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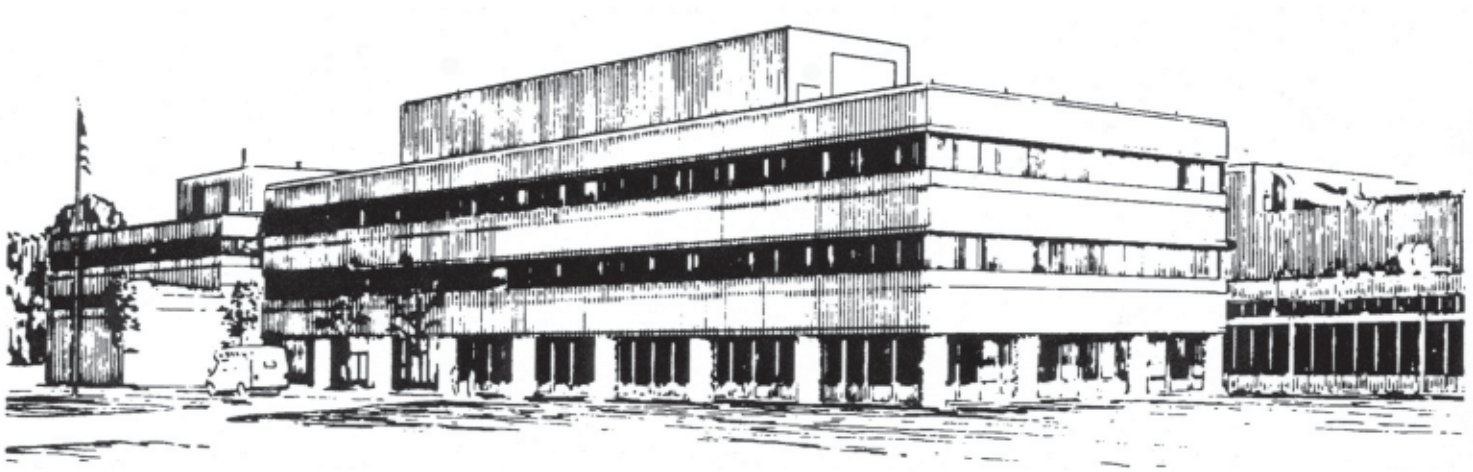

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CDX-U Operation with a Large Area Liquid Lithium Limiter

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Abstract: The Current Drive eXperiment – Upgrade (CDX-U) at the Princeton Plasma Physics Laboratory has begun experiments with a fully toroidal liquid lithium limiter. CDX-U is a compact (R=34cm, a=22 cm, $B_{toroidal}$ = 2 kG, I_P =100 kA, $T_e(0)$~100 eV, $n_e(0)$~ 5 × 10^{19} m^{-3}) short-pulse (<25 msec) spherical torus with extensive diagnostics. The limiter, which consists of a shallow circular stainless steel tray of radius 34 cm and width 10 cm, can be filled with lithium to a depth of a few millimeters, and forms the lower limiting surface for the discharge. Heating elements beneath the tray are used to liquefy the lithium prior to the experiment. Surface coatings are evident on part of the lithium. Despite the surface coatings, tokamak discharges operated in contact with the lithium-filled tray show evidence of reduced impurities and recycling. The reduction in recycling is largest when the lithium is liquefied by heating to 250 °C.

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Keywords: lithium, tokamak, limiter

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The use of flowing liquid metals, and in particular liquid lithium, as plasma-facing components (PFCs) in a tokamak reactor offers many potential benefits over conventional solid PFCs. These include high heat removal capability, self-healing, pumping of hydrogenics (including tritium, to limit the inventory captured in PFCs), possibilities for pumping helium ash, and enhanced magnetohydronamic (MHD) stability if the liquid metal flow velocity is sufficiently high. Experiments to test the use of liquid lithium as a PFC are presently underway at the PISCES-B divertor simulator facility,[1] the T11-M tokamak,[2] and the Current Drive experiment – Upgrade (CDX-U) at the Princeton Plasma Physics Laboratory. Tests of large area free-surface liquid lithium PFCs are presently underway in the CDX-U.[3] Previous experiments with lithium systems in CDX-U utilized a rail limiter [1,4] with a lithium-wet mesh which had a surface area of approximately 300 cm^2; the area of the limiter wet by the plasma was approximately 40 cm^2. The rail limiter experiments provided a first indication that liquid lithium could be successfully and safely employed as a plasma facing component, with no deleterious effects on the discharge. The ejection of small scale lithium droplets from the limiter due to MHD forces was observed, but the effect of these droplets on the discharge was minimal.[4] Following these tests, a circular tray 34 cm in radius, 10 cm wide, and 0.5 cm deep was mounted on the bottom of the CDX-U vacuum vessel and loaded with lithium. The lithium area was therefore increased to a maximum of 2000 cm^2. The area wet by the plasma varied, but was on the order of several hundred cm^2. Figure 1 is a photograph of the interior of CDX-U with the tray limiter installed.

The tray limiter is fitted with resistive disk heaters clamped to the lower surface, which are capable of heating the tray to 400 ^oC (lithium melts at 180 ^oC). The tray is

constructed in two halves, with a single toroidal electrical break. The two halves of the tray are connected to separate high current vacuum feedthroughs, so that the tray may be electrically grounded or floated with respect to the vacuum vessel. During operation of CDX-U, the tray serves as a fully toroidal limiter for the discharge, and hence forms a principal PFC for CDX-U.

The tray has been loaded with approximately 200 cm^3 of solid lithium. The loading operations were performed under vacuum or dry argon to minimize oxidation of the lithium surface. We note that the tray has not been uniformly wet and filled by the lithium. This may be due in part to surface coatings acquired by the tray during plasma operations after the tray was installed, prior to lithium loading, and in part to the 400°C limit on operating temperature of the austenitic stainless steel tray. Recent experiments at UCSD indicate that higher temperatures (in excess of 500°C) are needed for the initial wetting process.[5] For the experiments described here approximately 50% of the tray was covered with lithium to a maximum depth of approximately 5 mm. The lithium exhibits varying degrees of coating, which can only be partially removed by glow discharge cleaning.

During initial operation of tokamak discharges with the lithium tray limiter numerous unipolar arcs to the surface of the lithium fill were observed with a fast (10,000 frames per second) camera in the discharge scrape-off layer (SOL). These arcs ejected a lithium particulate, with a scale size of 1 mm or less, radially outward, which corresponds to the $\mathbf{J}_{arc} \times \mathbf{B}_{toroidal}$ direction. This particulate was deposited on the lower vessel heat shield (visible as semicircular plates in Figure 1), and has had no effect on plasma operations. The incidence of unipolar arcing dropped as plasma operations continued, an

indication that the lithium surface was being discharge cleaned. Unipolar arcing has not been observed on clean lithium surfaces which lack an insulating oxide coating.

Even with a partially filled tray which is subject to surface coatings, changes in the plasma edge and global effects on plasma performance have been observed. Figure 2 is a plot of the peak plasma current obtained versus line-averaged density for plasmas limited by the bare stainless steel tray, the room-temperature (solid) lithium filled tray, and the liquid lithium filled tray at 250°C. In each case the tray or fill surface was conditioned for several hours by argon glow discharge cleaning before tokamak discharges commenced. Higher plasma current is indicative of a hotter, cleaner discharge, since CDX-U operates with fixed loop voltage rather than plasma current feedback. It is clear that slightly higher current discharges were obtained with liquid lithium in the tray. This change in global performance is underscored by the observation that little or no conditioning is required to reach peak operating current in CDX-U when the lithium in the tray is liquefied. Prior to the installation of the toroidal lithium limiter, several hours of operation (involving dozens of discharges) at lower current were required before peak operating current was obtained.

Reduced impurity levels, particularly of oxygen, have a beneficial effect on discharge performance. Spectroscopy indicated significant changes in the edge impurities local to the tray. Figure 3 shows the effect of solid and liquid lithium limiting surfaces on the oxygen impurity in the plasma. There is a good correlation between higher plasma current and reduced oxygen levels. Note the segregation of the data; nearly all the discharges with a solid lithium limiter show lower oxygen than the discharges which are

limited by a bare stainless steel tray, and the discharges limited by liquid lithium show further reductions.

One indication of hydrogen pumping by the liquid lithium during these experiments (CDX-U uses deuterium as a working gas) is that the plasma density obtained with liquid lithium in the tray was lower than for solid lithium or the bare stainless steel tray, for similar gas puffing rates. Operation with liquid lithium also reduced recycling. A comparison between D_α emission from the SOL at the tray surface for operation with solid and liquid lithium is shown in Figure 4. Virtually all the discharges with liquid lithium in the tray show reduced D_α emission compared to the discharges with solid lithium. This result agrees with previously obtained data indicating that the recycling coefficient for hydrogenic species on liquid lithium is very low.[1] It is necessary that the lithium be liquid in these experiments so that the high mobility of hydrogenic species in liquid lithium diffuses deuterium out of the ion implantation zone, which only extends a few tens of Angstroms from the surface. It should also be stressed that while the viewed area represented in Figure 4 is primarily covered with lithium, parts of the stainless steel tray are still exposed and some of the lithium is oxide coated. Therefore, the residual recycling seen in the data with liquid lithium may be due to viewing of a small bare area on the tray, or a coated area on the lithium fill. The D_α emission data also shows the same correlation with plasma current evidenced by the oxygen emission data.

Reduced recycling is one hallmark of the enhanced performance modes observed in TFTR through the use of lithium pellets or coatings.[6] Global recycling data is not available for CDX-U, but a comparison of the area of the tray to the area of the

centerstack (visible in Figure 1 as the cylindrical column in the center of the device) and other room-temperature surfaces which contact the plasma indicates that the tray represents less than 40% of the total area of PFCs in CDX-U. In light of the limited area of the tray and the incomplete coverage of the tray by lithium, the tray cannot produce more than a 20% reduction in total recycling. It is not yet clear whether the enhanced performance seen with liquid lithium PFCs in CDX-U is due to a reduction in recycling or a reduction in impurities such as oxygen.

In Figure 5 we display the lithium emission as a function of plasma current. It can be seen that while lithium light is significantly higher in the liquid case, as compared to the solid, there is no negative correlation with plasma performance.

The CDX-U experiments provided a strong indication that liquid, rather than solid, lithium is required for low recycling PFCs. It can be seen from Figure 4 that liquid lithium provides a lower recycling surface than solid lithium. There is also evidence that a fresh, cold coating of lithium does not eliminate recycling. Data collected immediately after an accidental coating of the entire CDX-U vacuum vessel and centerstack with lithium due to a localized temperature excursion of the tray system indicate that recycling on the centerstack was in general somewhat higher. This may be indicative of the ejection of loosely bound deuterides from the surface of the lithium coating during the discharge.

To summarize, discharges struck on the lithium-filled limiter tend to outperform discharges struck on the bare stainless steel tray. Furthermore, discharges struck on a liquid-lithium filled limiter outperform those limited either by the bare stainless steel tray or by the solid lithium-filled tray. This effect is observed despite the fact that the tray is

only partially filled with lithium, and is at least partly coated with oxide and hydroxide layers.

The enhancement in performance is correlated with a strong reduction in both oxygen impurities and recycling at the lithium-filled limiter tray. The data on oxygen and D_α emission reveal that nearly all the discharges limited on liquid lithium show lower emissions than nearly all the discharges limited on solid lithium. Thus liquid lithium appears to be much more effective at removing oxygen and eliminating recycling than solid lithium. Solid lithium coatings are not effective at reducing recycling in CDX-U.

Upcoming experiments on CDX-U will utilize new filling techniques for the tray, developed in collaboration with the PISCES-B group at the University of California at San Diego, and new radio-frequency discharge cleaning techniques. The objective is to obtain full coverage of the tray with a uniform fill of lithium, and to develop improved techniques for removing surface oxide coatings. During 2003 a recirculating liquid lithium limiter is planned for installation in CDX-U.

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Figure Captions

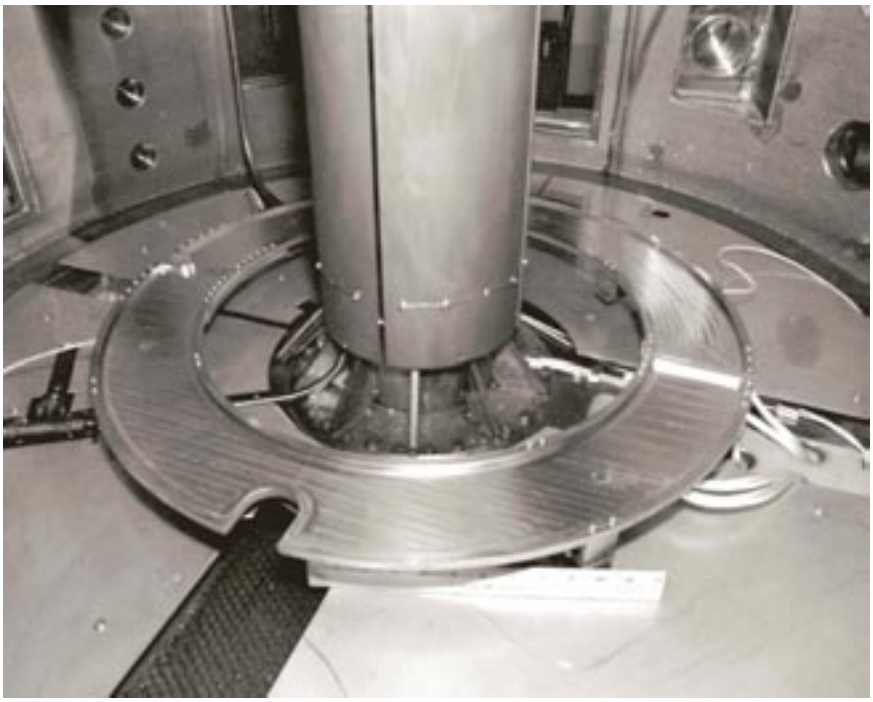
Figure 1. Photograph of the interior of CDX-U following installation of the tray limiter.

Figure 2. Plasma current – line averaged density operating space for CDX-U with an empty stainless steel tray limiter, a solid lithium fill, and a liquid lithium fill. The horizontal grouping of the density data is due to a binning algorithm.

Figure 3. Oxygen II emission at the surface of the tray, for discharges limited by the empty tray, a solid lithium fill, and a liquid lithium fill.

Figure 4. D_α emission at the lithium filled tray, for solid and liquid lithium limited discharges.

Figure 5. Lithium I emission at the lithium filled tray, for solid and liquid lithium limited discharges.



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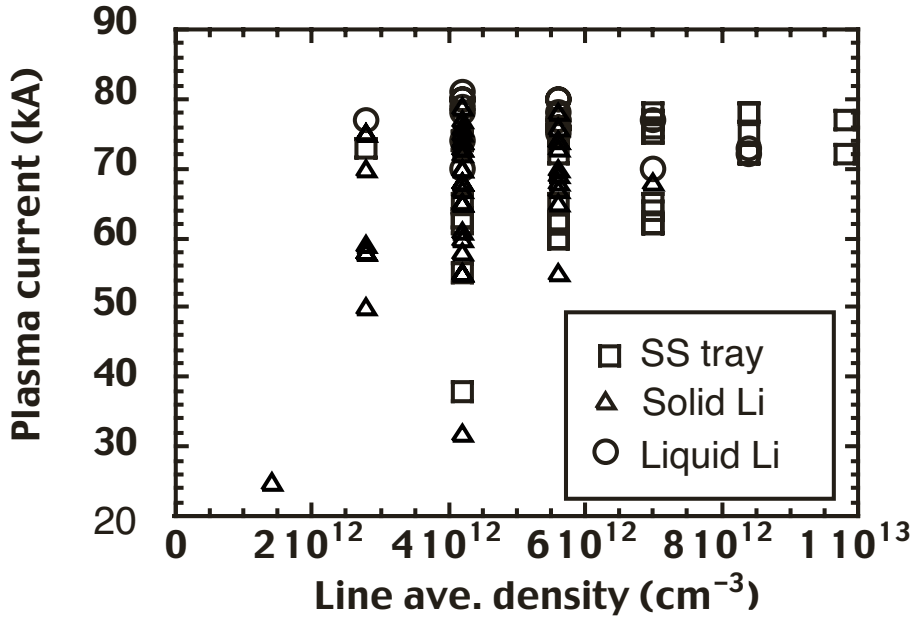

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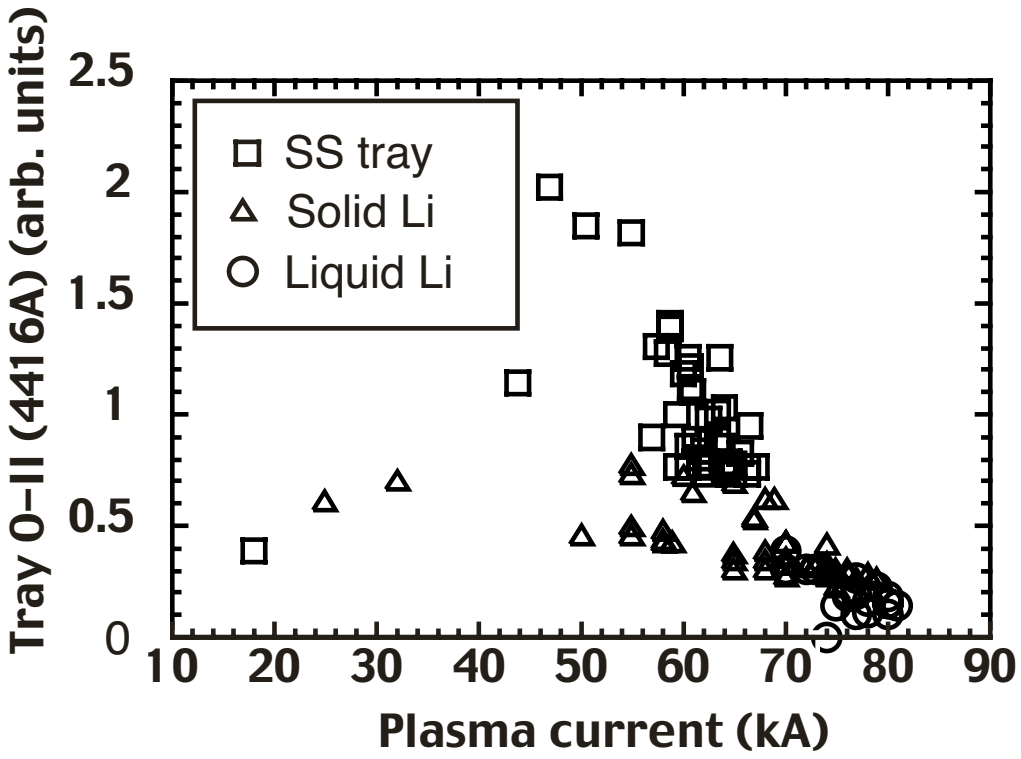

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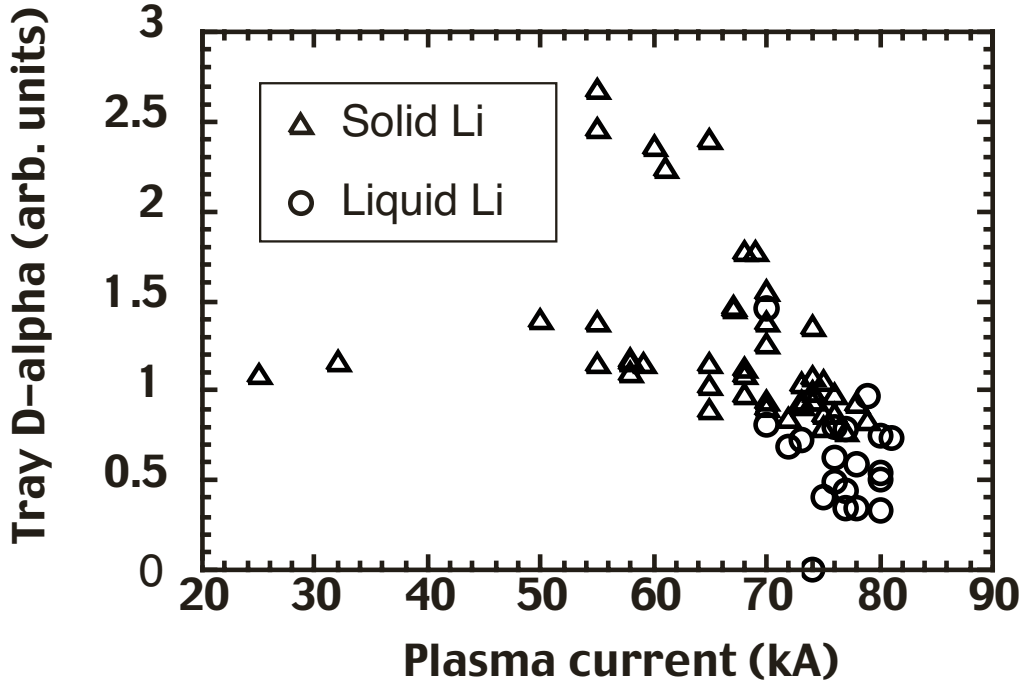

Figure 4. D_α emission at the lithium filled tray, for solid and liquid lithium limited discharges.

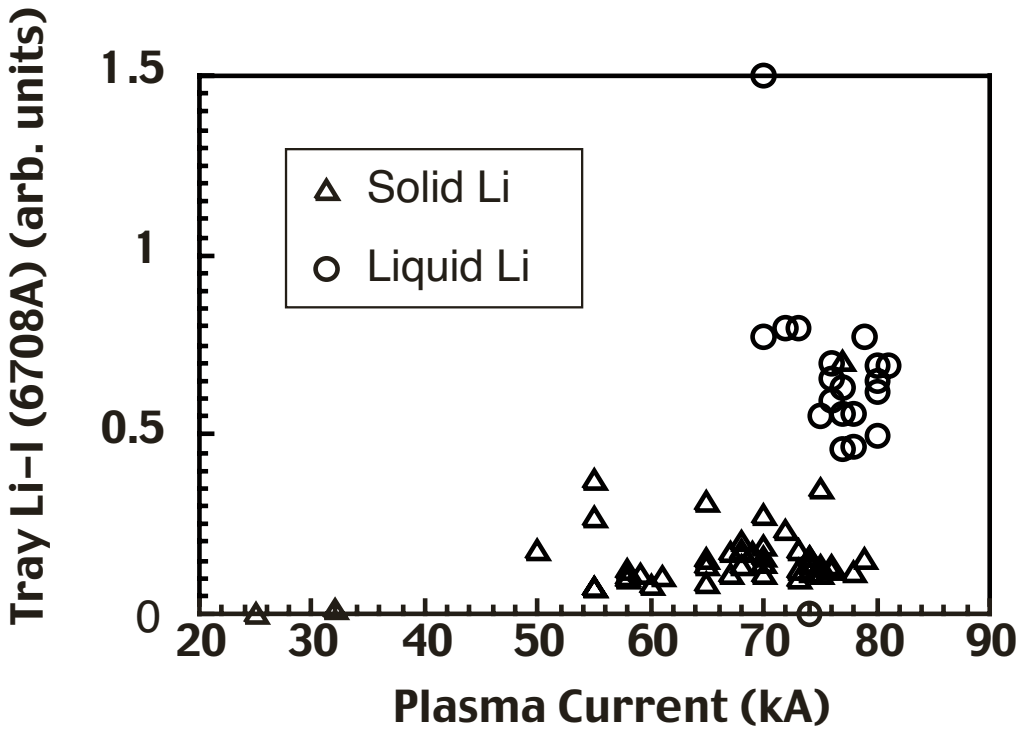

Figure 5. Lithium I emission at the lithium filled tray, for solid and liquid lithium limited discharges.

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