Liquid metals as plasma-facing components: progress and prospects*

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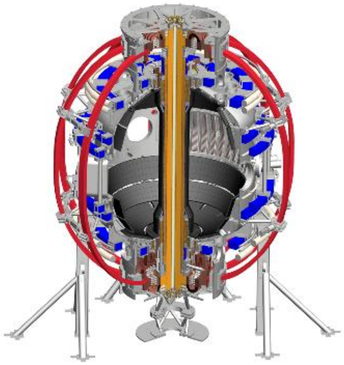


Organization of this talk

- Why (re)consider liquid metals as plasma-facing components (LM PFCs)?

- Overview of current topics in plasma-material interaction science for LM PFCs
  - Free-surface stability
  - PMI processes and complications
  - Liquid metal impact on the plasma

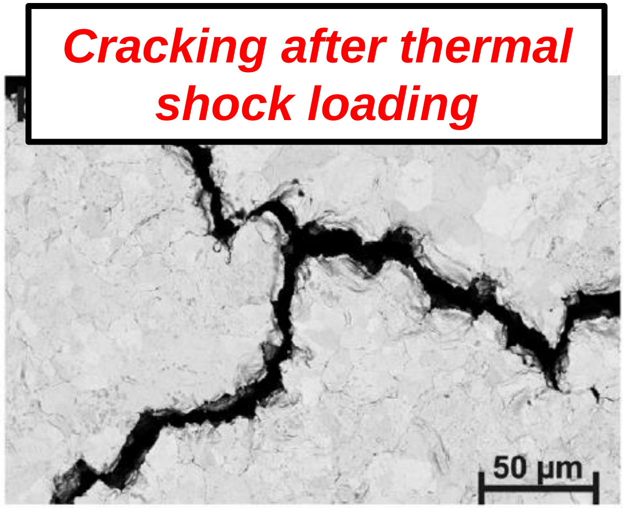
- Critical issues still to be addressed

What won't be covered in this talk?

- Cannot cover all topics in detail in such a short period!
- Will not discuss liquid metal blankets or non-PFC aspects
- Focus is on plasma-material interaction science issues
- Other recent reviews and meetings can provide more information
  - F.L. Tabares, Plasma Phys. Control. Fusion 2015
  - Y. Hirooka, et al., Fusion Sci. Tech. 2015
  - Biennial "International Symposium on Liquid Metal Applications for Fusion Devices" meeting (next: 2017, Russia)

Liquid metals are a potential PFC solution for power reactors

- 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
- Eliminates long-time constants associated with solid-wall material transport and evolution
- Greater power-exhaust potential



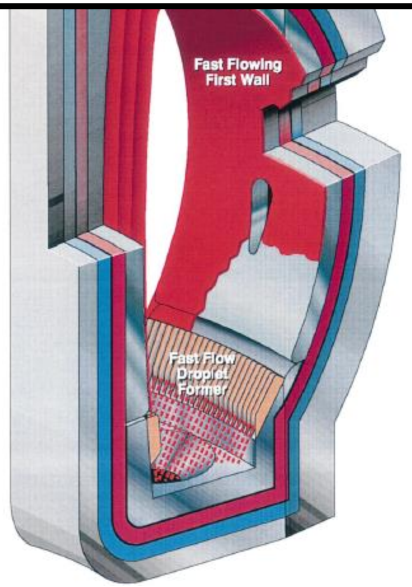
Wirtz, et al., JNM 2013

Coenen, et al., JNM 2013

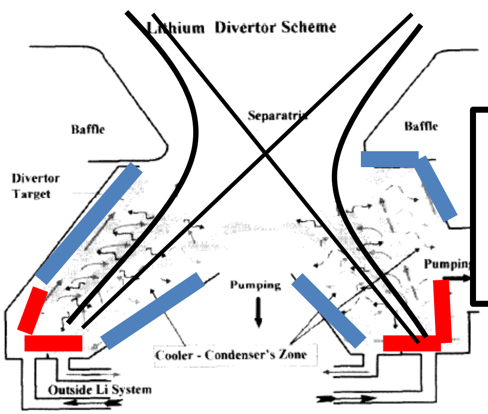
Liquid metal concepts range from ~10 m/s to ~few mm/s velocities

- LM concepts fall into two broad categories: fast and slow flow 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



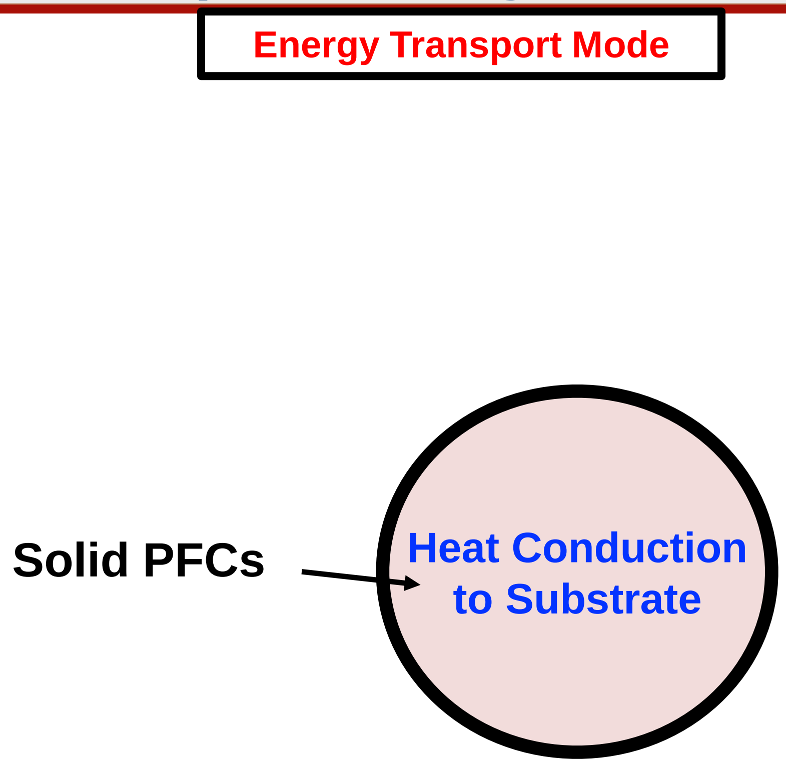
Abdou, et al., FED 2001
Golubchikov, et al., JNM 1996



High-temperature, lithium divertor concept

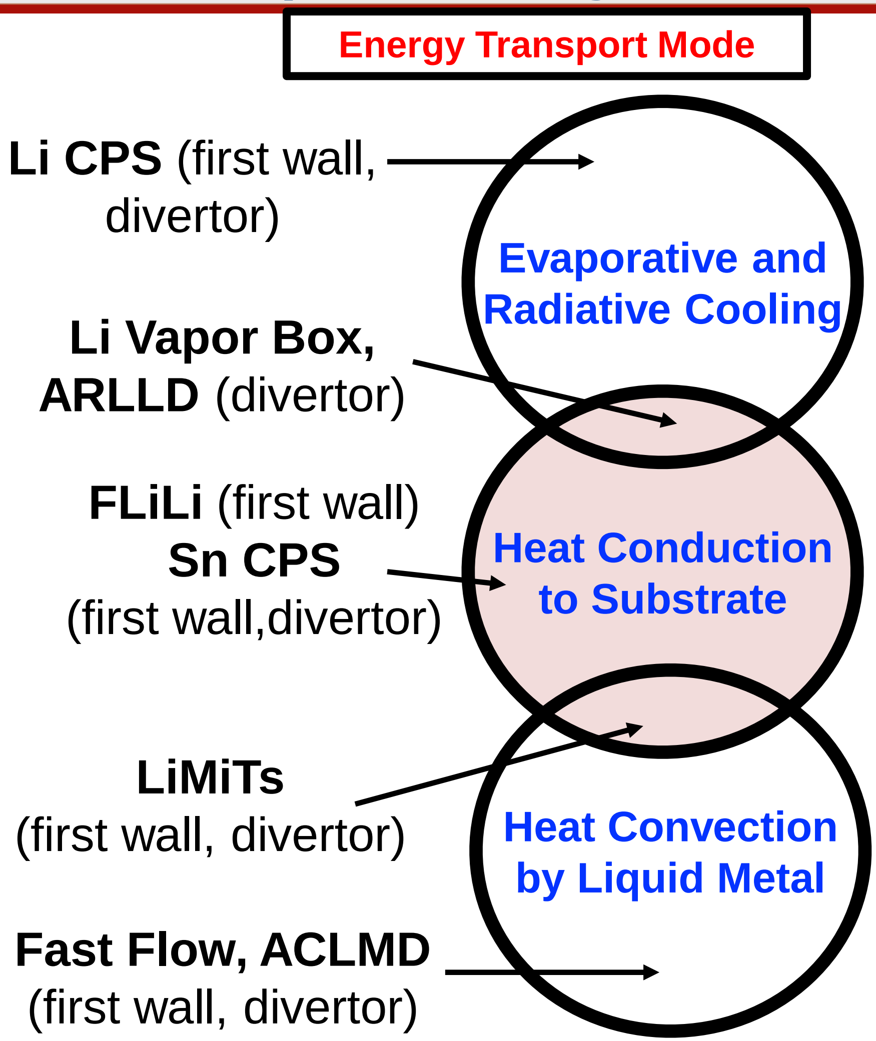
c.f. Mirnov 2009 JNM "emitter-collector"

Liquid metal PFCs provide additional pathways for energy transport



- Conventional, solid PFCs utilize extrinsic impurities to enhance radiation

Liquid metal PFCs provide additional pathways for energy transport



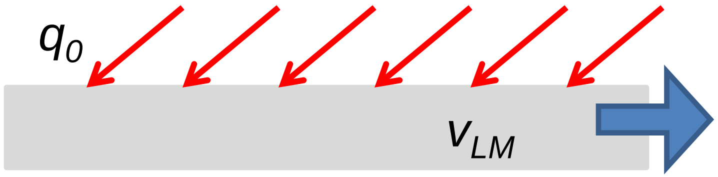
- Conventional, solid PFCs utilize extrinsic impurities to enhance radiation
- Demonstration of surface stability is key for all concepts
- Vast difference in pressure and flow requirements; expected operating temperatures

Power-handling capability is the greatest advantage of fast-flow concepts

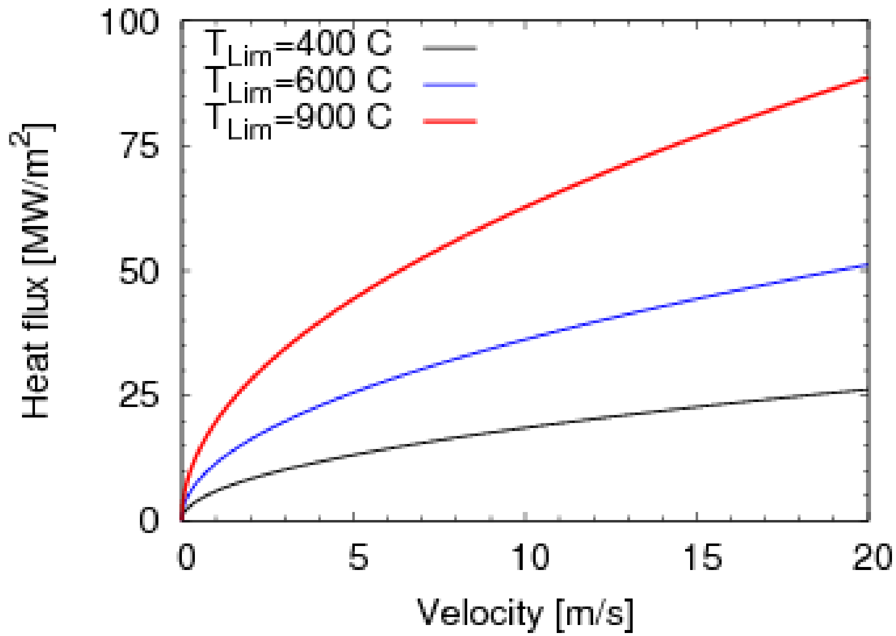
- "Moving slab" approximation for temperature rise
  - LM properties, conductivity k and thermal diffusivity α
  - Characteristic path length L_{char}
  - Limiting temperature rise ΔT_{Lim}

- Reduces need for complex cooling schemes in substrate

Incident heat flux vs. velocity

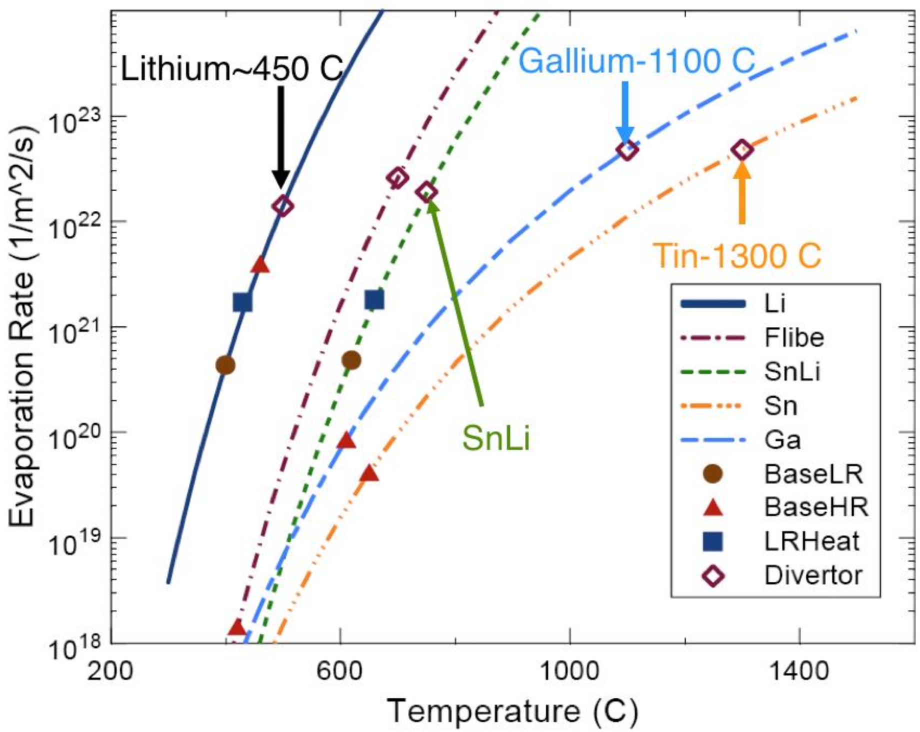


$$q_0 = \frac{\Delta T_{Lim} k}{2} \sqrt{\frac{\pi v_{LM}}{\alpha L_{char}}}$$



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 window
- Tin-Lithium alloy may feature benefits of both, little studied



Majeski, PPPL-4480, Jan. 2010

Parallel efforts over 45-year history of liquid metal concepts brings us to today

- 1973: UWMAK proposal for liquid-metal PFCs
- 1992: TFTR discovers "Li super-shot"
- 1992: Russian droplet curtain used on T-3M (Ga)
- 1990s: Capillary-porous targets developed in Russian Federation, demonstrated in tokamaks and linear devices
- Late 1990s~2004: ALPS/APEX program in the US – wide range of concepts considered
- 2004: DIII-D demonstrates Li ejection
- 2005: CDX-U operates with large-area Li tray limiter
- Mid-2000s: FTU and TJ-II begin experiments with lithium coatings and CPS
- 2005-2010: NSTX experiments w/ evaporated Li, including large-area divertor target
- 2011-present: EAST utilizes Li wall conditioning
- 2011-2015: LTX shell experiments w/ evaporated Li
- 2012-present: Tin experimental work expands
- 2015: EAST flowing lithium limiter

Ultimate decisions comparing approaches likely to turn on economic metrics

	Solid PFCs	Liquid PFCs
• Power density and transient loading		
• Maintenance cost and availability of power plant		
• Capital cost, complexity (including fuel recovery), safety		
• Demonstrated reactor scenario with all materials		

Ultimate decisions comparing approaches likely to turn on economic metrics

Solid PFCs | Liquid PFCs

- Power density and transient loading
- Maintena availabilit
- Capital c (includin safety
- Demonstrated reactor scenario with all materials

A detailed engineering design can objectively provide a cost/benefit analysis.

For Fusion: *an* approach that works is desired!

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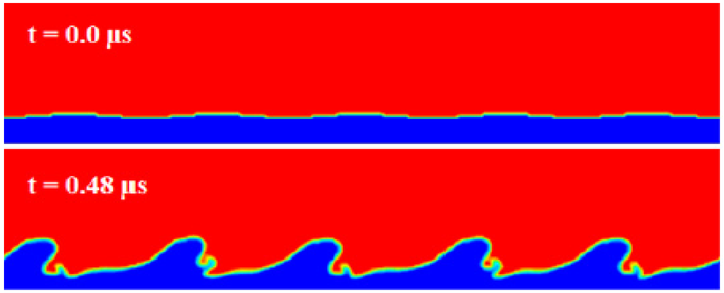
  - Free-surface stability
  - PMI processes and complications
  - Liquid metal impact on the plasma
- Critical issues still to be addressed

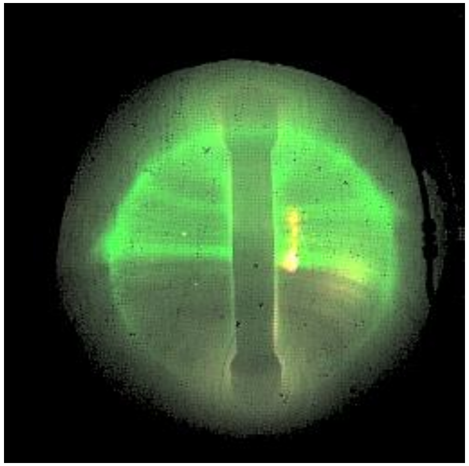
Current topics impinging feasibility of liquid metal concepts

- Stability demonstrated in capillary systems, remains issue for thick layers



- PMI processes complicated by temperature and mixed material effects

- Some positive results with use of liquid metals but obscured by complex PMI processes



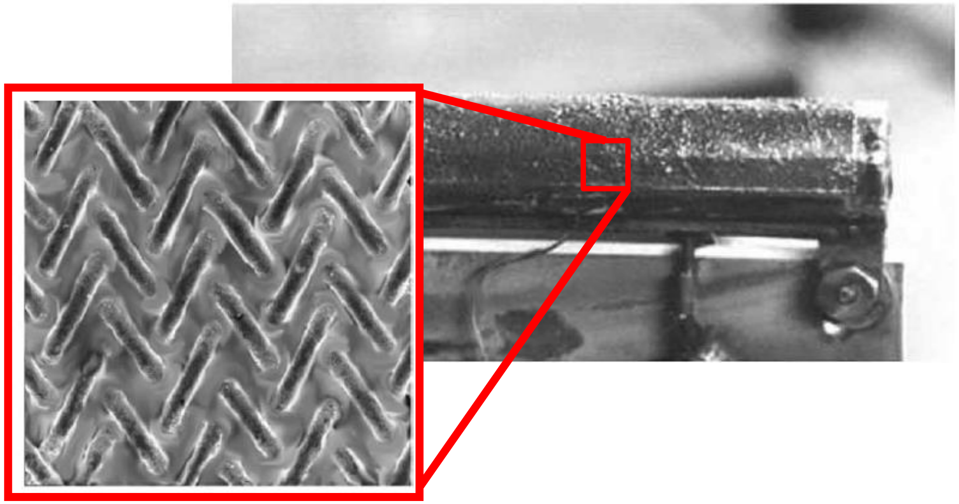
Miloshevsky, Hassanein, JNM 2011
Jaworski, et al., ISLA 2013
Mansfield, et al., FED 2010

Empirical observations demonstrate stability of slow-flow, capillary systems

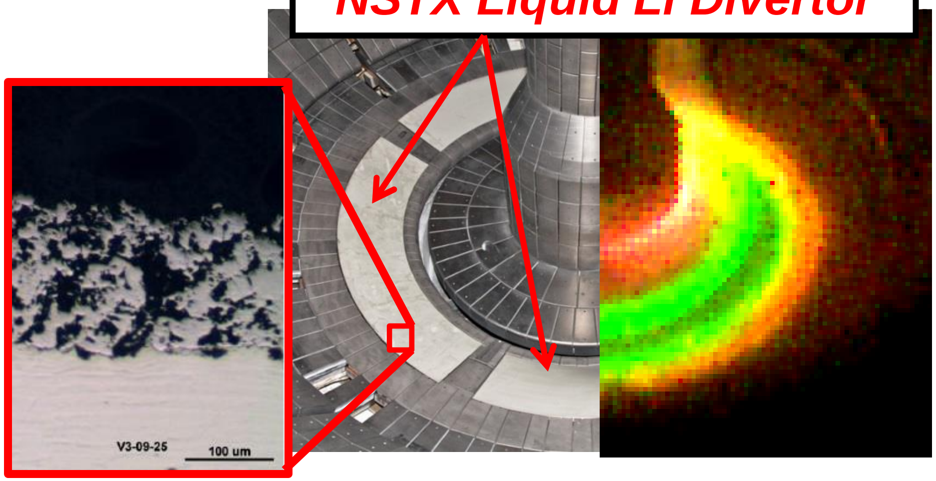
- Red Star Capillary-Porous System (CPS) embodies solution with mesh
  - Reducing mesh size enhances surface-tension effects (Evtikhin 2002 PPCF)
  - Operation of CPS in T-11M and FTU
  - NSTX "Liquid Lithium Divertor" demonstrated **divertor target** without ejection events (Jaworski 2013 NF)
  - Counter example to DIII-D Li-DIMES (Whyte 2004 FED)

- Micro-scale droplet emission sometimes still observed and subject of on-going investigation

Red Star CPS Limiter



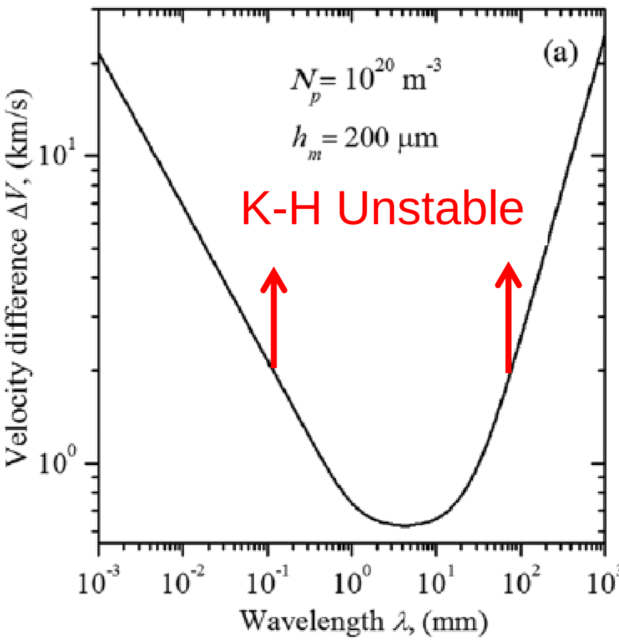
NSTX Liquid Li Divertor



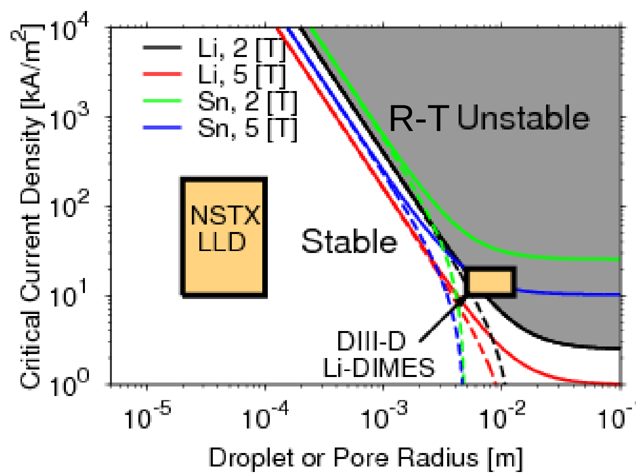
Lyublinski, et al., Plasma Dev. Ops. 2009;
Jaworski, et al., PPCF 2013

Theoretical basis for stability depends on technical approach

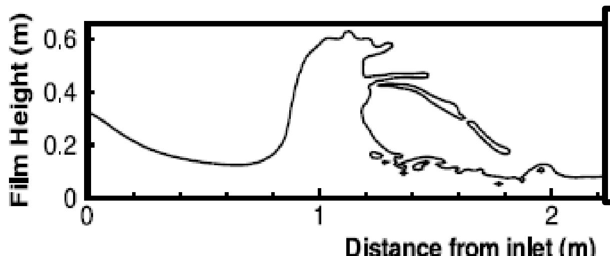
- Rayleigh-Taylor and Kelvin-Helmholtz instabilities both recently re-analyzed
  - K-H stable up to critical flow velocity depending on wavelength and fields (Miloshevsky 2014 NF)
  - R-T stable in porous target depending on field and currents (Jaworski 2013 NF)
- Fast-flow systems take various approaches for stability
  - Axisymmetric and injected currents (Zakharov 2003 PRL)
  - Non-axisymm. effects still require 3D modeling (Morley 2002 FED)



Miloshevsky, 2014 NF



Jaworski, 2013 NF



Fast-flow breaking wave in gradient B-field

Morley 2002 FED

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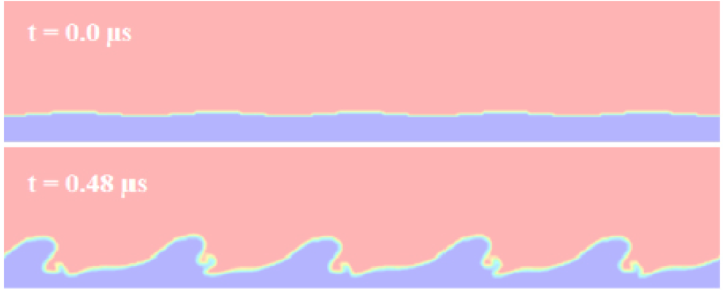

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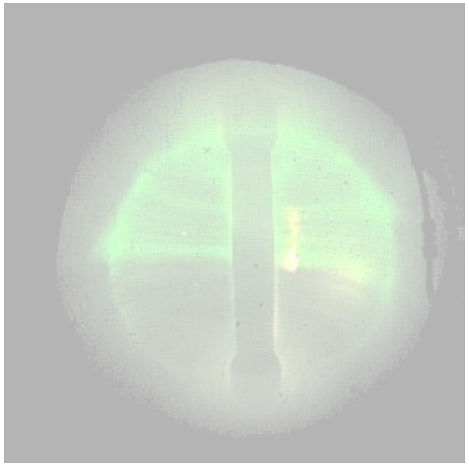


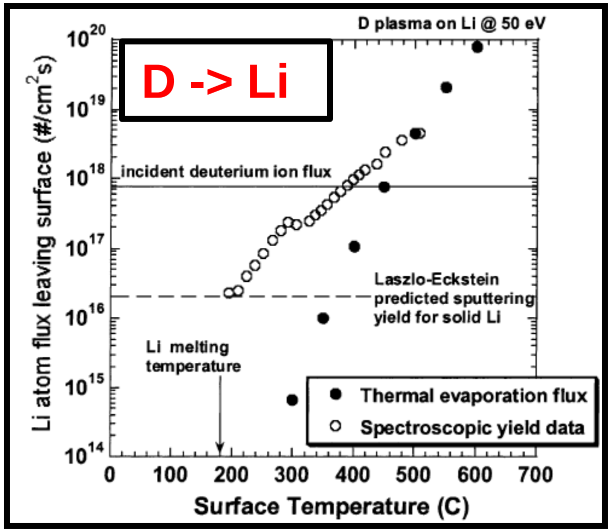
Miloshevsky, Hassanein, JNM 2011
Jaworski, et al., ISLA 2013
Mansfield, et al., FED 2010

Temperature effects on material erosion highlights close connection with engineering

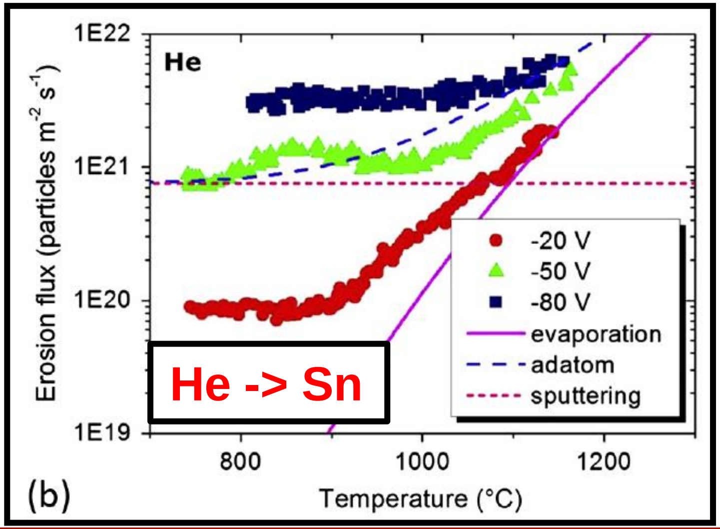
- Erosion of LM includes multiple mechanisms
  - Physical sputtering
  - Evaporation
  - Thermally-enhanced sputtering

- Slow-flow systems limited to heat conduction and evaporation into plasma
  - High surface temperatures
  - Erosion into near-plasma critical issue

- Drives examination of fast-flow concepts to limit temp. effects (e.g. Shimada 2014 NF)



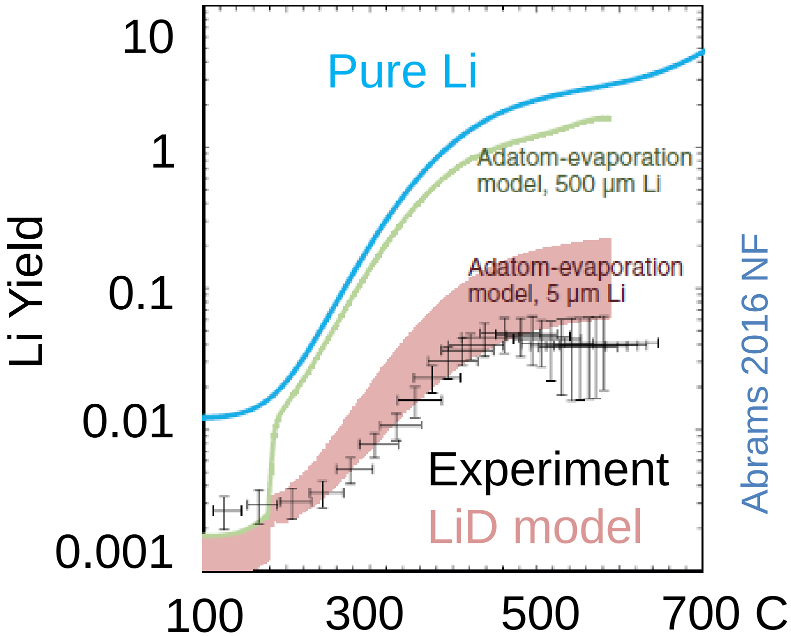
Doerner, 2001 JNM, cf. Allain 2007 PRB

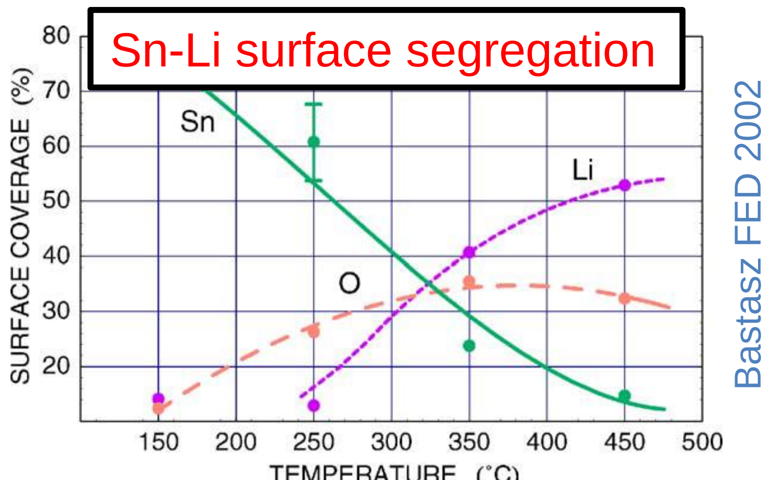


Morgan, 2015 JNM; cf. Coenen 2014 Phys. Scr.

Surface composition demonstrated to vary and has strong effect on PMI

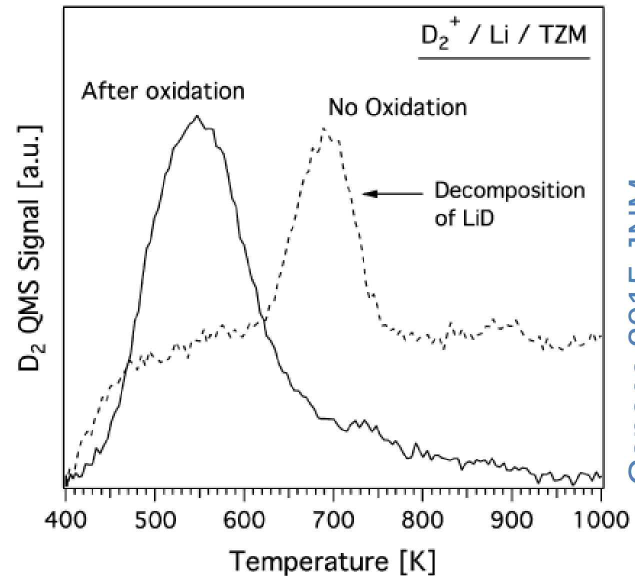
- Strong effect of LiD-Li mixed material during high-flux experiments (divertor-like) (Abrams NF 2016; Chen NF 2016)
- Indications of chemical interactions in high-flux tin experiments
(Morgan JNM 2015)
- Surface composition of alloy known to depend on temperature and constituents (Bastasz FED 2004)





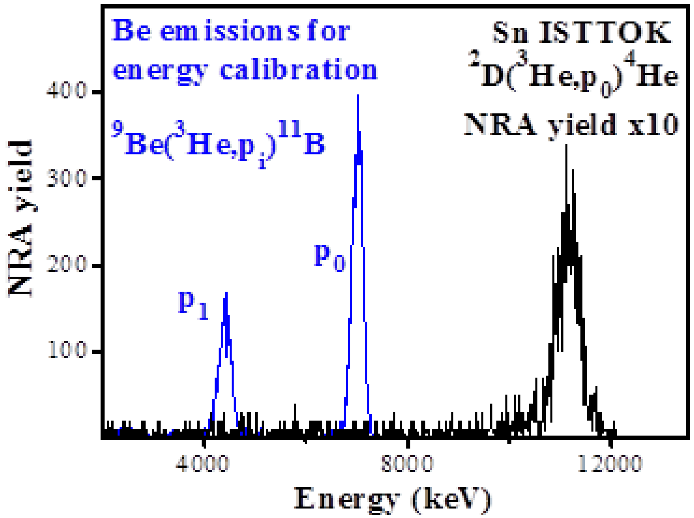
Deuterium retention in Li affected by oxides; Sn studies just beginning

- Oxygen can bind hydrogen and desorbs at low temperatures
  - Consistent with Oyarzabal (2015 JNM) and LTX tokamak (Lucia ISLA 2015)
  - **Indicates feasibility of thermal desorption process for fuel recovery at large hydrogen concentrations**



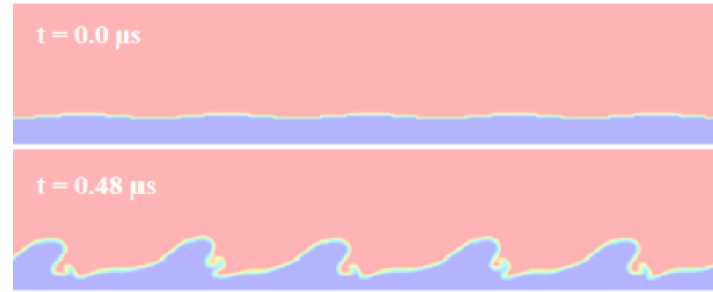
Capece 2015 JNM

- Initial results show low hydrogenic retention in Sn and Sn-Li (Loureiro ISLA 2015)
  - NRA spectra of ISTTOK sample shows 0.068% atomic in Sn
  - Undetectable retention in Sn-Li



Loureiro ISLA 2015

Current topics impinging feasibility of liquid metal concepts



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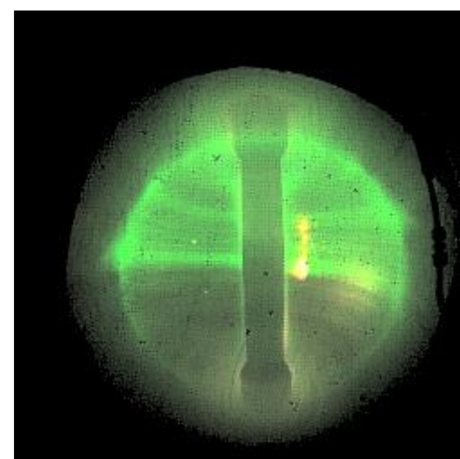
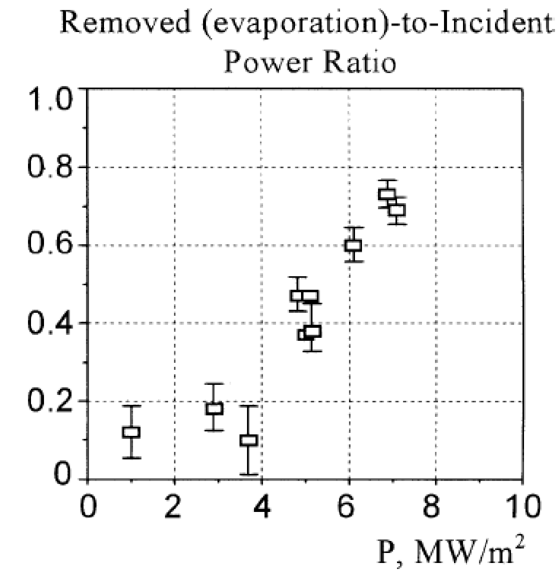


- Some positive results with use of liquid metals but obscured by complex PMI processes

Miloshevsky, Hassanein, JNM 2011
Jaworski, et al., ISLA 2013
Mansfield, et al., FED 2010

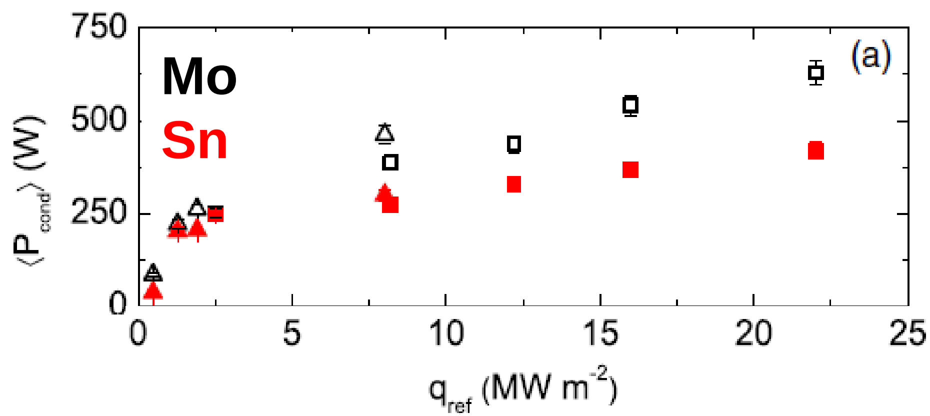
Lab and confinement device experiments show favorable initial results

- Power reduction with Li demonstrated in e-beam and pulsed plasmas



Khripunov 2003 JNM

- Exposures in high-flux linear machines show mixed results
  - Heat flux reduction with Sn (van Eden 2016 PRL) **(see O-20 Morgan)**
  - No heat flux reduction with Li yet reported (Martin-Rojo ISLA 2015, Jaworski ISLA 2013)

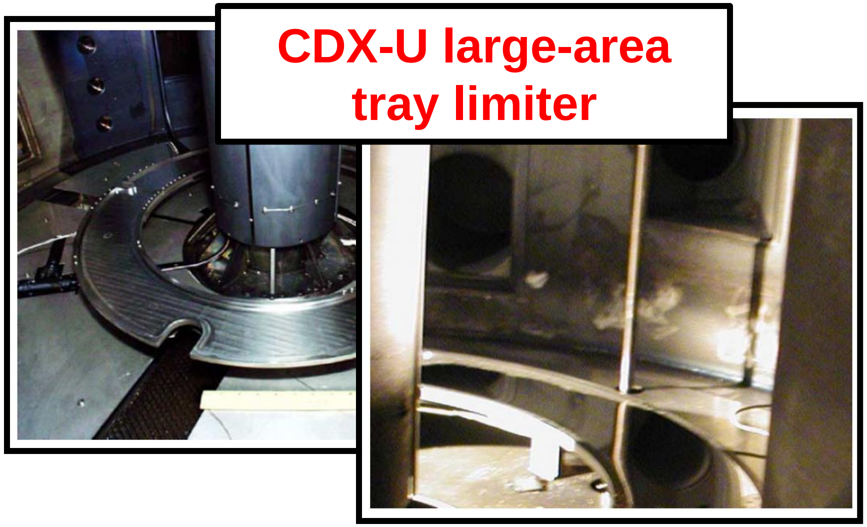


G.G. Van Eden 2016 PRL

- Li heat flux reduction in confinement devices still under study **(see I-9 next!)**

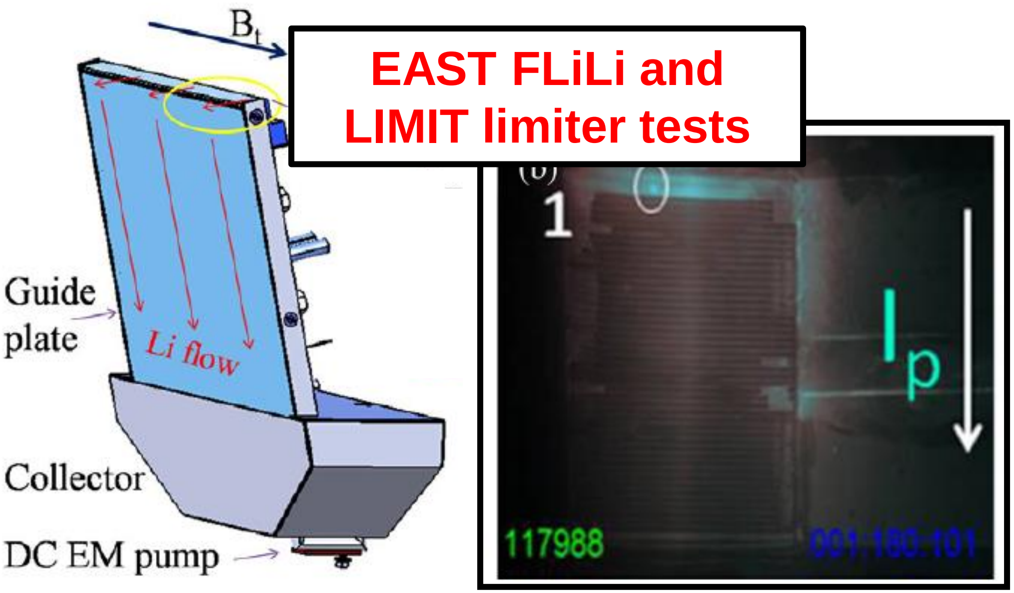
Database of impact on core plasma includes multiple "liquid metal" application methods

- Numerous studies of Li effects, few examples of Ga, and Sn to be attempted by FTU soon
- Small area limiters most common (TJ-II, FTU, T-10M, T-11M, EAST, HT-7)
- Large area evaporations also applied (e.g. NSTX, EAST, LTX*)
- Few examples of thick (>3mm) liquid targets (CDX-U tray, LTX*)
- Two examples of droplet/jet targets (ISTTOK, T-3M)



CDX-U large-area tray limiter

Kaita 2005 JNM



EAST FLiLi and LIMIT limiter tests

Hu 2016 NF; Ren 2016 FED

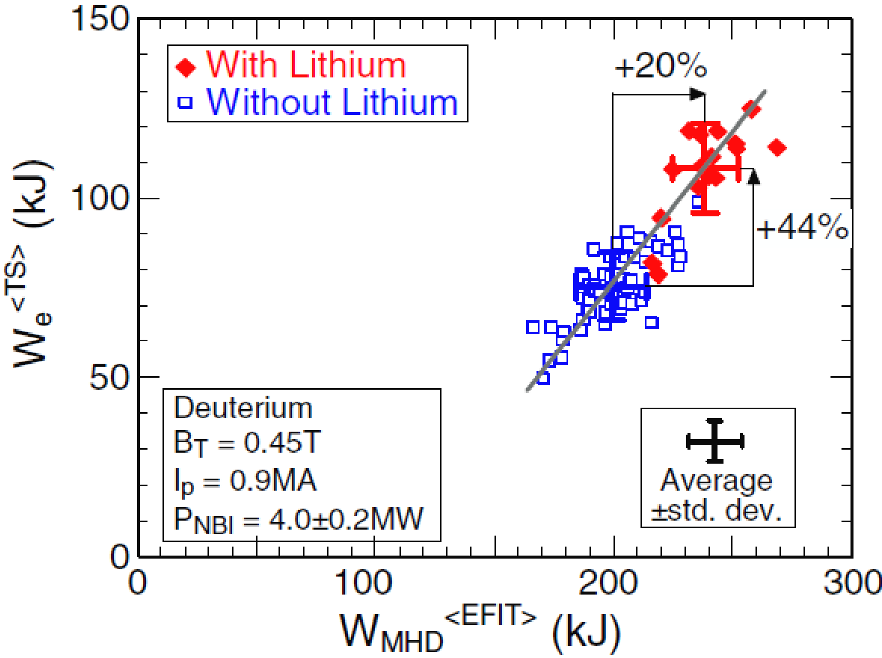
PMI complexities strongly motivate consistent experimental design

- Large amount of literature reports on evaporative wall conditioning
  - Confinement improvements
  - ELM modification/suppression

- Evaporation of Li onto graphite unlike expected LM PFCs for reactors
  - Rapid Li intercalation occurs immediately (Itou 2001 JNM)
  - Li-O-C complex shown with DFT modeling to bind D via oxygen bonds (Krstic 2013 PRL)
  - DFT consistent with in-vacuo surface diagnostics (Taylor 2014 PoP)

- **Evaluation of reactor-relevant scenarios demands attention to materials!**
  - Unknown issues for Sn, Ga, and SnLi
  - Caveat emptor for empirical demonstrations!

Stored Energy in NSTX with Li conditioning

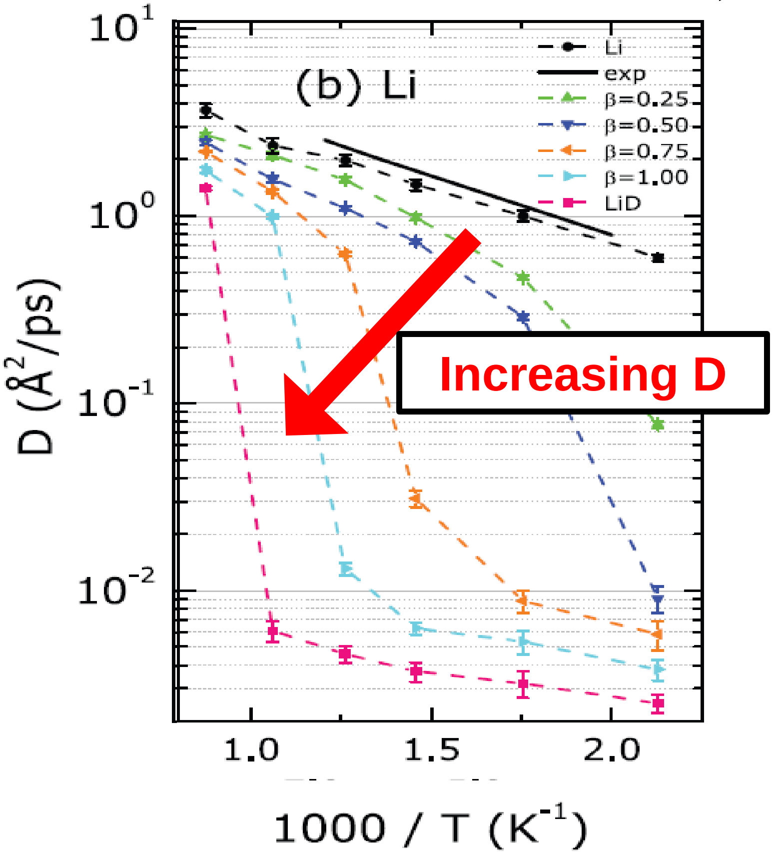


Bell 2009 PPCF

Material modeling increasingly able to capture complex PMI processes

- Reactivity and mobility recommends MD modeling to describe PMI
  - DFT approach calculates interatomic potentials (Chen 2016 NF)
  - Challenges remain in multi-scale modeling of all processes
- Plasma modeling typically conducted with conventional plasma-fluid codes (see also talks yesterday)
  - UEDGE (Rognlien 2001 JNM), TECXY (Pericoli-Ridolfini 2007 PPCF), SOLPS (Canik 2013 NF), NCLASS/NEO/MIST (Scotti 2013 NF)
  - Still require experimental data sets to "calibrate" transport

Modification of Li and D diffusivity in Li with increasing D content



Chen, et al., 2016 NF

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Demonstration of integrated scenario (core+edge+PFCs)

- **Ultimate configuration still debated!** (e.g. hot-walls + vapor-box divertor + added impurity seeding?)
- Larger areal coverage at representative temperatures
- Representative surface compositions
- Material redistribution and mixing means first-wall still needs attention for whole-machine assessment
- NSTX-U high-Z upgrade, KTM, DTT liquid metal mission element steps in this direction

Demonstration and analysis of fuel-cycle impact

- Liquid metals, even at small retention rates, could impact needed tritium breeding ratio in a reactor
  - E.g. Nishikawa's Tritium balance-of-plant analysis showed significant impact on needed TBR due to codeposition even with solid PFCs (2011 FST)

- Laboratory experiments demonstrate release at large concentrations (>1%) even at low temperatures (<600C for Li-D, <400C for oxidized Li)

- Recovery demonstrated from Li at ~1ppm level relevant to fast-flow systems (see IFMIF activity; Edao 2010 FED)
  - Fast-flow concepts still developing self-consistent recovery schemes

- Similar efforts will be required for Sn and Ga concepts to ensure no surprises!

Much progress made, still more needed

- Liquid metal PFCs offer possibility for improved survivability and increased power handling
- Much progress since initial LM concepts and accelerating progress due to renewed world-wide interest
- Slow, capillary-restrained PFCs present near-term technical solution and have been tested in lab and confinement devices with multiple metals
- PMI studies on liquid metals have illustrated great complexity due to reactivity and mobility
- Integrated demonstrations are required for all liquid metal candidates including an assessment of the attractiveness of the core scenario *for comparison* with similar data for solid PFCs
- Fuel retention and inventory control in an integrated demonstration remains looming issue for all concepts

Present state of knowledge built up by great number of contributors over years of effort

- Great many collaborators and contributors have built up the field to the present and this is just a snapshot!
- Progress has been made by overcoming both reactions - awe and fear - to liquid metals
- **Thank you for your attention!**

Backup