R. Majeski, J. W. Ahn, L. Berzak, T. Gray, R. Kaita, H. Kugel, T. Kozub, D. Mansfield, J. Spaleta, T. Strickler, J. Timberlake, L. Zakharov, PPPL, V. Soukhanovskii, LLNL, R. Maingi, ORNL, R. Doerner, UCSD – We summarize the results of five years of experiments in CDX-U with lithium systems, from experiments with a localized rail limiter covered with a 300 cm² lithium-wet mesh, to experiments with a 2000 cm² liquid lithium filled tray, to the final set of experiments which utilized a liquid lithium tray, in combination with aggressive e-beam generated solid lithium wall coatings. We find that the area of liquid lithium plasma-facing component is the most important factor determining plasma performance. Large areas of solid lithium wall coatings are not as effective. As a result, the low recycling discharges in CDX-U for which record confinement time enhancements were found [R. Majeski, et al., Phys. Rev. Lett. 97, 075002-1 (2006)] do NOT represent the best level of performance obtained with lithium walls. Confinement times are not available for discharges with the best performance. Continued improvement can therefore be expected for the Lithium Tokamak eXperiment (LTX), which will increase the liquid lithium plasma contacting area by 25×. We also summarize progress towards the completion of LTX which is scheduled to begin operation in FY07.

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Stepped approach taken to deploying liquid lithium systems in CDX-U

\[ \kappa \leq 1.6 \]

\[ R_0 = 34 \text{ cm} \]

\[ a = 22 \text{ cm} \]

\[ B_T(0) = 2.2 \text{ kG} \]

\[ I_p \leq 80 \text{ kA} \]

\[ A = \frac{R_0}{a} \geq 1.5 \]

\[ \tau < 25 \text{ msec} \]

\[ \Rightarrow \text{Not simultaneously installed} \]

UCSD liquid lithium rail limiter (retractable)
Argon glow discharge cleaning was used to condition the lithium rail limiter.

- Limiter in CDX-U during argon glow (from below)
  - Limiter (retracted) after argon glow
  - Limiter serves as cathode
  - Glow promoted wetting at lower temperatures (300 - 350 ºC)
Reduced recycling observed on clean lithium

- Filterscope view of the rail limiter
- Discharge densities were equal to ~5%
- Fueling requirements also increased

![Graph showing reduced recycling observed on clean lithium](image)

- "Dirty" limiter (oxidized)
- "Clean" limiter (after GDC)
Oxygen was reduced in discharges limited by the lithium rail

- With a “dirty”, solid lithium limiter oxygen emission from surface coatings dominates
- With a discharge-cleaned liquid limiter lithium emission is brighter than oxygen
  - OII drops during the discharge
  - Level of OII emission reduced from dirty limiter case

View was local to the limiter
Lithium droplet injection believed due to J×B forces

- Fast camera images (viewed from below) in Li-I light at 1000 fps
  - J×B is downward

![Image of lithium droplet injection](image_url)

\[\begin{align*}
\text{Intensity (arb. units)} & \quad 0.215s & 0.216s & 0.217s & 0.218s & 0.219s & 0.220s \\
\text{Time (sec)} & \\
\text{Plasma current (kA)} & \\
\text{Time (sec)} & \\
\end{align*}\]
Next experiments used a lithium-filled toroidal tray limiter

- 304 SS tray, 34 cm major radius, 10 cm wide, 0.64 cm deep.
  - 2000 cm² area.
  - **10x increase in lithium area**
- Fabricated in two halves with a toroidal electrical break
  - Isolated from vessel.
  - Halves connected to electrical feedthroughs.
- Heaters beneath for temp. control up to 500°C.
- Heat shield on center stack (TiC coated)
- Tray temperature monitored with edge, underside thermocouples
Tray filled with liquid lithium under argon (1.01 atm)

- Filling technique developed with UCSD
  - Load liquid lithium onto 500°C tray
  - High temperature promotes wetting
  - “Injection” of liquid lithium eliminates solid contaminants

- Thin coatings appear between runs
  - Removed/dissolved by GDC, heating

- One fill active for up to ~ 1 year
  - Pumped for hundreds of discharges

Tray during fill

Tray after plasma operations, during hot argon glow
Global recycling, oxygen reduced with liquid lithium limiter

- $D_\alpha$ emissions from the centerstack filterscope.
  - Tray reflectivity complicates measurements local to the lithium
- Oxygen is greatly reduced
  - Lithium eliminates all water
  - Reduced to noise level on RGA

Liquid Li (red) & bare SS tray (green)

Carbon emission reduced by 10×
Final phase: tray + wall coatings

- Lithium tray limiter
  - 300 g of lithium in a toroidal tray
- New electron beam lithium coating system
  - Used lithium in tray as source
- New resistively heated lithium evaporator
  - NSTX prototype
- Gas injection systems
  - Wall mounted piezo valve
  - Supersonic gas injector

Solid lithium wall coatings and 600 cm² of liquid lithium limiter formed the plasma-facing components.
Liquid lithium + coatings produce strong pumping

- 600 cm² liquid lithium limiter + 3000 cm² solid lithium coatings
- Exceeds wall particle pumping rate in a lithium-aided TFTR supershot
  - But: active wall area in CDX-U was two orders of magnitude smaller

(Discharge duration 25 msec)
Measured confinement times significantly exceed ELMy H-mode scalings

All discharges:
- 61kA < I_p < 78kA
- 2.1 kG
- Identical loop voltage waveforms
- 0.5 < \overline{p}_e < 1 \times 10^{19} \text{ m}^{-3}
- Gas puffing terminated several msec before peak in plasma current
  - “Pellet fueling” simulation

- **Pre-lithium confinement times:** 0.6 - 1.1 msec (kinetic)
  - New magnetics were not available

- ITER98P(y,1) included START data
- Confinement in CDX improved by 6\times or more with lithium wall coatings, partial liquid lithium limiter
- Exceeds scaling by 2-3\times
- **Largest increase in ohmic tokamak confinement ever observed**
Lithium discharges exhibit long confinement times, very low loop voltage

- Reconstruction of centerstack limited plasma from ESC
- Total coating of 13,000 Å (4 g) of lithium had been applied during preceding 2 hrs
  - 1000 Å applied <1 min. before discharge
- $\tau_E$ for this discharge 6 msec
- Surface voltage at current peak < 0.5V
  - 300 J stored energy
  - $L_i \sim 0.7$
  - Very low ohmic power input: 45 kW
  - Low ohmic power a future concern
  - LTX has no auxiliary heating
    » Higher ohmic power
    » But: pellet fueling may not be feasible
- $q_0$>1 in all analyzed lithium discharges
  - No sawteeth
  - No significant MHD
- Lithium area 600 cm$^2$ for the discharges for which reconstructions are available
Lowest recycling obtained with full tray
- Evaporative coatings less effective

- $D_\alpha$ emission at the centerstack
  - Lithium coated (solid)
  - Primary plasma contact

- ~3× reduction in $D_\alpha$ for full-tray liquid lithium operation (2000 cm$^2$)
- Bare tray: deuterium prefill only
  - Liquid lithium operation required
    - 8× increase in gas fueling

- Lithium reduces recycling coefficient $R$ from ~1 to ~0.3
  - Overestimate (background light)

- Lowest global $R$ ever obtained for a magnetically confined plasma
  - Approximately 2× minimum theoretical value for an edge temperature of 30 eV

- Global recycling for the rail limiter system not available
Fueling requirements with liquid lithium very high

- Fueling requirements were increased by more than an order of magnitude with lithium
- Rail limiter fueling requirements intermediate to bare/filled tray cases
- New fueling systems added for e-beam run

Total # of lithium atoms available for pumping in the centerstack coating.

- 2000 cm² area
- 100 Å thick

Liquid lithium tray (maximum available fueling)

Tray + e-beam evaporative coatings

Lithium rail limiter

Bare SS tray (~5x10¹⁸)

Rail limiter discharges after 100g in-vessel lithium spill
Best performance with largest area of *liquid* lithium

- External loop voltage behavior is a qualitative indicator of performance
- Typically, total fueling exceeds capacity of solid lithium centerstack coating

**Average loop voltage required for 2 MA/sec current ramp**

- **Bare tray - no lithium. No gettering (67 shots).**
- **Rail limiter + titanium gettering. 150 cm² exposed liquid lithium (59 shots).**
- **600 cm² liquid lithium in tray + 1000 Å/shot coating (39 shots).**
- **2000 cm² liquid lithium in tray + 10-100 Å/shot coating (64 shots).**
Lithium wall technology: molten thin films
- Heated (300° C), conformal wall
  » 304 SS liner explosively bonded to 3/8” copper
- Recoated with lithium (1000Å) between discharges
- Initial operation will use CDX-style “pool” in lower shell
- Replaceable
  » Second wall with plasma-sprayed porous molybdenum inner coating in preparation
Complete rebuild of CDX-U for larger, longer duration, higher current plasmas
- \( R=40 \text{ cm, } a=26 \text{ cm, } \kappa=1.55, B_T=3 \text{ kG, } I_p <400 \text{ kA} \)
Poloidal field, control system upgraded
Core fueling
- Gas jets
- NBI in next phase
  » Begin with 20kV, 10A, 50 msec source: loan from UW-Pegasus group
  » Expand NBI to longer pulses, higher current for full fueling of discharge via NBI
New LTX configuration

- New PF coils

- Support structure for shell
  - Loads transferred to external supports
LTX operation at $I_p > 100$ kA requires new PF coils
New coil set designed for $I_p \leq 400$ kA

- Equilibrium modeling shows that CDX plasmas with $I_p \geq 70$-$80$ kA scraped-off on outer limiter
  - Vertical field too low
  - One major factor limiting $I_p$
- New PF set, rearrangement of existing power supplies address this problem for LTX
- Toroidal field will increase to 2.4 kG
  - $R_0 =$0.4 m, $a=$0.26 m
- Poloidal field coil set designed for a 400kA equilibrium
  - Higher current may be necessary to offset lowered loop voltage
- Power supplies for all coils labelled to LTX
  - 7 twelve phase supplies, 20.5 MVA total from PBX-M
Shell support structure redesigned for significant disruptive forces

- Shell is electrically isolated from vessel
  - Ceramic breaks required for in-vessel mounting
- Disruptive forces modeled by Zakharov
- Maximum force $\sim 5 \text{ kN}$
  - Overturning moment on shell quadrant
  - Impulse rules out internal ceramic supports
- Load will be transferred to mounting points exterior to the vessel
  - G10 insulated external supports
ITER98P ELMy H-mode confinement estimates for LTX are strongly affected by the low loop voltage measurements from CDX-U.

- Very low power input, and $\tau_{98P} \sim P^{0.69}$
LTX status

- CDX-U has been disassembled
  - Vacuum vessel modified
- Shell support structure being modified to withstand disruptive forces
- Poloidal field coil set is being upgraded
  - Present set incapable of holding equilibria with $I_p>80$ kA
- Thomson scattering system being rebuilt
  - Based on existing ruby system
  - Will incorporate full amplifier set from PBX-M (~10-15J output)
  - 12 spatial channels
- Interferometer will utilize 1 fixed, 2 movable channels to provide a 5 point profile in 2 shots
- Upgrade magnetics (more flux loops, fast 3-axis sensors, shell current sensors)
- Reinstall spectroscopy diagnostics from CDX-U
  - But: shift from D-α to Lyman-α to reduce stray light problem
- Schedule is for first plasma in late FY2007
  - Only a limited diagnostic set will be available
Summary

- CDX-U experiments employed a rail limiter, a free-surface liquid lithium limiter, and wall coatings.
- Larger liquid lithium area = better performance
  - 2000 cm² + modest coatings provides better performance than 600 cm² + rapid between-shots coatings.
- Particle removal rates produced in CDX-U sufficient to pump a TFTR supershot.
- Global recycling coefficients of ~30%.
- 6 × or more enhancement in low recycling discharge confinement times over high recycling case (for constant \( n_e \), \( I_p \), \( B_T \), \( \kappa \), etc).
- Lithium stable under normal operation
  - Here “normal” includes VDEs, disruptions.
- Follow-on (LTX) will increase liquid lithium area to 5 m²
  - 90% of plasma surface area
  - Initial operation with fast-pulse gas fueling
  - Test confinement with initial NBI system from UW-Pegasus group.