Liquid Metal Plasma-Facing Components

Dick Majeski (PPPL), presented at the Research Needs Workshop (ReNeW),
UCLA, 4-6 March, 2009

A first wall in a fusion reactor faces formidable challenges

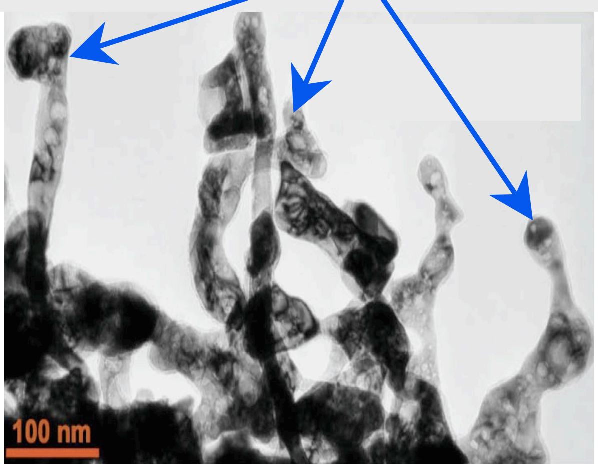
LTX

- D + T $\Rightarrow$ 14 MeV neutron + 3.5 MeV alpha particle
- A solid first wall (the plasma-facing components, or PFCs) must withstand:
  - High neutron fluence; of order 5 MW/m^2 or higher
  - High heat loads.
    - » 5 MW/m^2 neutron wall loading implies at least 1 MW/m^2 of distributed heat load for an ignited reactor.
    - » Most reactor designs employ divertors, which produce local heat loads of up to 20 MW/m^2 - comparable to the heat load on the leading edge of the shuttle wing during re-entry.
  - Energetic particle bombardment (D + T + alphas).
- Reactor PFCs cannot be easily or frequently replaced.
- Best candidate: tungsten at 800ºC (self - annealing)

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., T_s = 1250 K, ***t* = 36,000 s**, 3.5x10^{27} He$^+$/m^2, E_{ion} = 11 eV

PPPL
PRINCETON PLASMA PHYSICS LABORATORY

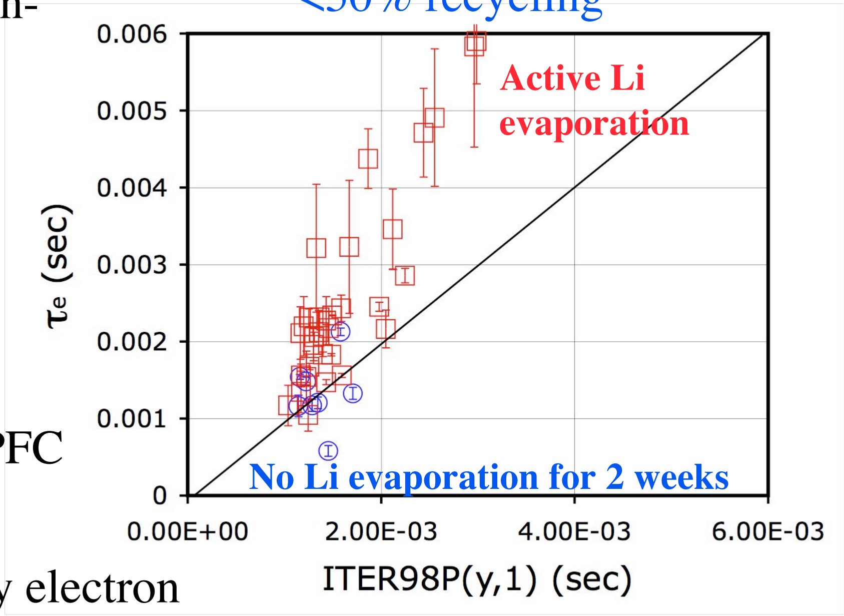
Common features of liquid metal walls

- Continuously renewed as new fluid enters the system
- Neutron damage not a concern for liquid metals
  - Caveat: neutron damage an issue for substrate/carrier, nozzles, etc.
- Plasma-material interactions (PMI) limited to sputtering + evaporation + redeposition
  - No long-term exposure effects
- Much thinner construction can be envisioned, since erosion not an issue
  - Must be consistent with disruptive, other forces
  - Allows 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 systems with capillary restraint (porous refractory metals)
  - *Multiple* possible solutions to the wall problem
- Potential for high wall power density solutions

Liquid metals differentiated into low recycling (hydrogen pumping) and high recycling (do not retain hydrogen)

- High recycling liquid metals include gallium and tin
  - Both feature high Z, low vapor pressure at T<800C, good conductivity. Gallium probably has an edge.
- Low recycling liquid metal: lithium (or possibly tin-lithium eutectic).
- *Engineering* implementation of either low or high recycling liquids similar
  - Specific differences in temperature range, viscosity of fluid
  - Significant differences in chemical activity

Suppression/strong reduction of anomalous electron transport in CDX-U with <50% recycling



- Lithium has few *engineering* advantages as a PFC
  - Potential advantages are physics:
    - » Improved core confinement, especially electron
    - » Impurity reduction/tolerance
    - » *Possible* effect of fast-flowing lithium coolant on MHD stability
  - Engineering advantages primarily low fluid mass, viscosity, high heat capacity
    - » Disadvantage: low maximum operating temperature (400C)

Summary of current liquid metal PFC research

- Tokamak deployment of porous refractory metal systems (which wick and entrain liquid lithium)
  - FTU - lithium capillary porous system as a limiter
    - Development by Red Star, Russian Federation
    - Initial deployment on T11-M, T10
  - NSTX, Liquid Lithium Divertor (LLD), deployment in FY10
  - LTX, second stage full lithium wall, porous molybdenum (~FY11)
    - First stage using surface tension to retain a 10-100,000 Å lithium coating
- Flowing film systems (all gallium/eutectics)
  - Extensive tests at UCLA
  - Surface wave studies at PPPL
  - Heat removal at PPPL, UIUC
- Jet systems (lithium)
  - Jet propagation in divertor-like magnetic fields (Sandia National Lab)
    - Constructed full recirculating lithium loop (LIMITS); now idle

ROSATOM

Federal State Unitary Enterprise “Red Star”

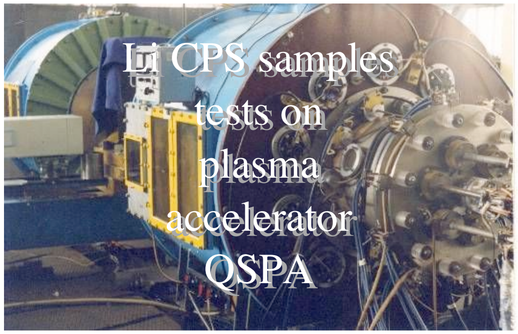
The organization of works in Russia on Lithium Capillary-Pore Systems problem

LTX

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

TRINITI


Li CPS samples tests on plasma accelerator QSPA


“Red Star”

Idea
Development
Manufacturing
Technology
Thermophysical tests

Kurchatov Institute


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

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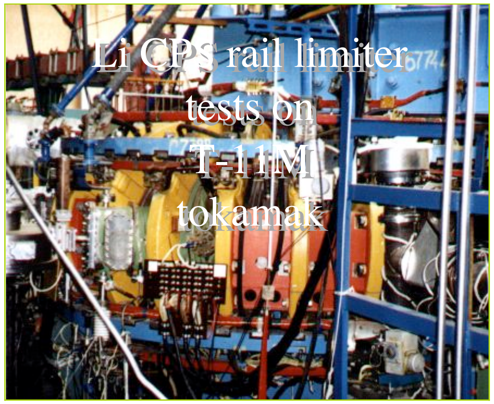

Li CPS rail limiter tests on T-11M tokamak

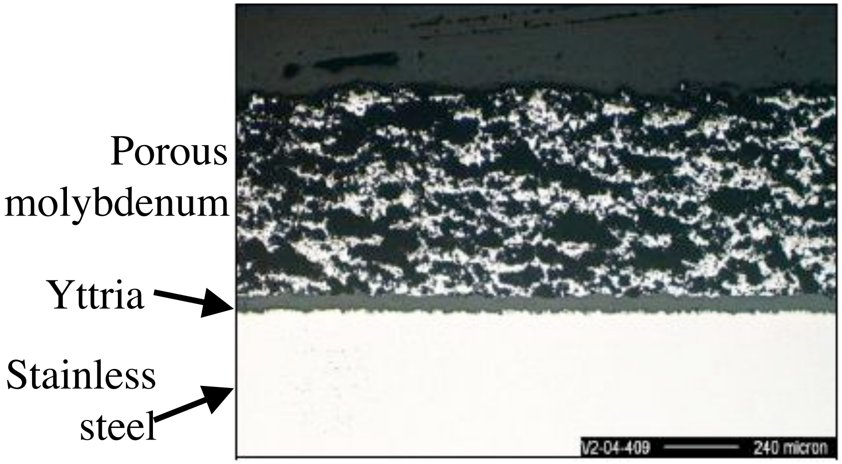
TRINITI


Li CPS samples tests on plasma accelerator MK-200

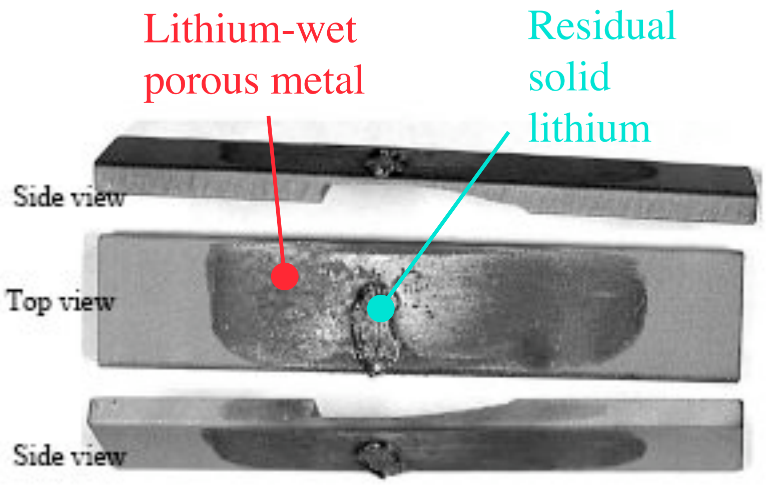
Liquid Lithium Limiter on FTU

Entire plasma-facing surface of a tokamak first wall can be faced with liquid lithium entrained in a porous metal

- Engineered porous molybdenum surfaces have been developed with Plasma Processes of Huntsville (Phase I & II SBIR)
- Plasma spray process can produce 70% porous molybdenum coatings
  - Interconnected porosity
- Porous metal readily wicks liquid lithium
  - Retention through surface tension
- Lithium-wicking porous metals have also been formed by sintering in stainless steel and tungsten



Lithium wetting tests on 70% porous plasma-sprayed molydenum, 304L stainless steel substrate

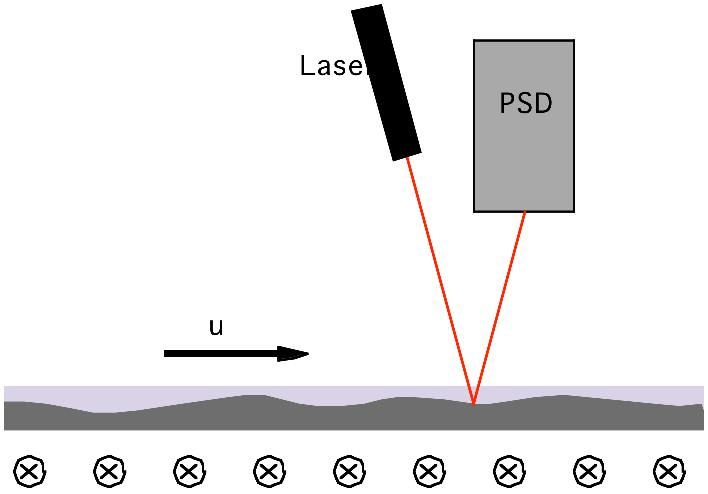


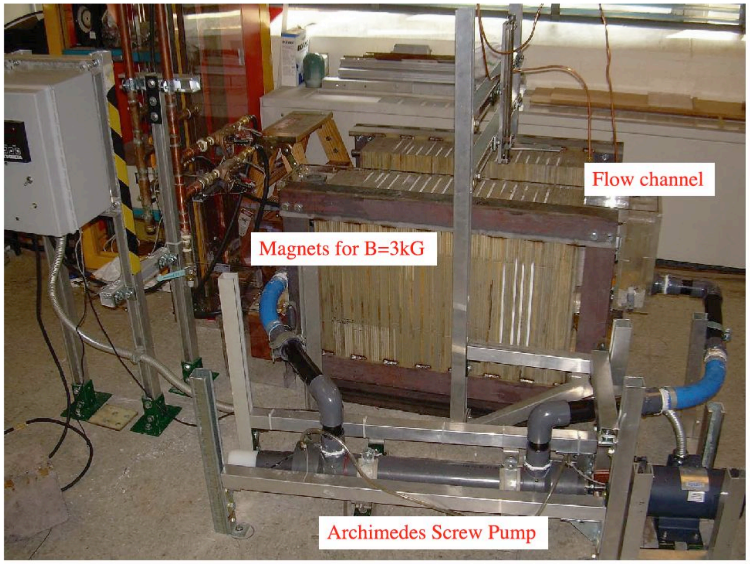
- Candidate actuators for lithium flow:
  - Gravity
  - Capillary forces
  - Marangoni effect (temperature-dependent surface tension)
  - Thermoelectric effect
  - **J×B** and ∇ **J×B** forces

Free-surface MHD Channel Flow Experiment at PPPL

- Surface wave experiments
    - Laser reflection system to measure wave dispersion (surface tension depends on presence of oxides)
      Nornberg *et al.*, Rev Sci Instr (2008)
    - Laser alignment sensor to gain good temporal and spatial resolution on surface fluctuations
    - Magnetic field modifies turbulent spectrum (goes from 3D to 2D)
- Effect of strong field on heat transport
    - Provide localized heat source
    - Diagnose variation of heat transport with magnetic field using thermocouples and IR sensor
- Effect of field gradients on flow

Supported by DOE basic plasma physics
⇒Astrophysics!





Thrust to develop LM PFCs and research gaps

- **1st component: Theory and modeling research thrust to address gap in understanding LM behavior in a tokamak**
  - Modeling of free-surface liquid metal flows, MHD
    - How is turbulence influenced by free surface, **B** at arb. surface angle?
    - How is convection influenced by heat deposition, magnetic field?
    - How is the heat transfer rate affected by all of the above?
    - Flows, fluid restraint in capillary systems
    - Self-consistent modeling of thermoelectric, MHD currents
    - Coupling of a LM wall to edge plasma models
  - PMI issues
    - Sputtering, evaporation, redeposition
    - Impurity transport, coupling to core accumulation
    - Influence of off-normal events
    - Surface purity, coating effects on recycling, secondary electron emission

Research gaps and thrusts (continued)

- **Second component: Test stand experiments to address gap in the knowledge base necessary to control LM under simulated tokamak conditions**
  - Absent the plasma interaction issues, most of the development work for liquid metal walls can be accomplished on test stands
    - Existing test stands at UCLA, University of Illinois, Purdue, Sandia (with restart of LIMITS), PPPL
    - Inlet/outlet systems for fast and slow, capillary flow
    - Wall transport systems
  - Significant requirement is an appropriate magnetic field structure, strength
    - Possible to conduct self-similar experiments at reduced field in some cases
  - Power load tests in high magnetic fields required
    - Loading limits, thermal transfer, tests of various techniques for enhancing power handling
  - Better diagnostics (ultrasound?) for the flow field needed
  - PMI measurements for sputtering, evaporation, retention (Purdue, UIUC, SNL)
    - H, He retention in eutectics, e.g. Sn-Li, and “high recycling” LM

Research gaps and thrusts (continued)

- **Final component: Deploy reactor-relevant LM PFCs in an operating tokamak**
  - All tokamak tests at present involve lithium
    - Most of the experience gained in handling lithium in a tokamak transfers directly to other liquid metals
    - Exceptions are PMI issues, impurity influx, other plasma physics issues
  - All tokamak tests at present involve capillary systems
    - Partial exception: LTX employs a thin layer of free-surface liquid
  - Equilibration time for liquids is much shorter than for solids
    - Exposure requirement imposed by fluid transit time ⇒few seconds at most
    - Scale of a dedicated DD experiment to test liquid metal PMI is much reduced, compared to solids
  - Use of liquids impacts requirements for DT experiments
    - Substrate subject to neutron damage, liquid is not
    - Substrate is not subject to plasma damage; can be tested in a fission-based neutron source
    - Tritium migration in the fluid, permeation through coolant channels may be an outstanding issue to be addressed in a CTF.