Liquid metal PFC development for power plants

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PPPL
PRINCETON PLASMA PHYSICS LABORATORY

Outline

- Why liquid metal PFCs?
- Liquid metal properties
- Hydrogen chemistry
- Applications for low and high recycling liquid metals
- Materials compatibility
- Temperature limits
- Flow rates
- Implementations
  - Jets and capillary systems
- Power handling
- New experiments with liquid lithium PFCs
- Recap and summary

Engineering features of liquid metal walls

- Continuously renewed as new fluid enters the system
- Neutron damage not a concern for liquid metals
  - Liquid metal is only subject to PMI
  - Substrate is only subject to neutron damage - need not be suitable for plasma exposure
    - » Neutronics, PMI become separable problems in fusion development
- PMI limited to sputtering + evaporation
  - No significant erosion/redeposition issue for liquids
- Much thinner mechanical construction of the plasma-coolant interface can be envisioned, since erosion not an issue
  - Low thermal impedance between heat load and coolant
  - Construction must be consistent with disruptive, other forces
    - » But - disruptive forces on the liquid metal not a structural issue
- Broad range of design approaches
- Liquids commonly considered: lithium, gallium, tin

Properties of liquid metals

- Gallium
  - Z=31, atomic 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 or minor chemistry with H, D, T
  - Only gallium has been tested in a tokamak; no report of reduced recycling
    - » Very modest retention of atomic D in gallium; no retention in tin (Bastasz, test stand)
  - Tin-lithium eutectics do exhibit reduced recycling (Bastasz)
- Lithium, however, readily forms a stable hydride
  - LiH decomposes at 688 °C, Ga_2H_6 at -50 °C, SnH_4 at -150 °C.
- Atomic hydrogen is efficiently pumped by lithium - very high sticking fraction
  - Diffusivity of hydrogen in liquid lithium is very high: ~10^{-4} cm^2sec^{-1}
    - » Concentration of D, T likely to be uniform in the liquid
  - LiD will precipitate out of the liquid metal if D concentration exceeds ~10-50%
- Liquid lithium must be cycled through a reactor quickly enough to avoid deuteride formation
  - Tritium must be removed externally before tritide forms
  - Possible approach is thermal desorption/evaporative release
- Low decomposition temperature for the hydride in tin, gallium eliminate this issue

High recycling liquids (gallium, tin) and lithium may have different fusion applications

- AIRES designs are large scale, ignited systems with $P_{fusion} > 1$ GW
  - Sufficient confinement is guaranteed by ignition requirements
  - Additional confinement would provide no or modest benefit
- Other engineering considerations are primary
  - High temperature wall for efficient thermal cycle
  - High recycling wall for reduced tritium throughput
- High temperature wall operation possible with gallium, tin
- Development, engineering advantages of LM walls
  - Separable development of liquid metal PFCs, neutron-tolerant substrates
  - Relaxation of constraints on the substrate material
    - » Need not be suitable as a PFC
  - Reduced in-vessel tritium inventory
  - Continuous renewal of wall permits thinner, low thermal impedance constructions

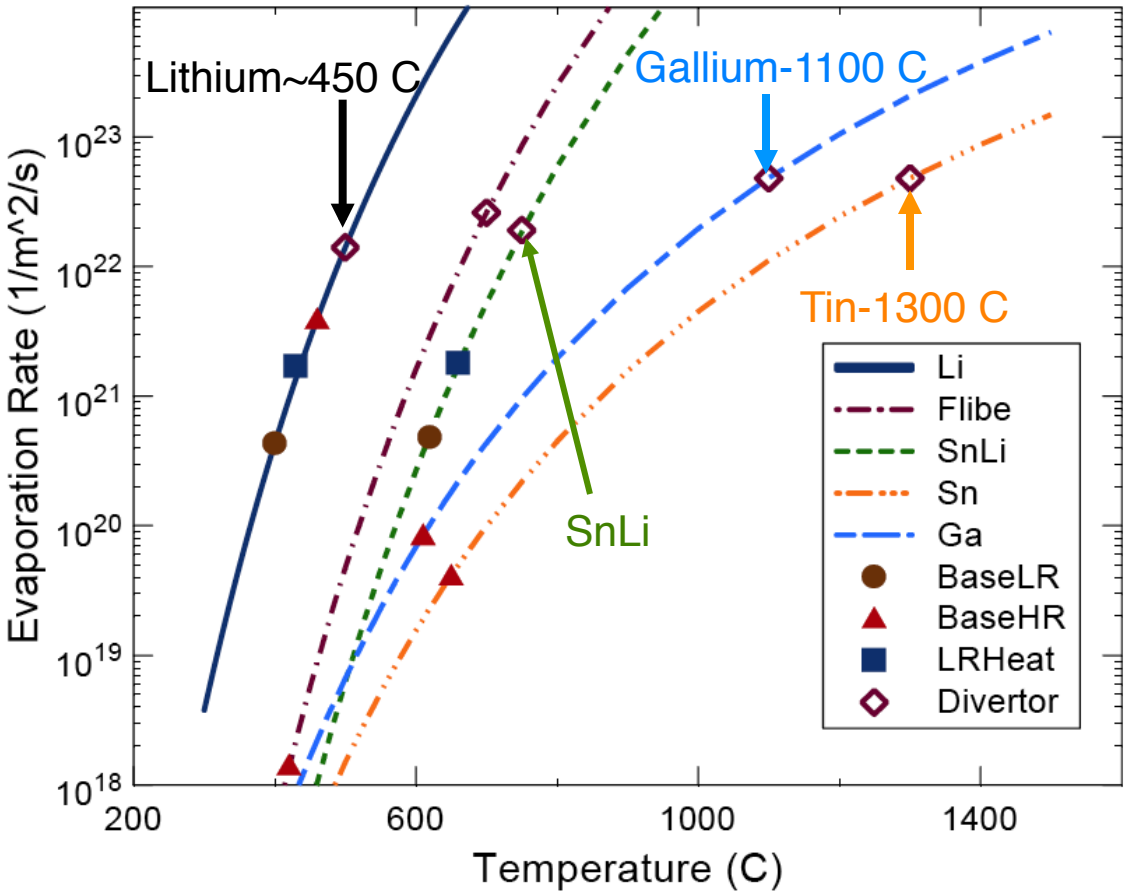
Core confinement improvement with lithium liquid metal PFCs may enable small fusion systems

- Low recycling lithium walls shown to increase energy confinement
  - Small scale size, driven tokamaks/spherical tokamaks possible
    - » First-orbit losses for alphas high; not ignited systems
    - » Reduced plasma current, liquid walls mitigate consequences of disruptions
  - High power density possible with P_{fusion} ~ few hundred MW
    - » Exploratory reactors with high tritium burnup fraction, low tritium inventory ("power on the net")
      - Sn-Li may allow operation at >500 °C
    - » Fusion-fission hybrids
    - » Neutron sources at high wall loading (>10 MW/m^2) for material testing
      - Shortened development cycle for liquids or solids
- Lithium walls may make small unit-size tokamak fusion systems feasible
- Lithium not well suited for a liquid metal wall in a large (~AIRES) device
  - Confinement advantages of low recycling, lithium walls less important

Materials issues with liquid metals

- Lithium is more aggressive than tin, tin is more aggressive than gallium
- Gallium:
  - Stable 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 even above the PFC evaporative temperature limit (400 °C)
  - Attacks most ceramics.
    - » T < 400 °C, MgO, BN are acceptable.
    - » 400 - 400 °C, only choices are yttria (Y_2O_3), erbium oxide (Er_2O_3)
  - No ceramic coatings have yet been developed to reliably insulate metallic piping from lithium contact at high temperatures
- Fast-flowing liquid metals greatly increase erosion rates
- Impurities can increase erosion rates greatly (e.g. nitrogen in lithium)

Evaporation limits the operating temperature range for liquid metals



- Total flux (sputtering + evaporation) imposes a lower temperature limit (Rognlien)
  - 500 – 600 °C for SnLi
  - 800 – 900 °C for Sn
- But sputtered lithium impurity invariably found to be insignificant in tokamaks
  - TFTR, NSTX, FTU, CDX-U, T11-M
- Only observation of significant lithium ingestion in a tokamak was in DIII-D (DIMES)

- 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

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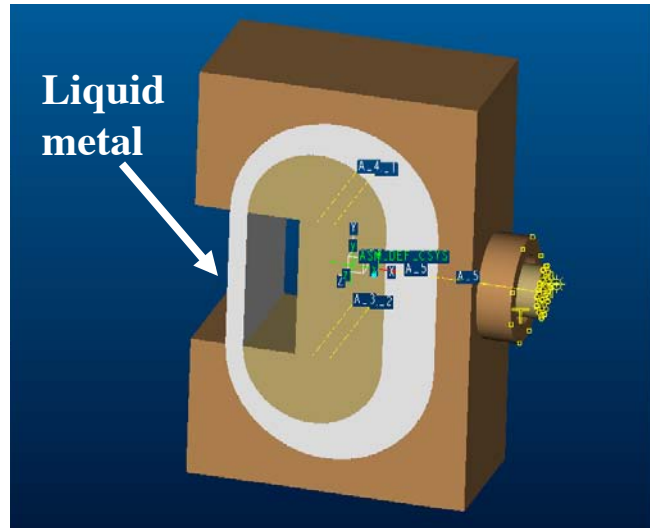
Required flow rates for liquid metal PFCs

- 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
- 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
- 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

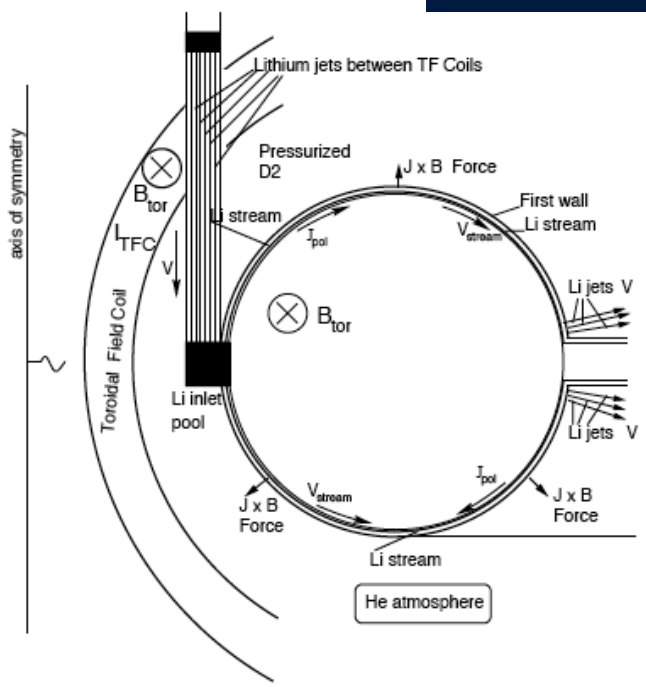
Film or jet liquid metal PFC systems

- 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
  - Liquid metal retained and propelled by J×B, ∇(J×B) forces

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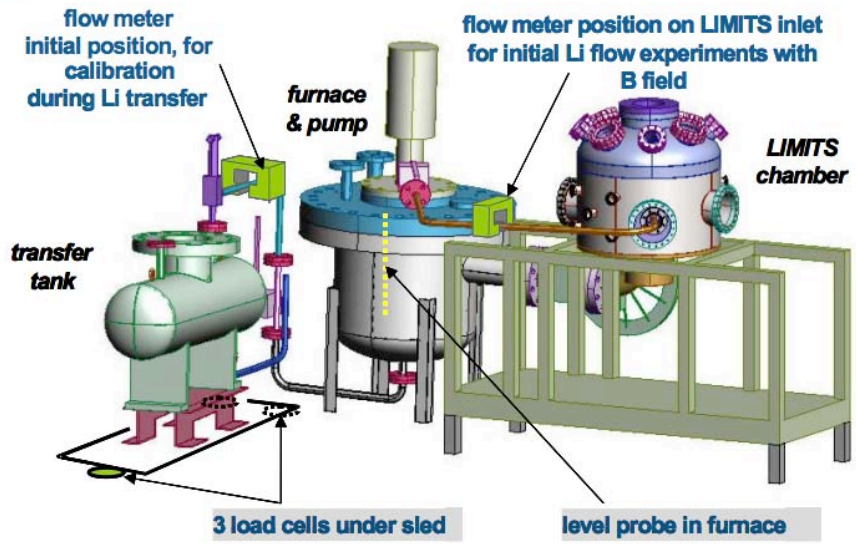
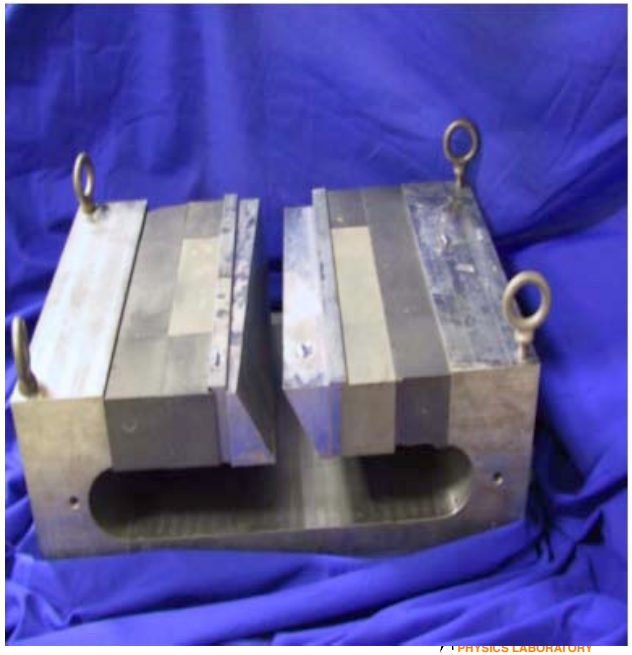
Lithium jet experiments were performed at SNL in the LIMITs test stand



LIMITS facility at Sandia

Permanent magnet for LIMITS to duplicate NSTX divertor field geometry

LIMITS in operation with unmagnetized lithium jet



Gallium jet experiment in ISTTOK

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

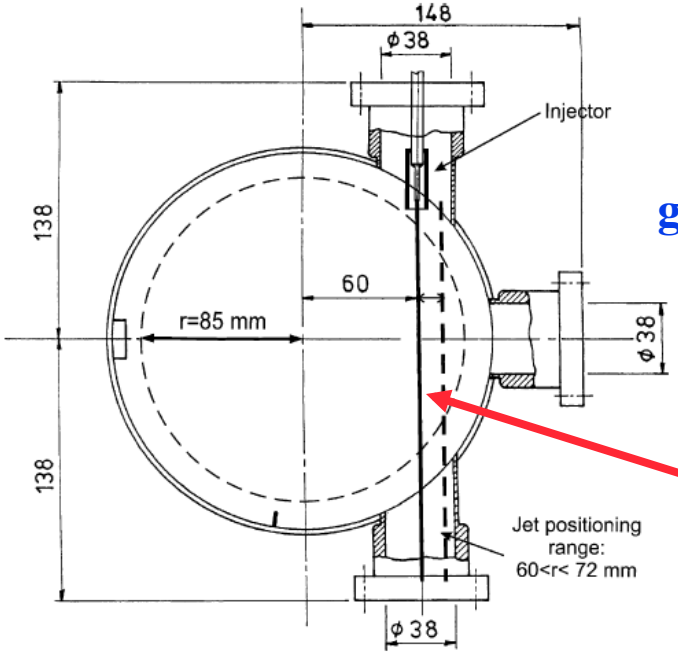
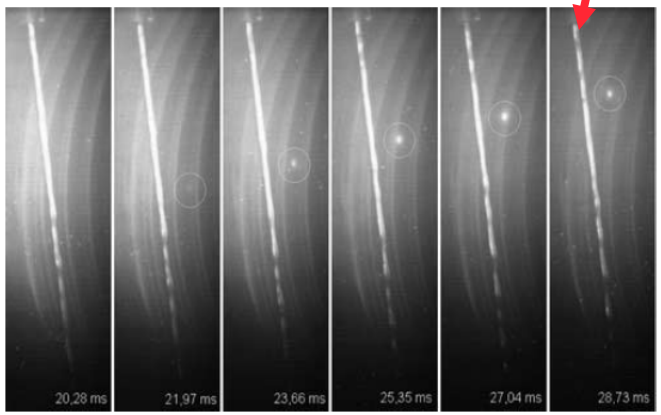
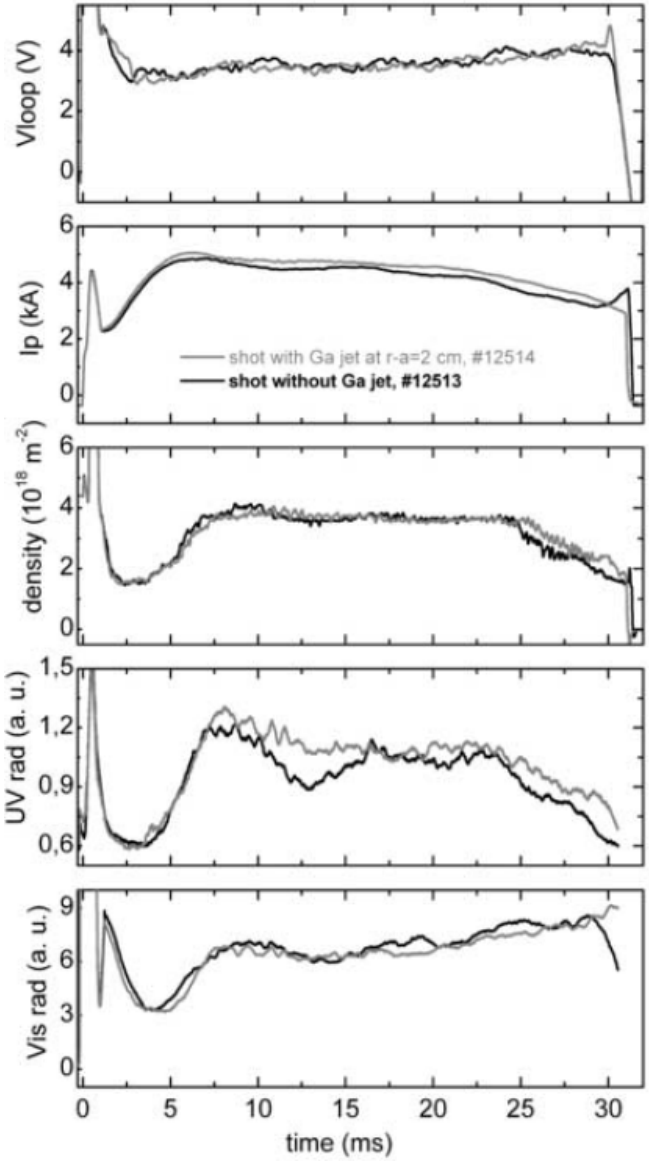


Fig. 3. Poloidal cross-section showing the position of the gallium jets in the tokamak vessel.

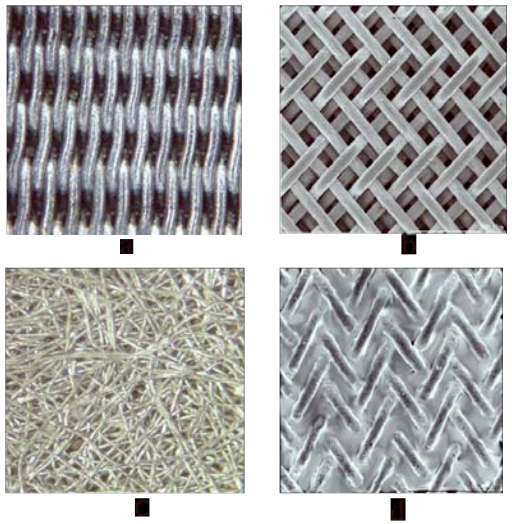
Discharge behavior is similar with gallium jet and graphite limiters

Gallium jet





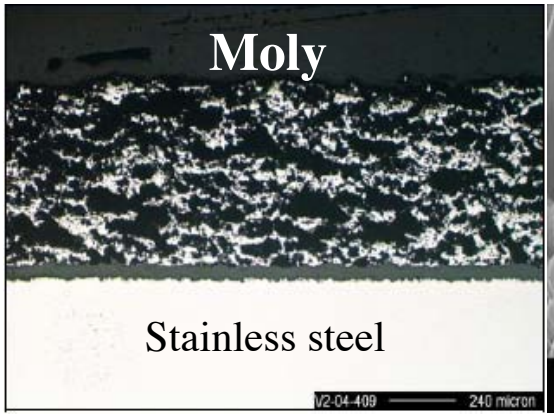
Capillary liquid metal PFC concepts



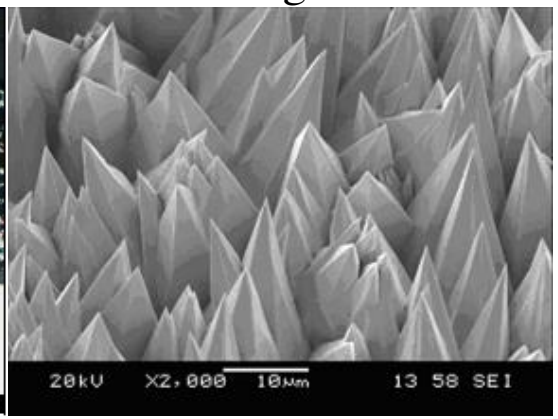
Meshes, tungsten felt (Red Star)

- Systems now being tested in tokamaks are primarily thin-film (capillary) systems, all in lithium
  - Thin: < 1 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 was successfully tested in CDX-U

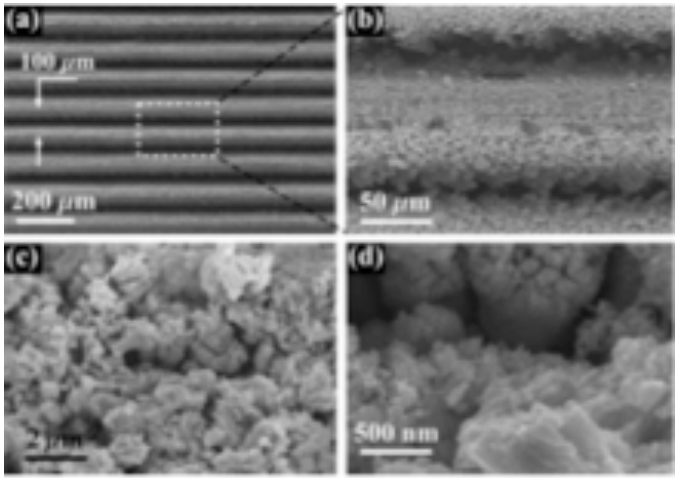
Porous sprayed molybdenum



CVD tungsten "wick"



Laser-machined wicking surfaces



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 greatly exceed 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, U. Illinois)
- Both approaches have issues for application in a tokamak
  - Lithium influx with evaporative technique may be prohibitive
  - High magnetic field may alter or 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

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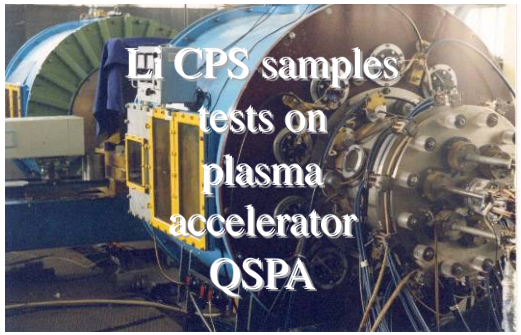

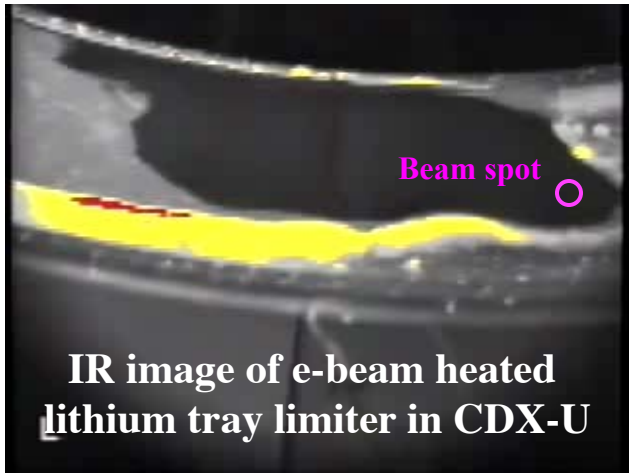

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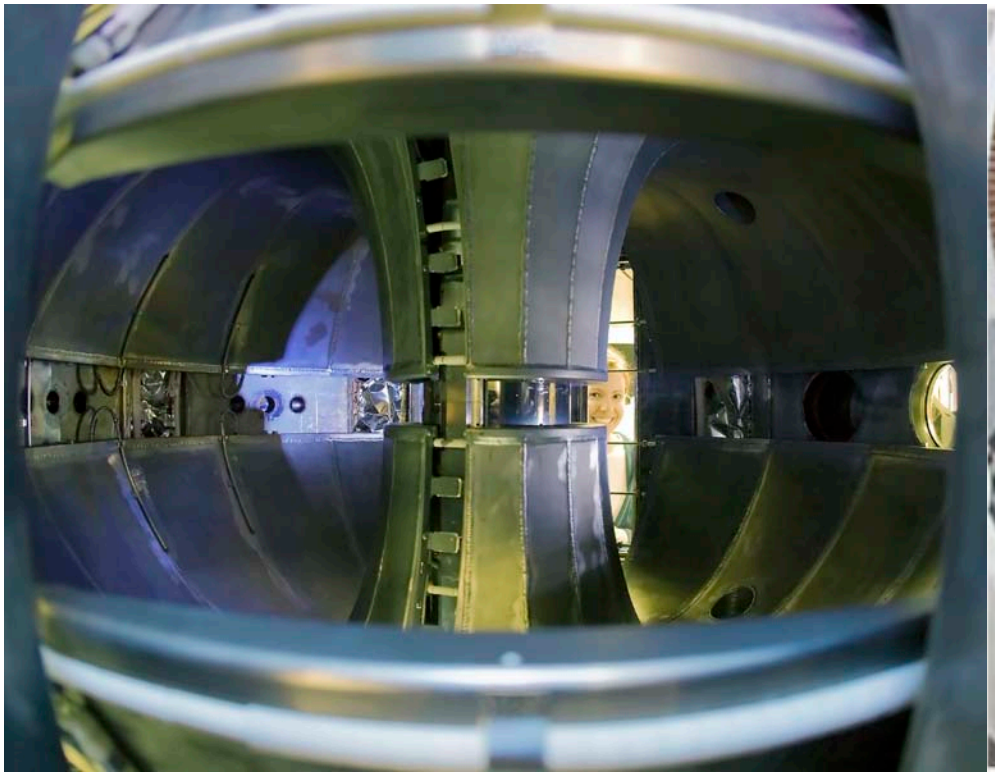
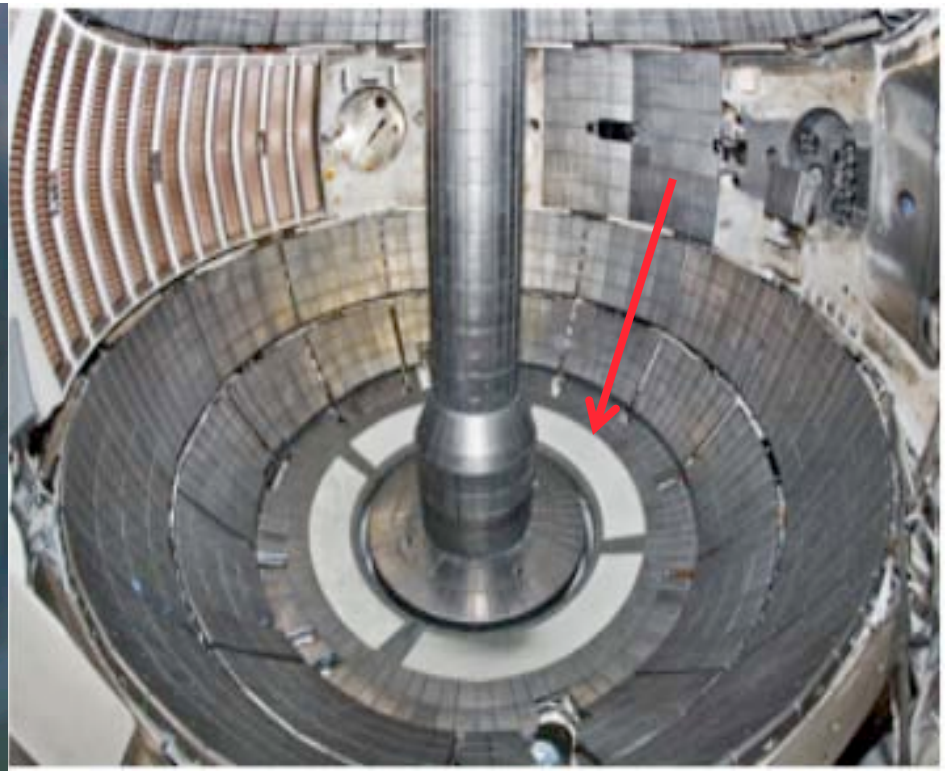
Liquid Lithium Limiter on FTU

New LM PFC experiments underway in LTX, NSTX





- View of the stainless-steel lined, heated copper shell in LTX
  - Will be fully coated with liquid lithium
  - Can test Sn-Li

- Looking down on the porous molybdenum coated, outer divertor target in NSTX
  - Now coated with lithium

Summary
Liquid metal PFCs for fusion power plants

- Liquid metal PFCs are at an early stage of development
  - Test stands at UCLA, SNL, U. Illinois, PPPL, UCSD
- Implementations of lithium in tokamaks primarily for wall conditioning
  - Valuable data on impurity production and transport
    - » Not much information for liquid metal PFC development
  - Very few experiments with *liquid* lithium as a PFC (T11-M, CDX-U, FTU)
    - » First-generation experiments started in NSTX, HT-7
    - » Second-generation tests to start in LTX
- Few (two!) experiments with gallium in tokamaks; none with tin
- Liquid metal PFC development may offer:
  - In-situ renewal of PFCs
  - Self-repairing walls (disruptions, ELMs)
  - Separability of neutron damage, PMI issues
  - Improved power handling
  - Access to new tokamak confinement regimes (lithium)