APEX Task I Summary Report for FY01

Content

APEX Task I has been aimed at exploring flowing liquid wall options and, within a 5-year time frame (~2004), operating a flowing liquid wall experiment in an experimental physics device. The goals of Task I are to help develop and provide liquid wall technology systems that meet experimental physics device (such as NSTX) conditions before installation.

I. Field Characterizations for Near Term Physics Devices (e.g. NSTX and CMOD)

The poloidal flux distribution in and near the plasma for NSTX and CMOD were computed obtained from the EQDISK file information. Only two cases were analyzed for NSTX; a) a high beta (23%) inner wall limiter plasma and b) a low beta lower single null plasma. A lower single null plasma with modest beta was the only case provided by CMOD. Since the parameters of a given machine are variable (plasma current, toroidal field, plasma pressure, etc. may all be varied over a range, while the sign of some values may also change), the design of a liquid surface module for a device can not be fixed in one set of conditions but rather to consider a range of operating points to assure the module is suitable. Additional cases will have to be analyzed before final design of a module to be placed in either device. Therefore, the field data documented in the APEX web site should only be used for scoping studies. The poloidal field is calculated from the vertical (z) and radial (R) gradients of the flux. The radial and vertical fields at the lower divertor plate in NSTX are shown in Figure 1. Divertor region fields for CMOD are shown in Figure 2. In addition, field gradients are computed. In general, due to the small size of C-Mod and NSTX the toroidal field gradients are larger than for DIII-D, ITER. Poloidal field gradients for NSTX and CMOD are shown in Figures 3 and 4 respectively. Note that poloidal field gradients in excess of 0.1 T/m are evident, whereas the gradients in the toroidal field exceed 1 T/m because of the small major radius of these devices.

II. Design Exploration for CMOD

Novel CMOD divertor concept has been proposed as shown in Figures 3 and 4. In the proposed concept, the modules form a continuous toroidal array, but would not form a continuous electrical loop, as there is an electrical break at each current feed. The intent is to provide as close to a toroidally continuous surface as possible, but there is an insulating break between each module. The module sides could be changed from radial to a 45 degree angle from radial at the front to facilitate complete coverage if this is deemed necessary. A current is applied perpendicular to the flow direction in the lithium channel that provides an electromagnetic propulsion effect, which in turn propels the liquid around the channel and out nozzles to form jets. Calculations indicate that the current direction is indeed across the channels and that no current is flowing in the jets themselves. Preliminary calculations based on 2-D MHD modeling show that a current of about 100 A is sufficient to provide a jet velocity of about 10 m/s in C-Mod, which has a toroidal field of around 10 Tesla (the field in CMOD is about 6 Tesla not 10, the current will probably need to be higher). The wall consists of multiple rows of jets that “shadow” each other. The present concept shows two modules attached to one bias electrode but other combinations are possible.

Although the design can be modified (for example, to raise the jet to a higher elevation to allow the plasma strike on the jet instead of the solid tile), urgent questions to be addressed for the proposed self-pumped divertor concept are: (1) will the surface area be large enough for particle pumping? and, (2) will the stable free jets (about 1-5 mm diameter and 20 cm tall) form in the proposed region (field gradient effect)? 3) can the flow former and flow catcher be shielded from plasma heat flux by geometry alone?

III. Design Analysis of NSTX Free Surface Flow Options

The goal of the analysis is to provide design information for the APEX study in order to evaluate the feasibility of a fast free lithium surface for particle and heat removal in a near term physics device. This is accomplished by the development of 3D MHD model. Considering that at any given point in time the velocity field of the main hydrodynamic quantity can be directly relating with the main electromagnetic one (the magnetic field) without any interference it is possible to build a MHD module into an existing CFD code (FLOW-3D [1] in this case), which has a verified Navier-Stoke’s solver for turbulent, free surface flows. The MHD effect is reflected in an additional term of Lorentz force in the momentum equation at each time step. In the present model, the MHD Lorentz force caused by the induced current is derived from the Ampere’s law by solving the induced magnetic field equations.

The flow of an electrically conducting fluid under the influence of an external magnetic field is governed by the following equations which express the conservation of mass and momentum,

$$\frac{\partial V}{\partial t} + (V.\nabla)V = -\nabla p + \frac{1}{\mathrm{Re}}\Delta V + N(j \times B), \qquad (1)$$

$$\nabla \cdot V = 0 \qquad (2)$$

together with the induced magnetic field equation and the conservation for the magnetic field under the classical MHD assumptions [2-3],

$$\frac{\partial B}{\partial t} - \nabla \times (V \times B) + \nabla \times (\frac{1}{\sigma \mu_m} \nabla \times B) = 0 \qquad (3)$$

$$\nabla \cdot B = 0 \qquad (4)$$

where the magnetic field B includes both the applied (B_o) and induced (B') fields. Two important features are utilized in the developed numerical method to obtain convergent solutions. First, a penalty factor is introduced in order to force the local divergence free condition of the magnetic fields. The second is that we extend the insulating wall thickness to ensure that the induced magnetic field at its boundaries is null. Numerically, the induction equation is discretized according to the central difference scheme, in which the induced magnetic field is specified at the cell center. The resulting set of algebraic equations are then solved iteratively using the Gause-Siedel technique applying boundary conditions at each time step.

The calculated results of the lithium fluid flow along the NSTX outboard midplane proceeding from a uniform, inlet of 10m/s and an initial film thickness of 2 mm is shown in Figure 7. As shown, much of the solid substrate has been left bare due to the fluid being pushed and spilling over one side of the chute. This feature of spilling over one side of the chute is the result of the poloidal (x direction) return current induced by the surface normal field gradient interacting with the toroidal field and can-not be shown with a 2D model. In order to overcome the phenomena in which the fluid is pushed to one side, leaving a bare zone, the center axis of the chute is titled 30 degrees away from the surface normal plane. This allows the flow to closely align with the field line, and reduces the magnitude and its effect of the surface normal field observed by the fluid. As a result (as shown in Figures 8 and 9), the undesired feature associated with the spanwise Lorentz force is eliminated, while no bare spot remains in this modified design. The low velocity magnitudes observed at the downstream can be resolved by increasing the inlet velocity (a velocity of ~10 m/s is desired from the surface heat flux removal point of view).

IV. Preliminary Experimental Study of Free Surface Flow Options Applicable to Near Term Physics Devices

Preliminary jet experiments using GaInSn under the effects of transverse field and transverse field gradient have been conducted in the M-Tor facility. The free jet proceeds out of a 5 mm circular nozzle, passes through a constant field and then an abrupt field gradient before leaving the coils. The toroidal field increases as the current passing through the coils increases. The M-Tor facility gives about 0.6 T at the inboard when it is run at the maximum current of 3400 A. To achieve higher field, a flux concentrator has been placed in the M-Tor to alter local flux distribution and produce a stronger field in the experimental area. The flux concentrator can also be shaped to provide a similar field gradient as seen in NSTX or CMOD. One of the task for year 02 is to design the flux concentrator to generate a prototypical field gradient. A permanent magnet system has been designed to allow similar experiments on flowing lithium in the LIMITS device at Sandia.

In this preliminary set of experiments, the maximum transverse (toroidal) field was about 0.93 T, while the maximum field gradient was 33 T/m. As observed, the turbulent circular GaInSn jet was strongly laminarlized when it passed through the field. The laminarized jet reflected back and forth (in radial direction) as it proceeded through the gradient region. Although video (documented in the APEX Web site under Task 1 conference call) has been taken to record jet's global behavior with respect to MHD effect, better diagnostics to accurately record the amount of jet deflection is an important task for the next year.

V. Disruption Analysis

During plasma disruptions on a liquid lithium surface, the net power flux reaching the surface, where the disruption originally occurred (due to the vapor-cloud shielding effect) is significantly reduced to <10 % of the initial incident power from the scrape-off layer. Mass losses from atomic surface vaporization due to this reduction in radiation power may be tolerated for the expected disruption frequency. However, mass losses due to splashing can be high. Splashing is defined as mass loss in the form of macroscopic particles (MPs), i.e., droplets of liquid metals. The MPs will interact with incoming plasma particles and with the vapor cloud above the surface. Therefore, the dynamic behavior of MPs in the vapor cloud and their influence on the total erosion rate are critically important problems.

Results of unique models and very detailed self-consistent magneto-hydrodynamic calculations are obtained. The dynamics of both vapor clouds and MP interactions are coupled with incoming plasma ions and electrons from the scrape-off layer during the disruption. Depending on the stability of the initially formed vapor cloud above the disruption area and on the physics of droplet interaction with this layer, the splashed lithium thickness can range from ~ 1 mm thick to ~ 4 cm for a typical disruption energy of 100 MJ/m^2 deposited in a 1 ms duration. Other disruption parameters will have different effects on the response of the liquid metal surface.

References

[1] FLOW-3D User's Manual, Version 7.7, Flow Science Inc., 2000.
[2] L. D. Landau, E. M. Lifshitz, L. P. Pitaevskii, Electrodynamics of Continuous Media, Pergamon Press, Oxford, 1984.
[3] H. Branover, Magnetohydrodynamic Flow in Ducts, Israel University Press, Jerusalem, Israel, 1978.

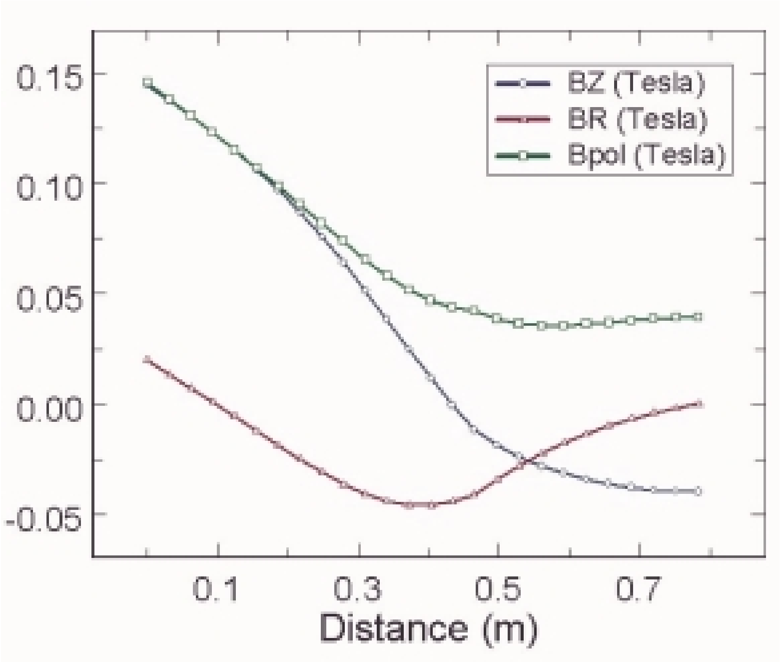

Figure 1. Poloidal field on the surface of the NSTX divertor plate as a function of the distance from the large major radius side.

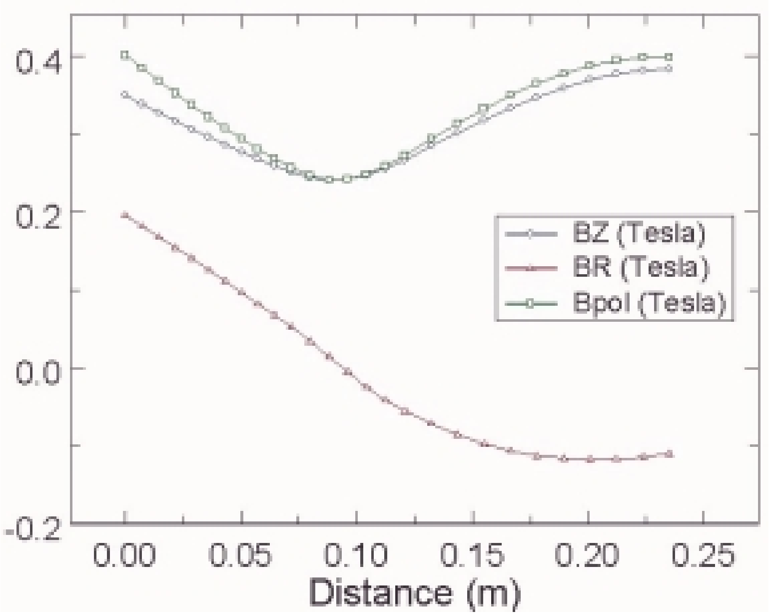

Figure 2. Typical poloidal field along the surface of the CMOD divertor plate starting at large major radius.

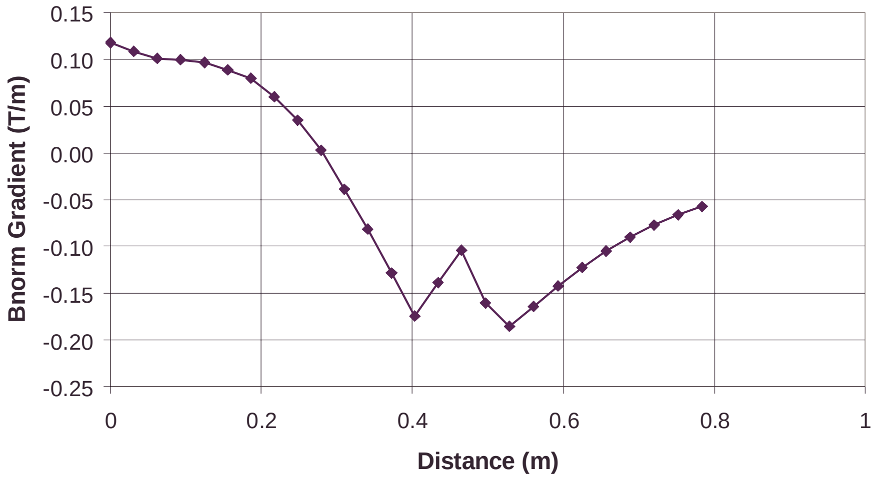

Figure 3. Poloidal field gradient at the NSTX divertor for a lower single null plasma.

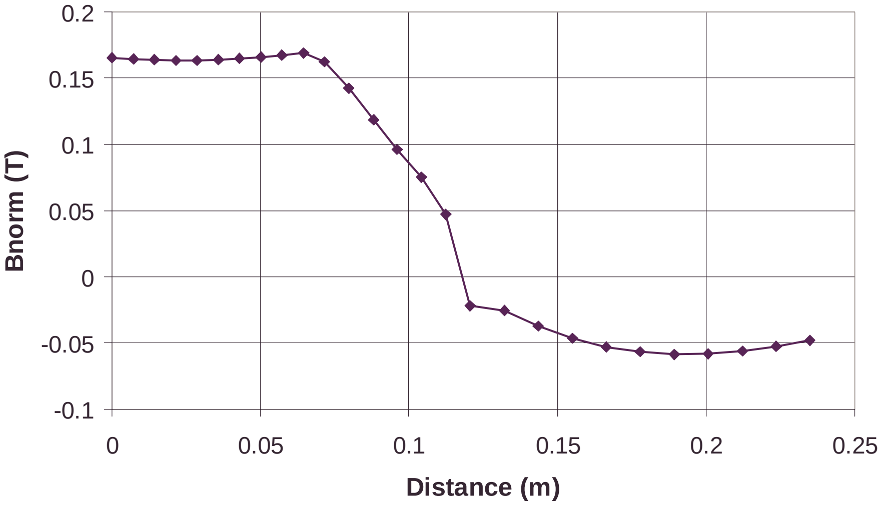

Figure 4.Typical poloidal field gradient along the surface of the CMOD divertor.

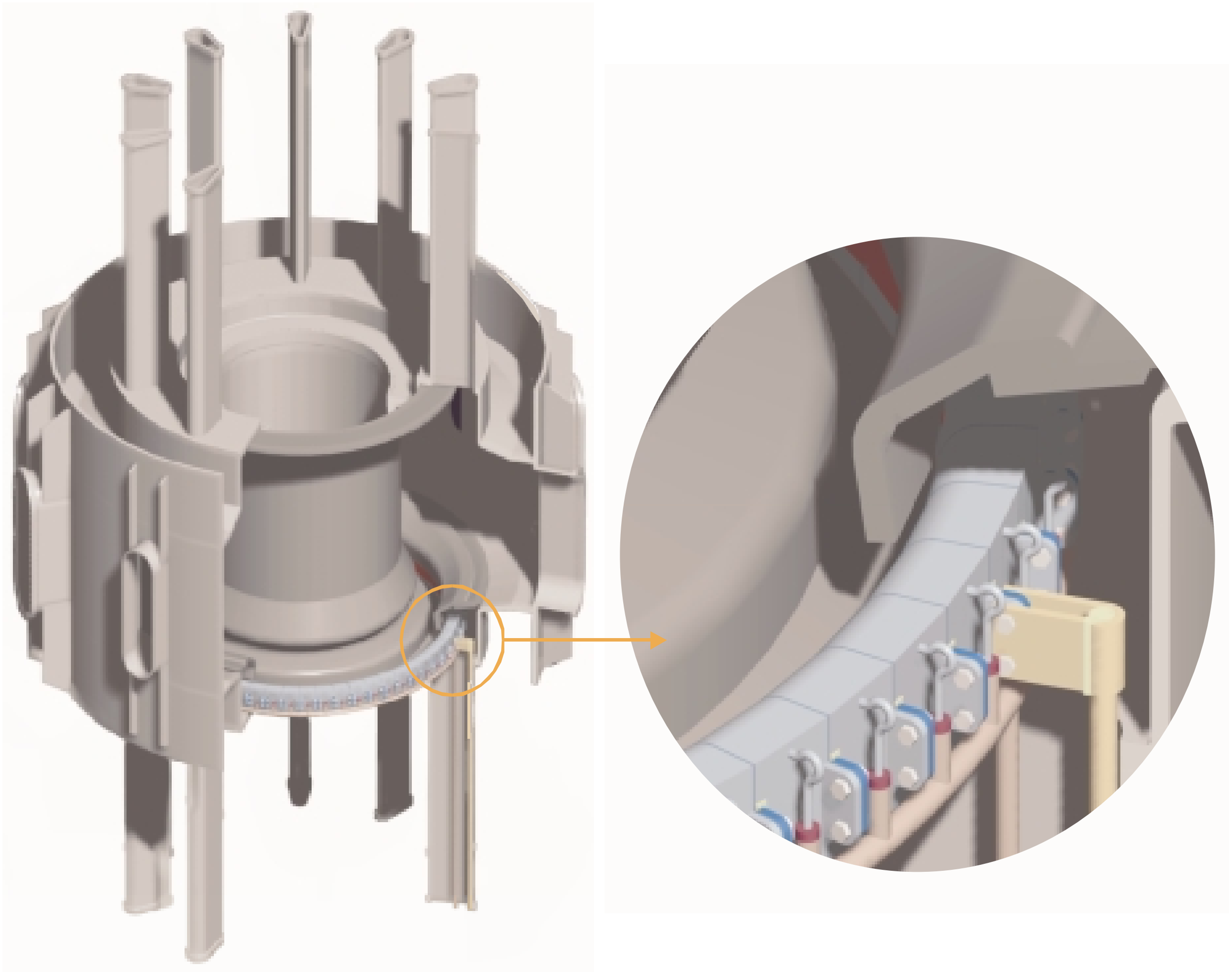

Figure 5 C-MOD shown with circulating liquid lithium modules installed

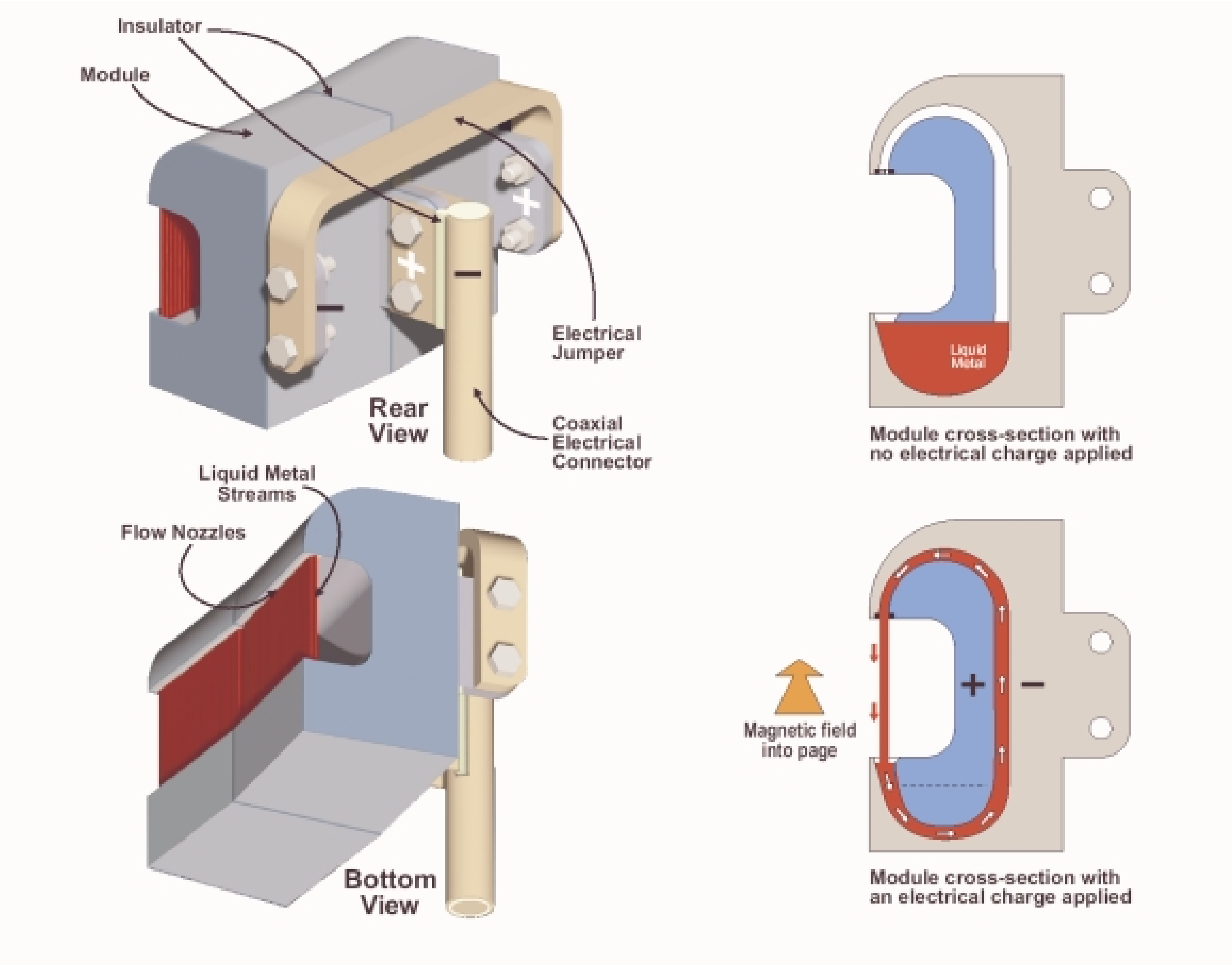

Figure 6 Preliminary concept for self-pumped lithium divertor module for C-MOD. Two modules shown in possible test configuration

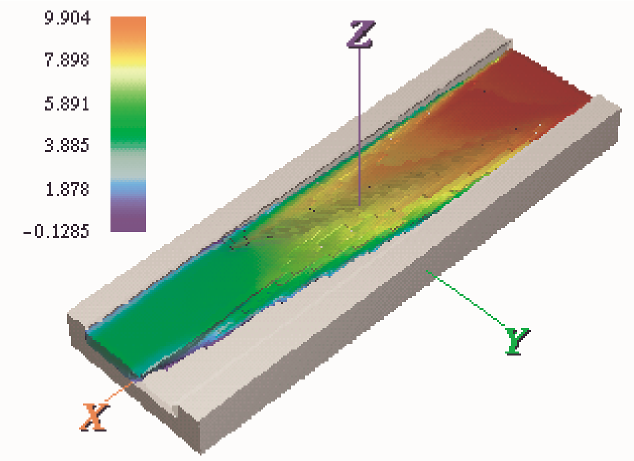

Figure 7. 3D free surface MHD fluid flow at the midplane of NSTX. Contours are u velocity variables.

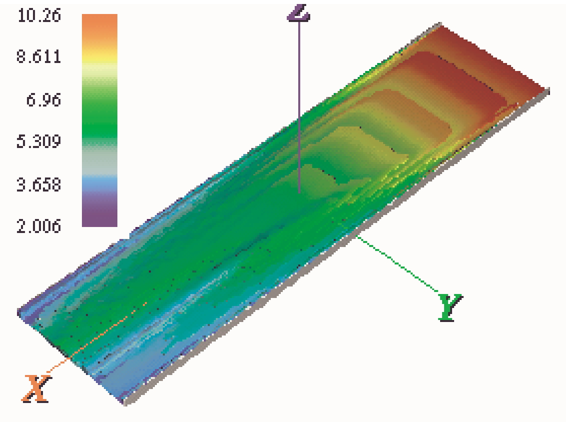

Figure 8. 3D free surface MHD fluid flow at the modified chute of NSTX midplane. Contours are u velocity variables.

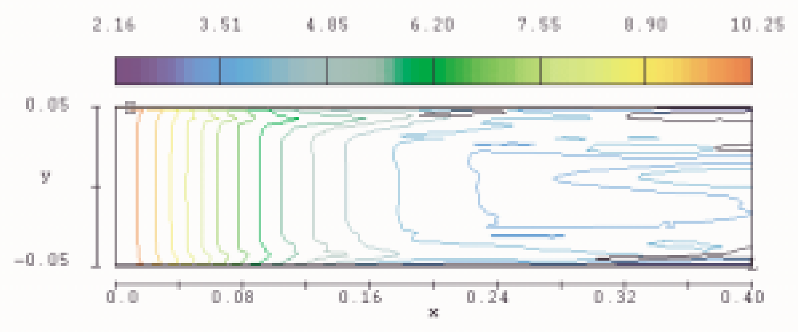

Figure 9. U velocity profile at XY plane of z=7mm.