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

Dick Majeski, PPPL

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PHYSICS LABORATORY

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 - 1000C
  - Subject to surface damage under D+He fluence
  - W a viable option for present reactor concepts, but:

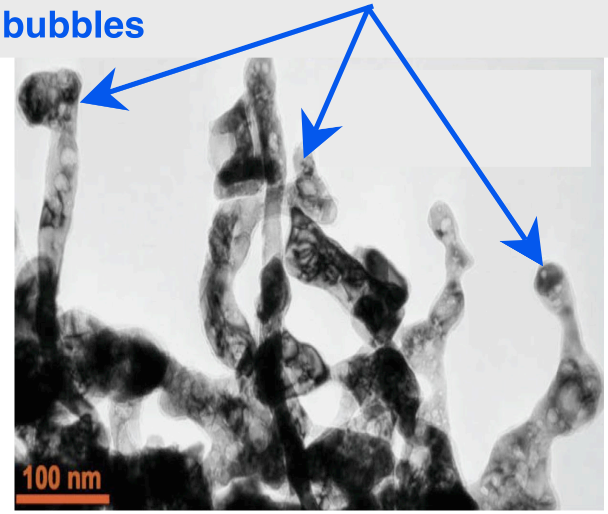
  ⇒**Imposes a hard limit for wall power density**
- Existence of a single wall solution strongly restricts reactor design
  - "Compact" reactors are not attractive at low wall loading
    - » Excludes substantially all innovative concept development, except small, low fusion power approaches
- Liquid walls may remove restrictions on wall loading
  - We will only consider liquid <u>metals</u>

    ⇒Salts (FLiBe) - are not discussed here

Tungsten surface after long-term plasma exposure

•Structures a few tens of nm wide

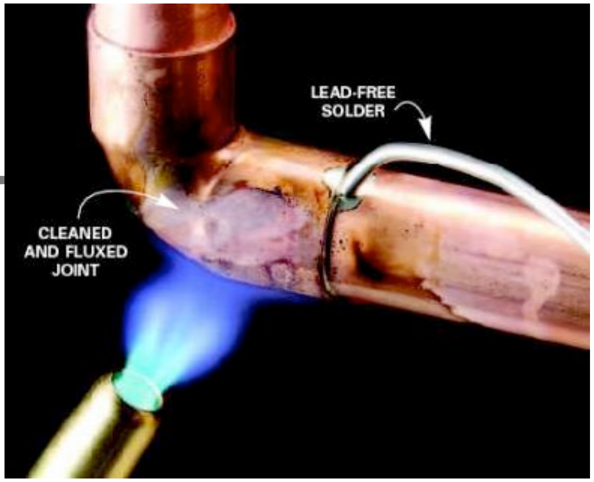
• Structures contain nano bubbles



<u>100 nm</u> (VPS W on C) (TEM)

NAGDIS-II: pure He plasma
N. Ohno et al., in IAEA-TM, Vienna, 2006, TEM - Kyushu Univ., T_s = 1250 K, **t = 36,000 s**, 3.5x10^{27} He$^+$/m^2, E_{ion} = 11 eV

Features of liquid metal walls



Ref: "Joe the Plumber" 2008 U.S. presidential campaign

- 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

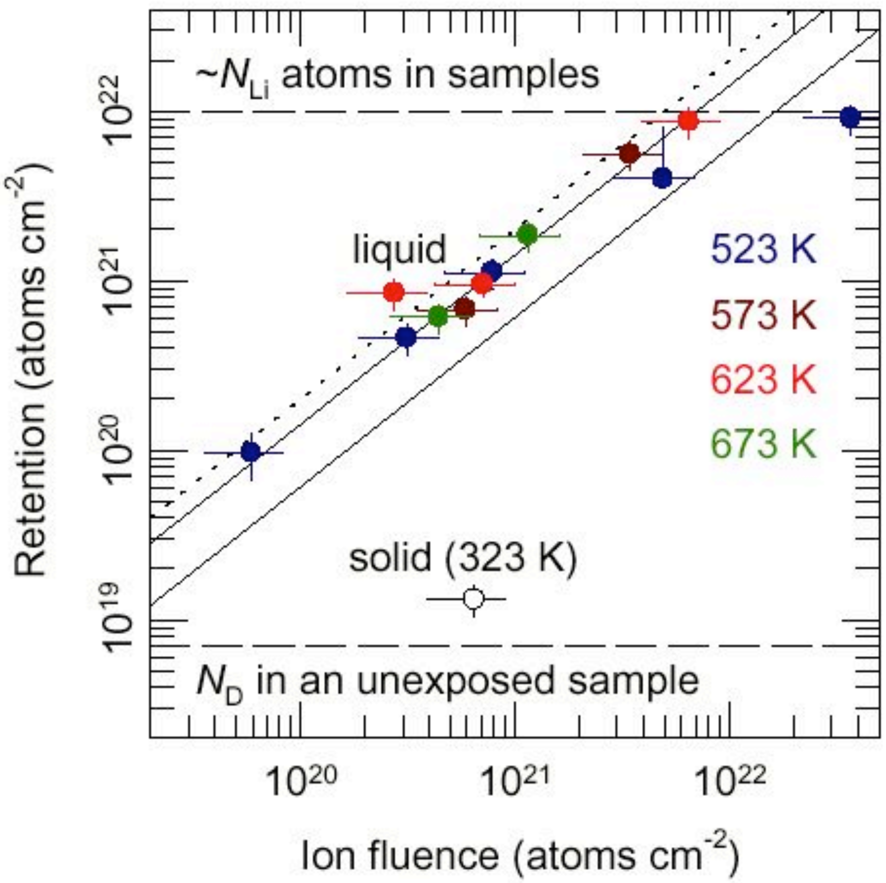
Properties of liquid metals

- Gallium
  - Z=31, stomic weight =69.7
  - Melting point = 29.8 °C, boiling point = 2204 °C
  - Liquid density=6.1g/cm^3, 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

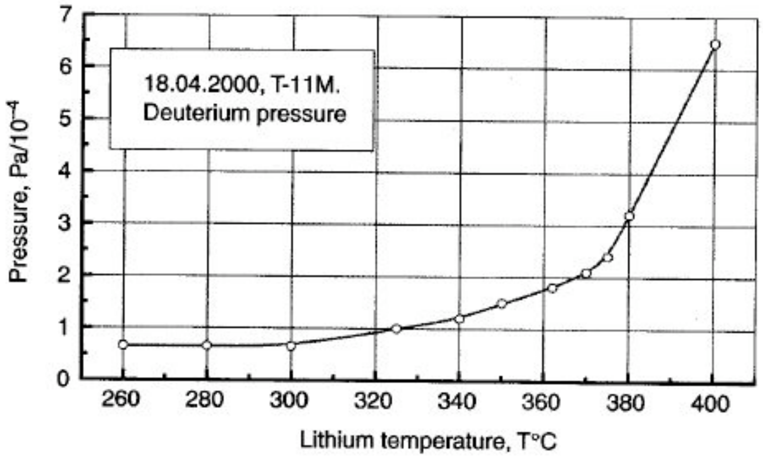
- Gallium, tin have no significant chemistry with H, D, T
  - No experimental observations of reduced recycling with Ga, Sn on test stands (e.g. PISCES, IIAX)
  - Note that some short-term retention of helium in gallium has been observed
    - Helium bubble formation in liquid metals possible at high 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: $\sim 10^{-4}$ $cm^2 sec^{-1}$
    - Concentration of D, T likely to be uniform in the liquid
  - LiD will precipitate out of the liquid metal if D concentration exceeds ~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)



M. J. Baldwin et al., Nucl Fusion **42** (2002) 1318

- 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 <u>will not saturate</u> in a discharge
- “Bound” hydrogen can be liberated by heating (T11-M results)
  - External process in a steady-state reactor

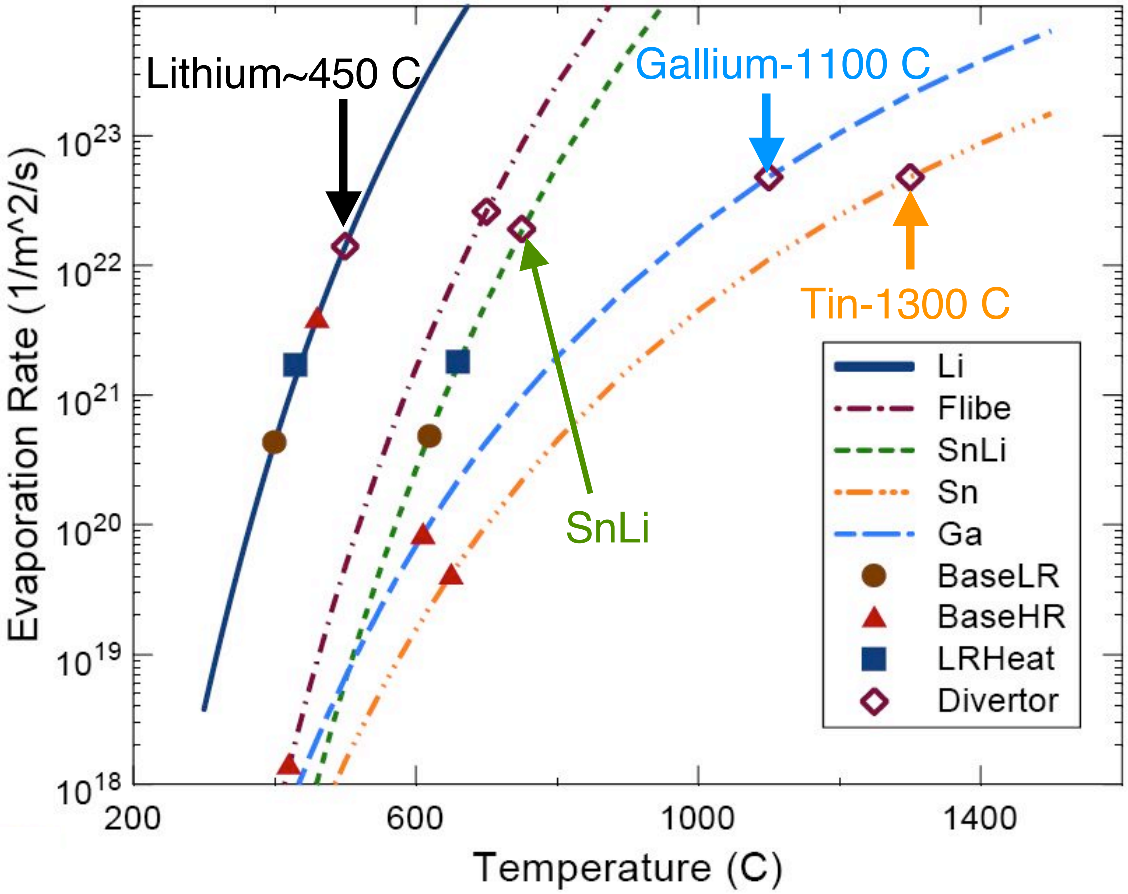


Results from T11-M (PP&CF **44**, 955) showing deuterium desorption vs. capillary lithium limiter temperature

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 (Y_2O_3, 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/m^2 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

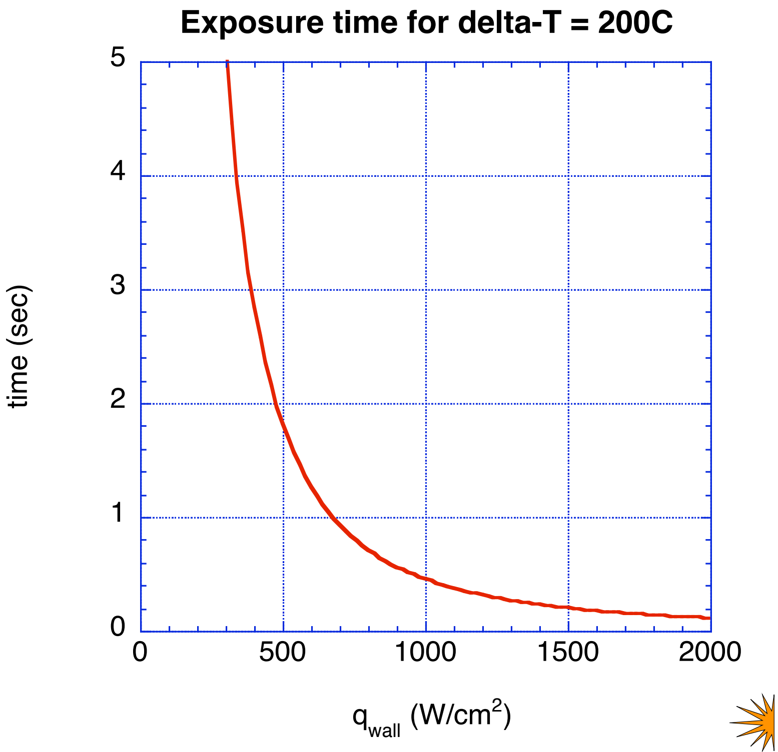
- Temperature rise determined by conduction:

$$\Delta T = 2q_{wall}(W/cm^2)\sqrt{\frac{t}{\pi\kappa\rho_m C_p}}$$

- Or time-to-temperature with a constant power flux:

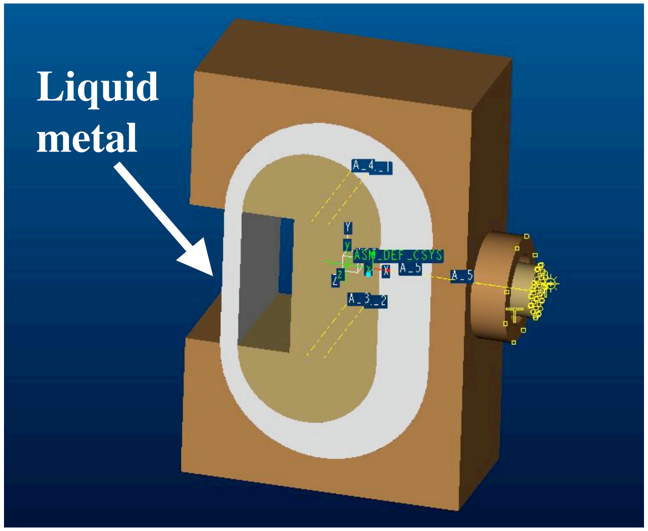
$$t = 11.4\left(\frac{\Delta T}{q_{wall}}\right)^2$$

- For the wall:
  - T_{wall} (initial) ~ 200C
  - T_{wall} (final) < 400C
- *Uncooled* rise
  - Determines maximum exposure time to power source for liquid
  - Maximum exposure time determines minimum flow velocity

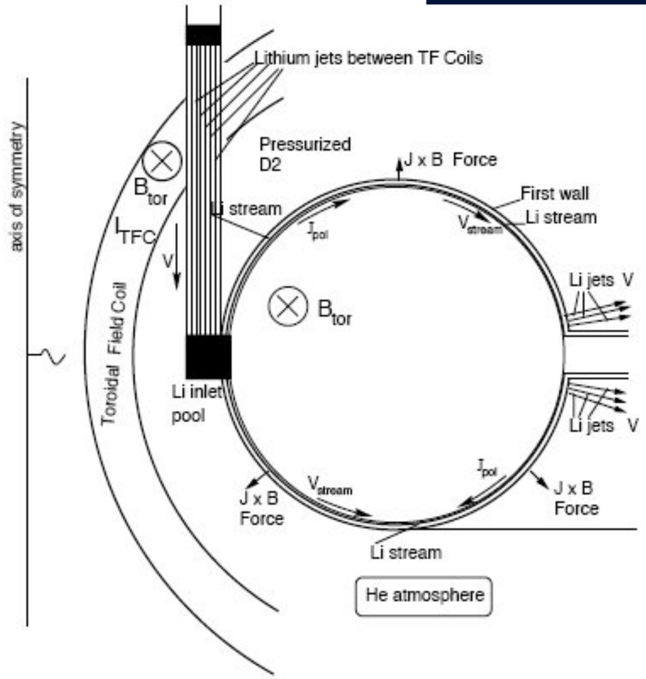


Film or jet liquid metal PFC systems

- 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)



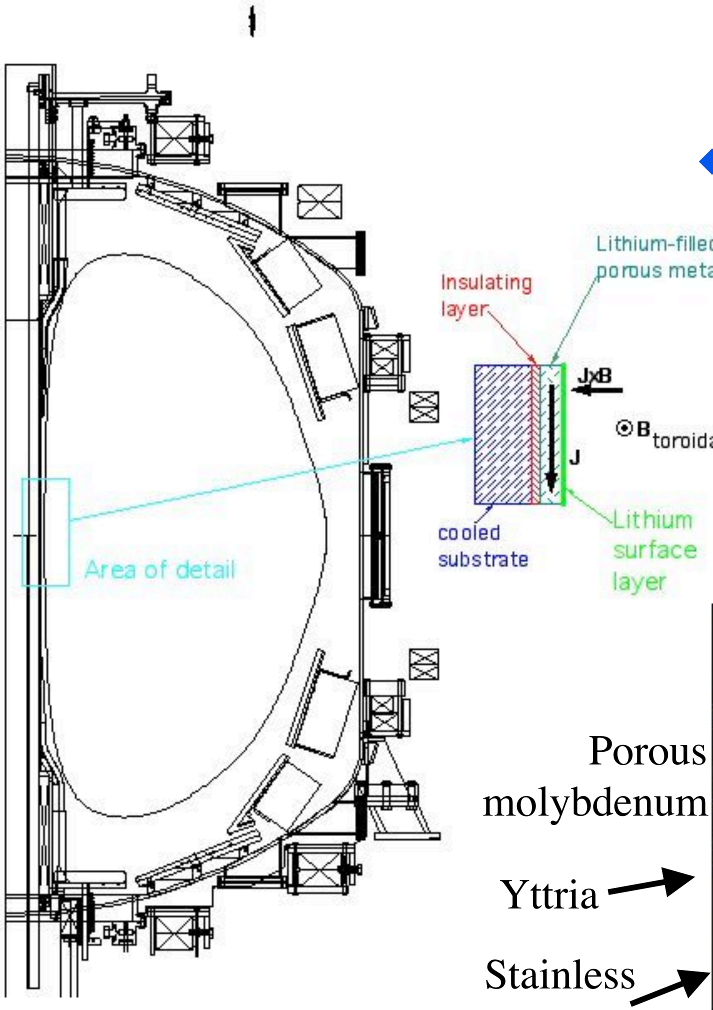
Recirculating LM film divertor concept for C-mod (B. Nelson, ORNL)



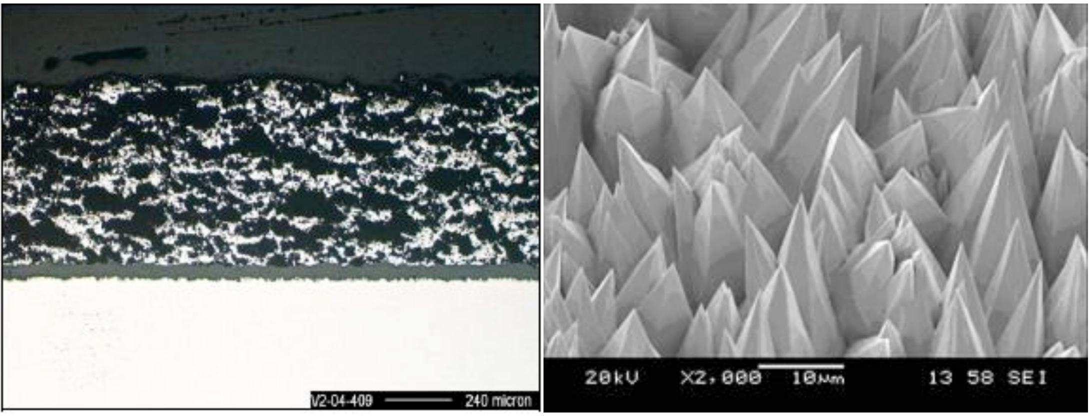
Concept for a lithium-film tokamak wall (L. Zakharov, R. Woolley, PPPL)

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

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



Porous 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/m^2

ROSATOM

Federal State Unitary Enterprise “Red Star”

The organization of works in Russia on Lithium Capillary-Pore Systems problem

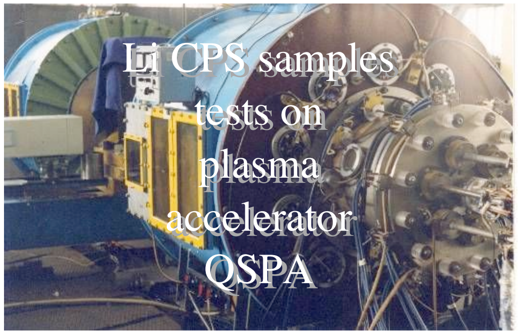
Very high power handling demonstrated - >50 MW/m^2 (25 MW/m^2 steady-state)

~60 MW/m^2, 300 sec. demonstrated with a 3 mm liquid lithium film on CDX-U

“Red Star”

Idea
Development
Manufacturing
Technology
Thermophysical tests

TRINITI

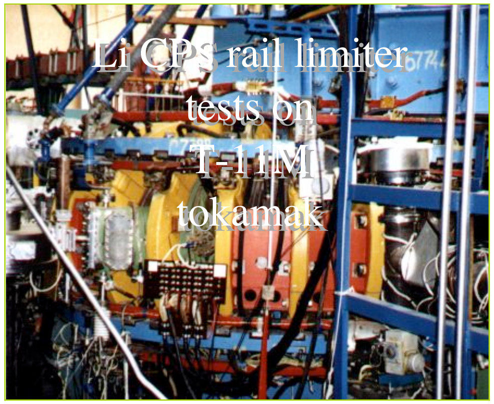


Li CPS samples tests on plasma accelerator QSPA

Kurchatov Institute

Tests of CPS with Li supplying system on electron beam device SPRUT-4

TRINITI



Li CPS rail limiter tests on T-11M tokamak

TRINITI

Li CPS samples tests on plasma accelerator MK-200

Liquid Lithium Limiter on FTU

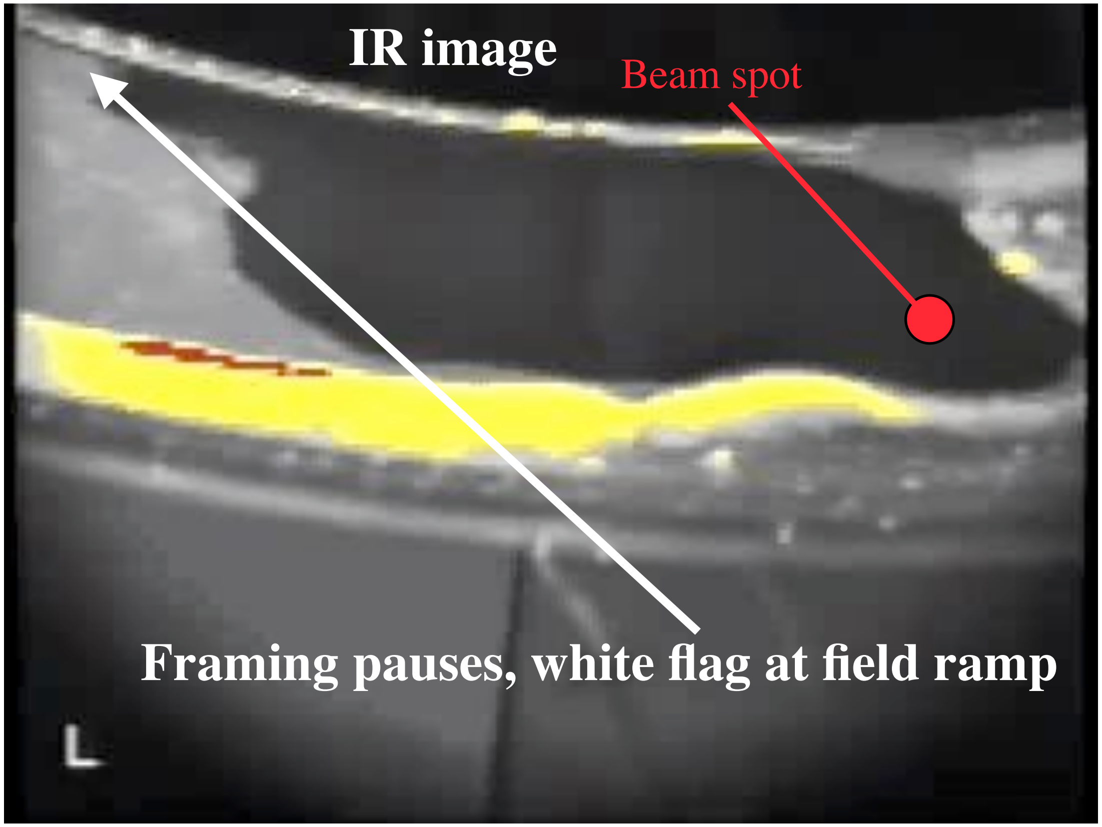
High power handling of 2-3 mm liquid lithium film target (CDX-U) Tolerates e-beam spot power densities in excess of 60 MW/m^2

CDX-U

LTX

R. Kaita et al., Phys. Plasmas 14(2007)056111

- 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 **1400ºC** 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

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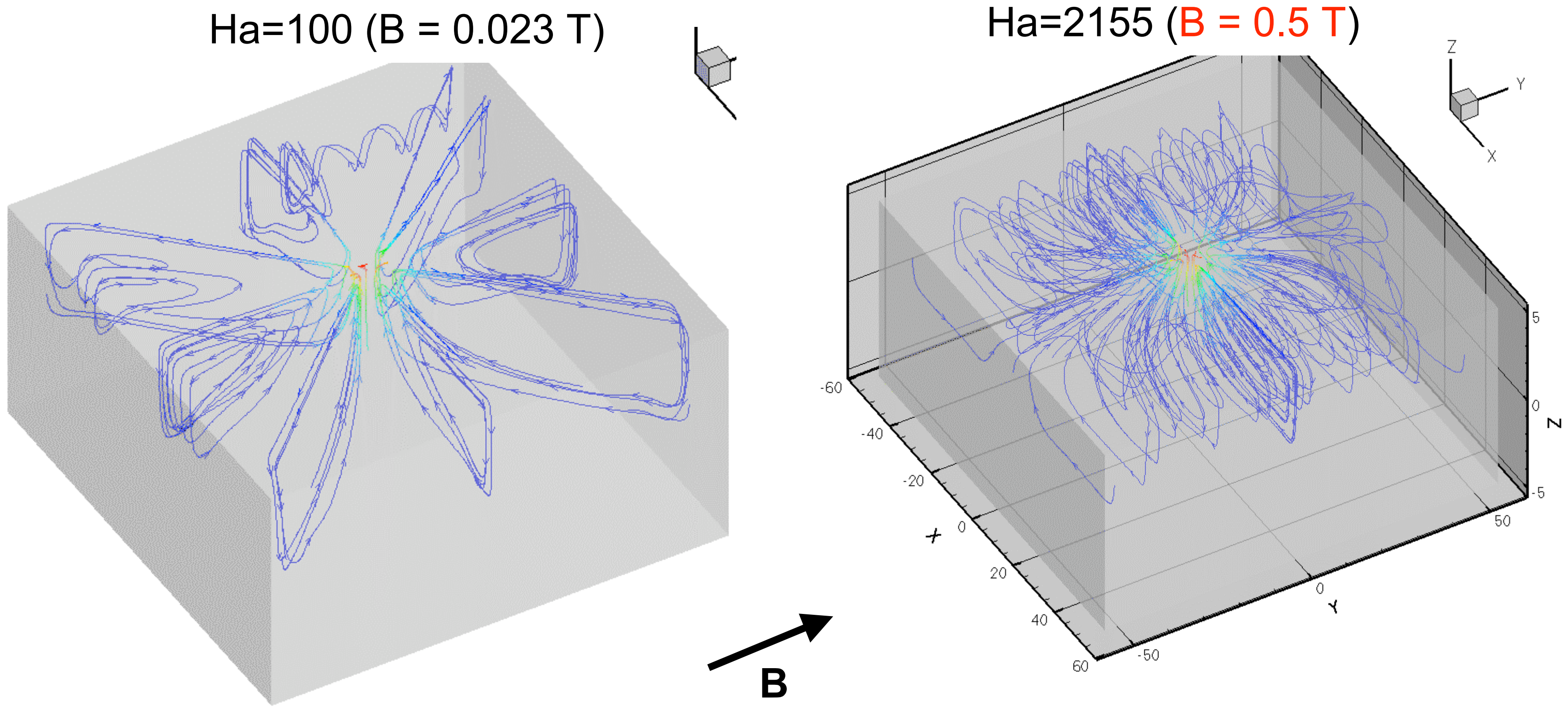
Effect of magnetic fields on thermally driven flows in free-surface liquid lithium has been modeled

Flow streamlines show tendency towards two-dimensionalization



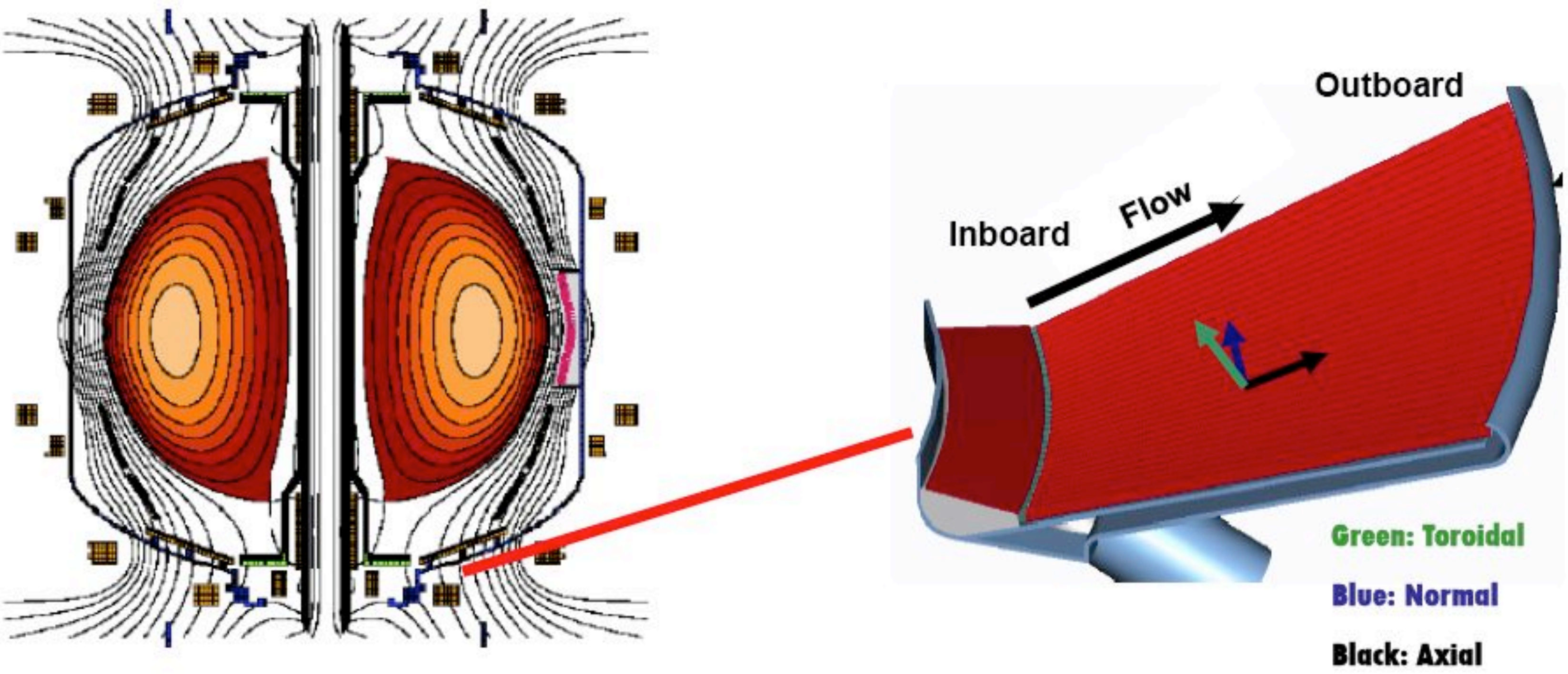
Ha=100 (B = 0.023 T)

Ha=2155 (B = 0.5 T)

Thermoelectric effect not included; may be significant

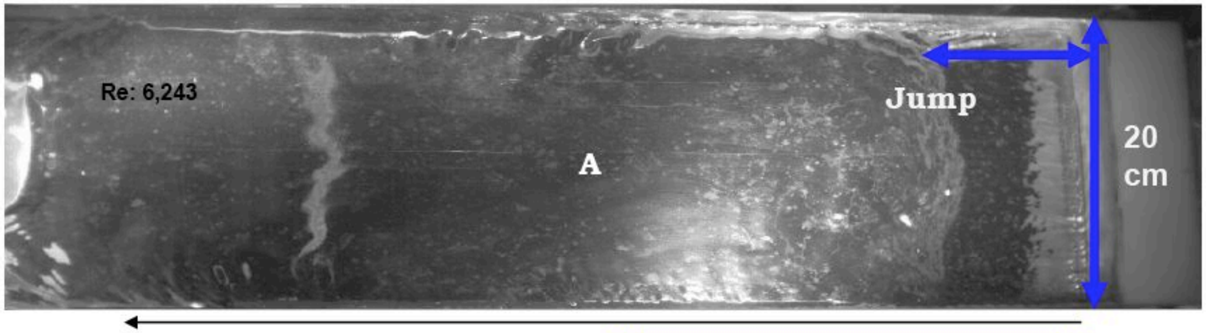
Flowing film systems have been considered for NSTX

- 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

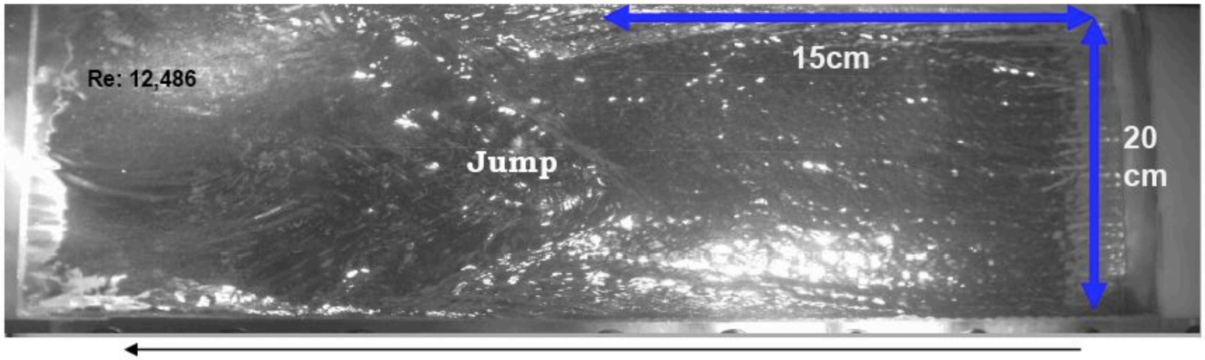


Film flow experiments show strong MHD effects

- 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

R.B.Gomes et al., Fus. Eng. Des. 83 (2008) p. 102

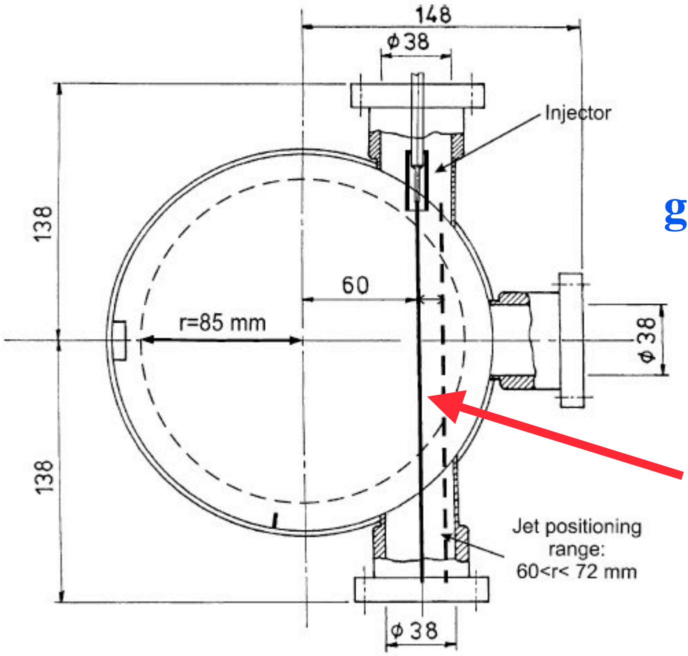
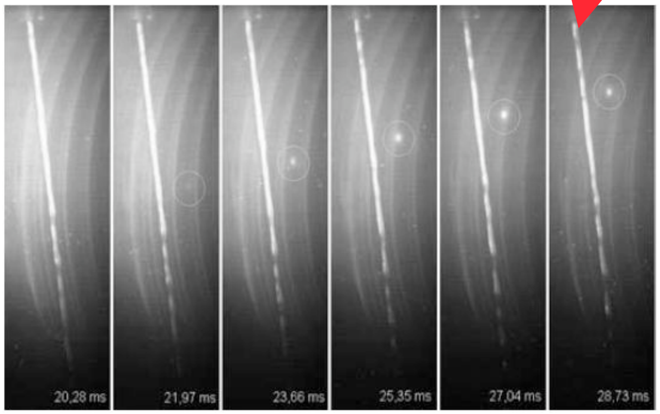
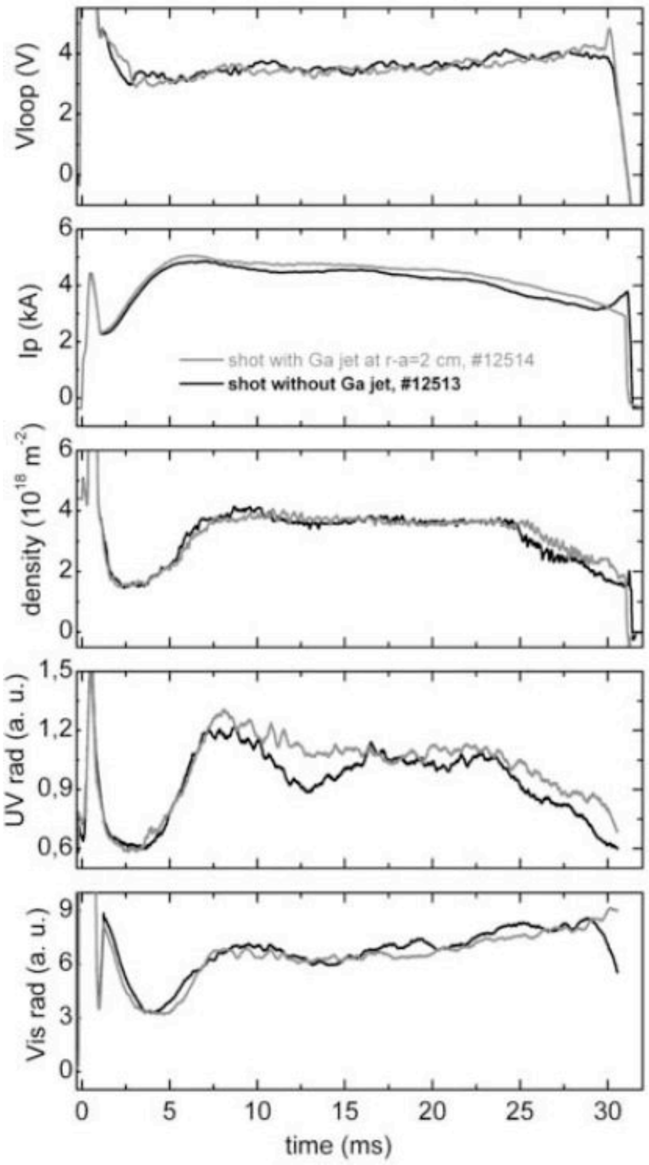


Fig. 3. Poloidal cross-section showing the position of the gallium jets in the tokamak vessel.

Discharge behavior is similar with gallium jet and graphite limiters

Gallium jet





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:

$$R \equiv \frac{\text{flux of neutrals from the wall into the plasma}}{\text{flux of deuterons from the plasma into the wall}}$$

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

$$\tau_p^* \equiv \frac{\tau_p\text{(particle confinement time)}}{1-R}$$

- 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} cm^{-2})(e.g. TFTR):

$$\frac{\langle n_e\rangle 2\pi^2 R_0 a^2}{10^{16}\,cm^{-2}\bullet 4\pi^2 R_0 a} \approx \frac{3\times10^{13}\,cm^{-3}\times 100cm}{2\times10^{16}\,cm^{-2}} = 0.15$$

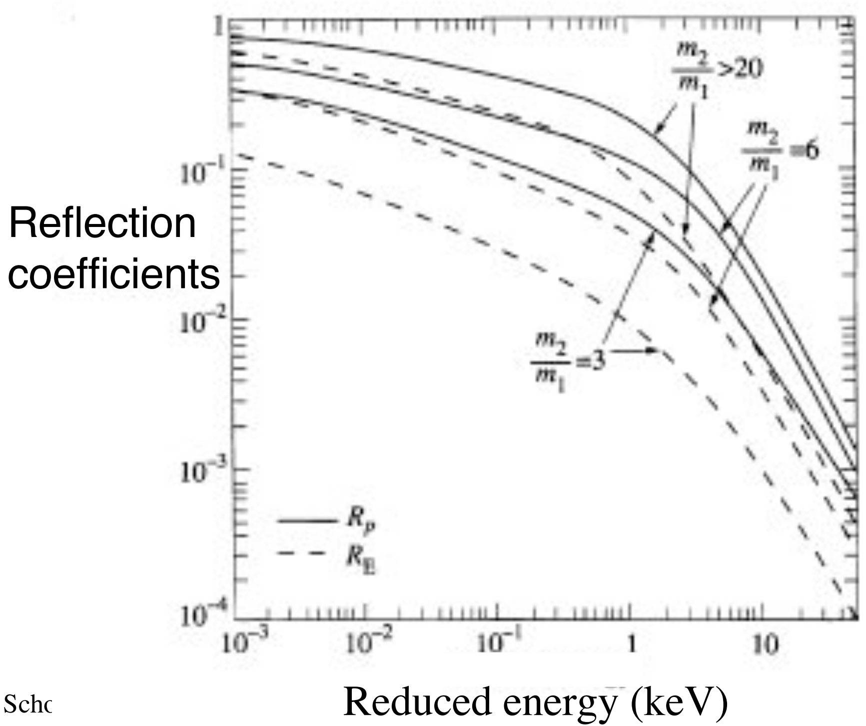
- Steady state operation in a tokamak with a solid wall must be fully recycling
  - Wall is fully loaded with hydrogenics within a few τ_p (<tens of seconds)
- **Recycling is the dominant fueling source in virtually all tokamaks**

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 ε:

$$\varepsilon \approx \frac{32.5 m_2 E}{(m_1 + m_2) Z_1 Z_2 (Z_1^{2/3} + Z_2^{2/3})^{1/2}}$$

  - Where (1) denotes the incident ion and (2) the target, E is the incident ion energy
  - R_p(——) = probability of particle reflection, R_E (– – –) = energy of the reflected particle

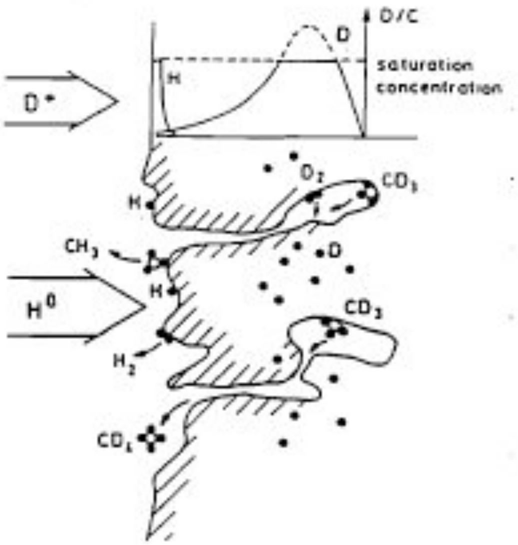


D⇒Li: ε=4.78 E
D⇒C: ε=2.24 E
D⇒Mo: ε=0.21 E
D⇒W: ε=0.10 E

- 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

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 - 350C
- 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 (300C or less)
  - Reactor operation expected to involve operation at T>600C (tungsten)

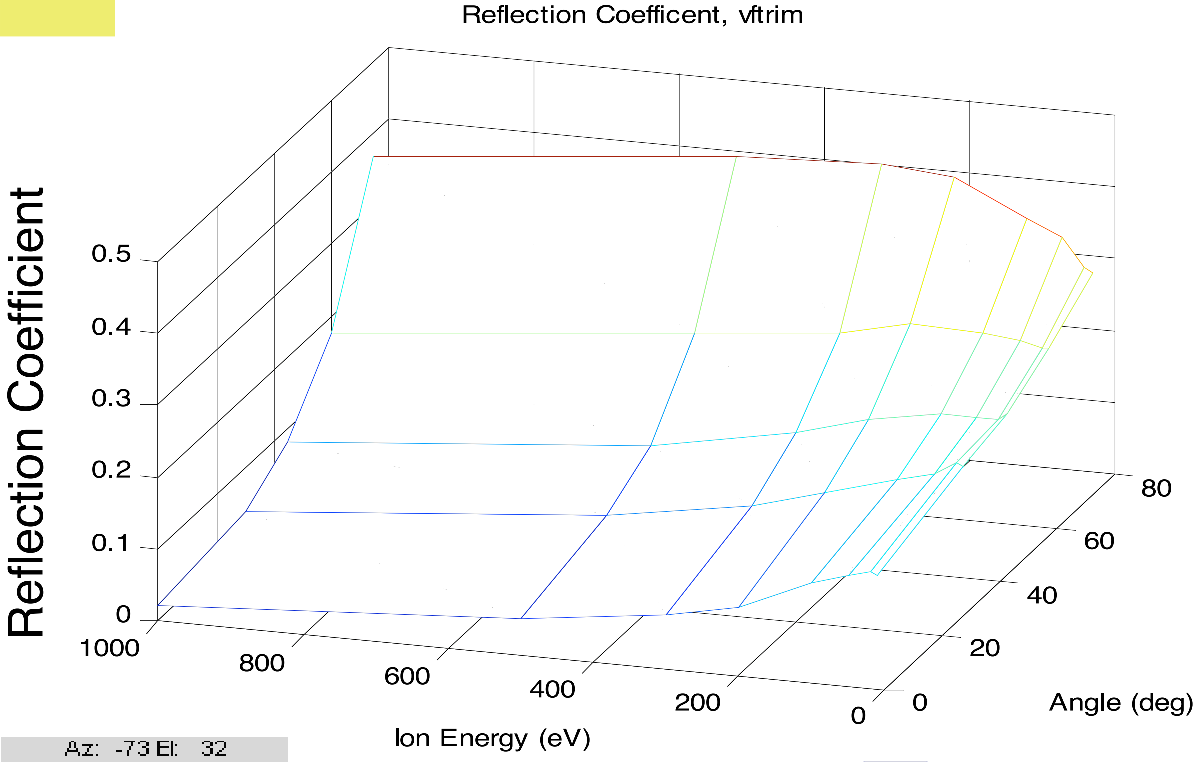


Recycling via direct reflection from lithium

D on 100nm of Li

Energy,Angle	0	30	45	60	75
10	0.1568	0.1966	0.2125	0.2492	0.2979
20	0.1613	0.2019	0.2046	0.2491	0.3045
50	0.153	0.1826	0.2054	0.2564	0.3425
100	0.1387	0.17	0.2042	0.2616	0.3639
200	0.0939	0.1411	0.1889	0.2647	0.4137
300	0.0746	0.114	0.1596	0.2435	0.4225
500	0.0509	0.0817	0.1237	0.224	0.4139
1000	0.0221	0.0401	0.0802	0.176	0.3672

- 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~30 eV)
- Drops to <10% for edge T_e ~ 300 eV



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:

$$q_{pe} = (2kT_e + e\varphi_0)\frac{0.6n_e c_s}{(1-\gamma_e)} - e\varphi_0\gamma_e\frac{0.6n_e c_s}{(1-\gamma_e)}$$

  - For $\phi_0 = -\alpha(kT_e/e)$, where ϕ_0 is the sheath potential at the wall/limiter/divertor, and typically α~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

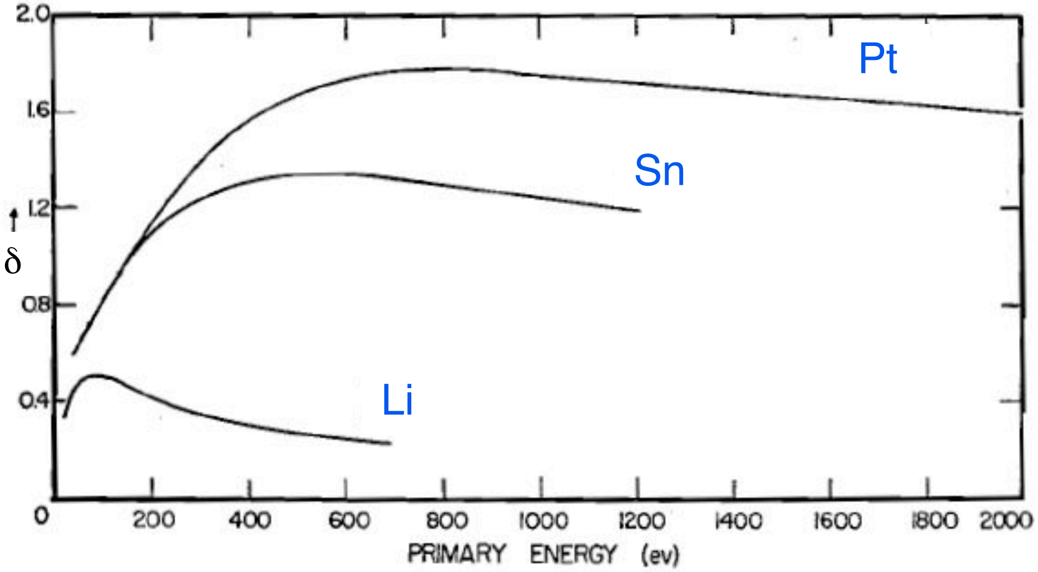
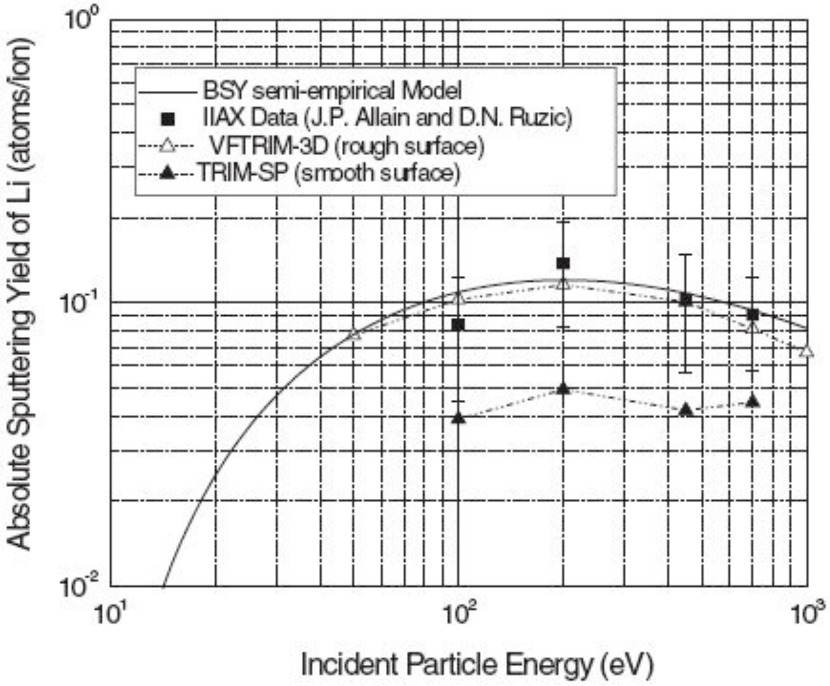


FIG. 2. The total yield as function of primary energy for some metals; for references, see Table I.

A. J. Dekker, in Solid State Physics, Advances in Research and Applications, Vol. 6 (Academic Press, New York, 1958) pp. 251-311

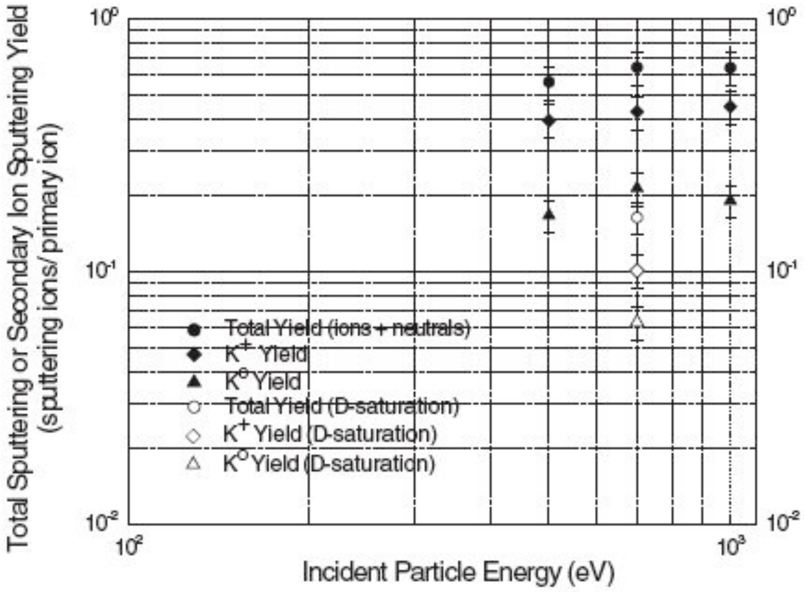
Lithium sputtering



- Li sputtering yield for D incident on deuterated Li, calculations and IIAX measurements (Allain and Ruzic, Nucl. Fusion 42(2002)202). Angle of incidence 45°
- 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 $T_{edge} \Rightarrow$ “pedestal”$\Rightarrow$ core confinement
- Simplest set of transport equations which shows this effect:

$$Q_\Gamma(\rho)+Q_{\nabla T}(\rho)\equiv 5T\Gamma_p(\rho)-K(\rho)\frac{dT}{d\rho}=Q_p(\rho)$$

where $T=T_e=T_i$(normalized minor radius ρ), Γ_p = plasma particle flux, $K(\rho)$ = effective heat conduction coefficient, $Q_p(\rho)$ = total particle + energy flux as a function of ρ, and $\gamma = \gamma_e + \gamma_i \sim 6\text{-}8$, with $\gamma_e \sim \gamma_i \sim 3\text{-}4$.

  - 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):

$$T_w=\frac{Q_p^w(a)}{\gamma\Gamma_{pl}(a)}$$

S. Krasheninnikov and P. Yushmanov, Sov. J. Plasma Phys. 16(1990)801
A. Dnestrovskij et al., Nucl. Fusion 31(1991)647

Recycling, $T_e(a)$, and confinement (continued)

- So $$\frac{Q_\Gamma^w}{Q_p^w} = \frac{5}{\gamma} \qquad \text{and} \qquad \frac{Q_{\nabla T}^w}{Q_p^w} = \frac{\gamma - 5}{\gamma}$$

And, recalling that γ ~ 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:

$$(\Gamma_p^w)_{W,C} \sim (\Gamma_p^w)_{recyc} >> \Gamma_{puff}, \Gamma_{pump}$$

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

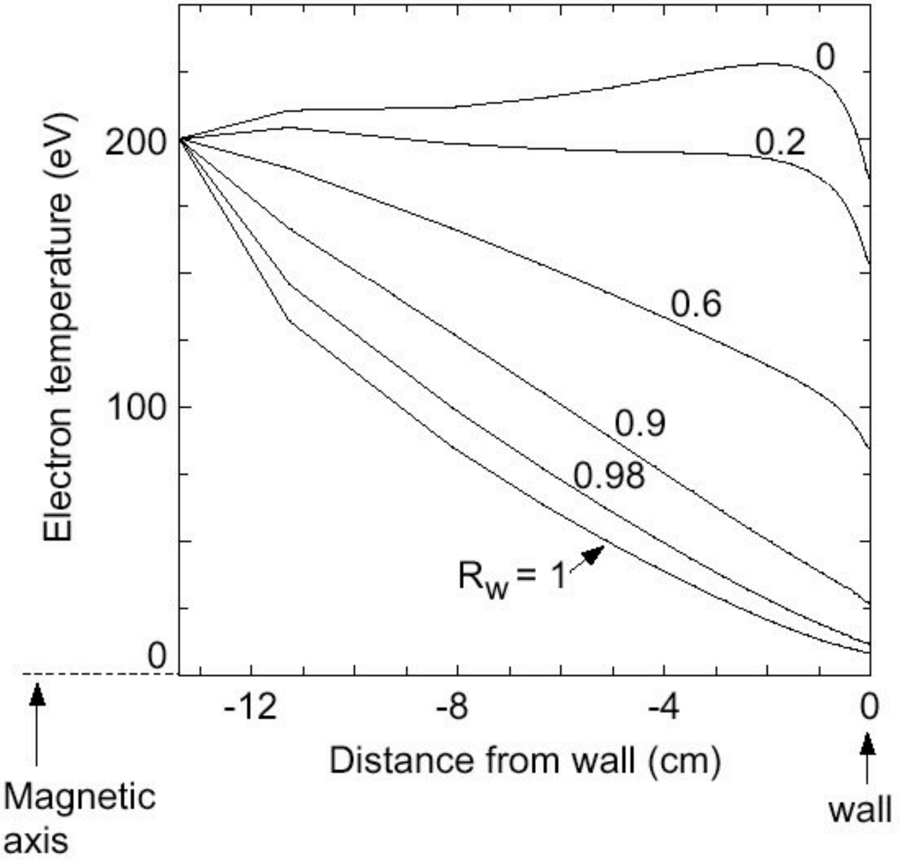
$$(\Gamma_p^w)_{Lithium} \sim \Gamma_{puff} \sim \Gamma_{pump} << (\Gamma_p^w)_{W,C} = (\Gamma_p^w)_{recyc}$$

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



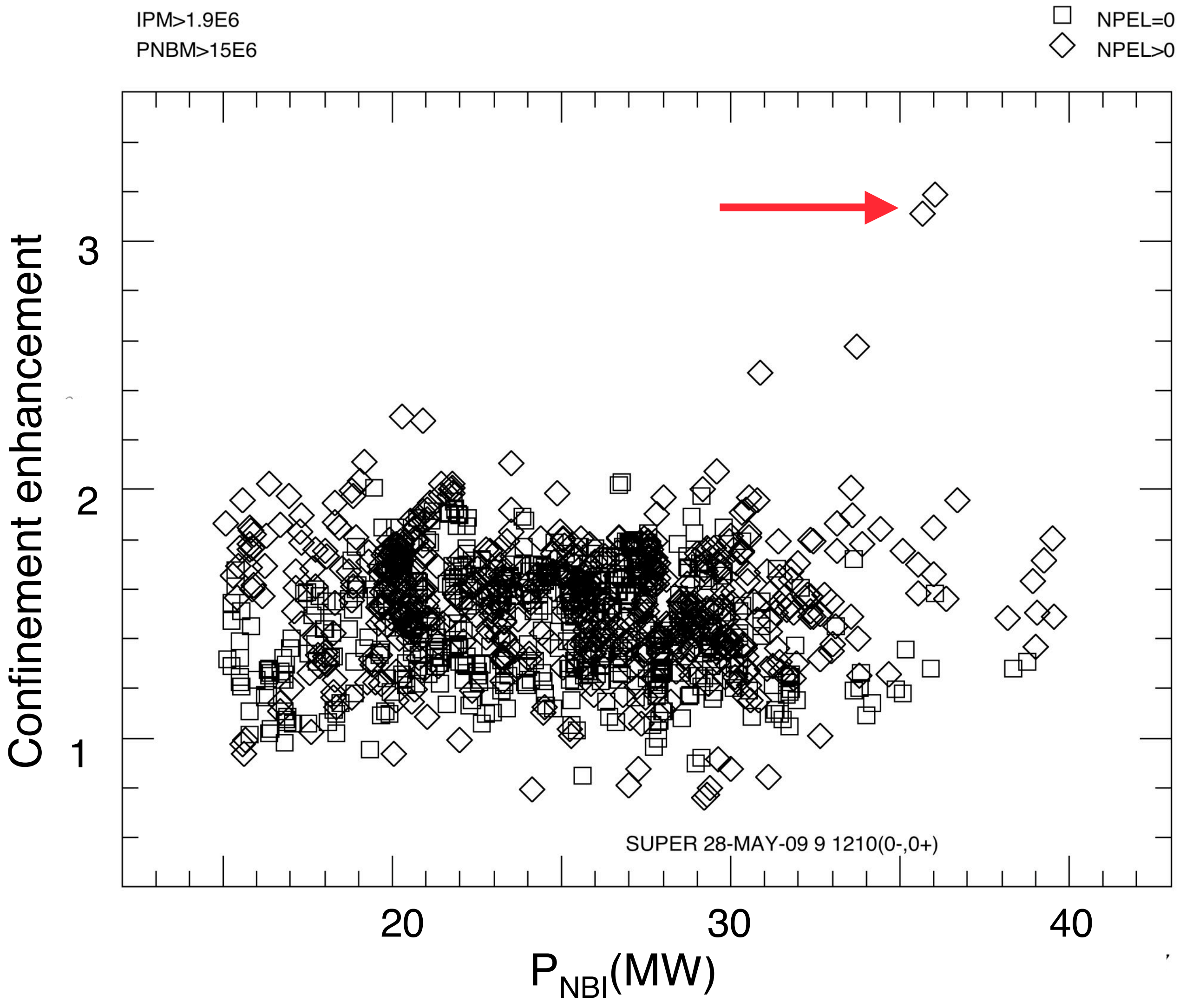
UEDGE modeling for CDX-U Tom Rognlein, LLNL

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 charateristics 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

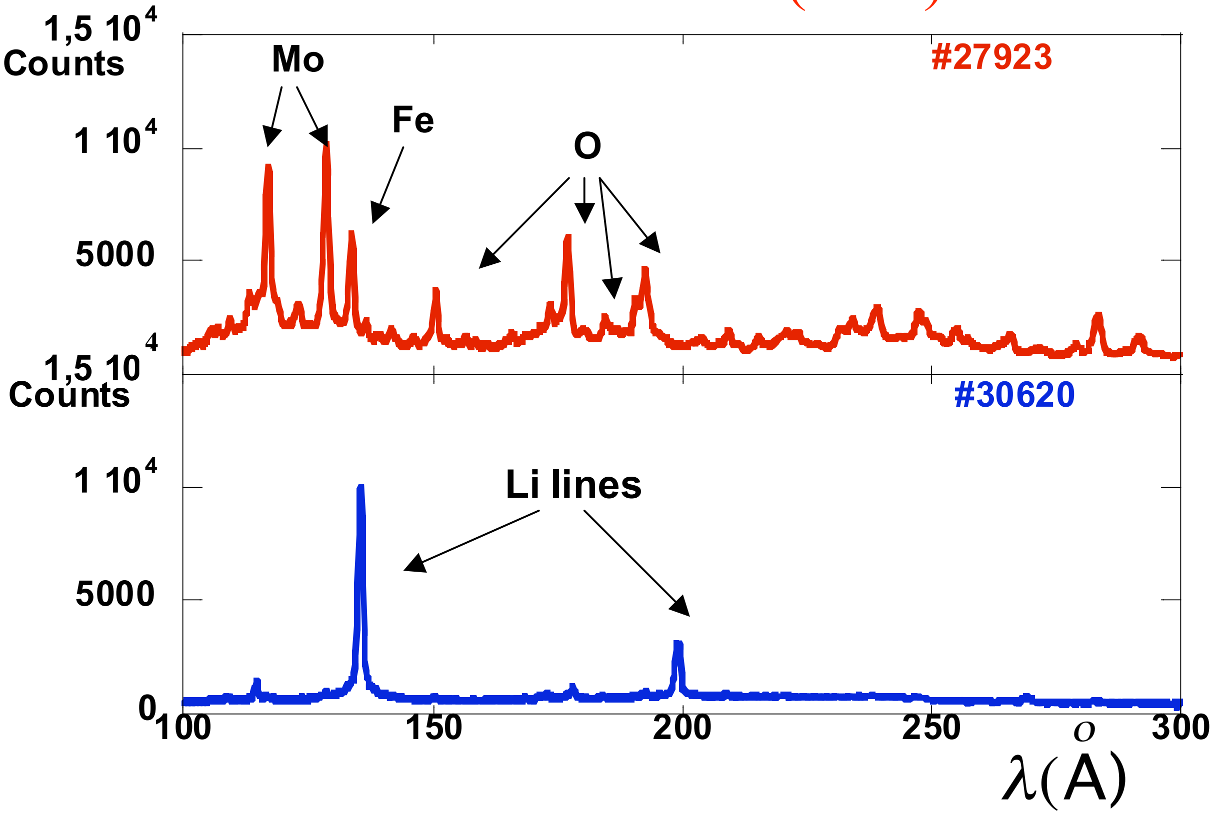
Lithium aided supershots in TFTR exhibited energy confinement times of up to 3.3× L-mode

- 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_{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

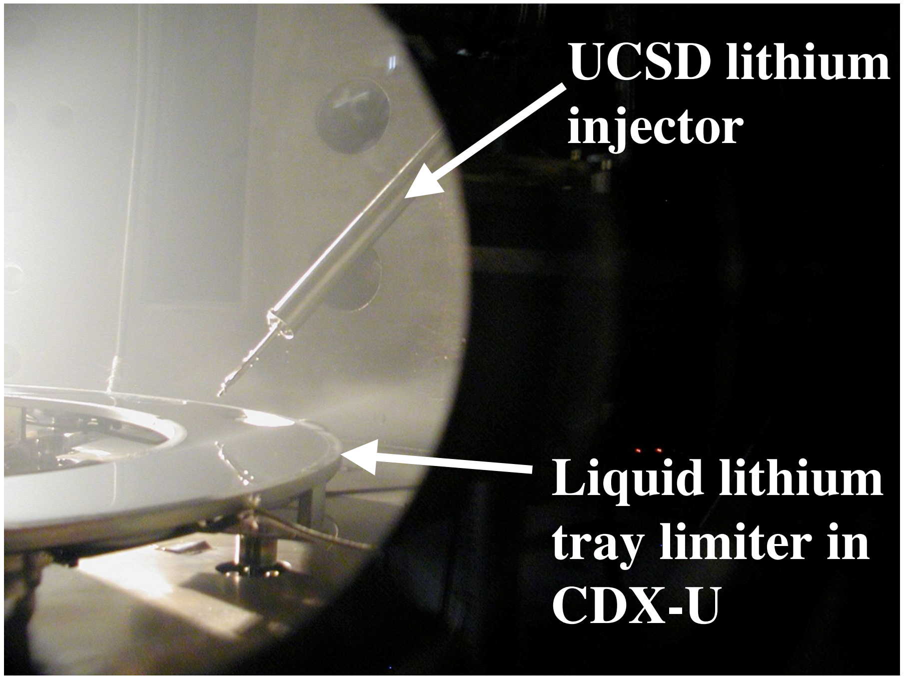
- All wall “conditioning” processes currently in use involve solid coatings
  - Includes titanium gettering in small tokamaks, boronization in large machines, lithium wall coatings (for T_{wall}<200 C)
- Clean coatings can produce a transitory reduction in recycling
  - Coatings are routinely cleaned 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

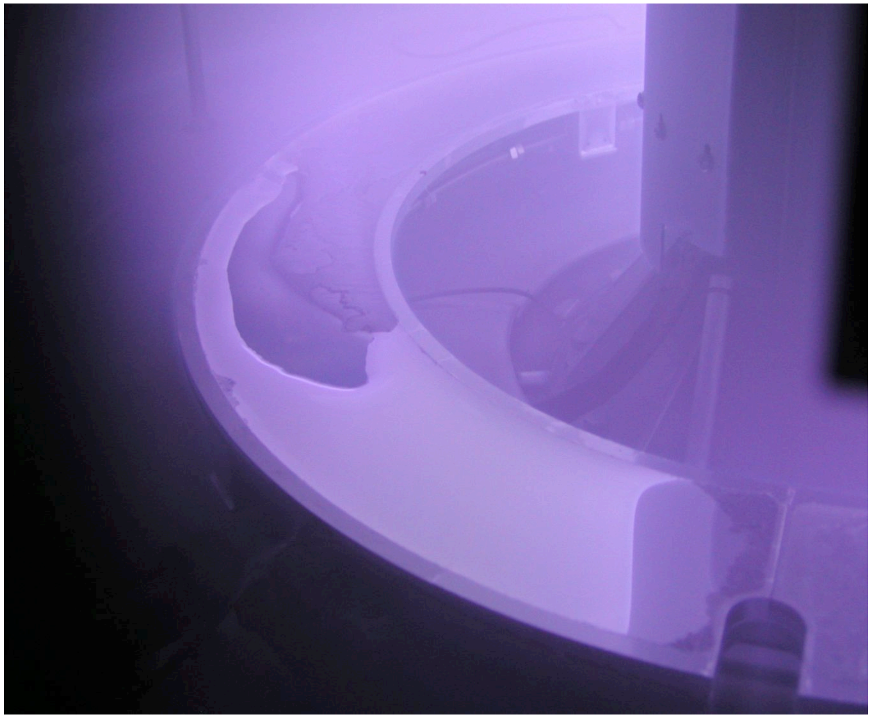
- R_0=0.34 m, a=0.22 m, κ≤1.6, $B_T(0)$ ≤2.1 kG, I_P ≤ 80 kA, τ_{disch}<25 msec, $T_e(0)$~100 eV, $n_e(0)<6\times10^{19}$ m^{-3}
- Tray lies approximately in a flux surface
  - Minimal normal **B ⇒ reduces MHD effects on the liquid metal**
- Thin coatings appear between runs
  - Removed/dissolved by GDC, heating
- One fill active for up to ~ 1 year
  - Pumped for hundreds of discharges



UCSD lithium injector

Liquid lithium tray limiter in CDX-U

Tray during fill

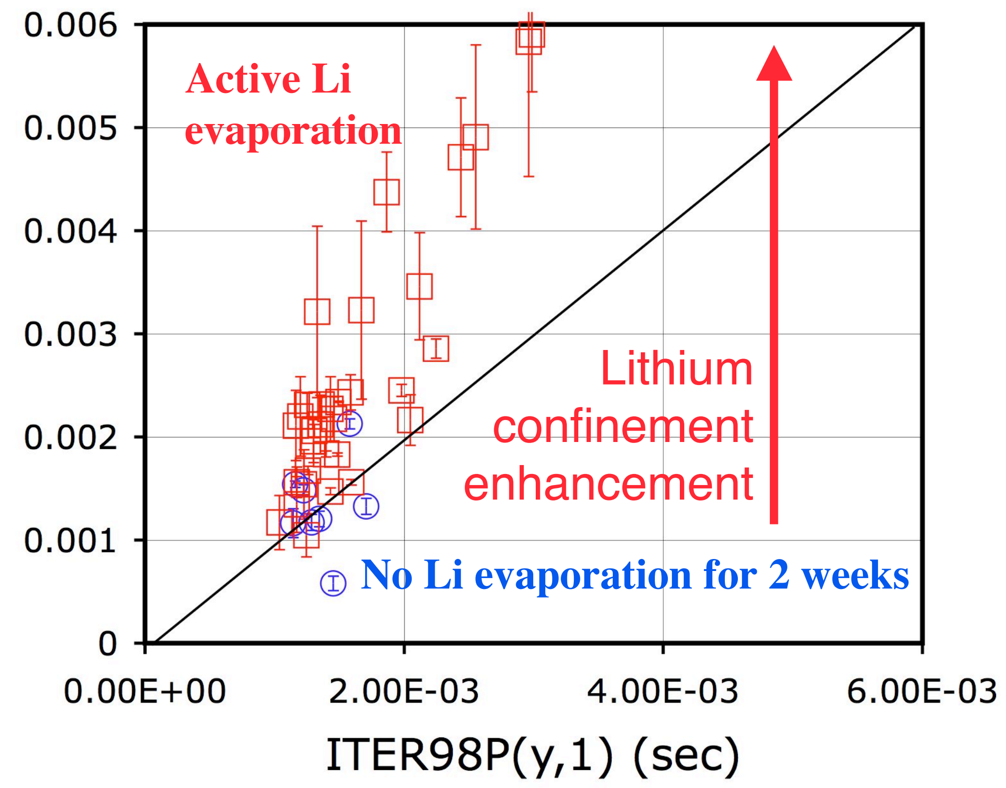


Tray after plasma operations, during hot argon glow

Energy confinement in CDX-U was significantly increased with a low recycling lithium boundary

R. Majeski et al., Phys. Rev. Lett. 97 (2006) 075002

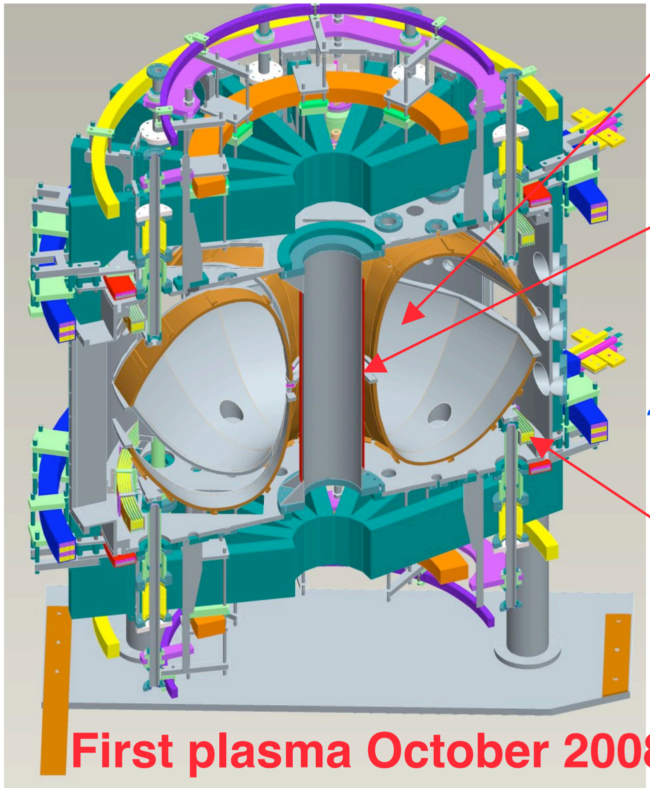
- τ_E~ 2-3× ELMy H-mode scaling
  - Note increase in ITER98P due *solely* to drop in loop voltage = lower power input
    - » ITER98P ~ $P^{-0.69}$
  - All discharges at similar plasma density, current, same toroidal field
- τ_E~ 6× best pre-lithium CDX-U results (kinetic measurements, Ti gettered)
- τ_E~ 10× modeling from TSC
- 30× 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
  - $\nu^*_{i,e} < 0.1$



• **Largest relative increase in Ohmic tokamak confinement ever observed**

LTX - full, 5 m^2 liquid lithium coated SS-Cu hot wall

Second shell: porous molybdenum inner layer



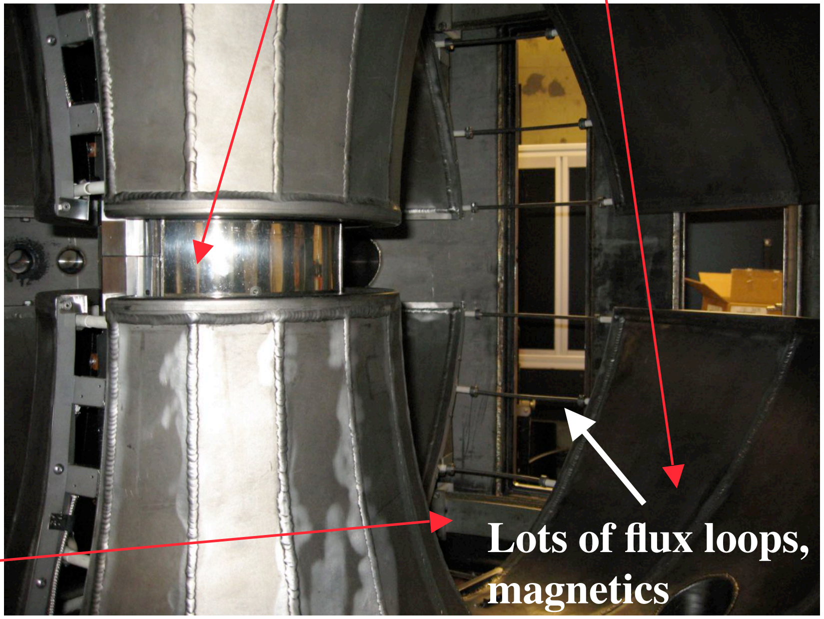
First plasma October 2008

Inner heated shell (explosively bonded SS on copper)

Heat shielded centerstack

Fast, uncased internal coil

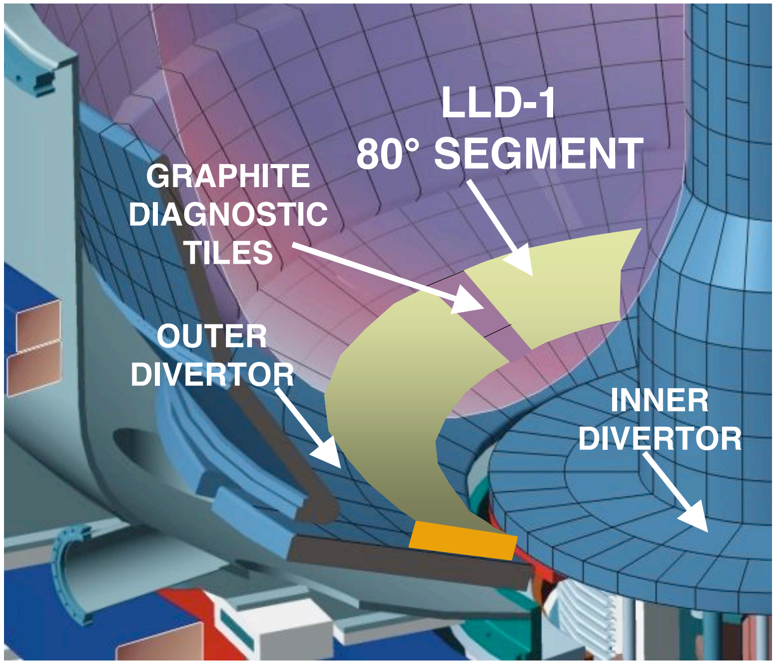
Expected $\tau_E \sim$ 60 ms

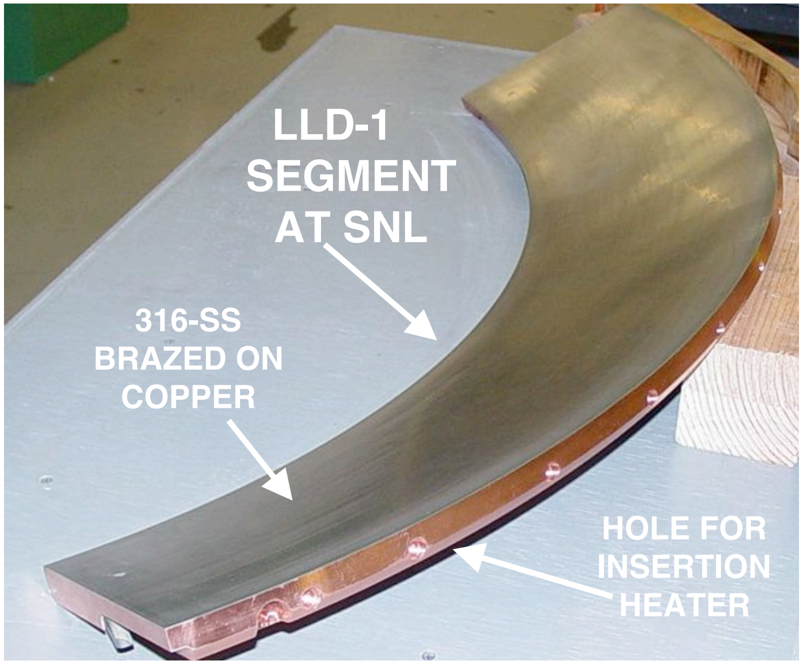


Lots of flux loops, magnetics

Parameter	CDX-U	LTX
Major radius	0.34 m	0.4 m
Minor radius	0.22 m	0.26 m
Toroidal field	0.21 T	0.34 T
Plasma current	100 kA	400 kA
Current flattop	5 ms	>100 ms
Ohmic flux	30 mV-s	160 mV-s (centerstack maximum: 225 mV-s)
Wall temp.	20 °C	**> 600 °C intermittent, > 500 °C continuous**

NSTX Liquid Lithium Divertor (LLD-1) Will Be Tested in 2010



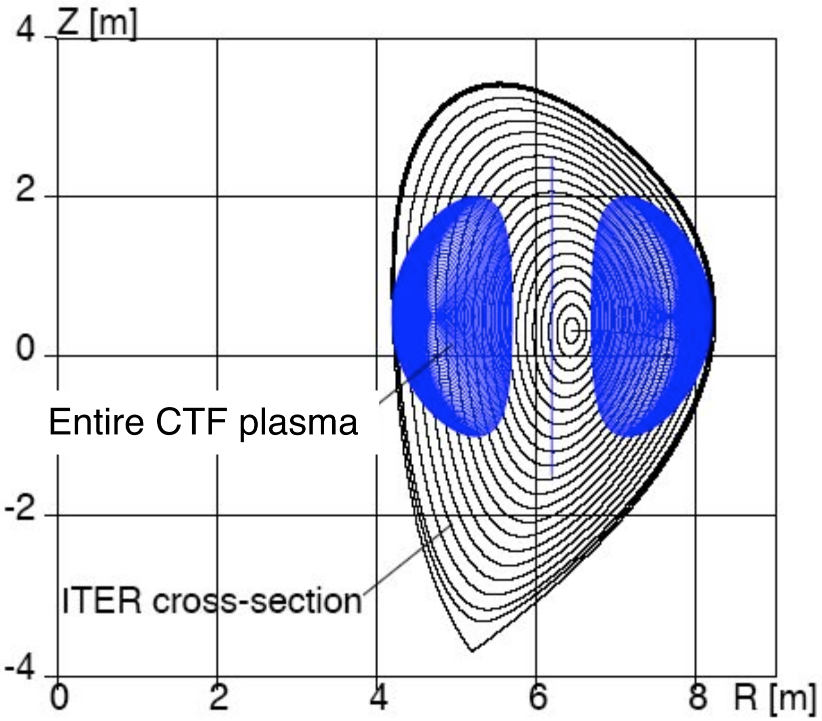


- Construction: Thin (0.5 mm) SS brazed under pressure; similar to HIPping
  - Approach allows for a thinner SS barrier than alternative fabrication
  - Example of alternatives: LTX employs explosively bonded material - requires 1.5 mm minimum thickness SS
- SS surface will be plasma-sprayed with porous 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 ~1/2 - 2/3
  - What is the optimum configuration? ⇒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 (~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 β limits?
  - Hot, low collisionality plasma extends to a *very* near conducting wall, at r~0.01a

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



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

- 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=1.25m, a=0.75m, A=1.66, κ=2, 3.5T, 11 MA
- At 30% β, P_{fusion}=400 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

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