First-wall, plasma-material interaction, liquid metals, and strategic elements for advancing liquid metal science and technology

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Presentation to the NAS Committee for a Strategic Plan for U.S. Burning Plasma Research
April 12th, 2018

Outline of material

- Overview of charge letter
- Recent community assessments of the state of first-wall and PMI challenges
- Potential for liquid metal concepts to solve fusion challenges
- Some current US research highlights on first-wall and liquid metal concepts
- Strategic elements for advancing liquid metal science and technology

Charge letter requested information in several categories

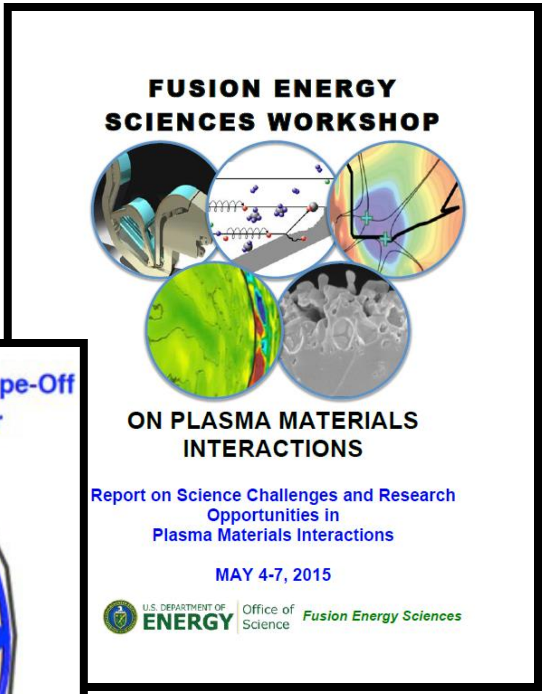
- Guidance from Co-chairs on content for talk received 3/26/18
  - Directed to give a talk “as a member of the community” who happens to be a PPPL employee (apologies in advance if highlights are, at times, parochial)
  - Views expressed are my own

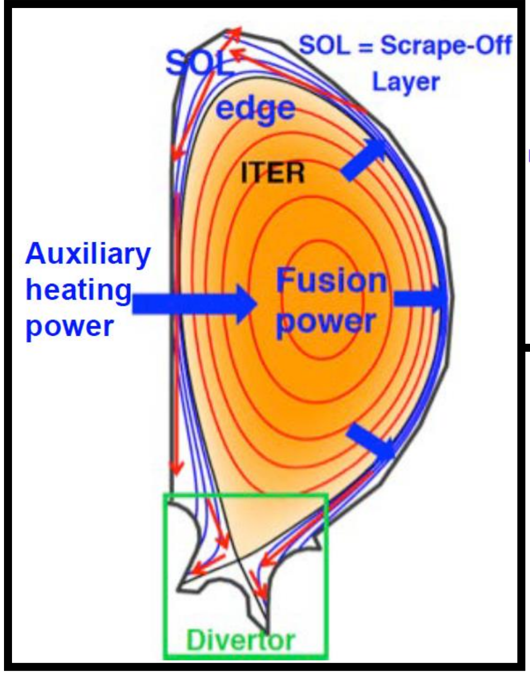
- Three topical areas of the charge letter:
  - First-wall
  - Plasma-material interaction (PMI) challenges, and
  - Liquid metals (LMs)

- Strategic elements for advancing liquid metal technologies

Does the community think it has sufficient knowledge in first-wall and PMI challenges?

- PMI community workshop report issued 2015
- Essential picture: understanding the impact of *boundary conditions* on the system
  - Material interactions mediated by edge plasma
  - Core-edge coupling
- Community identified 5 priority research directions (PRDs) and cross-cutting opportunities





PMI report. Fig. I-1, p. 2.

Community workshop highlights need to develop tools that can extrapolate to a reactor

- **PRD-A:** Identify the present limits on power and particle handling… for solid and liquid plasma-facing components (PFCs)… **(including liquids)**
- **PRD-B:** Understand, develop and demonstrate innovative dissipative/detached divertor solutions… **(including liquids)**
- **PRD-C:** Understand, develop and demonstrate innovative boundary plasma solutions for main chamber wall components, including tools for controllable sustained operation…
- **PRD-D:** Understand the science of evolving materials at reactor-relevant plasma conditions and… enable improved plasma performance **(including liquids)**
- **PRD-E:** Understand the mechanisms by which boundary solutions and plasma facing materials influence pedestal and core performance…

Community workshop highlights need to develop tools that can extrapolate to a reactor

- **PRD-A:** Identi… ndling… for solid and liqui… **ng liquids)**

  Power Handling (PFC Material + Design)

- **PRD-B:** Unde… dissipative/de…

  Power Handling (Plasma physics + Design)

- **PRD-C:** Understand, develop and demonstrate innovative boundary plasma… or controllable sustained operation…

  Main Chamber Erosion and Transport (Plasma physics)

- **PRD-D:** Unde… actor-relevant plasma condi… ance **(including liquids)**

  Material Evolution (Materials science)

- **PRD-E:** Unde… by which boundary solutions and plasma facing… destal and core performance…

  Core-Edge Coupling

Power exhaust challenge previously covered in presentations to this committee

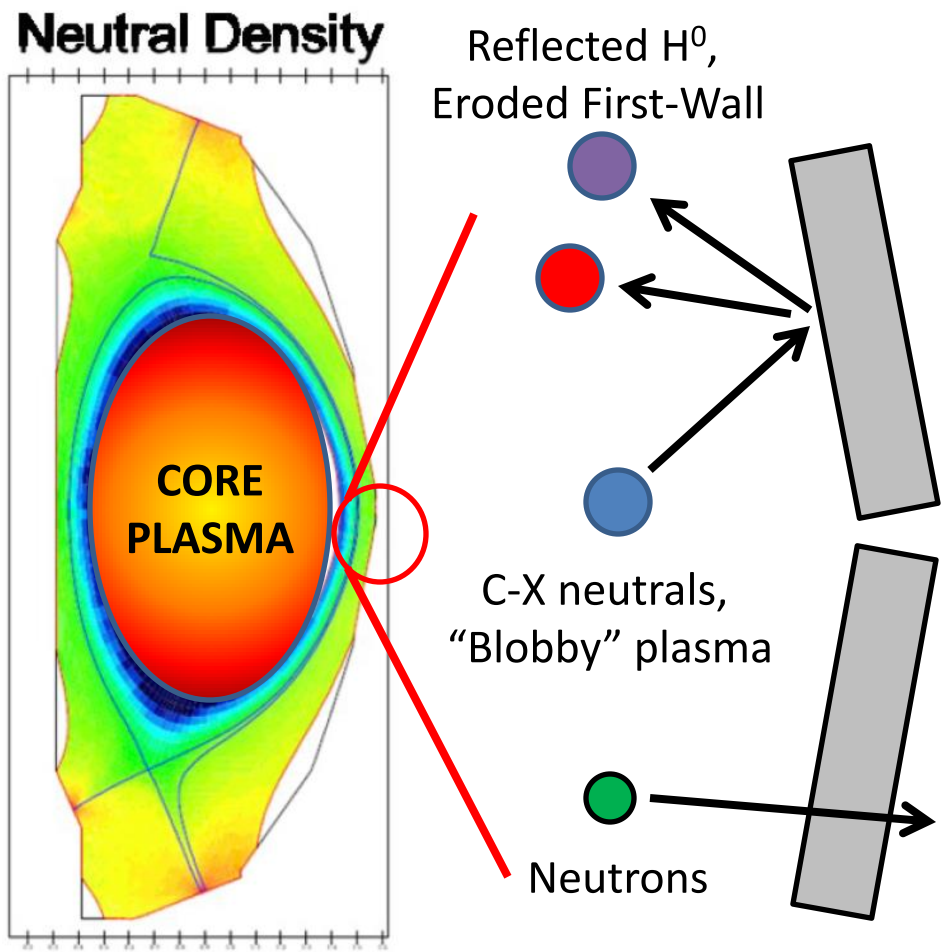
- Two presentations by EU authors highlighted the fusion power-exhaust challenge
  - T. Luce, “The Science of ITER”, Feb. 2018
  - G. Federici, “EU DEMO Design and R&D Activities”, Feb. 2018

- Highlighted points from Luce:
  - Empirical scaling of exhaust width indicates heat flux challenge is 3-4x as difficult as initial design (p. 24)
  - Full-scale ELM transients exceed surface melt limit of ITER tungsten divertor targets (p. 28)

- Highlighted points from Federici:
  - “ITER solution may be marginal for DEMO” – dedicated, €500M machine Divertor Test Tokamak seeks advanced solutions (p. 16)
  - Conventional divertor technology is one driver to R>7m (p. 19)

PRD-C, -D, and –E deal with main-chamber materials, their evolution, and core-edge coupling

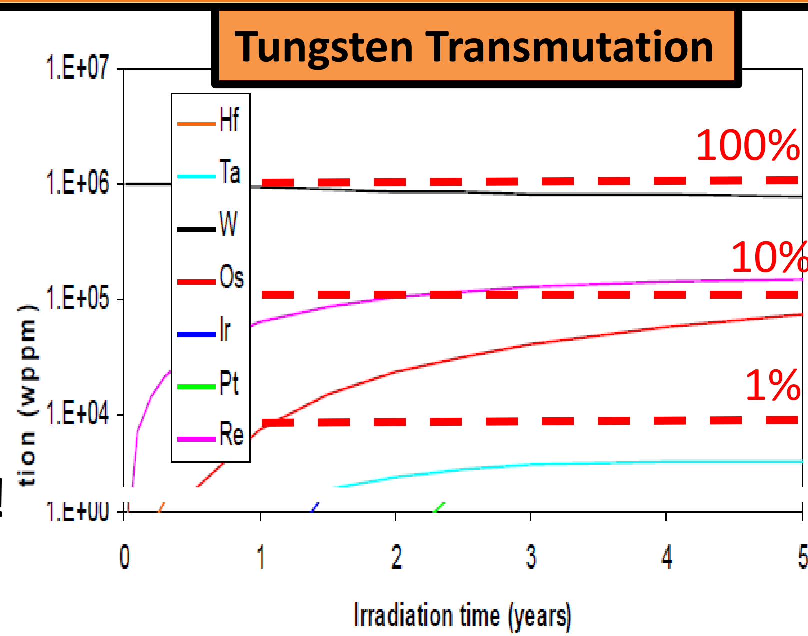
- PRD-C: first-wall erosion and transport
  - Neutrals at edge undergo “charge-exchange” (C-X) and can erode first-wall
  - Plasma transports eroded material
- PRD-D: fusion reactor modifies all materials over time
  - Plasma continuously destroys and creates material surfaces
  - Neutrons continuously transmute materials in a reactor
- PRD-E: the boundary conditions affect core performance



J. Nichols, PhD Thesis, Princeton U. 2018

Material erosion and evolution is significant and inconvenient

- Neutron transmutation converts W to almost 10% Re in the first year
- Steady erosion of the first wall estimated to move **~8000 kg** of W per full-power year!
- Timescale of modification is inconvenient!
  - Too slow to allow system to equilibrate
  - Too fast to ignore; may force maintenance



Forrest, et al., "Handbook of Activation Data…" UKAEA Report FUS 552, March 2009.

Table 1
Rough estimate of net erosion rate of main walls based on assumptions in text. Assumes 100% wall coverage by Be, B, C or W.

Device	P_{heat} (MW)	τ_{annual} (s/yr)	E_{load}^{year} (TJ/yr)	Tungsten net wall erosion rate (kg/yr)
DIII-D	20	10^4	0.2	0.16
JT 60SA	34	10^4	0.34	0.27
EAST	24	10^5	2.4	1.8
ITER	100	10^6	100	92 (41)[a]
FDF	100	10^7	1000	740
Reactor	400	2.5×10^7	10,000	7900 (5000)[b]

Stangeby, *J. Nucl. Mater.* **415** (2011)

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Potential for liquid metal PFCs

1. What advantages are common to all liquid metals?

2. Which liquid metals are commonly considered?

3. How could liquid metal PFCs enable greater power exhaust?

4. What are concepts for integrating such PFCs in a reactor?

5. What confinement impacts have been observed with lithium-conditioned PFCs?

Liquid metals present *intrinsic* advantages over solid PFCs in several areas

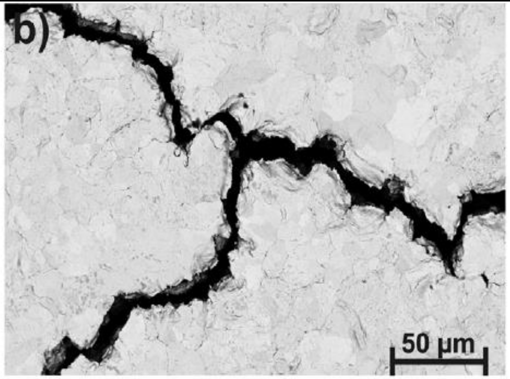
- Liquid metals provide a self-healing/renewable plasma-facing material
  - Immune to thermo-mechanical stresses
  - Returns to equilibrium after perturbations
  - Replenishment eliminates net-reshaping by plasma bombardment

- Separates neutron damage effects from plasma-material interactions

- **Fundamentally alters material time-scales and enables continuous control**

- Potential for increased power handling capability

Cracking after thermal shock loading



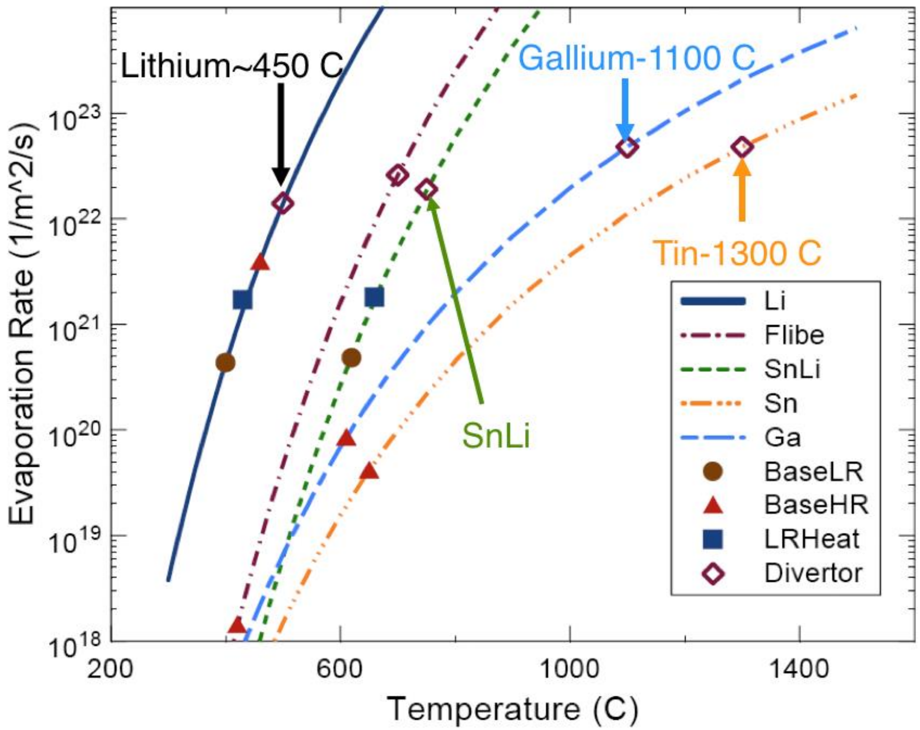
Wirtz, et al., JNM 2013

CMOD W-lamellae

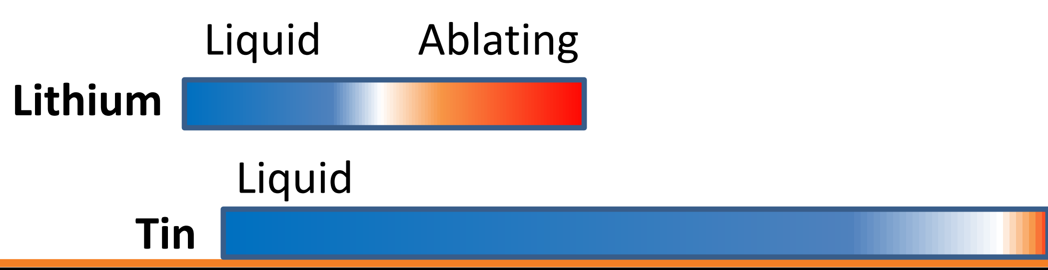
Coenen, et al., JNM 2013

Liquid metal options cover wide range of atomic number

- Three metals most often discussed
  - Li (3), Ga (31), Sn (50)
  - Sn-Li alloy also considered
- Lithium most studied – lowest Z, relatively benign in core
- Tin features largest temperature range for liquid concepts

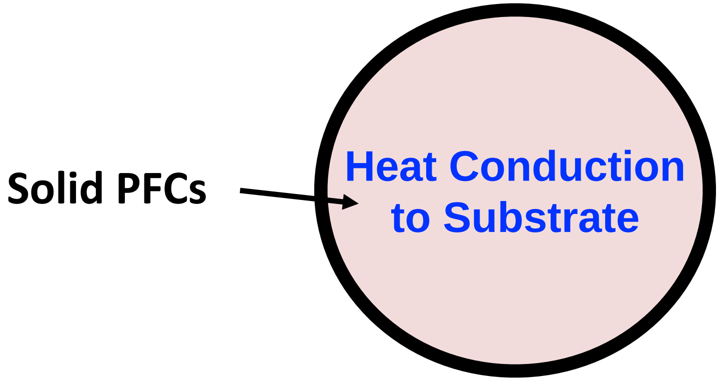


Majeski, PPPL-4480, Jan. 2010



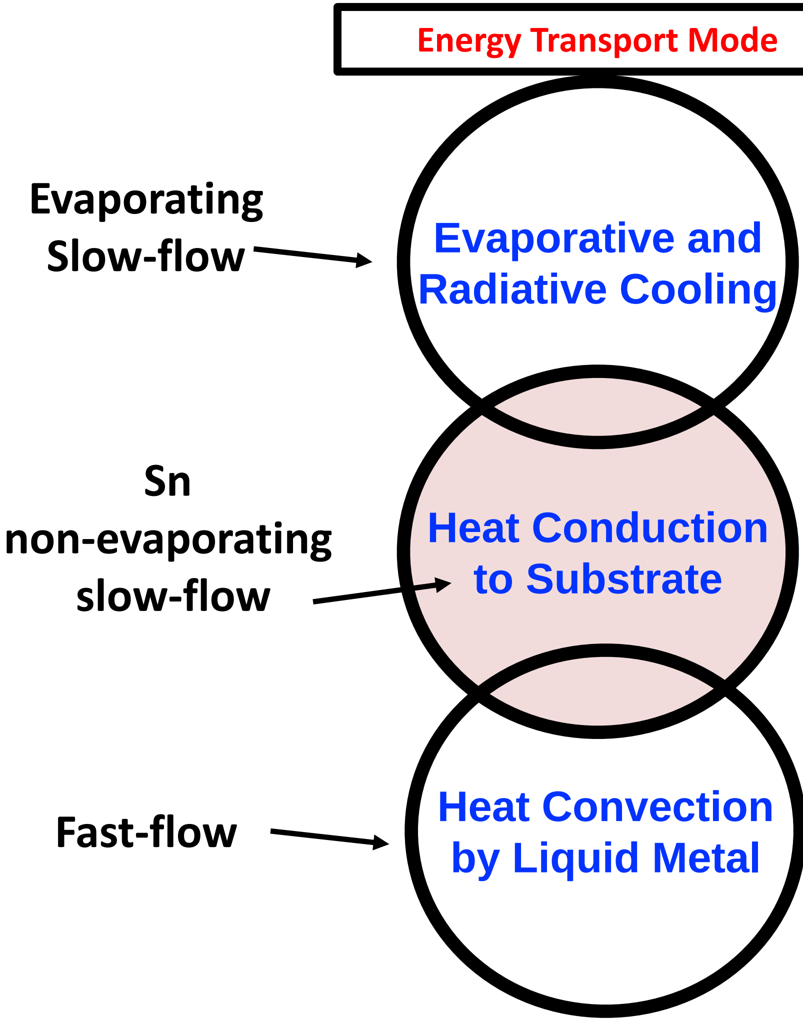
Liquid metal PFCs provide additional pathways for energy transport

Energy Transport Mode



- Conventional, solid PFCs utilize extrinsic impurities to enhance radiation
- Demonstration of surface stability is key for all concepts
- Significant differences in technological requirements; expected operating temperatures

Liquid metal PFCs provide additional pathways for energy transport



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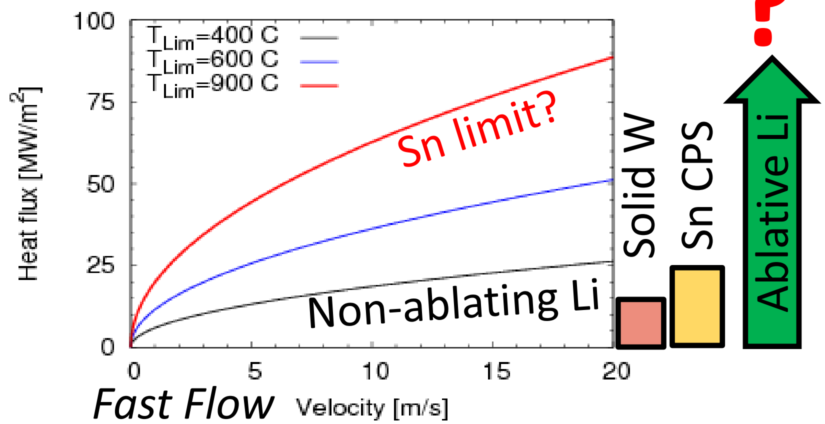
Liquid metal PFCs can absorb more heat flux than do leading tungsten technologies

- Actively cooled tungsten expected to survive **5-15 MW m^{-2}** steady-state

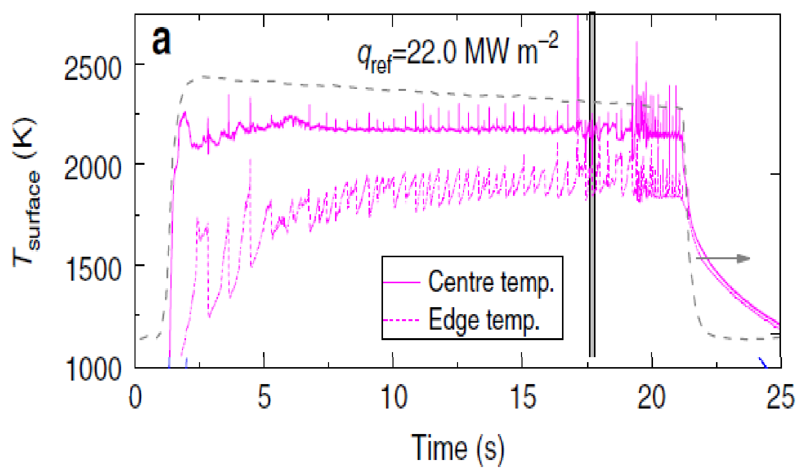
- Fast-flow systems advect power away from heating zones
  - Limiting temperature, heating size, and velocity determine limiting heat flux
  - Li, Ga, Sn are all possible metals for use

- Slowly flowing liquid targets recently demonstrated in multiple configurations
  - Non-vaporizing, water-cooled tin demonstrated at **20 MW m^{-2}** in Magnum-PSI[a]
  - Vapor-shielded tin achieved self-regulated temperature up to **22 MW m^{-2}** in Magnum-PSI[b]

Perpendicular Heat Flux Limit



Steady vapor-shielding Sn

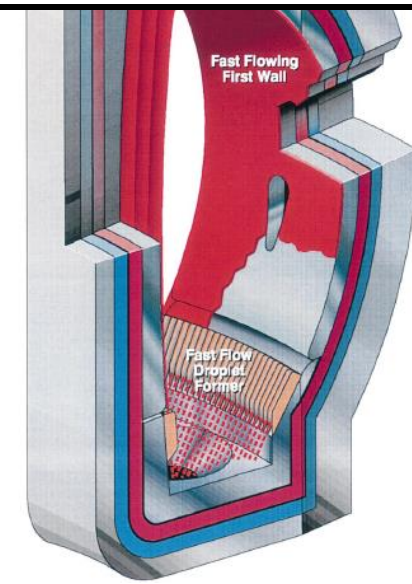


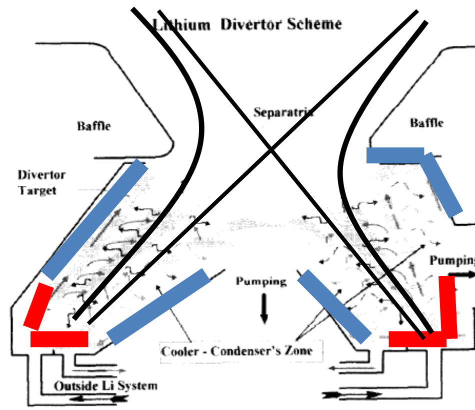
[a]Morgan, 2017 *Nucl. Mater. Energy*; [b]S. Van Eden, et al., *Nature Comm.* **8** (2017) 192.

Liquid metal concepts range from ~10 m/s to ~few mm/s velocities

- LM concepts fall into two broad categories: fast and slow flow ("hybrid" in FESAC TEC report) concepts
  - Fast-flow typically >1cm thick
  - Slow-flow typically capillary-restrained, <1mm thick
- Fast vs. slow approaches differ in maturity of physics and technology
  - Fast flow: less mature technology, less physics maturity for surface stability
  - Slow flow: more mature technology, less physics maturity for ablating targets
- **Reactors expected to feature large areal coverage and continuous flow**

Fast-flow, first-wall and divertor concept





Evaporation
Condensation

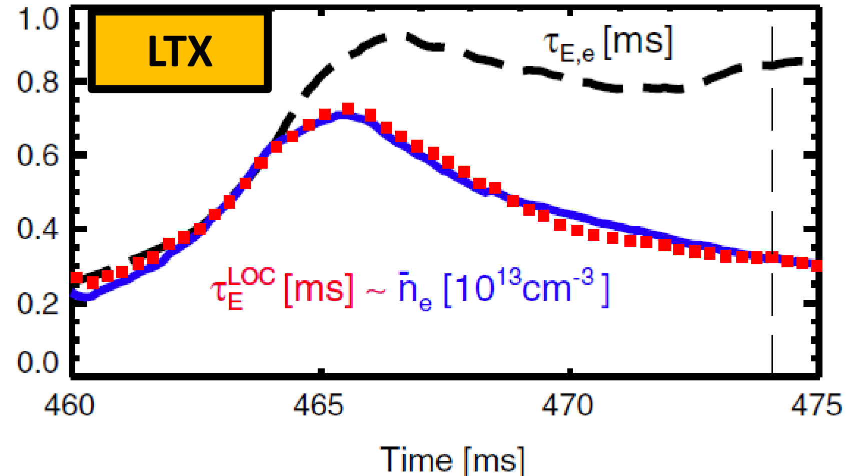
High-temperature, lithium divertor concept

Abdou, et al., *FED* 2001; Golubchikov, et al., *JNM* 1996; Goldston, et al., *Phys Scr.* 2016

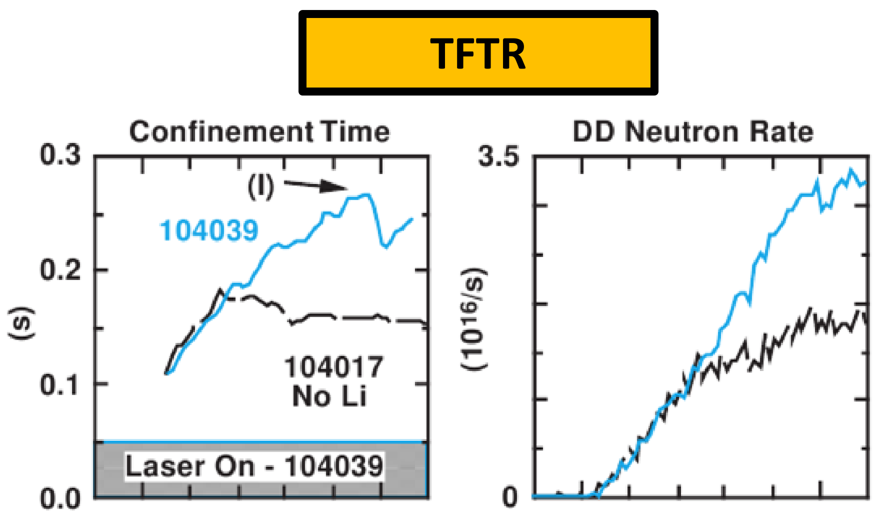
c.f. Mirnov 2009 *JNM* "emitter-collector"

Lithium conditioning observed to increase energy confinement time in multiple machines

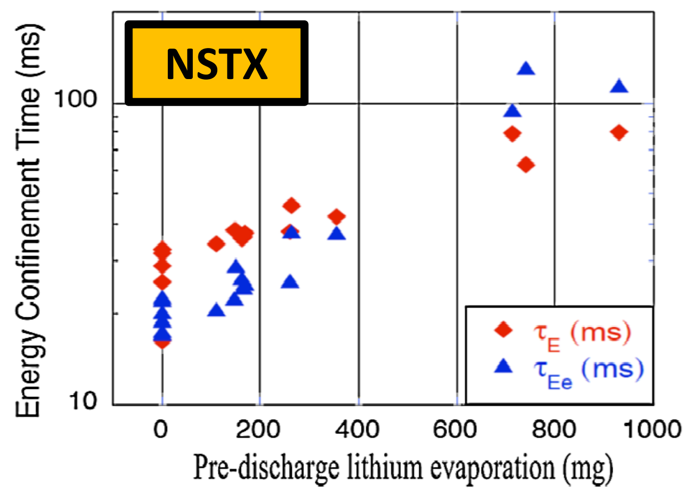
- Confinement improvement attributed to reduced recycling
- LTX coated metallic PFC + Li pool is latest demonstration
- Follows historical trend in wall-conditioning dating to TFTR
  - See also FTU, T11-M, HT-7, EAST, DIII-D, TJ-II, RFX



D. Boyle, et al., *Phys. Rev. Lett.* **119** (2017) 015001.



Strachan, et al., *J. Nucl. Mater.* **217** (1994)



R. Maingi, et al., *Phys. Rev. Lett.* **107** (2011) 145004.

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Some highlights from current US research

1. Liquid Metal Fusion Energy System Study activity

2. Ongoing confinement-device studies in
   LTX-β (PPPL), EAST (CN), and
   HIDRA (U-Illinois)

3. First-wall evolution code validation and material transport studies underway at PPPL and GA

(Solid PFC research areas covered by J. Rapp)

LM-Fusion Energy System Study (FESS) broadly examining issues with LM deployment

- System study group considering Fusion Nuclear Science Facility (FNSF) with liquid metal PFCs
  - Liquid metal choice (Sn, Li, Sn-Li, Pb-Li, etc.)
  - Range of PFC concepts (fast, slow/hybrid, jets)
  - Plasma response and power loads (e.g. Li vapor divertors)
  - Interactions with substrates and sub-systems (e.g. corrosion, embrittlement)
  - Integration issues (e.g. tritium recovery, LM filtration, maintenance impacts)

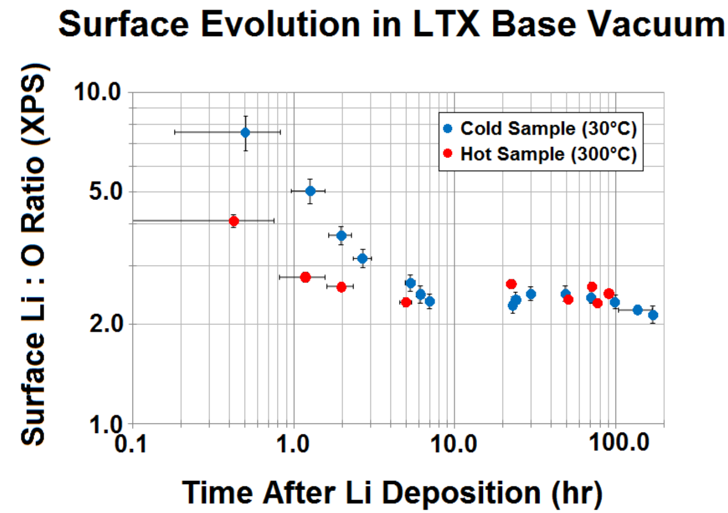
- Example: can the power extracted by fast-flow liquid metal be converted to electricity?
  - Cycle efficiency favors large temperature rise in LM
  - Initial analysis indicates fast-flow tin better integrates than fast-flow Li

Kessel, 2017, ICFRM.

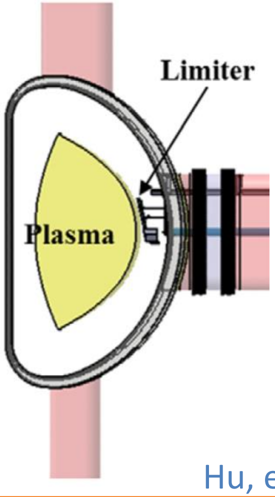
Confinement-device impact examined in LTX(-β) and EAST-PMI projects

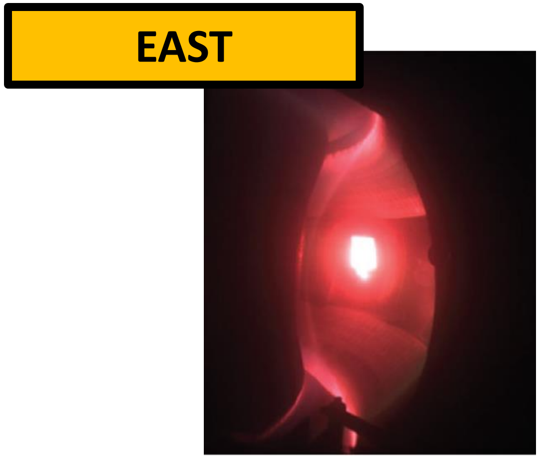
- LTX-β will explore lithium on metallic substrate impact in auxiliary-heated ST

- EAST-PMI project deploying mid-plane limiters in addition to Li evaporations
  - Studying impact on machine performance and operations
  - Technology prototyping and testing in U-Illinois on HIDRA alongside EAST tests



M. Lucia, PhD Thesis, Princeton University. 2015.

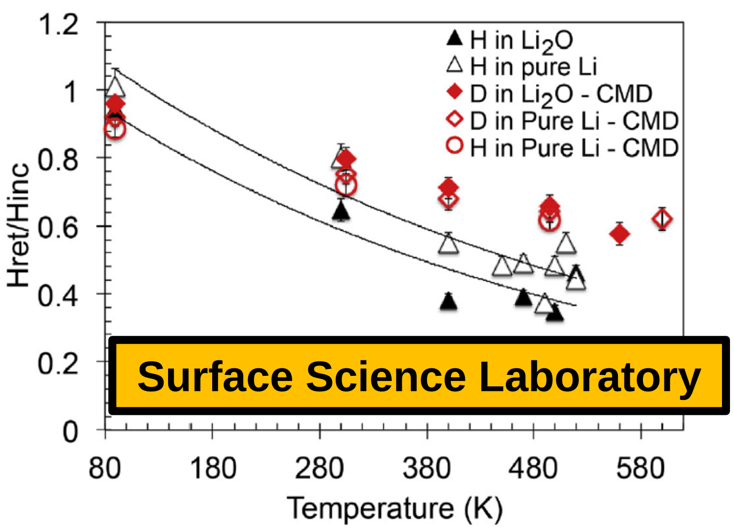




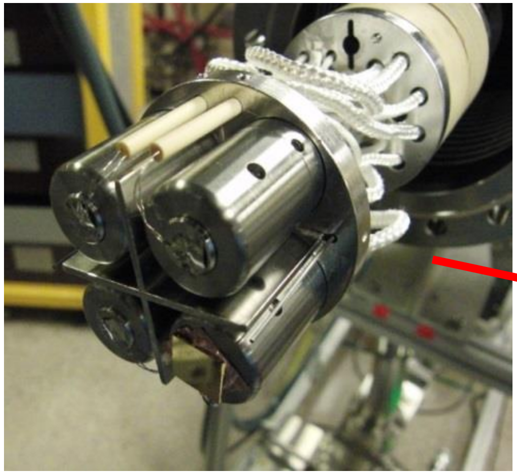
Hu, et al., *Nucl. Fusion* **56** (2016) 046011.

Atomistic- thru machine-scale theory and modeling validation studies of coatings and solid materials

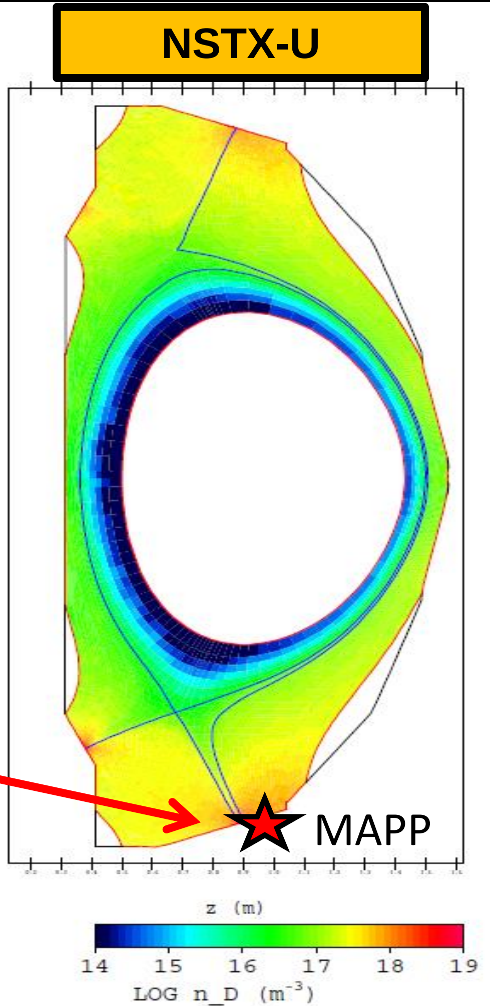
- Laboratory studies of mixed-materials directly compared with ab-initio models (theory + laboratory studies)
- MAPP diagnostic successfully deployed in NSTX-U 2016 run campaign – part of validation data set for whole-device transport modelling
- Whole-device material transport studies also conducted on **DIII-D (e.g. metal-ring campaign)**



L. Buzi, et al., *J. Nucl. Mater.* **502** (2018).



In-vacuo surface science (U-Illinois)



J. Nichols, Princeton Univ. PhD. 2018

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Decision for a liquid metal reactor needs answers to these questions

1. What does the integrated scenario look like for a given liquid metal/temperature combination?

2. Can the tritium breeding ratio be maintained, including any LM fuel-retention effects?

3. What is the life-time limit of the LM components?

4. Can these systems be made safe, reliable, and maintainable?

Integrated scenario provides assessment of liquid metal choice and technology

- Fusion core performance to determining overall plant size and capacity (e.g. compact vs. large scale)
- Core-edge integration is linked to the operating temperature (e.g. absorbing vs. ablating Li, other metal)
- Control of material temperature limited by technical capabilities (e.g. fast/slow flow and plasma configuration)
- Power extraction potential impacted by ability to utilize liquid metal heat (cycle efficiency)

Core-edge integration can only be experimentally demonstrated with a confinement device

Tritium breeding essential to successful D-T reactors

- New mass-flows in and out of vacuum vessel create potential losses for fusion fuel (common to all LM concepts)

- Lithium absorbs hydrogen so requires a robust strategy for closing the fuel cycle
  - New technologies in development at SRNL
  - Slow-flow concepts target higher concentrations to ease extraction

Plant component lifetime and maintenance schedule impacts cost of operating

- Important value proposition for liquid research:
  - If solid component lifetime justifies liquid usage, then liquid component must exceed solid lifetime
  - Technical solution must truly eliminate plasma-based erosion

- Liquid metal interactions with substrate material (including transmuted materials) could limit component life

Operations and licensing of a fusion plant depends on safety, reliability, and maintainability

- No one will agree to an unsafe nuclear reactor
- No operator will keep a reactor that isn't profitable
- Sodium fast-reactors provide a dataset of the challenge of large-scale, alkali metal, nuclear systems

Range of facilities is needed to develop critical data set

- Definitive contributions
- Supporting contributions
- Hashed: no single, definitive contribution

	Laboratory Scale	Test-Stands, Linear Plasma Devices	Experimental Confinement Devices	Theory, Design, and Modeling
Integrated Scenario Development				
First Wall and Divertor PFC Design & Operation				
Power and Particle Handling				
Plasma Scenario Assessment				
Tritium Breeding Ratio and Fuel Recovery				
Lifetime of Components				
Safety, Reliability, Maintainability				

DOE views universities, national labs, and industry as essential partners in energy innovation

- Laboratory-scale experiments and studies can be conducted at universities
- High-power confinement devices operated by National Labs and industrial partners
- Sub-components could be basis of spin-off technologies for industrial partners
  - e.g. spray coating development for slow-flow PFCs

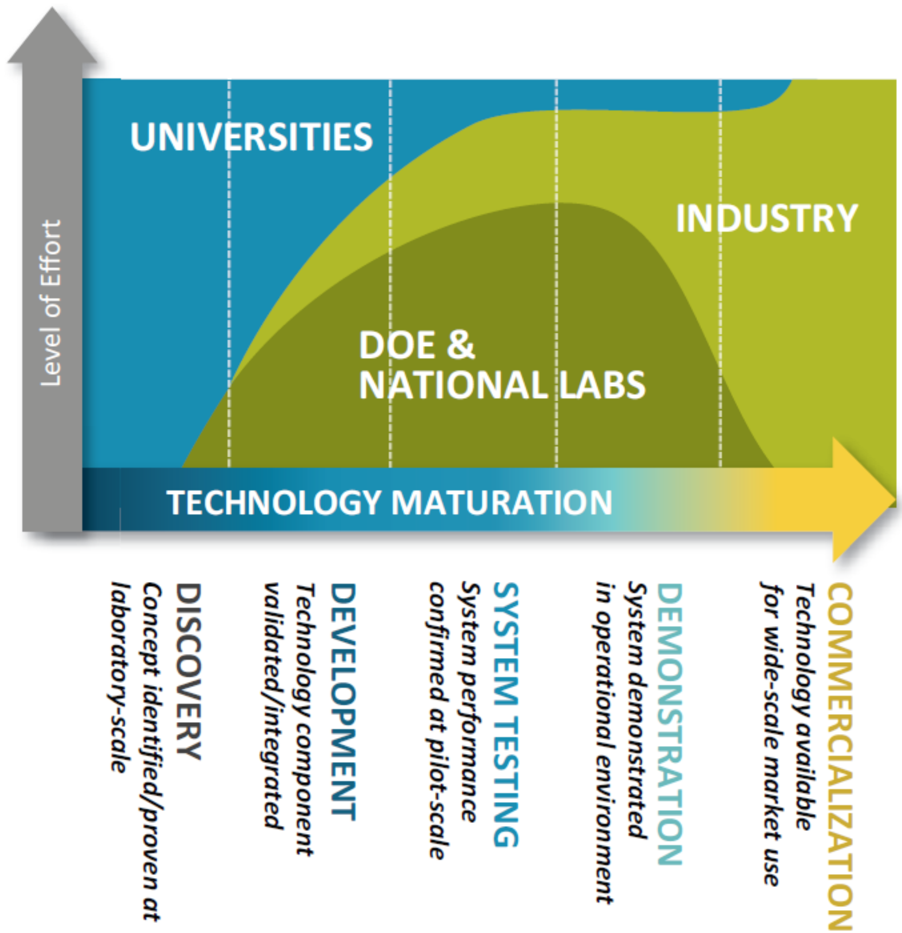

Fig. 2-2, "Annual Report on the State of the DOE National Laboratories", DOE Report, Jan. 2017

Potential “show-stoppers” in all critical areas suggests parallel effort

- Integrated assessments could eliminate liquid metal and technology choices
- TBR process challenges could eliminate metals
- Corrosion/life issues could make liquids metals unattractive
- Safety and reliability could make liquid metals unattractive

Sustained R&D progress could be enabled with Shared R&D or User Facility model

- Following DOE model: National labs could provide LM-capable devices for tests of new concepts and technologies
  - Core-edge integration assessment implies large areal coverage, high-power (>10MW/m^2), multiple confinement times (> 1s)
  - High-heat flux, pre-filled lithium targets could be implemented into a confinement device in ~3-5yr timeframe
  - Fast-flow concepts require additional development time, but facility would be prepared for LM tests
  - **Implies acceptance of machine redirection**

- Similar R&D facility model could be implemented for TBR, and corrosion/lifetime, and safety assessments

Less tangible aspects of aggressive R&D…

- CRENEL report: DOE sets forth the mission; labs and others execute the mission

- Experimental results can eliminate or demonstrate concepts –
  have to be willing to move on

- Need to accept that there is **RISK** in doing new things

There is a Way; is there a Will?

- Community assessment indicates there is development needed for reactor extrapolations
  - EU colleagues emphasized power exhaust challenge
  - Plasma- and neutron-induced material evolution is significant

- Liquid metal plasma-facing components provide many intrinsic advantages
  - Provide means of control for long-time scale evolution of material
  - Do require a lot of technical development to give clear comparison with solid PFCs

- Critical questions facing LM reactor proposed with facility mix
  - University, National Lab, and Industrial partners are all needed
  - **Liquid metals are not a "less-trodden" path, they are a *never*-trodden path**

Thank you for this opportunity