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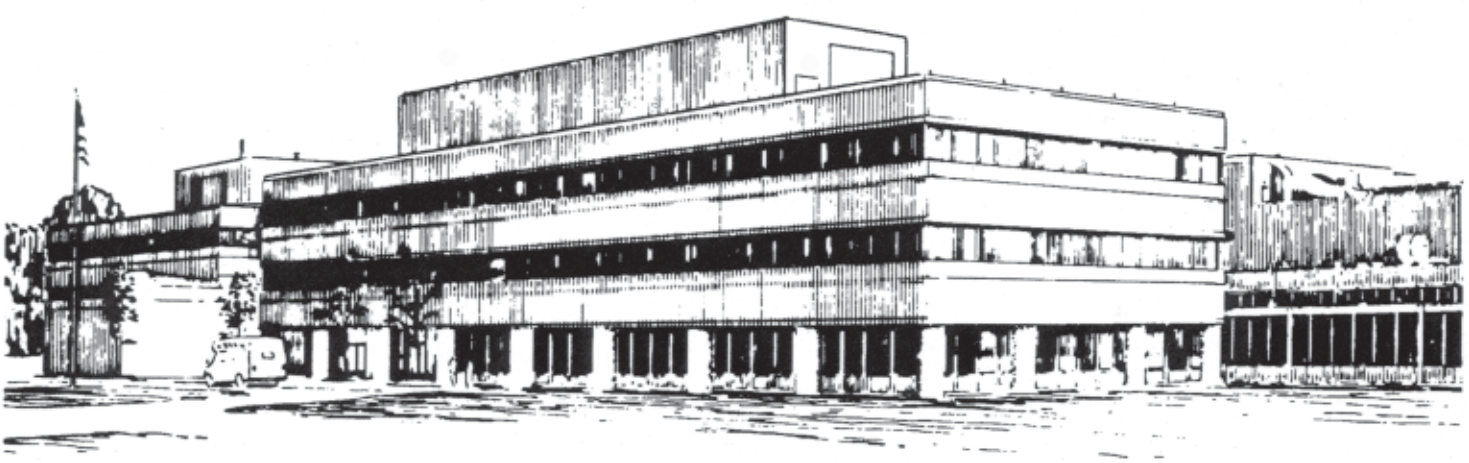

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Testing of Liquid Lithium Limiters in CDX-U

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Abstract: Part of the development of liquid metals as a first wall or divertor for reactor applications must involve the investigation of plasma-liquid metal interactions in a functioning tokamak. Most of the interest in liquid metal walls has focused on lithium. Experiments with lithium limiters have now been conducted in the Current Drive Experiment-Upgrade (CDX-U) device at the Princeton Plasma Physics Laboratory. Initial experiments used a liquid lithium rail limiter (L3) built by the University of California at San Diego. Spectroscopic measurements showed some reduction of impurities in CDX-U plasmas with the L3, compared to discharges with a boron carbide limiter. While no reduction in recycling was observed with the L3, which had a plasma-wet area of approximately 40 cm^2, subsequent experiments with a larger area fully toroidal lithium limiter demonstrated significant reductions in both recycling and in impurity levels. Two series of experiments with the toroidal limiter have now been performed. In each series, the area of exposed, clean lithium was increased, until in the latest experiments the liquid lithium plasma-facing area was increased to 2000 cm^2. Under these conditions, the reduction in recycling required a factor of eight increase in gas fueling in order to maintain the plasma density. The loop voltage required to sustain the plasma current was reduced from 2V to 0.5V. This paper summarizes the technical preparations for lithium experiments and the conditioning required to prepare the lithium surface for plasma operations. The mechanical response of the liquid metal to induced currents, especially through contact with the plasma, is discussed. The effect of the lithium-filled toroidal limiter on plasma performance is also briefly described.

I. Introduction

Reactor studies[1] have identified liquid walls and divertors as a promising solution to magnetic fusion energy (MFE) first-wall problems, such as heat load and erosion limits of dry walls, neutron damage and activation, reliability/maintainability of first walls and divertors, and tritium inventory and breeding. The CDX-U device[2] at the Princeton Plasma Physics Laboratory (PPPL) is pursuing a systematic series of studies which are intended to identify promising methods of implementing liquid lithium walls and divertor targets in larger devices, and to explore the consequences of such implementations on plasma performance. Initial investigations were performed with a liquid lithium rail limiter (L3) probe supplied by the University of California at San Diego (UCSD). These experiments were followed by discharges utilizing a large area liquid lithium pool as the target.

The benefits of a surface that has low or no recycling conditions have been demonstrated during the "Deposition of Lithium by Laser Outside of Plasma" (DOLLOP) lithium wall conditioning experiments,[3] for example, in the Tokamak Fusion Test Reactor (TFTR). Lithium limiter experiments have also been performed on the T-11M device,[4] where a Capillary Porous System (CPS) was used to form a "self-restoring" liquid lithium limiter surface.[5]. The CDX-U experiments are the first to extend these studies to a system in which a large fraction (~50% of the plasma-contacting surface is liquid lithium.

Surface conditioning was identified as a critical issue in both the TFTR and T-11M experiments. The DOLLOP process was a technique where the graphite plasma facing components in TFTR were coated with a lithium surface film. This was effective in improving plasma performance, however, only after the graphite surface was subject to extensive discharge conditioning prior to the deposition of the lithium. Particle recycling in T-11M was reportedly reduced only after plasma operations were conducted long enough to clean the CPS limiter surface. The experience on CDX-U was consistent with these observations, where periods of argon glow discharge cleaning (GDC) were routinely employed to clean both solid limiting surfaces and the lithium itself.

This paper provides a brief description of CDX-U (Section II). This is followed by a discussion of experiments with the L3 in Section III. Results from the first series of experiments with the toroidal lithium tray limiter are described in Section IV. Cleanup of CDX-U from these experiments is discussed in Section V, and the second series of experiments with the reinstalled toroidal tray in Section VI. Finally, a summary and conclusions are presented in Section VII. Since this paper is intended to present a summary of lithium experiments in CDX-U up until the present, it should be

noted that much of the material presented in Sections III and IV has been previously published [6,7,8,9]

II. Description of CDX-U and the L3 probe

The CDX-U facility (Fig. 1) is capable of spherical plasma operations in toroidal fields up to 2.1 kG with a "flattop" of 100 ms. Power supplies for the vertical and shaping fields permit discharges with plasma current up to 150 kA for greater than 25 ms. Capacitor banks provide the Ohmic heating (OH) current. The achievable current ramp rate and pulse duration of about 20 ms with the present OH supply, however, limit the plasma current to about 90 kA. With the exception of the capacitor banks for the OH system and the field null formation coils, the power supplies are preprogrammed and controlled by digital to analog waveform generators. The basic discharge parameters are summarized in Table 1.

The Ohmic heating system is capable of providing 0.2 MW to CDX-U, and the facility also has a radio frequency (RF) heating system[2] that is rated at 0.3 MW. The resulting parallel and normal heat fluxes will be 8-10 MW/m^2 and 2-3 MW/m^2, respectively, because of the compact ST geometry. At present, there is no feedback control on the plasma current. For this reason, the plasma current achieved is a measure of plasma performance in CDX-U. In all of the experiments described in this paper, deuterium was the working gas.

III. Experiments with the L3 probe

The L3 probe was developed at UCSD for the first experiments involving the use of solid and liquid lithium as a plasma limiter in CDX-U. The head of the L3 probe is a lithium covered rail 5 cm in diameter and 20 cm long. The rail is inserted or removed via a double gate valve airlock system to prevent exposure of the lithium to air. When the limiter is fully inserted, it forms the upper limiting surface for the discharge and is intended to define the last closed flux surface for the discharge (Fig. 1). If the limiter is retracted, ceramic boron carbide rods form the upper limiting surface for the discharge. The limiter has an internal heater and has been operated in contact with the plasma over a temperature range of 20 - 300^o C.

The CDX-U plasma interacted strongly with the L3 head. Figure 2 shows a sequence of images taken with a fast framing camera through a LiI (6708 Å) interference filter. The L3 head formed the upper rail limiter (Fig. 1), and the camera viewed the underside surface that faced the plasma. The frames in Fig. 2 are 1 ms apart. The location of the bright atomic lithium emission varies as the

plasma moves radially with time, and its contact points change. Occasionally, a lithium droplet is ejected, as seen in the fourth and fifth frames. Since the L3 probe head is grounded, plasma-generated current which flows in the direction of the major radius to ground, through the surface of the L3 head, produces a vertical (downward) J × B force on the lithium covering the head. The rapid downward motion of the droplet seen in Fig. 2 is far larger than expected from gravitational acceleration, and is thought to be due to the J × B force.[6]

Such events had little effect on the plasma. The lower panels in Fig. 2 show the time evolution of the OII (4416 Å), LiI (6708 Å), and D_α (6561 Å) emission, and the plasma current. The vertical lines correspond to the times the camera images were taken. While bursts were observed in the spectroscopic measurements, correlations with the ejection of the lithium were not always clear. As seen in the plasma current trace, the lithium droplets also did not cause major phenomena like large internal reconnection events[10] or disruptions.

The L3 experiments were useful in addressing the practical issues of lithium handling and the compatibility of liquid lithium with spherical torus plasmas. The general absence of any significant effect related to the L3 on plasma performance, however, is believed to be due to the relatively modest lithium surface area it presented. This issue was addressed with the fully-toroidal lithium tray limiter (Fig. 1). Experiments with the limiter are described in the next section.

IV. Results from the first campaign with a toroidal liquid lithium limiter

The tray for the toroidal lithium limiter has an inner diameter of 58 cm and an outer diameter of 78 cm. Its area of about 2000 cm^2 thus represents an increase of more than a factor of ten over the L3 lithium surface facing the plasma. The tray includes a single toroidal electrical break, and is mounted on insulators to provide thermal and electrical separation between the limiter target and the vacuum vessel. Typically one end of the tray is connected to ground, and the current flowing from the edge plasma to ground through the tray is monitored with a current transformer. Like the L3, the tray has electrically isolated heaters for controlling the lithium temperature. The tray isolation also permits GDC in a manner similar to the technique developed for the L3 head.

The first challenge was to fill the tray with lithium. Because of its size, this had to be done with the tray already placed in the CDX-U vacuum vessel. The chamber was filled with argon, and four quantities of solid lithium were placed on the tray with a manipulator inserted through ports in the lid. Each of the four loads consisted of four small lithium rods that were 1 cm in diameter and 5 cm

long. This was intended to provide a layer of liquid lithium 0.5 millimeter thick, if the tray was uniformly coated.

Melting the lithium to provide such a coating proved to be difficult. The tray heaters were able to raise its temperature well above the lithium melting point of 181°C. Even at 350 °C, however, the lithium rods only deformed to create oblate lumps roughly 5 centimeters in diameter. It appeared that a lithium hydroxide coating formed on the rods, and this prevented any liquid lithium from flowing. The base pressure in the stainless steel CDX-U vacuum vessel is 1-3 x 10^{-7} T, with residual gas analyzer (RGA) measurements showing that the primary contribution was due to water. A coating could thus be readily created as the water reacts with the lithium surface.

Argon AC GDC was performed for durations approaching thirty hours, both with the tray unheated and heated to 250 °C. In the latter case, the base pressure rose to about 10^{-6} T, and RGA spectra indicated that the main contribution was from hydrogen. While this was presumably liberated from the lithium hydroxide, the coating on the lithium lumps persisted.

A manipulator with an articulated stainless steel tip was inserted through the same ports used for loading the lithium. It was able to break through the coating, and spread the lithium to its maximum reach of a few centimeters along the surface of the tray. While this process did not disperse the lumps, lithium was seen to flow well beyond them. From visual inspection of the tray surface, over half of the surface area appeared to be covered with lithium.

Discharges were obtained with this degree of lithium coverage, and there were clear differences in plasma behavior and spectroscopic emissions with solid and liquid lithium limiters. The primary diagnostic used for visible spectroscopy on CDX-U is the filterscope.[11] In this instrument, light from the plasma is imaged onto optical fibers and conducted to sensors located remotely from the machine. The light is split into multiple paths, each of which is terminated with a detector that consists of an optical bandpass filter and a photomultiplier tube. The detectors are mounted in a single box that can accommodate up to five channels. Spectroscopic measurements from a direct view of the limiter indicated that the deuterium-alpha emission was consistently lower when the lithium was a liquid, at a temperature of 250 °C, than when it was a solid. This is shown in Fig. 3, where the measurements from liquid limiter plasmas are all clustered below the values from solid limiter discharges. There was also spectroscopic evidence for significantly reduced oxygen emission (Fig. 4). The data in Figures 3 and 4 are from a typical day of CDX-U operation under each condition. With an empty tray or a solid lithium limiter, the first plasma of the day had a low current, which increased as successive discharges conditioned the plasma-facing surface. With the

liquid lithium limiter, discharges near the highest plasma currents were immediately obtained, and no period of lithium surface conditioning was needed to achieve low deuterium-alpha and oxygen emission. The electron temperature as indicated by soft x-ray emissions increased by as much as a factor of 2 – 3 for the liquid lithium discharges. [8]

One possible explanation for the difference in performance with a liquid lithium limiter may be due to the fact it, like the solid, reacts readily with water to form lithium hydroxide and hydrogen. However, lithium hydroxide remains dissolved in liquid lithium, rather than forming a surface coating which passivates the lithium, as is the case for the solid. Atomic deuterium (from the plasma flux) is also expected to remain dissolved in the liquid lithium. If the atomic concentration of deuterium dissolved in the lithium increases to greater than about 10%, lithium deuteride may be formed. Lithium deuteride remains a solid at temperatures below 680 °C, and is denser than liquid lithium, so as the deuteride forms it should precipitate out to the bottom of the lithium layer. This scenario could account for the increase in the hydrogen (mass 2), decrease in the water (mass 18), and a lack of deuterium (mass 4) in the RGA spectrum, as well as for the longevity of the effects.

During initial operation with the lithium filled tray numerous short lived bright spots were observed at the tray-plasma interface with a fast framing camera (see Figure 5). These bright spots appeared to be unipolar arcs, perhaps occurring at the oxide coated regions on the lithium. The vertical current channel of the arc produces an outwardly directed (i.e. towards increasing major radius) $J \times B$ force at the arc contact point. A consequence of the arcing is that a lithium particulate was ejected from the tray by this $\mathbf{J} \times \mathbf{B}$ force and coated the lower vacuum vessel heat shield near the tray. The incidence of arcing decreased significantly, to near zero, as plasma operations continued.

During one attempt at melting the lithium in the tray, a local region of strong heating developed. This may have been due to inhomogeneities in the lithium distribution resulting from the tray loading process. The resulting vaporization created a thin metallic layer of lithium, which appeared to cover a large area of the vacuum vessel that had direct ("line-of-sight") exposure to the tray. As a result, the machine base pressure dropped to about 6×10^{-8} T, or about a factor of two below typical levels for CDX-U. Residual gas analyzer (RGA) "before" and "after" data for CDX-U are shown in Figure 6. It should be noted that the conductance from the main vacuum vessel to the RGA is limited, since it is necessary to keep the RGA head far from the machine during tokamak operations. Therefore while the RGA data taken under various conditions may be compared, the RGA is not an accurate indicator of the pressure in the main vacuum vessel. Discharges were first attempted without GDC, and 85 kA plasmas were achieved at very low densities of about 3-4 x 10^{12}

cm^{-3}. It was impossible to fuel the discharge via gas puffing to normal operating densities, which are in the 1-2 x 10^{13} cm^{-3} range for CDX-U.

Further experiments were performed to determine if conditioning the lithium surface on both the toroidal tray limiter and the vacuum vessel walls affected the behavior of CDX-U discharges. Argon AC GDC was conducted prior to plasma operations. Plasma currents in excess of 90 kA were observed. These were among the highest currents ever achieved on CDX-U, but the plasmas were in an even lower line-averaged density range of about 2-3 x 10^{12} cm^{-3}. A sodium iodide detector outside of the stainless steel vacuum vessel usually does not detect hard X-rays, but their presence in these low density plasmas suggest the generation of runaway electrons.

Subsequent plasmas with identical discharge control programming had lower currents, higher densities, and higher impurity levels. This suggests that the GDC may have improved the surface conditions of the lithium, but that the effect did not persist. This is presumably because the walls that were coated were not heated, and the lithium compounds subsequently formed on the surface remained there.

V. Cleanup of CDX-U after lithium operations

After approximately nine months of experimentation with the first toroidal tray limiter it was determined that the lithium was virtually entirely oxidized or otherwise reacted with residual gases in the vacuum chamber. Coatings had accumulated on most of the windows which were not mounted on gate valves, and thus could not be cleaned without a vent. CDX-U was therefore vented in Spring 2002.

Prior to removal of the vessel port covers forced ventilation of the chamber was used to react any lithium deuteride which may have formed during the experiments. A 300 CFM blower was used to circulate air through the chamber for 72 hours. HEPA filters were incorporated into the inlet and outlet of the blower system in order to inhibit discharge of any lithium compounds into the CDX-U test cell, and vacuum gate valves were used for the inlet and outlet to the chamber.

Following the forced ventilation cycle, the vacuum chamber was opened and cleaning commenced. The toroidal tray limiter was removed, cleaned, and reinstalled. Minor cleaning was performed on the centerstack heat shield and vessel walls. A significant amount of lithium had accumulated on the lower vessel heat shield during early phases of plasma operation with the tray. The lithium had been ejected from the tray by $\mathbf{J} \times \mathbf{B}$ forces produced by unipolar arcing to the lithium. Arcing subsided

later in the run period, but not before several tens of cubic centimeters of lithium had been ejected onto the shields. The shields were removed and cleaned prior to the reinstallation of the tray limiter. In all cases cleaning up from the lithium experiments was straightforward, and presented no significant safety challenges. Following the cleaning procedures, the CDX-U vessel was evacuated and plasma operations were begun with the bare stainless steel tray acting as the limiter.

VI. Results from the second campaign with a toroidal liquid lithium limiter

After data on plasma operations with a high recycling bare stainless steel limiter was obtained, the tray was refilled with lithium. A new lithium filling system was designed and built by the UCSD PISCES group for the second set of lithium limiter experiments.[12] This fill system is designed to inject liquid lithium onto a high temperature (500C) stainless steel tray, in order to fully wet the tray and obtain uniform coverage. The new system was successful in producing a uniform, nearly complete fill of the tray. Figure 7 is a view of the filled tray through a vacuum vessel window. After the tray was refilled, RGA data indicated that residual water in the vacuum vessel had dropped to negligible levels (see Fig. 8). Subsequent heating and glow discharge cleaning cycles produced 100% coverage of the tray, and a highly reflective metallic surface, in contrast to the primarily oxidized surface achieved during the first set of experiments.

The mechanical behavior of the lithium in the second set of experiments also differed markedly from the initial tray experirments. No unipolar arcing was observed, and no measurable amount of lithium was ejected from the tray after hundreds of tokamak discharges using liquid lithium as the main limiter. This was true despite the routine occurrence of plasma events such as vertical displacements or disruptions, which produced short duration currents of up to several hundred amps to vessel ground through the tray. A time trace of the total current from the edge plasma to ground through the tray, monitored via current transformer as described in Section IV, during a representative event is shown in Figure 9(a). Figure 9(b) is a summary plot of the intensity and duration of events producing edge plasma currents to the tray. The plot includes all liquid lithium discharges with tray currents of more than 20 A (peak). Note that the cross section of the lithium layer in the tray is approximately 4 cm^2; thus current densities in the lithium near the grounded end of the tray were commonly 20 – 30 A/cm^2, and for short durations in excess of 100 A/cm^2. The lack of mechanical motion of the lithium due to $J \times B$ forces stands in stark contrast to the DIII-D results [13], where liquid lithium was consistently ejected from the DIMeS probe into the plasma. This difference is probably due at least in part to the design of the CDX-U tray, which forces all currents conducted to ground through the tray to flow in the toroidal direction, parallel to the major component of the confining magnetic field.

Plasma operations with the newly filled lithium limiter produced higher current discharges, and required significantly less loop voltage to sustain the plasma current. Very low recycling was observed. In order to maintain a plasma density comparable to that obtained during operation with the empty stainless tray limiter, it was necessary to increase plasma fueling by a factor of 6-8. A comparison of two discharges, one of which was operated with a bare stainless steel tray and the other of which utilized a liquid lithium limiter, is shown in Figure 10. In addition, the edge oxygen impurity was virtually eliminated. Quantitative data on the electron temperature behavior in these discharges was not available; however, the reduction in loop voltage for liquid lithium operation is striking, and is suggestive of a significant increase in core electron temperature. Lithium coatings of the windows proved to be a significant problem, however, and rendered several spectroscopic systems useless or suspect, which limited direct comparisons with the earlier data shown in Figures 3 and 4. Lithium operation with the second generation system was interrupted after approximately one month of run time by a vacuum accident which vented the machine to a pressure of approximately 1 Torr during a liquid lithium run. The accidental vent had no significant consequences other than the oxidation of the lithium surface, to the point where it was judged that the limiter tray ought to be cleaned and refilled. A photograph of the interior of CDX-U immediately following the vent to air is shown in Figure 11. Coatings on the walls and center stack heat shields are evident as a result of evaporation of lithium from the tray, but no instances of macroscopic ejection of lithium from the tray are apparent. The white particulate seen on the lower surface of the vessel (the lower heat shield) is oxidized lithium. This sparsely distributed particulate began to appear on the lower heat shield and tray before the tray was refilled with lithium, following either tokamak operations or glow discharge cleaning. Since the particulate began to appear before the tray was refilled with lithium, it is apparent that some lithium oxide remained in the vessel after cleanup operations were complete. Small lithium signals were also evident on the spectroscopy prior to the refill of the tray.

VII. SUMMARY AND CONCLUSIONS

The CDX-U experiments to date with liquid lithium limiters have clearly shown significant improvements in plasma performance as an increasing fraction of the total PFC area is converted to liquid lithium. These improvements include a strong reduction in impurities, especially oxygen, an increase in the electron temperature, a decrease in recycling and resultant control over the plasma density. A strong reduction in the plasma resistivity was observed, as evidenced by a approximate factor of four reduction in the loop voltage required to sustain the plasma current. Few, if any,

preceding modifications to PFCs in a magnetic fusion device have produced such striking improvements in plasma performance.

Although clearly the incorporation of liquid lithium limiters into an operating tokamak presents challenges, the experiments described here were accomplished with few modifications to tokamak systems and posed no safety problems (even in the case of an accidental vent). Techniques have been developed which permit the introduction of a large area clean liquid lithium PFC to a tokamak. The surface cleanliness of the lithium was maintained, and even enhanced, for an operating period of approximately one month. Window coatings are the primary problem observed so far. Finally, restoration of the tokamak to pre-lithium conditions has now been performed twice without problem.

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Figure Captions

Fig. 1 - Elevation of CDX-U showing the vacuum vessel, field coil configuration, and L3 limiter assembly. The plasma contact points with the L3 limiter head and the fully-toroidal liquid lithium limiter are also indicated.

Fig. 2 - Data from a CDX-U plasma with the L3 as a limiter. The upper row of panels shows fast camera images of the L3 head through a LiI (6708 Å) interference filter. The lower panels show the time evolution of the D_α (6561 Å), LiI (6708Å), and OII (4416 Å) emission (arbitrary units) from detectors viewing the L3 head, and the plasma current (kA) as a function of time.

Fig. 3 - D_α (6561 Å) emission measured with a detector viewing the limiter tray as a function of plasma current. The triangles are for the case of solid lithium (≈23°C) in the tray, and the circles represent data obtained with liquid lithium (250°C) in the tray.

Fig. 4 - OII (4416 Å) emission measured with a detector viewing the limiter tray as a function of plasma current. The squares correspond to no lithium in the tray, the triangles are for the case of solid lithium (≈23°C) in the tray, and the circles represent data obtained with liquid lithium (250°C) in the tray.

Fig. 5 - Fast framing camera images of arcing observed at the edge of the plasma in contact with the toroidal lithium tray limiter. In this case, the lithium was solid; however, no reduction in arcing were observed when the tray was heated above the melting point of lithium. Three images are shown, at successive 1 msec intervals during the discharge.

Fig. 6 – Residual gas analyzer (RGA) traces taken before (a) and after (b) the interior of the CDX-U vacuum vessel was coated with lithium. The insert in (b) indicates that the water peak in the spectrum (at mass=18) was reduced by a factor of ~20. Please note the differences in scales.

Fig. 7 – Photograph of the tray in the interior of the CDX-U vacuum chamber, refilled with highly reflective liquid lithium.

Fig. 8 – RGA traces before (a) and after (b) the tray was refilled with liquid lithium. Note the differences in scale, and the presence of residual argon as a result of the fill procedure.

Fig. 9 – (a) Transient current from the plasma to the lithium tray limiter for one representative discharge, and (b) summary plot showing the distribution of peak current versus duration of current transient (full width at half maximum) for liquid lithium operations. All discharges operated with liquid lithium in the tray were surveyed.

Fig. 10 – Comparision of plasma current, density, and gas fueling for discharges with a stainless steel limiter and a liquid lithium limiter.

Figure Captions (cont.)

Fig. 11 – Photograph of the interior of CDX-U immediately following venting after the second lithium tray campaign. The central columnar structure is the center stack, with heat shields. The tray encircles the center stack, and at this point is filled with oxidized lithium. The notch visible in the left foreground permits an on-axis interferometer chord. The floor is the lower vessel heat shield.

Major Radius (R_0)	34 cm
Minor Radius (a)	22 cm
Aspect Ratio (R_0/a)	$\geq$ 1.5
Elongation (κ)	κ 1.6
Triangularity (δ)	> 0.2
Toroidal Field (B_t)	0.21 Tesla
Ohmic Current (I_p)	$\sim$ 90 kA
$P_{auxiliary}$ (radio frequency heating)	$\sim$ 0.3 MW

Table 1. CDX-U parameters.

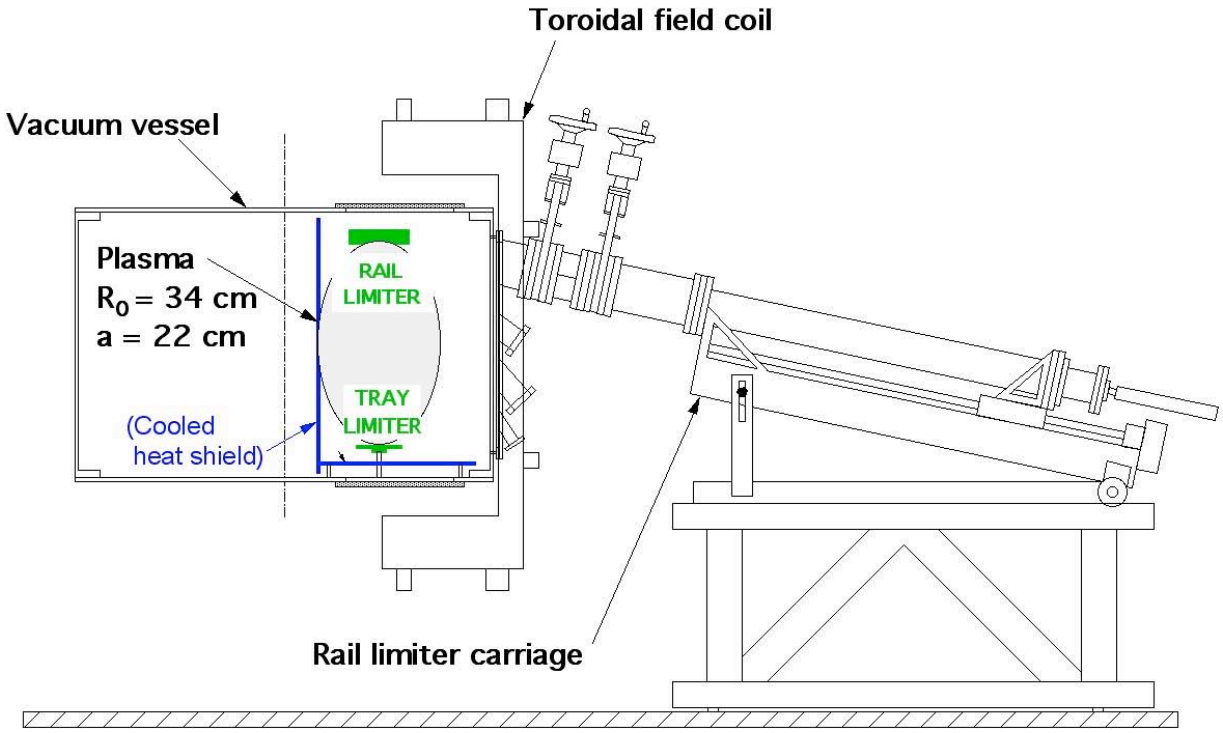
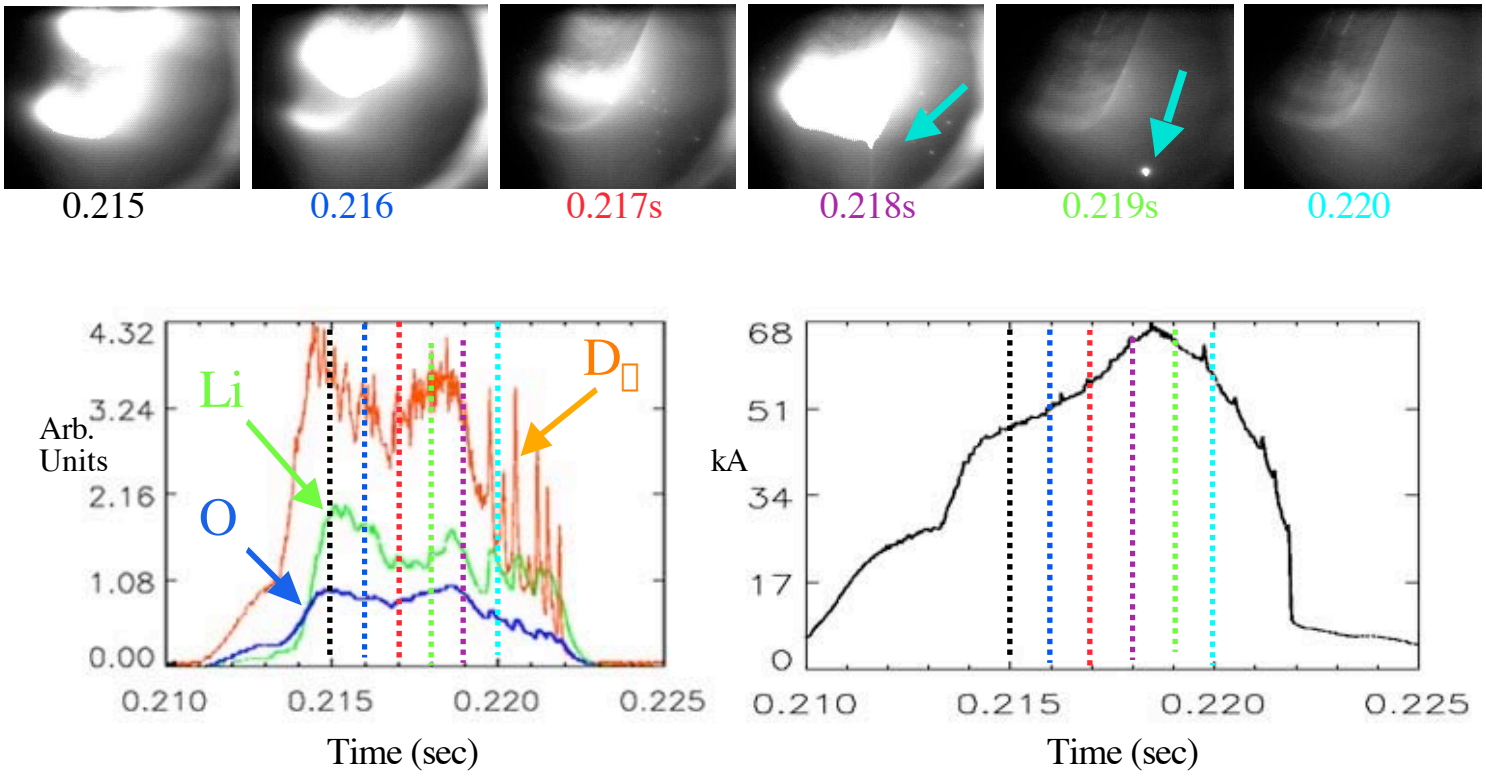

Toroidal field coil
Vacuum vessel
Plasma
R_0 = 34 cm
a = 22 cm
RAIL
LIMITER
TRAY
LIMITER
(Cooled
heat shield)
Rail limiter carriage

Figure 1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Arb. Units
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3.24
2.16
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0.00
Li
O
D
0.210
0.215
0.220
0.225
Time (sec)
kA
68
51
34
17
0
0.210
0.215
0.220
0.225
Time (sec)

Figure 2

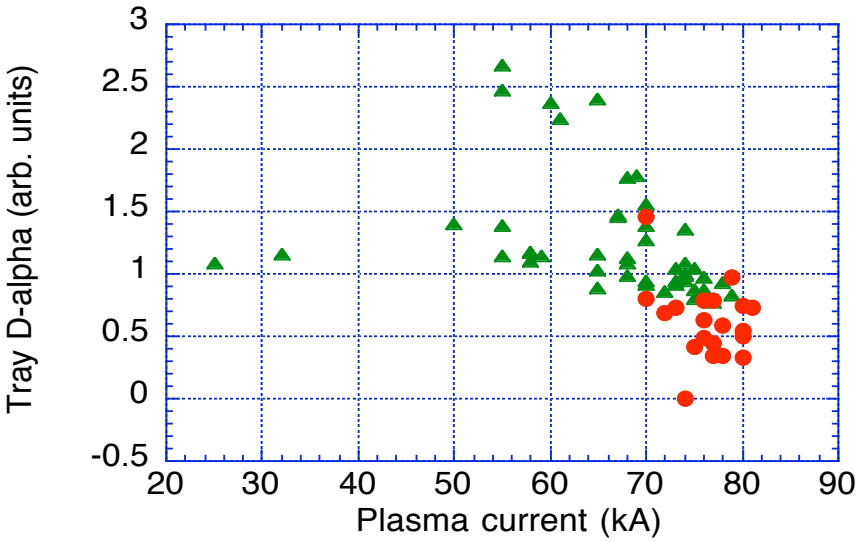

Tray D-alpha (arb. units)
3
2.5
2
1.5
1
0.5
0
-0.5
20
30
40
50
60
70
80
90
Plasma current (kA)

Figure 3

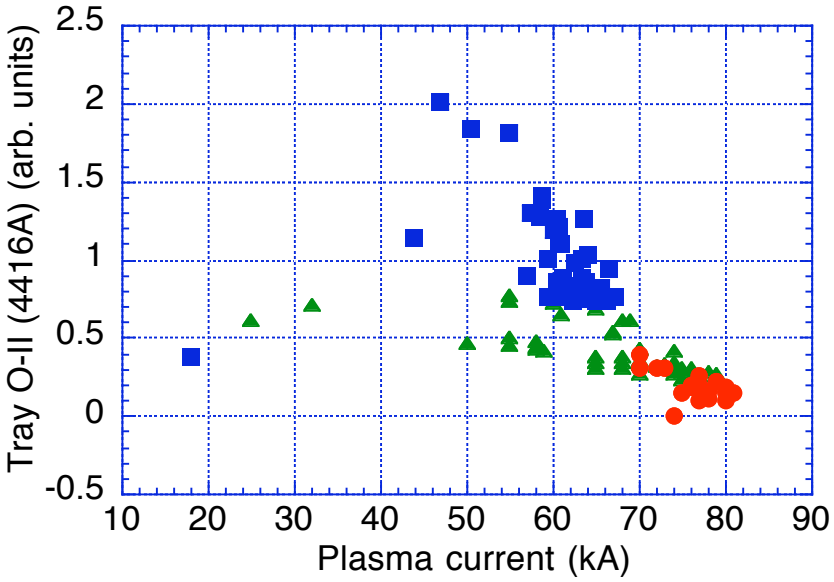

Tray O-II (4416A) (arb. units)
2.5
2
1.5
1
0.5
0
-0.5
10
20
30
40
50
60
70
80
90
Plasma current (kA)

Figure 4

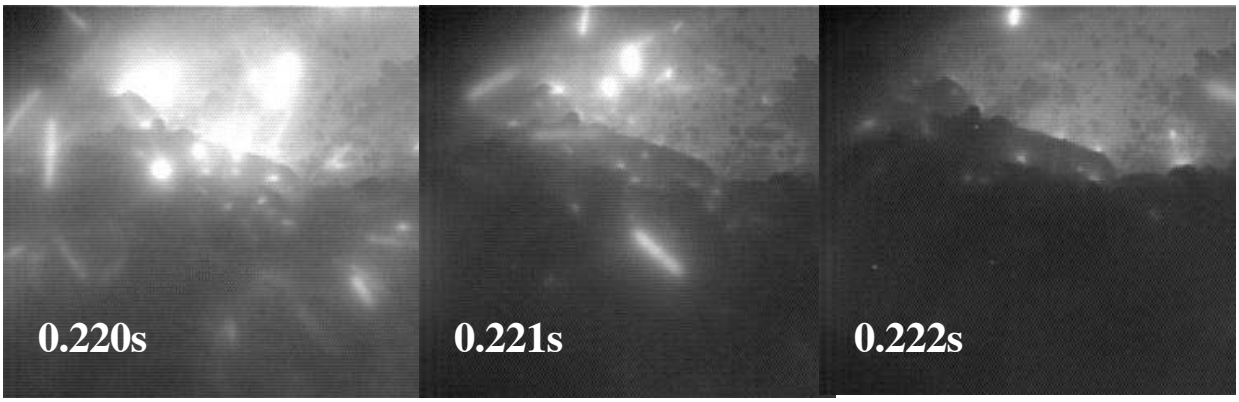


Figure 5

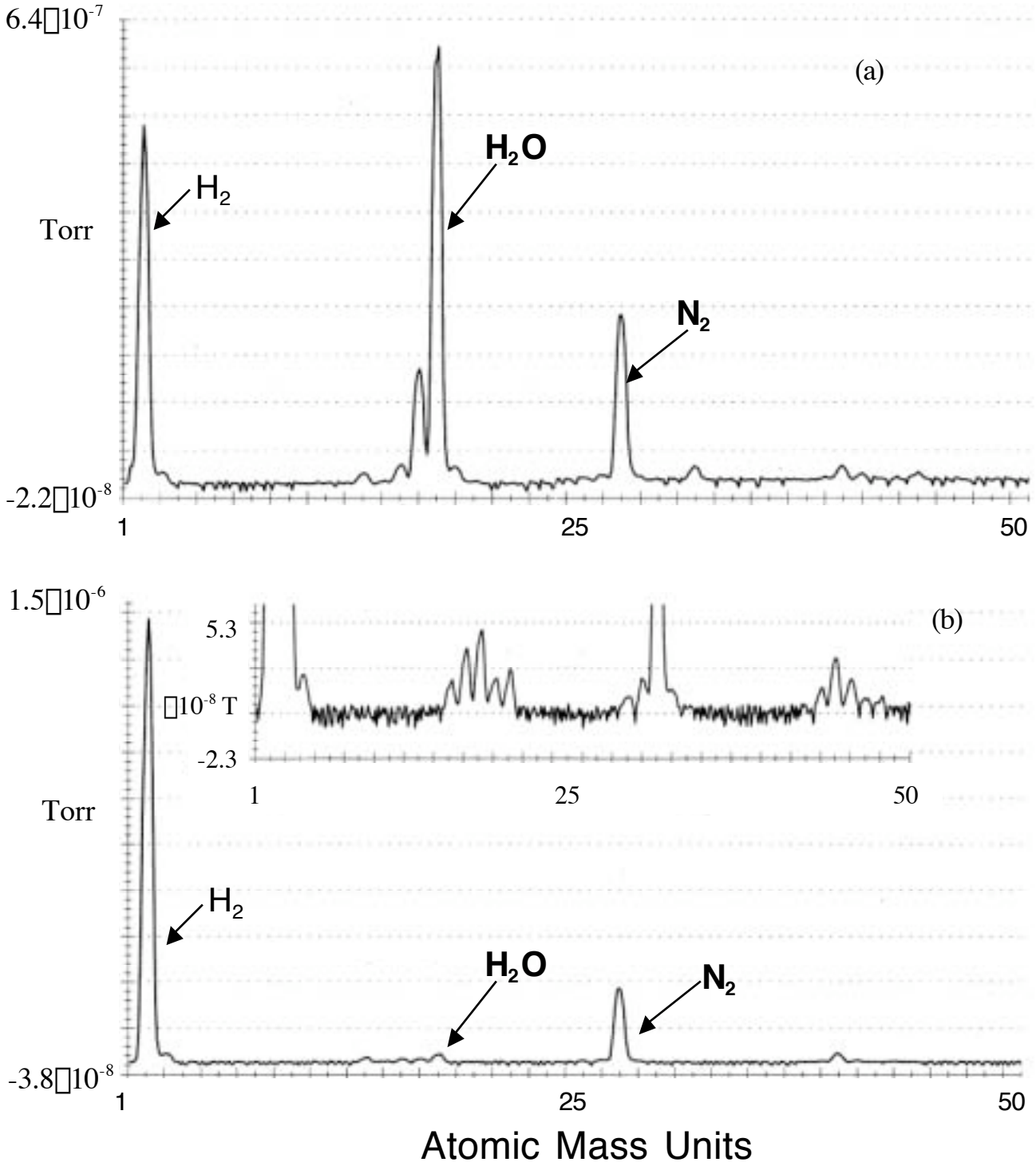

6.4□10-7
(a)
H2O
H2
Torr
N2
-2.2□10-8
1
25
50
1.5□10-6
(b)
5.3
□10-8 T
-2.3
1
25
50
Torr
H2
H2O
N2
-3.8□10-8
1
25
50
Atomic Mass Units

Figure 6

Figure 7

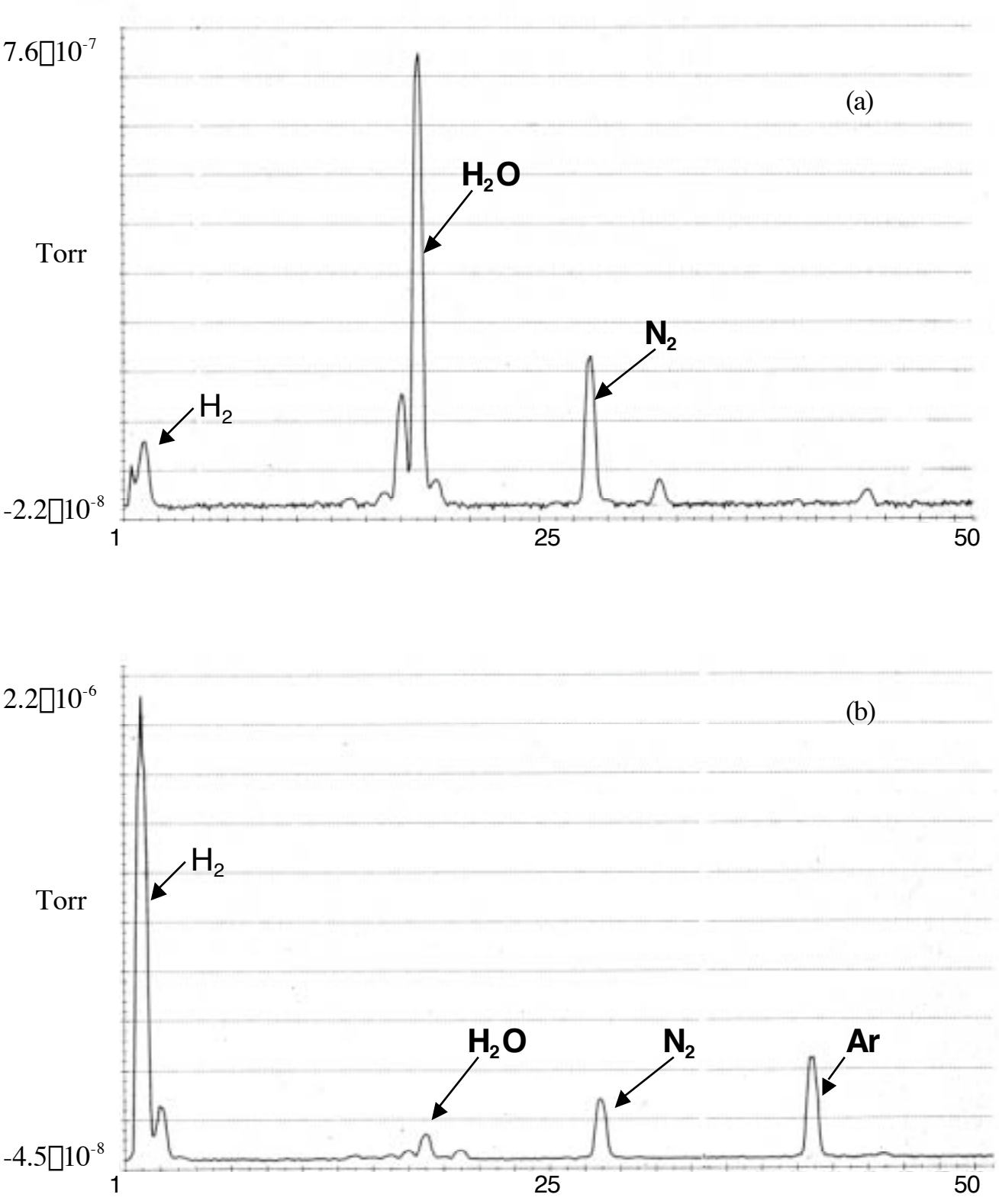
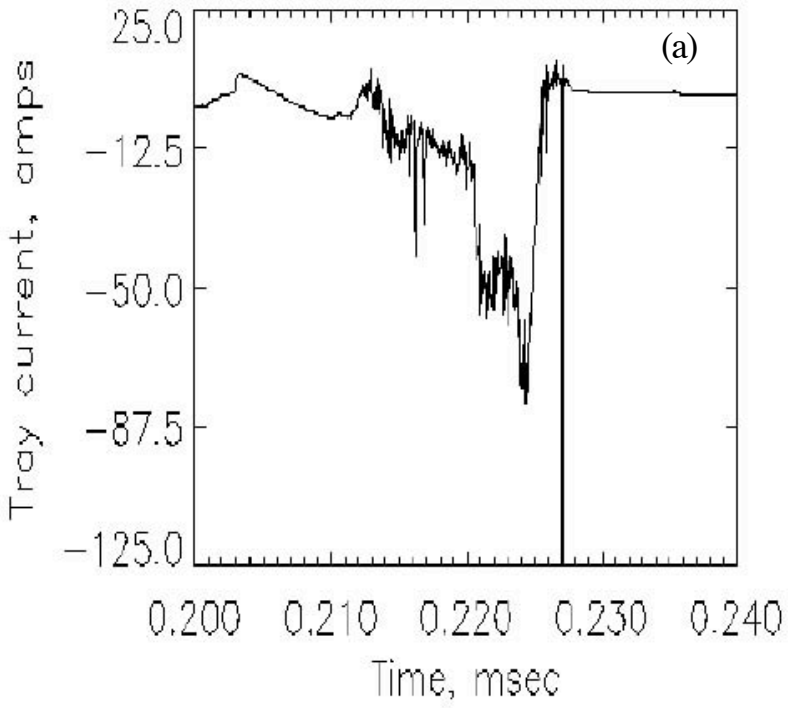

7.6□10-7
Torr
-2.2□10-8
1
25
50
(a)
H2O
N2
H2
2.2□10-6
Torr
-4.5□10-8
1
25
50
(b)
H2
H2O
N2
Ar

Figure 8


(a)
25.0
−12.5
−50.0
−87.5
−125.0
Tray current, amps
0.200
0.210
0.220
0.230
0.240
Time, msec

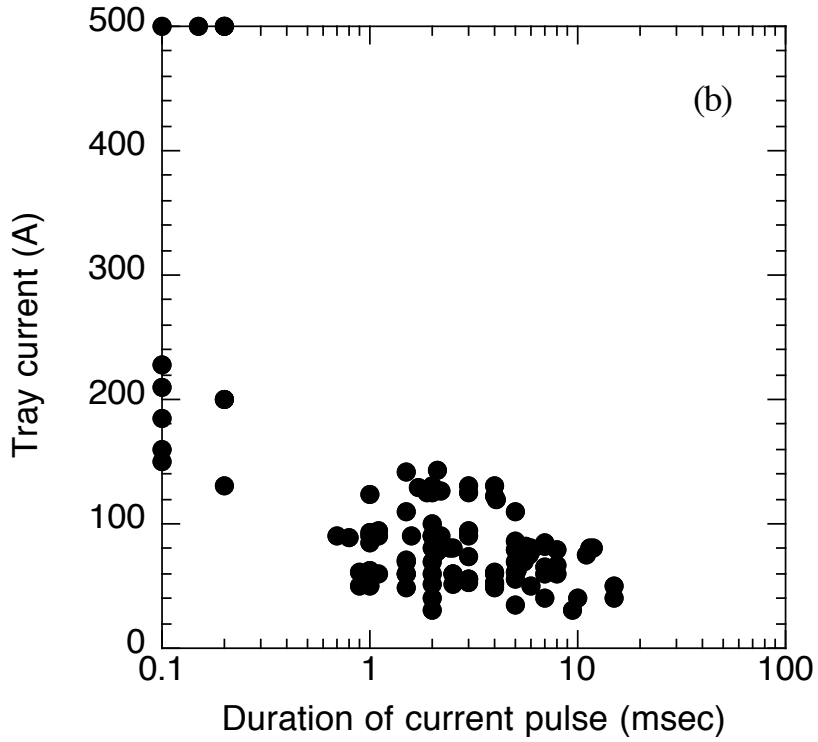

(b)
500
400
300
200
100
0
Tray current (A)
0.1
1
10
100
Duration of current pulse (msec)

Figure 9

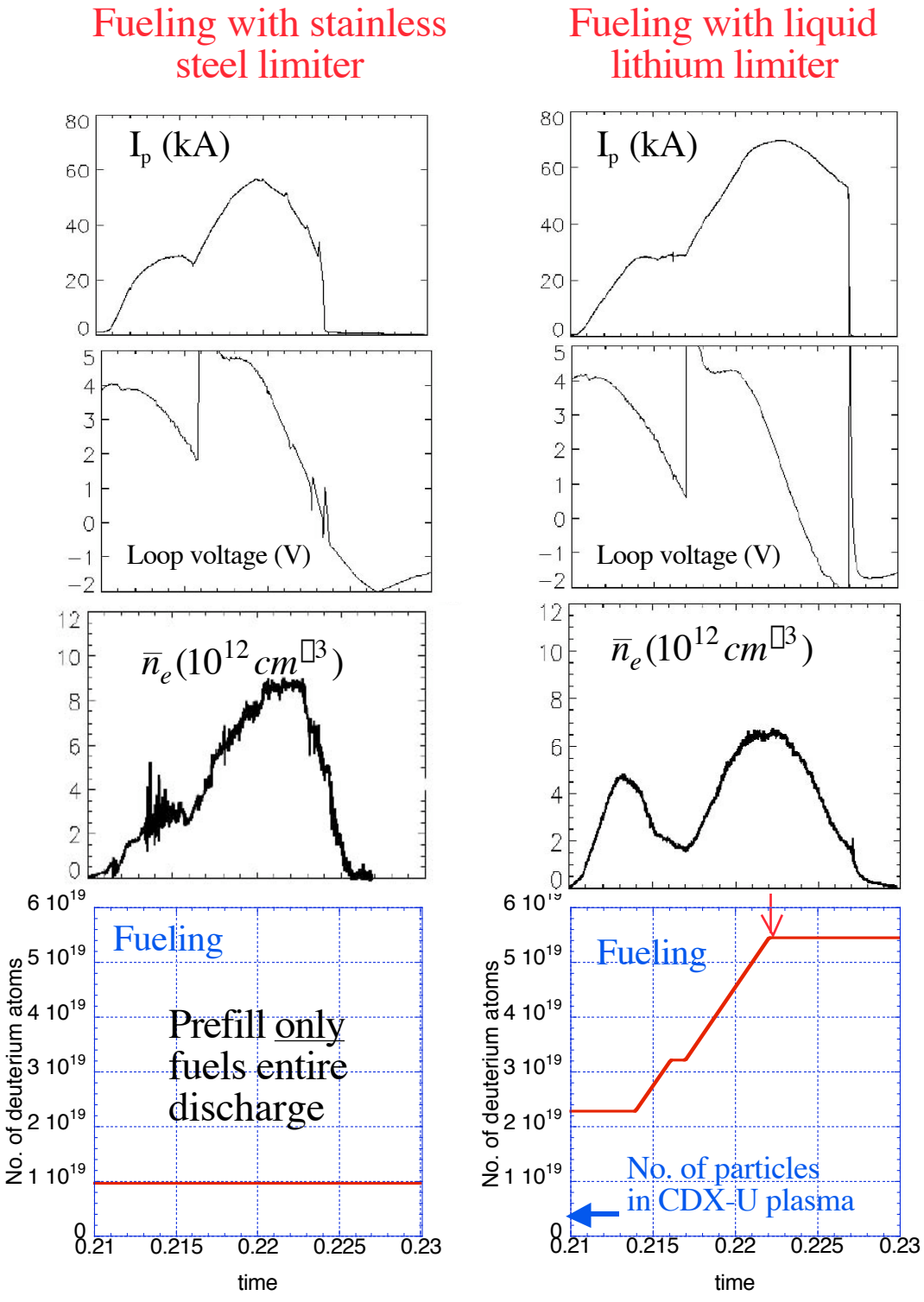

Fueling with stainless steel limiter
Fueling with liquid lithium limiter
I_p (kA)
Loop voltage (V)
$\bar{n}_e(10^{12}cm^{-3})$
Fueling
Prefill only fuels entire discharge
No. of deuterium atoms
time
No. of particles in CDX-U plasma

Figure 10

Figure 11

External Distribution

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Professor João Canalle, Instituto de Fisica DEQ/IF - UERJ, Brazil

Mr. Gerson O. Ludwig, Instituto Nacional de Pesquisas, Brazil

Dr. P.H. Sakanaka, Instituto Fisica, Brazil

The Librarian, Culham Laboratory, England

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