b) Guide wall with two lithium streams at the top and bottom halves of the chamber.

An example of the improved stability of tokamak free-boundary modes in with lithium streams is shown in Fig. 1.4-2. They depict the results for pressure driven kink modes. With the liquid metal flow, stability gaps appear for finite-beta plasma even for a uniform current distribution. For a given toroidal mode number n, the size of these gaps is not sensitive to the poloidal mode number m for both current and pressure driven free-boundary modes. Thus, both low and high-m modes can be stabilized by the lithium flow. The stabilizing effect depends on the Reynolds number of the flow, and in particular, when it exceeds 1. In contrast to a “rotating” wall, the m = 1 pattern of the stream flow may lead to a more promising means of stabilizing the plasma.

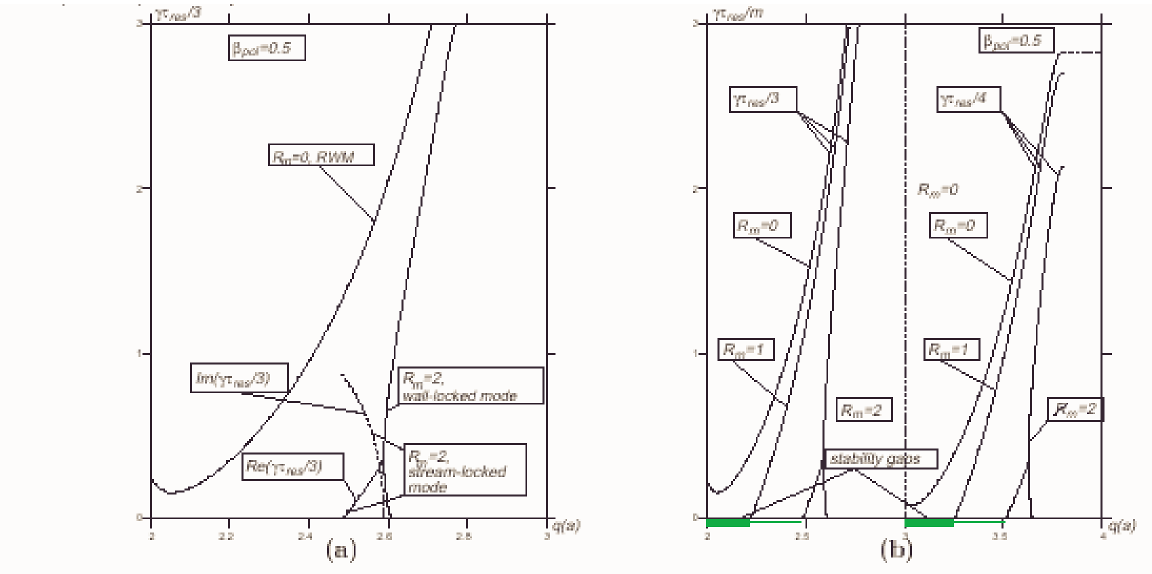


Fig. 1.4-2: Normalized growth rates and rotation frequencies ($\gamma\tau_{res}$) of resistive wall modes for a circular plasma (aspect ratio R/a = 4) with a uniform current distribution and $\beta_{pol} = 0.5$. For various magnetic Reynolds numbers R_m, the graphs show a) results for the wall and stream-locked m = 3 mode, and b) the stability diagram for safety factor range $2 < q_a < 4$.

Task B also supported analytical studies of resistive wall modes in the presence of liquid walls. This work was published by H. Rappaport of the Institute for Fusion Studies at the University of Texas in a paper entitled “Coupling of the Resistive Wall Mode to Liquid Wall Surface Modes.”[7] This was an analysis of the resistive wall mode of a fusion plasma surrounded by a cylindrically symmetric rotating thin liquid metal shell. To investigate the coupling between the resistive wall mode and free fluid boundary surface modes, the cases shown in Fig. 1.4-3 were considered. The consequences of fluid perturbations induced in the wall on the wall mode growth rate were found to be greater when the wall fluid had a vacuum–fluid interface, rather than when the fluid was forced to flow between solid bounding shells.

The effect of the fluid perturbations was always found to be destabilizing, except close to the wall mode/surface mode resonance. When the wall mode/surface mode coupling is nonresonant, the effect of the fluid velocity perturbations on the growth rate is controlled by the degree to which the wall mode excites fluid motions in the liquid shell, and the wall mode rotation is locked to the fluid rotation.

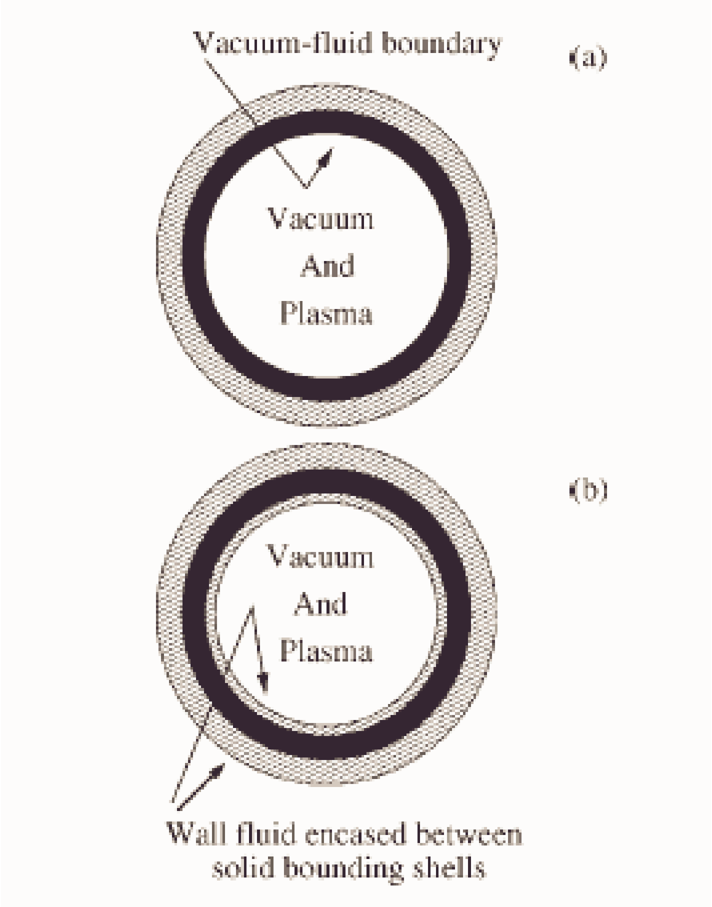


Fig. 1.4-3. Liquid wall configurations considered were (a) where a vacuum–fluid boundary or ‘‘free’’ liquid boundary is present, and (b) where the wall fluid (dark solid band) is trapped between solid bounding shells.

Resonance occurs in the regime where the complex wall mode frequency is very close to the surface mode frequency. Since the wall mode is assumed to be unstable, and the forces on the surface mode introduce wave damping, the resonance effect is strongest when the surface mode is weakly damped and the wall mode is weakly growing. If the surface modes are weakly damped, the surface mode frequency increases with fluid shell thickness. On the other hand, the wall mode frequency decreases with fluid shell thickness, so there is a critical fluid shell thickness for resonance.

The strength of the resonance thus depends on the ratio of the real part of wall mode frequency to the wall mode growth rate. The excitation of surface waves appears as a peak and a dip in the wall mode growth rate with increasing fluid shell thickness, as seen in Fig. 1.4-4. Because of this resonance effect, it may be possible to utilize the stabilizing effect of the surface mode excitation in conjunction with other wall mode stabilizing effects.

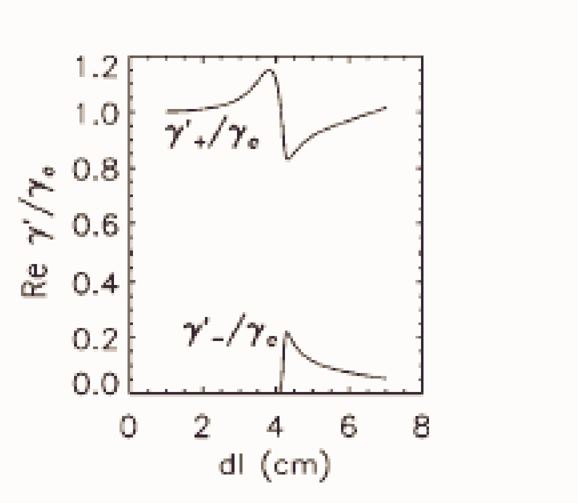


Fig. 1.4-4 Wall mode and surface mode growth rates as a function of fluid shell thickness. Growth rates are normalized to the growth rate found for a solid shell with the same resistivity and shell thickness.

Further studies of resistive wall mode stabilization with flowing liquid walls that were supported by Task B are summarized in the Task V report.

[1] M. Ulrickson, “Poloidal Field in ARIES-RS, CMOD, CDX-U, and NSTX,” May 16, 2001, and M. Ulrickson, “Corrected Poloidal Field Files,” June 19, 2001.

[2] L. Lao *et al.*, Nucl. Fusion **25,** 1611-1622 (1985)

[3] “Summary of ALIST Meeting: May 7-8, 2001,” July 5, 2001

[4] R. Woolley, “Calculated TF Inductance Estimate for the MTOR Facility,” February 6, 2001

[5] R. Ramakrishnan and R. Woolley, “MTOR Grounding and Fault Detection Scheme,” March 1, 2001

[6] L. Zakharov, “Stabilization of Tokamak Plasma by Lithium Streams,” accepted for publication in Plasma Physics and Controlled Nuclear Fusion (2002)

[7] H. Rappaport, Physics of Plasmas **8**, 3620-3629 (2001)