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Abstract— The Liquid Lithium Divertor (LLD) on NSTX will be the first test of a fully-toroidal liquid lithium divertor in a high-power magnetic confinement device. It will replace part of the lower outboard divertor between a specified inside and outside radius, and ultimately provide a lithium surface exposed to the plasma with enough depth to absorb a significant particle flux.

There are numerous technical challenges involved in the design. The lithium layer must be as thin as possible, and maintained at a temperature between 200 and 400 degrees Celsius to minimize lithium evaporation. This requirement leads to the use of a thick copper substrate, with a thin stainless steel layer bonded to the plasma-facing surface. A porous molybdenum layer is then plasma-sprayed onto the stainless steel, to provide a coating that facilitates full wetting of the surface by the liquid lithium.

Other challenges include the design of a robust, vacuum-compatible heating and cooling system for the LLD. Replacement graphite tiles that provided the proper interface between the existing outer divertor and the LLD also had to be designed, as well as accommodation for special LLD diagnostics.

This paper describes the mechanical design of the LLD, and presents analyses showing the performance limits of the LLD.

Keywords-component; formatting; style; styling; insert (key words)

I. INTRODUCTION *(HEADING 1)*

Development of a practical first wall is a critical component of the path forward to a working fusion reactor. In recent years, the use of flowing liquid metals, particularly lithium, for this purpose, has attracted interest [1]. A liquid lithium first wall offers many benefits including self-healing, high heat removal capability, and pumping of hydrogen and its isotopes.

As a first step towards the goal of a flowing liquid metal first wall, experiments have been performed with liquid, non-flowing lithium limiters on machines such as FTU [2], CDX-U [3], and T-3M and T-11M [4]. In addition, a thin layer of lithium has been evaporated onto the plasma facing tiles of NSTX. The promising results of these experiments have led to the plan to install a liquid lithium divertor (LLD) on the National Spherical Torus Experiment (NSTX).

II. DESIGN OVERVIEW

A portion of the lower outboard divertor is to be replaced by the liquid lithium divertor. The area to be replaced is an annulus, spanning ~8in [20cm] radially, and starting ~2in [5cm] from the inboard edge of the divertor (Fig. 1).

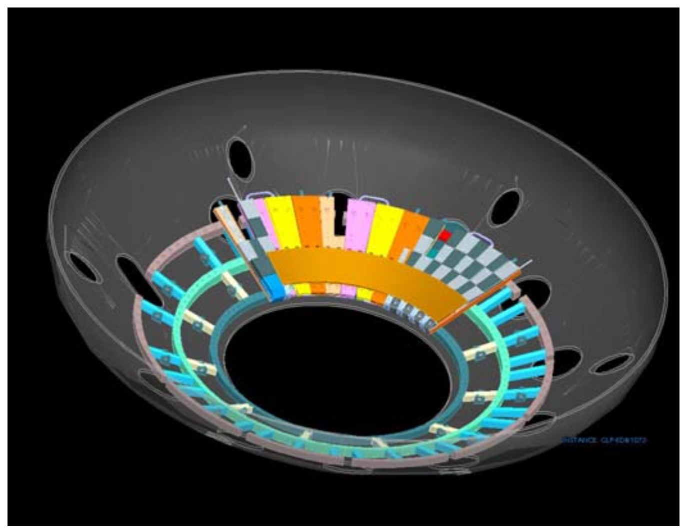

Figure 1. Location of LLD Quadrant on Lower Outboard Divertor

The outboard divertor describes a conical surface, and is made from 48 copper plates attached to mounting rails. Five radial rows of graphite tiles mount to the copper plates. The inner two rows of tiles will be removed when the LLD is installed. A row of shorter tiles will replace row 1. The tiles in the third row will be designed so that they mate properly with the LLD (Fig. 2).

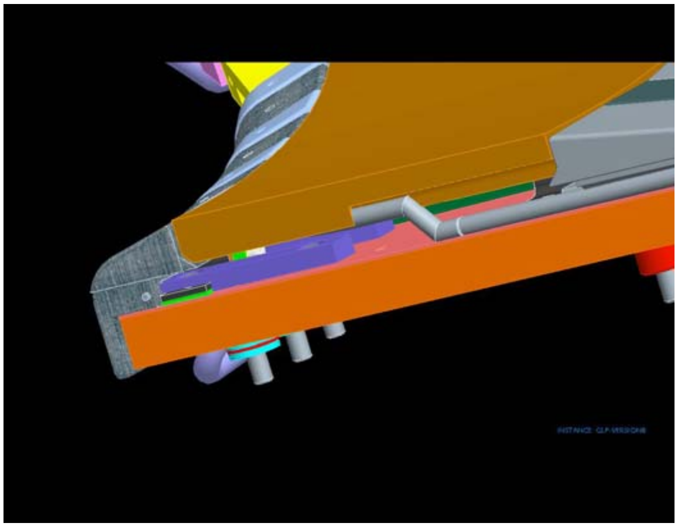

Figure 2. Side View of LLD and Divertor Tiles

Although the area covered by the LLD is an annulus, the LLD must, as a practical matter, be segmented so that it can be installed in the vacuum vessel. The LLD is thus made in four segments, each of which subtends an angle of 82.5deg toroidally. Graphite tiles occupy the space between LLD quadrants. In addition to serving as a proper interface between segments, these tiles will be equipped with various diagnostics

The LLD will be made from a copper substrate, with a thin layer of stainless steel bonded to the plasma face, and a thin layer of porous molybdenum plasma sprayed onto the stainless steel. The molybdenum layer retains the lithium and causes it to wet the surface, rather than bead up. A heating and cooling system will be required to maintain the lithium within its narrow operating temperature range. Four insulating supports at the corners of each quadrant, along with a conducting plug at the center, locate the divertor segment, accommodate thermal expansion, and react the forces caused by eddy currents during a plasma disruption.

III. Design Description

The fundamental challenge associated with the LLD is that of keeping the temperature of the lithium within a narrow operating range. The melting point of lithium is 200 degrees Celsius, and at 400C the vapor pressure begins to increase rapidly, causing unacceptable outgassing. Given that the LLD is in the divertor region, where heat fluxes on the order of $1000W/cm^2$, the problem of maintaining the lithium temperature within this operating range is daunting.

The use of a thick copper plate as a substrate provides good thermal diffusivity. Scoping calculations during the conceptual design phase indicated that a thickness of 0.875in [2.22cm] would, in conjunction with sweeping the strike point of the plasma, keep the front surface temperature within an acceptable operating range. A thin, 0.010in [0.25mm] thick layer of stainless steel is bonded to the plasma side of the copper plate to provide a barrier between the lithium and the copper. Finally, a thin ~0.015in [.4mm] layer of porous molybdenum is plasma sprayed onto the stainless steel. Because of the relatively poor thermal diffusivity of the stainless steel and lithium, the top two layers must be as thin as possible, in order to minimize the front surface temperature rise.

Electric cartridge heaters (Fig. 3) are used to heat the plate to its initial operating temperature. Each quadrant uses twelve 500W heaters, for a total power of 6kW. This provides almost twice the power needed to balance radiation losses at 200C, and allows the heating time for the LLD to be within reason. Thermal analyses showed that, if one heater were to fail, the temperature drop between heaters would not be excessive. Temperature control is accomplished by feedback from eight thermocouples in each quadrant. Each heater is equipped with an integral thermocouple, which is used in control circuits that protect the heater from excessive temperatures.

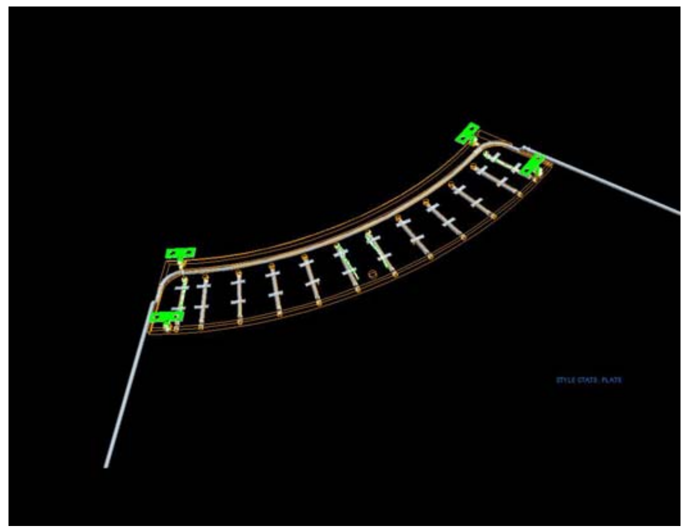

Figure 3. Cartridge Heater and Support Locations on LLD Plate

Radiation cooling is almost, but not sufficient, to return the LLD plates to their initial temperature between pulses. A gas cooling system was chosen for the plate. Using forced helium or nitrogen in a 0.375in [10mm] diameter tube, the LLD quadrant is returned to its initial operating temperature in between pulses. Each quadrant has its own independent cooling line.

The thickness of the tiles on the existing outboard divertor is 1.0in [25.4mm]. The thickness of the LLD plate, and the need for some clearance underneath, requires that it be located 1.50in [38.1mm] above the copper plates that are underneath the divertor tiles. The replacement tiles for the row 1 [innermost] locations are thus thicker than the original row 1 tiles, in order to match the height of the LLD. The tiles for the row 3 locations are made with a profile that blends to the LLD height at one end, and matches the unchanged row 4 tiles at the other.

The LLD must be maintained in its position, but significant differential thermal expansion between it and the outboard divertor structure must be accommodated. The change in length of the outboard edge of the LLD, if the entire plate reached 400C, would be roughly 0.20in [5mm]. Assuming that a locating plug is at the mid-span of the plate, the supports at each end would need to be able to accommodate 0.1" [2.5mm] of relative motion. Further, it is desired to have no more than one ground point on a given LLD quadrant. The corner supports consist of pivoting links, which allow relative motion in the toroidal direction. A slight vertical displacement accompanies this motion as the links pivot, but the magnitude is insignificant. The central support, located roughly midspan on the outer edge of the quadrant, is a round plug that engages a matching hole in the bottom of the LLD plate. Sliding, spring-loaded electrical contacts on the plug provide a reliable single-point ground for the plate. (Fig. 4)

Figure 4. Pivoting Corner Supports

IV. THERMAL ANALYSIS

Scoping calculations were performed during the conceptual design of the LLD to establish the thickness of the plate, the number, power and location of heaters, and the size of the cooling tube. During the final design, a detailed finite element thermal analysis was performed at Sandia National Labs. This analysis modeled a segment of the LLD plate containing three heaters. (Fig. 5)

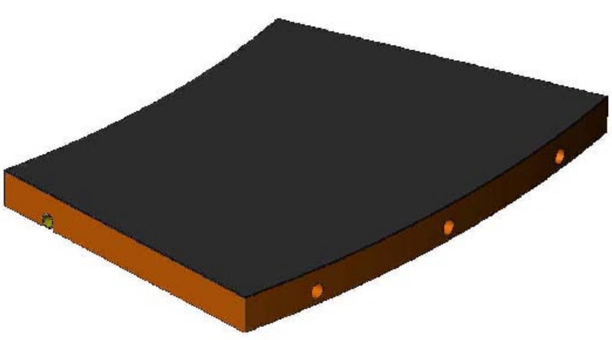

Figure 5. LLD Thermal Model Showing Locations of Heaters and Cooling Tube

This analysis verified the calculations from the conceptual design, and then was used for several detailed analyses. These included an assessment of the time required to heat the LLD plate, the effect of the failure of one heater, and the effectiveness of the cooling system. Another important result of the analysis was a determination of the required sweep rate of the divertor strike point. Because the front surface temperature of the plate must not exceed 400C, the strike point cannot remain at one radial location during a pulse. It must be swept over the surface of the LLD, so that the high heat flux is moved away from a given location before the surface temperature exceeds its allowed value. The analysis showed that a sweep rate of 500mm/sec is required. This information will be used during machine operations with the LLD.

V. ELECTROMAGNETIC ANALYSIS

Eddy currents induced in structures during a plasma disruption, and the forces that they induce, must be reacted by the structure and its supports. A transient SPARK model of the LLD plate, including relevant parts of the vacuum vessel, was constructed and run. (Fig. 6)

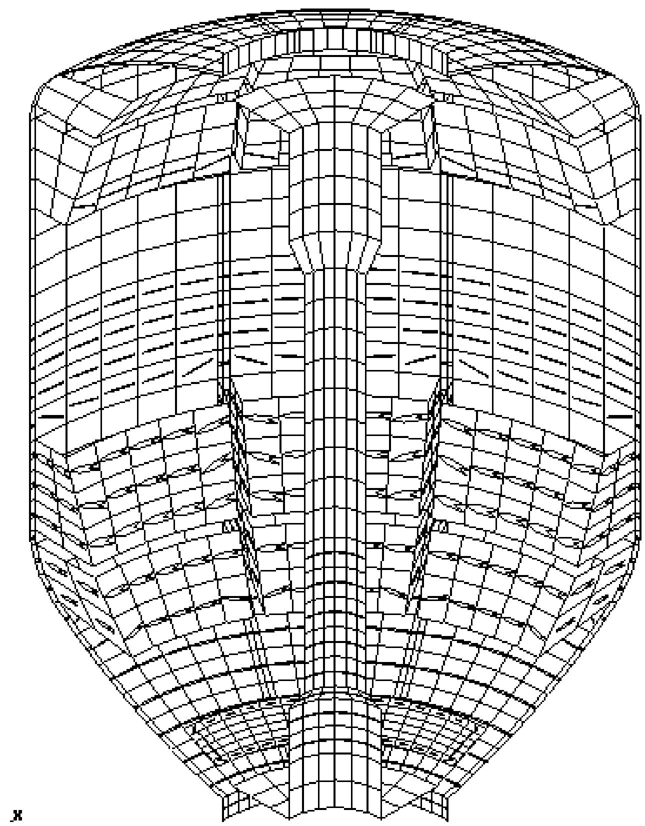

Figure 6. SPARK Electromagnetic Model

The normal flux change through the LLD plates was found to be 60T/s for 3 ms. Peak current in the LLD was 21.4kA. The maximum running load was ~65lbf/in on the radial edges of the plate, and ~25lbf/in on the toroidal edges.

VI. Fabrication

The plates for each quadrant are fabricated, by Sandia, by spinning a conical ring from copper, machining the surfaces and features, and then cutting the plate into quadrants. The thin stainless steel sheet is then brazed to the plasma facing (concave) side of each quadrant. A layer of porous molybdenum is plasma sprayed onto the stainless steel surface. Following the plasma spraying and shipment to PPPL, the heaters, thermocouples, supports and wires are installed.

VII. Conclusions

The NSTX Liquid Lithium Divertor is an important step in the evolution of liquid metal first wall technology. The fabrication of the plates is almost complete, and installation in NSTX is scheduled for 2010.

Acknowledgment

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