Liquid metal walls, lithium, and low recycling boundary conditions in tokamaks

Dick Majeski, PPPL
Outline

- Liquid metal plasma-facing components
  - Rationale for liquid metals as PFCs
  - Candidate liquid metals
  - Implementing liquid metal PFCs
  - Experiments
- Liquid lithium and low recycling walls
  - Introduction
  - Impact of nonrecycling PFCs
    » Implications for confinement
  - Short survey of experimental results
- Future work
  - Near-term experiments
  - Implications for fusion devices

A new wall for the box holding the sun

Fundamental change in boundary conditions for the plasma in the box
Rationale for liquid metal PFCs

- Only viable candidate solid material for reactor-grade PFCs is tungsten
  - Alloys brittle at <700 °C
    » But self-annealing at 700 - 1000°C
  - Subject to surface damage under D+He fluence
  - W a viable option for present reactor concepts, but:
    ⇒Imposes a hard limit for wall power density

- Existence of a single wall solution strongly restricts reactor design
  - “Compact” reactors are not attractive at low wall loading
    » Excludes substantially all innovative concept development, except small, low fusion power approaches

- Liquid walls may remove restrictions on wall loading
  - We will only consider liquid metals
    ⇒Salts (FLiBe) - are not discussed here

Tungsten surface after long-term plasma exposure
• Structures a few tens of nm wide
• Structures contain nano bubbles

100 nm (VPS W on C) (TEM)

NAGDIS-II: pure He plasma
N. Ohno et al., in IAEA-TM, Vienna, 2006, TEM - Kyushu Univ., Te = 1250 K, t = 36,000 s, 3.5x10^27 He+/m², Eion = 11 eV
Features of liquid metal walls

- Continuously renewed as new fluid enters the system
- Neutron damage not a concern for liquid metals
- PMI limited to sputtering + evaporation
  - No long-term exposure effects
- Much thinner mechanical construction of the plasma-coolant interface can be envisioned, since erosion not an issue
  - Must be consistent with disruptive, other forces
    » Disruptive forces on the liquid metal not a structural issue
  - Low thermal impedance between heat load and coolant
    » “hypervapotron” or heat-pipe-like cooling solutions possible
- Broad range of design approaches
  - Fast flowing jets, wall-adhered flows, slowly flowing capillary systems
  - Multiple possible solutions to the wall problem
- Potential for high wall power density solutions

⇒ Difficult to implement
  - Staged approach: static fluids, then tackle flow
## Properties of liquid metals

- **Gallium**
  - Z=31, atomic weight =69.7
  - Melting point = 29.8 °C, boiling point = 2204 °C
  - Liquid density=6.1g/cm³, sp. heat capacity = 0.37 J/g °C
  - Thermal conductivity: 40.6 W/m°C, electrical res. = 140 nΩ m
  - Vapor pressure = 10⁻⁷ Torr at 900 °C

- **Tin**
  - Z=50, atomic weight=118.7
  - Melting point = 232 °C, boiling point = 2602 °C
  - Liquid density = 7.0 g/cm⁻³, sp. heat capacity = 0.23 J/g °C
  - Thermal conductivity: 66.8 W/m°C, electrical res. = 115 nΩ m
  - Vapor pressure = 10⁻⁷ Torr at 1000 °C

- **Lithium**
  - Z=3, atomic weight =6.9
  - Melting point = 180.5 °C, boiling point = 1342 °C
  - Liquid density = 0.5 g/cm⁻³, sp. heat capacity = 3.58 J/g °C
  - Thermal conductivity: 84.8 W/m°C, electrical res. = 93 nΩ m
  - Vapor pressure = 10⁻⁷ Torr at 400 °C
Chemistry of hydrogen with liquid metals

- Gallium, tin have no significant chemistry with H, D, T
  - No experimental observations of reduced recycling with Ga, Sn on test stands (e.g. PISCES, IIAX)
  - Note that some short-term retention of helium in gallium has been observed
    » Helium bubble formation in liquid metals possible at high fluence
- Lithium, however, readily forms a hydride
- Atomic hydrogen is efficiently pumped by lithium - very high sticking fraction
  - Diffusivity of hydrogen in liquid lithium is very high: $\sim 10^{-4} \text{ cm}^2\text{sec}^{-1}$
    » Concentration of D, T likely to be uniform in the liquid
  - LiD will precipitate out of the liquid metal if D concentration exceeds $\sim 10\%$
    » Melting point 688°C, exceeds operational limit for lithium
  - Molecular hydrogen is not readily pumped by (static) lithium
- Liquid lithium must be cycled through a reactor quickly enough to avoid deuteride formation
  - Tritium must be removed externally before tritide forms
  - Simplest approach is thermal desorption/evaporative release
    » Recombined molecular hydrogen is not readily re-absorbed by lithium
- Gallium, tin do not trap hydrogen - retention issue does not exist
High capacity of liquid lithium to store deuterium demonstrated in PISCES-B experiments (UCSD)

- Liquid lithium retains atomic deuterium up to a nearly 1:1 Li:D ratio
  - Deuterium is dissolved in the lithium; *does not form a stable deuteride*
  - High diffusivity precludes large surface concentration
- Liquid Li will not saturate in a discharge
- “Bound” hydrogen can be liberated by heating (T11-M results)
  - External process in a steady-state reactor

Results from T11-M (PP&CF 44, 955) showing deuterium desorption vs. capillary lithium limiter temperature

M. J. Baldwin et al., Nucl Fusion 42 (2002) 1318
Materials issues with liquid metals

- Lithium is more aggressive than tin, tin is more aggressive than gallium
- Gallium:
  - Alloys with many metals
  - Does not readily attack ceramics
- Tin:
  - Compatible with alumina, quartz at elevated temperatures (!)
  - Compatible with refractories, including niobium
- Lithium:
  - Compatible with refractory metals, vanadium, niobium, steels up to PFC evaporative temperature limit (400 C)
  - Attacks most ceramics at T~400 C. Best choices are yttria (Y₂O₃, highest binding energy of any oxide), MgO, BN.
  - No ceramic coatings have been developed to reliably insulate metallic piping
- Sodium (LM coolant; not suitable for a PFC - high vapor pressure)
  - Usable with many ceramics
  - Used as a fission reactor coolant for decades; much experience (but not in a B-field)
Temperature limits for liquid metal PFCs set by the evaporation rate (allowable influx to the plasma)

- Lithium has a low temperature limit in comparison to gallium and tin
  ⇒ Lithium would not be a candidate for a LM PFC except for its recycling properties
  - Another possible plus - highest heat capacity of any solid
  ⇒ Possible reduced recycling alternative is tin(~80%) - lithium(~20%) eutectic
Required flow rates for liquid metal PFCs

- In a reactor, the liquid metal PFC must flow at some rate for replacement
- Flow rate is set by limits in *erosion, temperature* or *D-T inventory* in the liquid
  - Temperature, hydrogenic inventory limits more restrictive than erosion limit
- Required flow rate is high for all “self-cooled” concepts (thermal limit)
  - “Self-cooling” refers to heat removal with the bulk liquid
  - Flow rate determined by heat flux, flow path
  - Typical flow rates: 5-10 m/sec or higher for 2-5 MW/m² power flux (lithium)
    » ~ meter-scale flow path
    » Estimate assumes only heat conduction, not convection
    » *Power limits much higher for gallium, tin*
- Capillary or thin-film systems rely on cooling from *behind* the liquid substrate.
  - Flow rate of liquid not determined by heat removal
- For gallium, tin thin-films, required flow rate is determined by erosion replacement
  » Very low required replacement rate
- For lithium, flow rate is determined by requirement that liquid be removed before LiD(T) forms, precipitates
  - Typical required flow rates ~ few mm/sec - 1 cm/sec

Very wide range of possible flow rates for liquid metal PFCs
Power limits for “thick” liquid lithium layers

- Temperature rise determined by conduction:
  \[
  \Delta T = 2q_{wall} \left( \frac{W}{cm^2} \right) \sqrt{\frac{t}{\pi \kappa \rho_m C_p}}
  \]

- Or time-to-temperature with a constant power flux:
  \[
  t = 11.4 \left( \frac{\Delta T}{q_{wall}} \right)^2
  \]

- For the wall:
  - \( T_{wall} \) (initial) \( \sim \) 200C
  - \( T_{wall} \) (final) < 400C

- Uncooled rise
  - Determines maximum exposure time to power source for liquid
  - Maximum exposure time determines minimum flow velocity

Exposure time for \( \Delta T = 200C \)

- \( q_{wall} \) (W/cm\(^2\))
- time (sec)
Film or jet liquid metal PFC systems

- Jet or film liquid metal divertor target concepts involve forcing flow of liquid metal across the magnetic field (pumps), or employing J×B forces (inductive pumping).

- Conceptual concepts for a full lithium wall in a tokamak have been developed
  - Retained and propelled by J×B, V(J×B) forces

Recirculating LM film divertor concept for C-mod (B. Nelson, ORNL)
Capillary liquid metal PFC concepts

- Systems now being tested in tokamaks are primarily thin-film (capillary) systems
  - Thin = fraction of a millimeter
- No flow on the time scale of a discharge
  - Lithium has capacity for many seconds of particle flux
  - Reduces required inventory of lithium
  - Static thicker-film (~0.5 cm) system has been successfully tested in CDX-U

Porosity sprayed molybdenum  CVD tungsten “wick”

Micrographs of candidate lithium-retaining surfaces
High power handling tests of lithium systems

- Two approaches have been developed using lithium which allow very high power handling
- Both approaches successful at exceeding conduction-limited power density limits
  - First approach (Red Star, Russian Federation) uses evaporation of lithium in a porous mesh target
    » Employs heat of evaporation
    » Evaporating lithium provides vapor shielding of target
  - Second approach employs naturally generated (convective) flows in free surface liquid lithium for redistribution of heat (PPPL)
- Both approaches have issues for application in a tokamak
  - Lithium influx with evaporative technique may be prohibitive
  - High magnetic field may suppress self induced flows
- But both techniques have demonstrated heat handling capability in excess of 50 MW/m²
The organization of works in Russia on Lithium Capillary-Pore Systems problem

Very high power handling demonstrated - >50 MW/m² (25 MW/m² steady-state) ~60 MW/m², 300 sec. demonstrated with a 3 mm liquid lithium film on CDX-U

TRINITI

Li CPS samples tests on plasma accelerator QSPA

“Red Star”

Kurchatov Institute

Tests of CPS with Li supplying system on electron beam device SPRUT-2

Liquid Lithium Limiter on FTU

TRINITI

Li CPS rail limiter CPS on TRINITI tokamak

TRINITI

Li CPS samples tests on plasma accelerator MK-200

ITER School 2009
22-26 June 2009
High power handling of 2-3 mm liquid lithium film target (CDX-U)

Tolerates e-beam spot power densities in excess of 60 MW/m²

- Beam power: 1.6 kW, <3 mm spot size
- IR camera movie of 25 sec. of a 300 sec. beam run
- Yellow denotes +55°C, red denotes +110°C
- If only conduction were active, area under beam would heat to 1400°C in 0.1 sec.

Localized heat deposition induces flow
  - Marangoni effect; temperature-dependent surface tension
  ⇒ Unclear if result extends to high magnetic field (~0.5 kG here)

No detected local heating under beam spot
Effect of magnetic fields on thermally driven flows in free-surface liquid lithium has been modeled.

Flow streamlines show tendency towards two-dimensionalization.

Thermoelectric effect not included; may be significant.
Flowing film systems have been considered for NSTX

- Pumped systems
  - Tests have been conducted with scaled systems (not lithium)
  - Test films were a few millimeters thick
  - Primary objective: gauge MHD effects on a flowing liquid metal
Film flow experiments show strong MHD effects

- Surface normal magnetic field with gradient similar to NSTX
  - “Hydraulic” jump, turbulence evident in flow
- Note that currents flowing to the LM, MHD activity in plasma will also affect the LM

1 m/sec
Jump 7 cm downstream

2 m/sec
Jump 15 cm downstream

3 m/sec
Jump flushed downstream
Flow begins to pinch
Gallium jet experiment in ISTTOK

Discharge behavior is similar with gallium jet and graphite limiters

Gallium jet

Fig. 3. Poloidal cross-section showing the position of the gallium jets in the tokamak vessel.
Recap - status of research into liquid metal PFCs

- Fast-flowing liquid metals
  - Trial system designs have been developed
  - Test stand evaluation of liquid metal film and jet flow
    » Jets were tested at Sandia National Laboratory on the LIMITS facility
  - Two tests to date in tokamaks
    » Gallium droplet system in T-3M (Troitsk, 1980’s)
    » Gallium jet test in ISTTOK (2007 on)
- Prototype liquid metal systems have demonstrated very high power handling
  - Relevance to tokamaks yet to be established
- Static, “thick” film liquid lithium tested on CDX-U (more later)
- Thin film static liquid metals - restrained by capillary forces
  - Approach currently favored in most of the world’s experiments
  - Tests in T11-M, CDX-U, FTU, T10
    » Replenished between shots from an in-vessel reservoir
  - Near-term tests scheduled in NSTX, LTX
Recycling

Recycling coefficient R is defined as:

\[ R = \frac{\text{flux of neutrals from the wall into the plasma}}{\text{flux of deuterons from the plasma into the wall}} \]

*Effective* particle confinement time \( \tau_p^* \) (characteristic density decay time with \( R > 0 \)):

\[ \tau_p^* = \frac{\tau_p \text{(particle confinement time)}}{1 - R} \]

Particles may be recycled by reflection/backscattering from the surface, or desorption from surface layers.

Number of particles in a tokamak discharge, compared to the # of particles in a monolayer on the wall of a tokamak (~10^{16} \text{ cm}^{-2})(\text{e.g. TFTR}):

\[
\frac{\langle n_e \rangle 2\pi^2 R_0 a^2}{10^{16} \text{ cm}^{-2} \cdot 4\pi^2 R_0 a} \approx \frac{3 \times 10^{13} \text{ cm}^{-3} \times 100 \text{ cm}}{2 \times 10^{16} \text{ cm}^{-2}} = 0.15
\]

Steady state operation in a tokamak with a solid wall must be fully recycling
– Wall is fully loaded with hydrogenics within a few \( \tau_p \) (<tens of seconds)

Recycling is the dominant fueling source in virtually all tokamaks
Recycling mechanisms: direct reflection

- Direct reflection: scattering due to hard-sphere collisions between the incident ion and the wall
  - Provides an irreducible minimum recycling coefficient
  - Function of the reduced energy $\varepsilon$:
    \[
    \varepsilon \approx \frac{32.5m_2E}{(m_1 + m_2)Z_1Z_2(Z_1^{2/3} + Z_2^{2/3})^{1/2}}
    \]
  - Where (1) denotes the incident ion and (2) the target, $E$ is the incident ion energy
  - $R_p(\text{---}) =$ probability of particle reflection, $R_E(\text{---}) =$ energy of the reflected particle

- Surface layers of carbon, oxygen can affect direct reflection from lithium
- Surface layers a few 100Å thick can readily accumulate between discharges, at typical tokamak base pressures

D$\Rightarrow$Li: $\varepsilon$=4.78 E  
D$\Rightarrow$C: $\varepsilon$=2.24 E  
D$\Rightarrow$Mo: $\varepsilon$=0.21 E  
D$\Rightarrow$W: $\varepsilon$=0.10 E
Other wall-localized sources of gas for recycling

- Carbon walls have significant hydrogenic inventories
  - Chemistry of carbon with hydrogen guarantees that hydrocarbons will form in the wall
- Hydrogenic inventory is available for sputtering, thermal release
- Removal of hydrogen from carbon requires $T>300 - 350^\circ C$
- Erosion of carbon surface leads to dust formation
  - Dust will be highly tritiated in a D-T device
- Hydrogen retention with metallic walls a current research topic
  - Retention in a tokamak has only been investigated at low temperatures ($300^\circ C$ or less)
  - Reactor operation expected to involve operation at $T>600^\circ C$ (tungsten)
Recycling via direct reflection from lithium

Lithium has the lowest probability of direct reflection of any candidate PFC material.

For an average incident angle of 45°, the reflection coefficient at low energy is ~20% (edge \( T_e \sim 30 \text{ eV} \)).

Drops to <10% for edge \( T_e \sim 300 \text{ eV} \). 

![Graph showing reflection coefficient vs. ion energy and angle](image-url)
Secondary electron effects

- “Recycling” is typically thought of as an ion process
- Electrons are also “recycled” via secondary electron emission
  - Secondaries cool the edge plasma. Power flow from the edge electron population to the wall/limiter/divertor:
    \[ q_{pe} = \frac{(2kT_e + e\phi_0)}{(1 - \gamma_e)} - e\phi_0 \gamma_e \frac{0.6n_e c_s}{(1 - \gamma_e)} \]
  - For \( \phi_0 = -\alpha(kT_e/e) \), where \( \phi_0 \) is the sheath potential at the wall/limiter/divertor, and typically \( \alpha \sim 3 \)
- Lithium has the lowest secondary electron emission coefficient of any metal
- Effect of secondaries in a magnetic field, in the edge plasma, is very difficult to model
- Secondary electron emission is very sensitive to very thin (10s of Å) layers of surface impurities

![Graph showing secondary electron emission coefficients for Li, Sn, and Pt](image)

**Fig. 2.** The total yield as function of primary energy for some metals; for references, see Table I.

Lithium sputtering

- At 700 eV the yield is 9%
- Fraction of sputtered lithium = redeposited is high
  - Low ionization energy - ionized in the sheath

- Fraction of lithium which is sputtered as an ion ~60% for incident ion energy ~0.5 - 1 keV. He⁺ incident at 45°

- Self-sputtering of Li on D-treated Li:
  - 24.5% at 700 eV
  - 15.8% at 1 keV
Recycling, confinement, and the edge temperature

- Substantially all large tokamaks have found confinement increases with reduced recycling
  - Recycling affects $T_{\text{edge}} \Rightarrow \text{“pedestal”} \Rightarrow \text{core confinement}$
- Simplest set of transport equations which shows this effect:
  \[
  Q_T(\rho) + Q_{VT}(\rho) = 5T\Gamma_p(\rho) - K(\rho)\frac{dT}{d\rho} = Q_p(\rho)
  \]
  where $T = T_e = T_i$ (normalized minor radius $\rho$), $\Gamma_p$ = plasma particle flux, $K(\rho)$ = effective heat conduction coefficient, $Q_p(\rho)$ = total particle + energy flux as a function of $\rho$, and $\gamma = \gamma_e + \gamma_i \sim 6-8$, with $\gamma_e \sim \gamma_i \sim 3-4$.
  - First term on L.H.S. = convective flux, 2nd = conductive part

- To close the above equation, we must relate the plasma energy flux $Q_p^w = Q_p(\rho=1)$, and the particle flux $\Gamma_p^w = \Gamma_p(\rho=1)$, to the material wall bounding the plasma. If the particle distribution function is characterized by a single parameter (the effective temperature $T_w$):
  \[
  T_w = \frac{Q_p^w(a)}{\gamma\Gamma_p^l(a)}
  \]
Recycling, $T_e(a)$, and confinement (continued)

- So
  \[
  \frac{Q_T^w}{Q_p^w} = \frac{5}{\gamma} \quad \text{and} \quad \frac{Q_{VT}^w}{Q_p^w} = \frac{\gamma - 5}{\gamma}
  \]

And, recalling that $\gamma \sim 6$-8, we see that most of the energy is carried by convection near the wall.

- Since:
  \[
  T_w = \frac{Q_p^w(a)}{\gamma \Gamma_{pl}(a)}
  \]

and recycling is the dominant source of particles for solids, most liquid metals:

\[
(\Gamma_p^w)_{W,C} \sim (\Gamma_p^w)_{\text{recyc}} \gg (\Gamma_{puff},\Gamma_{pump})
\]

Therefore the particle flux is large, and dominated by recycling. But for a low recycling lithium boundary:

\[
(\Gamma_p^w)_{\text{Lithium}} \sim \Gamma_{puff} \sim \Gamma_{pump} \ll (\Gamma_p^w)_{W,C} = (\Gamma_p^w)_{\text{recyc}}
\]

So that with a low recycling wall, $T_w$ can be high, provided that the external fueling rate need not be increased to the level of recycling.

⇒ This is found empirically to be the case.
Numerical modeling also indicates that reduction in recycling to \( R < 50\% \) will reduce the internal electron temperature gradient.

- Very low recycling expected to produce a large edge “pedestal” temperature
  - Limiter equilibrium modeled
    » Not a traditional H-mode
- Similar simulation results from other numerical codes
  - TSC (Tokamak Simulation Code)
  - ASTRA (Model briefly discussed in R. Majeski et al., Nucl. Fusion 49 (2009) 055014)
- Similarity to a supershot edge in TFTR
  - Documented recycling coefficient in TFTR was 0.85
  - Documented recycling coefficient was 50 - 70% in CDX-U
- Recycling coefficient can be *tailored*
  - Material choice
  - Substitution of edge gas puffing for recycling gas source

UEDGE modeling for CDX-U Tom Rognlein, LLNL
Tests of lithium as a PFC

- First extensive use of lithium for wall conditioning was on TFTR
  - Primary techniques for applying lithium:
    » Multiple lithium pellet injection
    » Lithium aerosol injection in the edge plasma (DOLLOP)
- Plasma-material interactions were a complex interplay of lithium and carbon
- All high confinement discharges on TFTR relied on reduced recycling
  - Obtained via discharge cleaning of the carbon PFCs, with or without boronization
    » Documented global recycling coefficient $R$ of 0.85 for cleaned carbon
    - Discharges with lithium conditioning exhibited characteristics of lower recycling, but $R$ was not determined for these experiments
- Lithium coating now routinely performed in FTU with a capillary porous system
  - FTU lithium limiter typically withdrawn from LCFS during operation
  - Larger system with higher power handling capability in the design stage
- Lithium coatings used for several years in NSTX
Lithium aided supershots in TFTR exhibited energy confinement times of up to $3.3 \times$ L-mode

- Average enhancement over L-mode for cleaned carbon walls: 1.5
Lithium influx in FTU

ECRH + LH Discharges in FTU with the Liquid Lithium Limiter (LLL)

- $Z_{\text{eff}}$ is reduced by at least a factor 2 in lithium discharges in FTU
- Measured lithium content with lithium conditioning in TFTR: 0.5%
  - In NSTX lithium content in core plasma only 0.1%
Solid vs. liquid lithium walls

- All wall “conditioning” processes currently in use involve solid coatings
  - Includes titanium gettering in small tokamaks, boronization in large machines, lithium wall coatings (for $T_{\text{wall}} < 200$ C)
- Clean coatings can produce a transitory reduction in recycling
  - Coatings are routinely cleaned between discharges in present-day devices with helium glow discharge cleaning
    » Low density, unmagnetized plasma discharge which sputters D
- Range of an ion, accelerated in the wall or divertor sheath, $\phi_0 = \sim [-3.3(kT_e/e)]$, ranges from 100 - 200 Å to ~1000 Å (alphas)
- Wall inventory available for hydrogen binding = first few hundred Å of the wall
  ⇒ A solid wall can provide pumping for a short-pulse discharge
    ⇒ Effect cannot extend to steady state discharges
- Surface coatings are more difficult to remove from a solid
  - **Only first few 100 Å count for ion recycling**
  - **Only the first few angstroms count for secondary electron emission**
- Coatings are more readily dissolved into a liquid
  - Dissolution can be aided by circulating the liquid
Small tokamak (CDX-U) experiments with liquid lithium PFCs

- \( R_0 = 0.34 \text{ m}, a = 0.22 \text{ m}, \kappa \leq 1.6, B_T(0) \leq 2.1 \text{ kG}, \)
  \( I_p \leq 80 \text{ kA}, \tau_{\text{disch}} < 25 \text{ msec}, T_e(0) \sim 100 \text{ eV}, \)
  \( n_e(0) < 6 \times 10^{19} \text{ m}^{-3} \)
- Tray lies approximately in a flux surface
  - Minimal normal \( B \Rightarrow \text{reduces MHD effects on the liquid metal} \)
- Thin coatings appear between runs
  - Removed/dissolved by GDC, heating
- One fill active for up to \( \sim 1 \text{ year} \)
  - Pumped for hundreds of discharges

UCSD lithium injector

Liquid lithium tray limiter in CDX-U

Tray during fill

Tray after plasma operations, during hot argon glow
Energy confinement in CDX-U was significantly increased with a low recycling lithium boundary

- $\tau_E \sim 2-3 \times \text{ELMy H-mode scaling}$
  - Note increase in ITER98P due *solely* to drop in loop voltage = lower power input
    » $\text{ITER98P} \sim P^{-0.69}$
  - All discharges at similar plasma density, current, same toroidal field
- $\tau_E \sim 6\times$ best pre-lithium CDX-U results
  (kinetic measurements, Ti gettered)
- $\tau_E \sim 10\times$ modeling from TSC
- $30\times$ neo-Alcator scaling
- Low density Ohmic discharges
  - $\tau_{i-e} > \tau_E$, ions and electrons decoupled
  - Confinement improvement in electron channel
- Discharges at low collisionality
  - $v^*_{i,e} < 0.1$

- Largest relative increase in Ohmic tokamak confinement ever observed
LTX - full, 5 m² liquid lithium coated SS-Cu hot wall
Second shell: porous molybdenum inner layer

**Expected**
\[ \tau_E \sim 60 \text{ ms} \]

- Inner heated shell (explosively bonded SS on copper)
- Heat shielded centerstack
- Fast, uncased internal coil
- Lots of flux loops, magnetics

<table>
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<tr>
<th>Parameter</th>
<th>CDX-U</th>
<th>LTX</th>
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<tbody>
<tr>
<td>Major radius</td>
<td>0.34 m</td>
<td>0.4 m</td>
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<tr>
<td>Minor radius</td>
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<td>&gt;100 ms</td>
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<td>Ohmic flux</td>
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<td>160 mV-s (centerstack maximum: 225 mV-s)</td>
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<tr>
<td>Wall temp.</td>
<td>20 °C</td>
<td>&gt; 600 °C intermittent, &gt; 500 °C continuous</td>
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NSTX Liquid Lithium Divertor (LLD-1) Will Be Tested in 2010

- Construction: Thin (0.5 mm) SS brazed under pressure; similar to HIPping
  - Approach allows for a thinner SS barrier than alternative fabrication
  - Example of alternatives: LTX employs explosively bonded material - requires 1.5 mm minimum thickness SS
- SS surface will be plasma-sprayed with porous molybdenum layer
- Porous moly layer will be evaporatively filled with lithium
- Installation this summer for operation in 2010
**Liquid lithium PFC research issues**

- What is the minimum attainable global recycling coefficient for a tokamak?
- What is the *optimum* recycling coefficient for a tokamak?
  - Experiments: lower is better, but minimum R to date is $\sim 1/2 - 2/3$
  - What is the optimum configuration? $\Rightarrow$ NSTX (divertor) + LTX (wall-limited)
- What equilibria can be achieved with *pumping walls* and *core fueling*?
  - Small volume and lack of charge-exchange losses in LTX allow full NB fueling with modest sources ($\sim 30A$ at 10-15 keV)
- What is the effect of very low recycling on tokamak profiles?
  - Will the core electron temperature profile flatten, as predicted?
  - What limits the edge electron temperature?
  - What will determine the density (and by extension, the pressure) profile?
  - How will the current profile be modified?
- How will the confinement be affected?
  - Reduction in anomalous transport
- What is the effect on MHD stability and $\beta$ limits?
  - Hot, low collisionality plasma extends to a *very* near conducting wall, at $r \sim 0.01a$
Consequences of very high confinement for fusion system design can be significant

- PFC: 0.1-0.5 mm “creeping” lithium film constrained in an engineered tungsten surface
  - Required replacement rate: ~10 liter/hour (flow rate < 1 cm/sec)
  - Small size = access for core fueling with positive-ion NBI

- \( R_0 = 1.25 \text{m}, a = 0.75 \text{m}, A = 1.66, \kappa = 2, 3.5T, 11 \text{ MA} \)

- At 30\% \( \beta \), \( P_{\text{fusion}} = 400 \text{ MW} \) (~ITER)
  - Plasma volume =26 m\(^3\)
  - 3\% of ITER
  - Manageable tritium requirements for reactor development

- High recirculating power
  - Power reactor would likely move to higher A

Balance of reactor with TF, PF and blanket could be comparable in volume to present-day light water fission reactor pressure vessel (~100 m\(^3\))

-but at lower power

**A low recycling, low aspect ratio tokamak may lead to a compact fusion development facility**
Summary

Liquid metals, lithium, and low recycling tokamaks

- Liquid metal PFCs may offer a long life, high power alternative to tungsten
- High recycling liquid metals - gallium, tin - offer high temperature first-wall operation (>600 °C)
- Low recycling lithium has a restricted temperature range (~400 °C max)
  - First wall power removed by coolant cannot be as efficiently converted to electricity (low thermodynamic efficiency)
- But: a low recycling wall offers access to a core-fueled, edge-pumped tokamak equilibrium
  - Tokamaks have never entered this operational space (!)
- Limited experimental results support theoretical models predicting significantly higher confinement with low recycling walls
  - Many more experiments, more modeling needed
- Implications for fusion power production are very broad