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by

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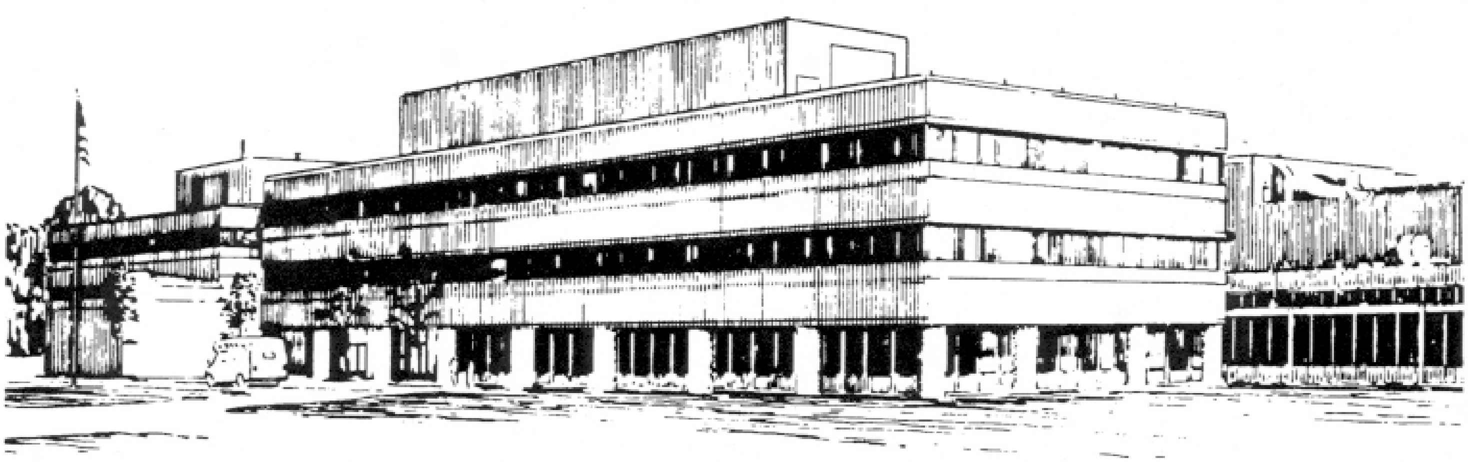

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Modeling of Spherical Torus Plasmas for Liquid Lithium Wall Experiments

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***Abstract*--Liquid metal walls have the potential solve to first-wall problems for fusion reactors, such as heat load and erosion of dry walls, neutron damage and activation, and tritium inventory and breeding. In the near term, such walls can serve as the basis for schemes to stabilize magnetohydrodynamic (MHD) modes. Furthermore, the low recycling characteristics of lithium walls can be used for particle control. Liquid lithium experiments have already begun in the Current Drive eXperiment-Upgrade (CDX-U). Plasmas limited with a toroidally localized limiter have been investigated, and experiments with a fully toroidal lithium limiter are in progress. A liquid surface module (LSM) has been proposed for the National Spherical Torus Experiment (NSTX). In this larger ST, plasma currents are in excess of 1 MA and a typical discharge radius is about 68 cm. The primary motivation for the LSM is particle control, and options for mounting it on the horizontal midplane or in the divertor region are under consideration. A key consideration is the magnitude of the eddy currents at the location of a liquid lithium surface. During plasma start up and disruptions, the force due to such currents and the magnetic field can force a conducting liquid off of the surface behind it. The Tokamak Simulation Code (TSC) has been used to estimate the magnitude of this effect. This program is a two dimensional, time dependent, free boundary simulation code that solves the MHD equations for an axisymmetric toroidal plasma. From calculations that match actual ST equilibria, the eddy current densities can be determined at the locations of the liquid lithium. Initial results have shown that the effects could be significant, and ways of explicitly treating toroidally local structures are under investigation.**

I. INTRODUCTION

Liquid walls offer many potential advantages over solid walls in the design of fusion energy systems.[1] Among them are the capability for high power density, which can eliminate thermal stress and wall erosion as limiting factors. This can also lead to smaller and lower cost components, such as chambers, shielding, vacuum vessels, and magnets. Other advantages are improved disruption survivability and reduced radiation damage in structural materials. Reduction in the volume of radioactive waste is also anticipated.

Liquid metal walls can result in improvements in plasma stability and confinement. These may permit plasmas with higher β, or ratio of plasma pressure to the pressure of the confining magnetic field. Exploration of the relationship between liquid metal walls and magnetohydrodynamic (MHD) instabilities has begun,[2,3] but many issues remain.

One of the features of a liquid lithium wall is its predicted effect on particle control. The benefits of a surface that has low recycling were shown with the "Deposition of Lithium by Laser Outside of Plasma" (DOLLOP) lithium wall conditioning experiments in the Tokamak Fusion Test Reactor (TFTR). [4] Effects on plasma density were also seen on the T-11M device,[5] where a Capillary Porous System (CPS) was used to form a "self-restoring" liquid lithium limiter surface.[6]

Experiments on the Current Drive Experiment-Upgrade (CDX-U) have recently begun with a fully toroidal lithium limiter.[7] The objective on CDX-U is to study auxiliary-heated discharges whose surface contact is primarily with a large-area liquid lithium limiter.

There are also plans to install a liquid surface module (LSM) on a large toroidal magnetic fusion device, such as the National Spherical Torus Experiment (NSTX) or Alcator C-Mod. A schematic of such a device for NSTX is shown in Fig. 1. The LSM is the thin rectangular structure on the right side of the figure. It spans the horizontal midplane of the vacuum vessel, and extends almost the full length of the space between the upper and lower passive stabilizer plates.

Studies have been performed of the hydrodynamics and MHD effects in liquid walls for various reactor concepts, including the spherical torus. They have already suggested certain special considerations for the ST. This confinement scheme has higher elongation compared to large aspect ratio devices (e. g., ARIES-

RS[8]), so the centrifugal force acting on the liquid as it moves poloidally along the wall is less. This force can be increased if the flow is caused to swirl in the toroidal direction, and it may actually improve its hydrodynamic stability.

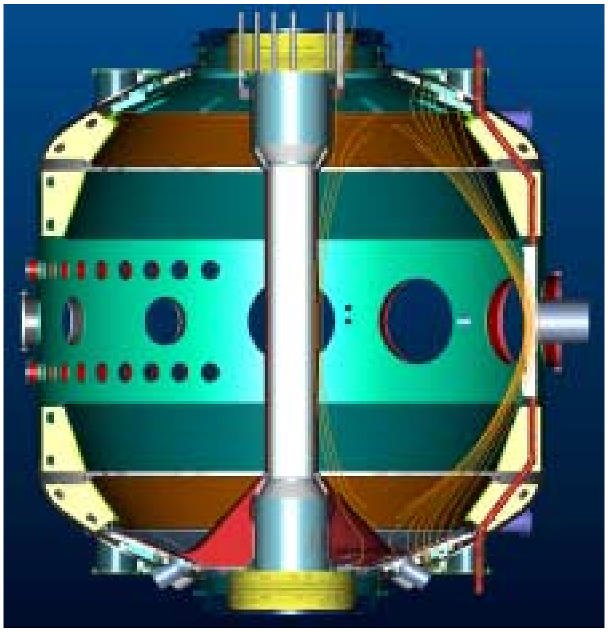

Fig.1. Cross section of NSTX with liquid lithium module. The field lines for a double null divertor configuration intersect the module on the midplane of the vacuum vessel.

Such investigations, however, have not included any dynamic calculations of the plasma itself. This paper identifies some of the issues that need to be addressed in such an integrated approach, and a first attempt at estimating the effects of an ST plasma on a liquid metal wall.

The Tokamak Simulation Code (TSC)[9] is the program that was used in this work. This is described in Section II. Two ST cases have been considered. The first involved the simulation of an NSTX plasma. Because measurements of the discharge parameters are available, this case provides a means of checking the validity of the TSC model. The second case focused on a burning plasma spherical torus (BP-ST) design. The two sets of simulations are compared in Section III. A summary of this preliminary study and issues to be addressed in future TSC are summarized in Section IV.

II. DESCRIPTION OF THE TOKAMAK SIMULATION CODE

The TSC is a program that calculates two-dimensional free boundary equilibria for fusion plasmas. It advances the magnetohydrodynamic (MHD) equations to determine the evolution of a magnetized toroidal plasma on a transport time scale.

The code evolves the magnetic field in a rectangular computational domain as it solves the Maxwell MHD equations for the plasma. Coupling to the circuit equations for the poloidal field coils occurs through the plasma boundary conditions.

The plasma model uses functional forms for the electron and ion thermal conductivities, the particle diffusion coefficients, and the plasma electrical resistivity. The transport mode is semi-empirical, in that it uses adjustable parameters to fit values from an experimental database. Reference [9] contains a detailed description of TSC.

III. TSC SIMULATIONS OF NSTX AND BURNING PLASMA SPHERICAL TORUS DISCHARGES

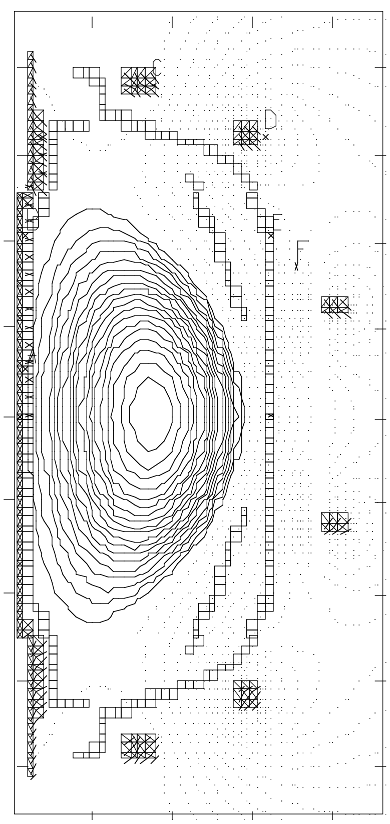

Fig.2. TSC simulation of 1 MA NSTX equilibrium

The TSC program has been used simulate NSTX plasmas. Figure 2 shows some of the features of the model. It includes a vacuum vessel with DC breaks to permit different potentials for the inner and outer sections. This is a requirement for coaxial helicity injection,[10] which is a means for the noninductive initiation and sustainment of the plasma current.

The passive stabilizer shell, which is composed of curved copper plates above and below the midplane, is also in the model. The six rectangles outside of the vacuum vessel correspond to the poloidal field coils. The poloidal flux near the1 MA peak of the plasma current is shown inside the vacuum vessel.

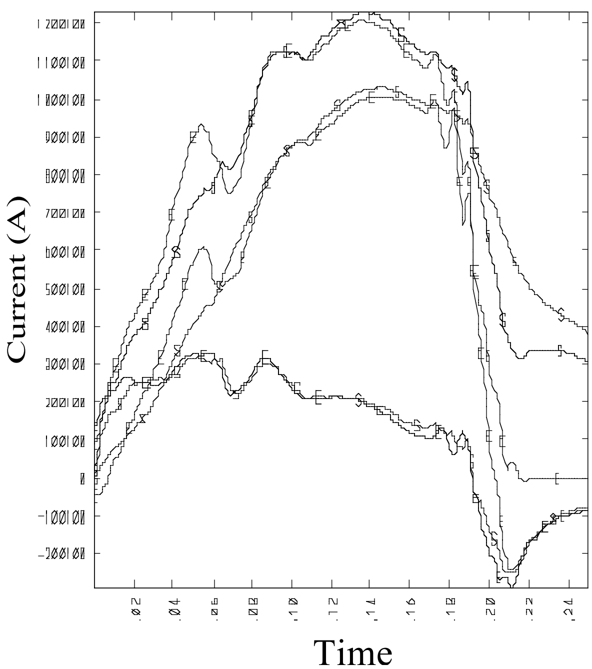

Fig.3. Comparison of TSC results with experimental measurements for 1 MA NSTX discharge

The TSC simulation of the time evolution of a typical 1 MA NSTX plasma is shown in Fig. 3. The uppermost curves show the sum of the currents in the plasma and the vacuum vessel. The plasma current alone is represented in the middle curves, and the vacuum vessel current is indicated in the lowermost curves. Each set of curves compares the TSC results with experiment, and the good agreement is reflected in how well they overlay.

A BP-ST discharge was also simulated with TSC. In this case, the plasma current was ramped up to its maximum value of 12 MA in 4 seconds. The poloidal flux at the peak of the plasma current is plotted on a cross section of the vacuum vessel in Fig. 4.

As in Fig. 2, the rectangles outside of the vacuum vessel correspond to the eight poloidal field coils. Unlike NSTX, however, the vacuum vessel is continuous conductor, and there is no passive stabilizer shell.

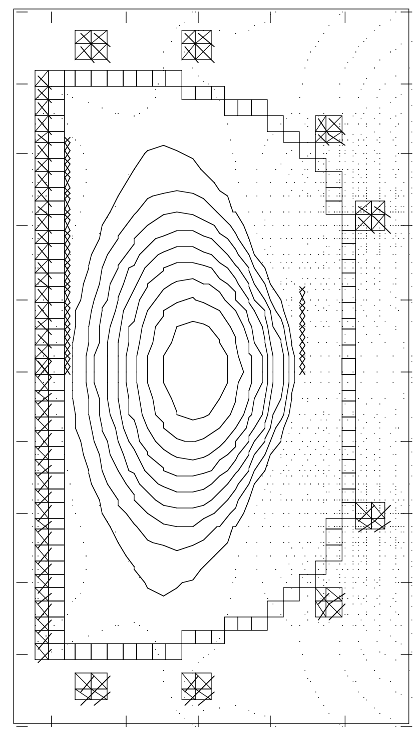

Fig.4. TSC simulation of 12 MA BP-ST equilibrium

As a first step in estimating the electromagnetic (***jxB***) forces of plasmas on liquid lithium walls in the NSTX and BP-ST cases, the current densities induced at the location of a possible lithium surface were calculated with TSC. This was chosen to be at the vacuum vessel wall in the horizontal midplane of each device. The conductivity of lithium is similar to that of the stainless steel vacuum vessels typically assumed in the TSC simulations.

The current density determined for NSTX was about 4 x 10^5 A/m^2. With a magnetic field at the vacuum vessel wall of about 0.15 T, this translates into a force of about 6 newtons per square cm. For the BP-ST, the value was approximately 3 x 10^4 A/m^2. The lower value reflects the slower current ramp of 3 MA/s in the latter case. The magnetic field at the vacuum vessel wall is about 0.8 T, so that the corresponding force is 0.24 newtons per square cm.

Although these forces appear to be modest, how they translate into the liquid lithium thicknesses and flow rates required for the MHD effects to be counteracted by the viscous force needs to be determined. This requires a simulation of the free fluid surface, and there is no model for it in TSC at this time.

IV. SUMMARY AND ISSUES FOR FUTURE TSC SIMULATIONS

Spherical torus plasmas have been modeled with the TSC program. Calculations of NSTX plasmas show good agreement with experimental measurements. A useful model for an ST fusion reactor has also been provided with the BP-ST simulation. The TSC calculations have resulted in estimates of current densities at the vacuum vessel wall in the horizontal midplane of each machine.

The relationship between the current densities obtained from TSC and the requirements for liquid lithium flow is not yet known. The next step in determining this is to develop a code to model a free liquid lithium surface at the plasma boundary.

The TSC treats the region between the plasma and the wall as a high-resistivity fluid with uniform properties. The best solution for calculating the motion of the free lithium surface might be to take the electromagnetic loads from TSC and use these as input to another, more specialized code that can follow the motion of the lithium surface.

In contrast with the effects of a plasma on a liquid lithium wall, some of the consequences of such a wall on a plasma may be easier to simulate. The lithium surface is expected to be fully non-recycling. Its effects can be investigated with TSC by varying the particle confinement time and edge parameters. They would be changed in a manner consistent with the expected influence of the lithium, and this is planned for the next calculations with TSC.

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