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


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Oak Ridge, TN


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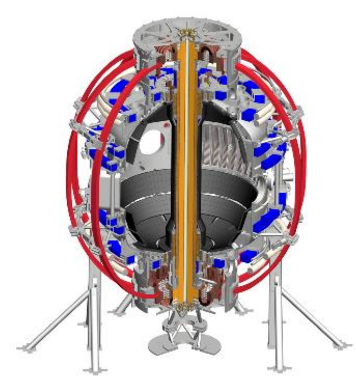


# Organization of this talk

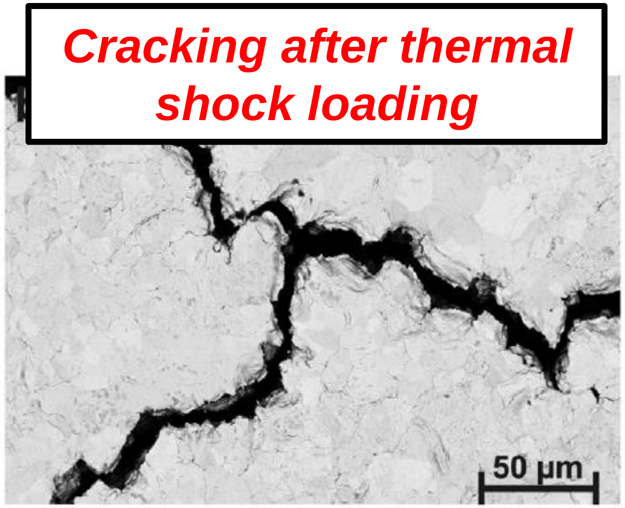
- Why (re)consider liquid metals as plasma-facing components (LM PFCs)?
- Overview of current topics in plasma-material interaction science for LM PFCs
  - Free-surface stability
  - PMI processes and complications
  - Liquid metal impact on the plasma
- Critical issues still to be addressed

# 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

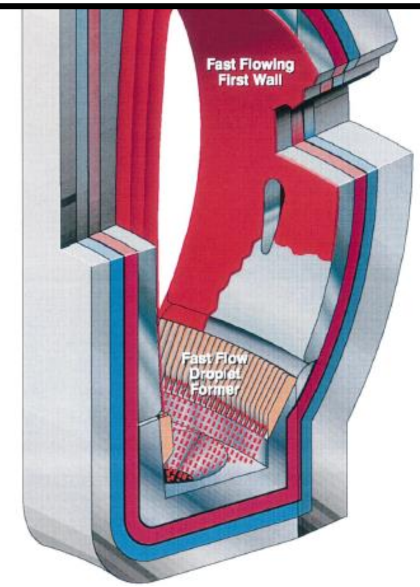
# Liquid metal concepts range from ~10 m/s to ~few mm/s velocities

- 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**

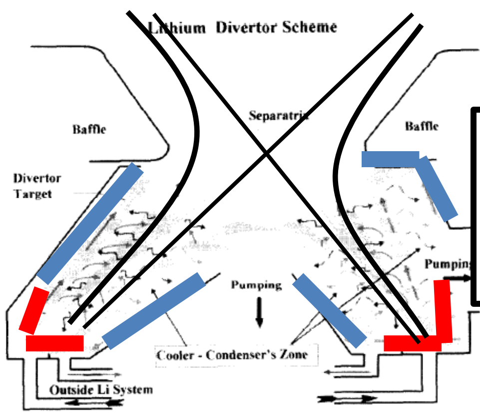
**Fast-flow, first-wall and divertor concept**




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

Evaporation

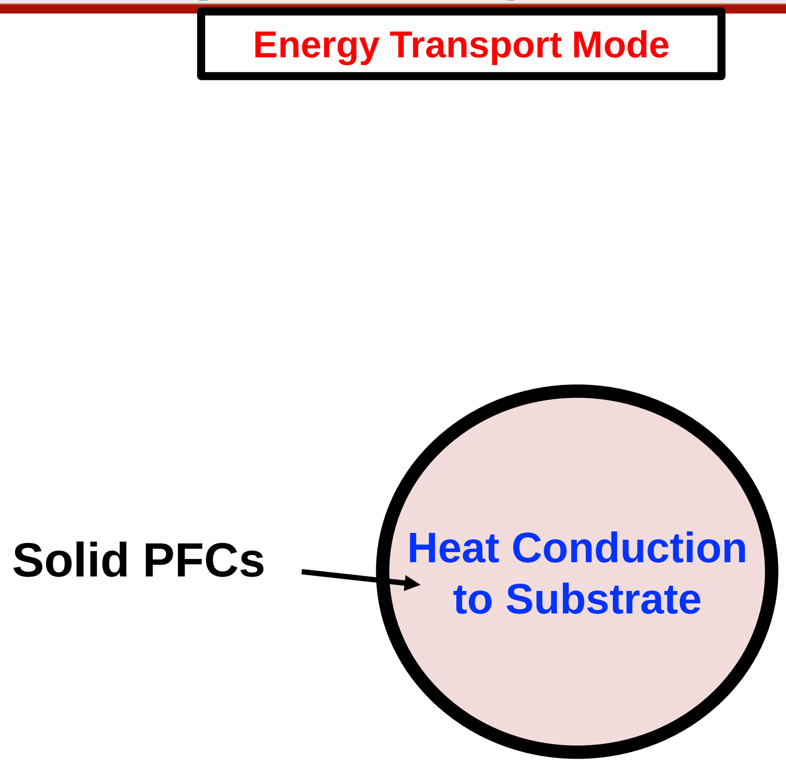
Condensation




**High-temperature, lithium divertor concept**

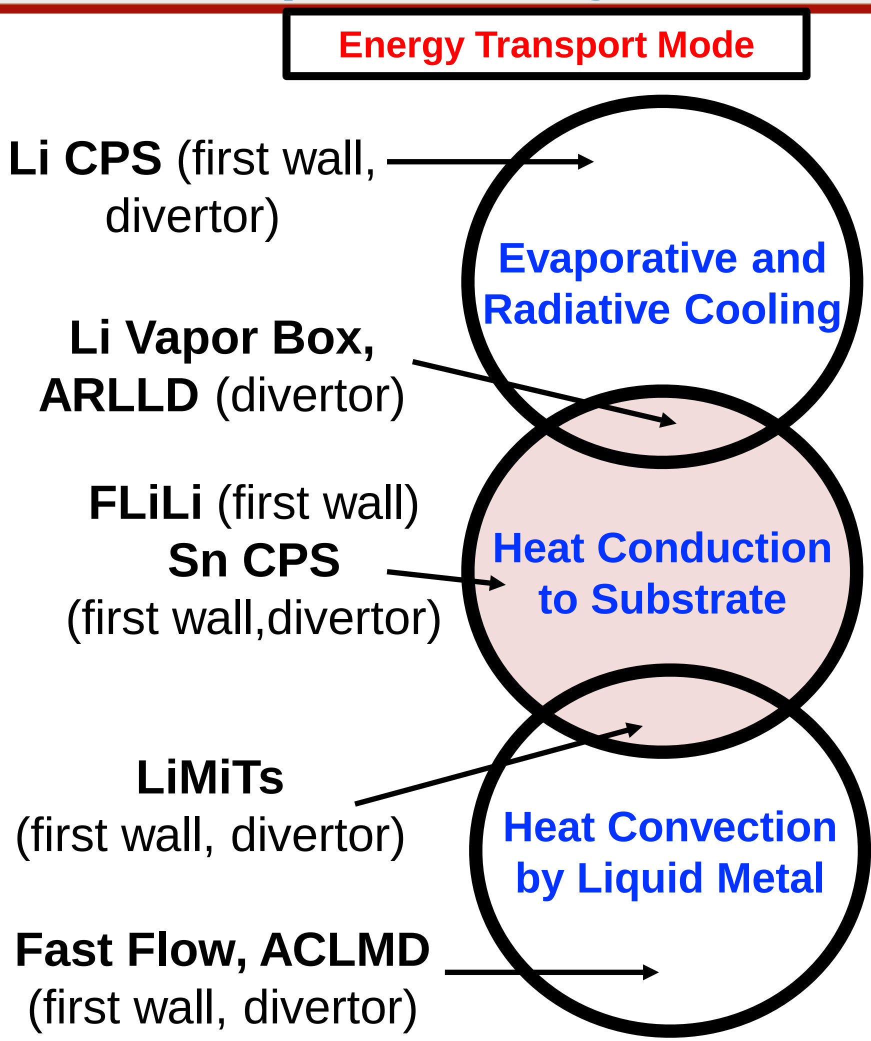
c.f. Mirnov 2009 JNM “emitter-collector”

# 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

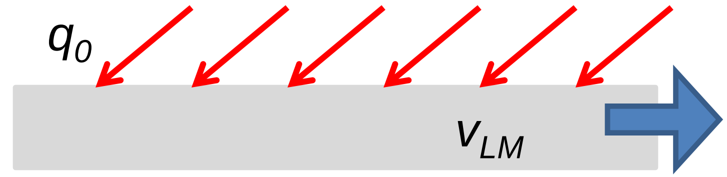



- Conventional, solid PFCs utilize extrinsic impurities to enhance radiation
- Demonstration of surface stability is key for all concepts
- Vast difference in pressure and flow requirements; expected operating temperatures

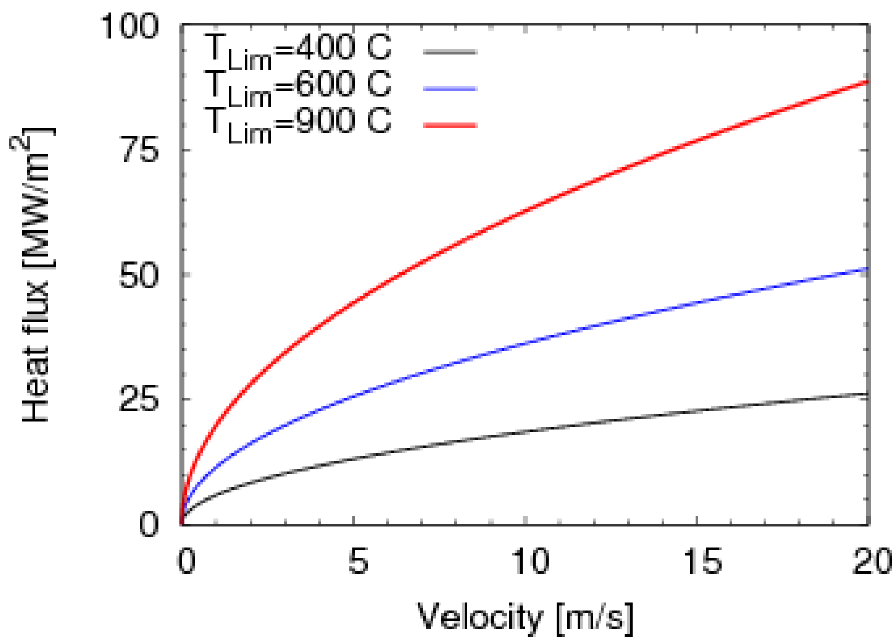
# Power-handling capability is the greatest advantage of fast-flow concepts

- "Moving slab" approximation for temperature rise
  - LM properties, conductivity *k* and thermal diffusivity *α*
  - Characteristic path length $L_{char}$
  - Limiting temperature rise $\Delta T_{Lim}$
- Reduces need for complex cooling schemes in substrate

**Incident heat flux vs. velocity**

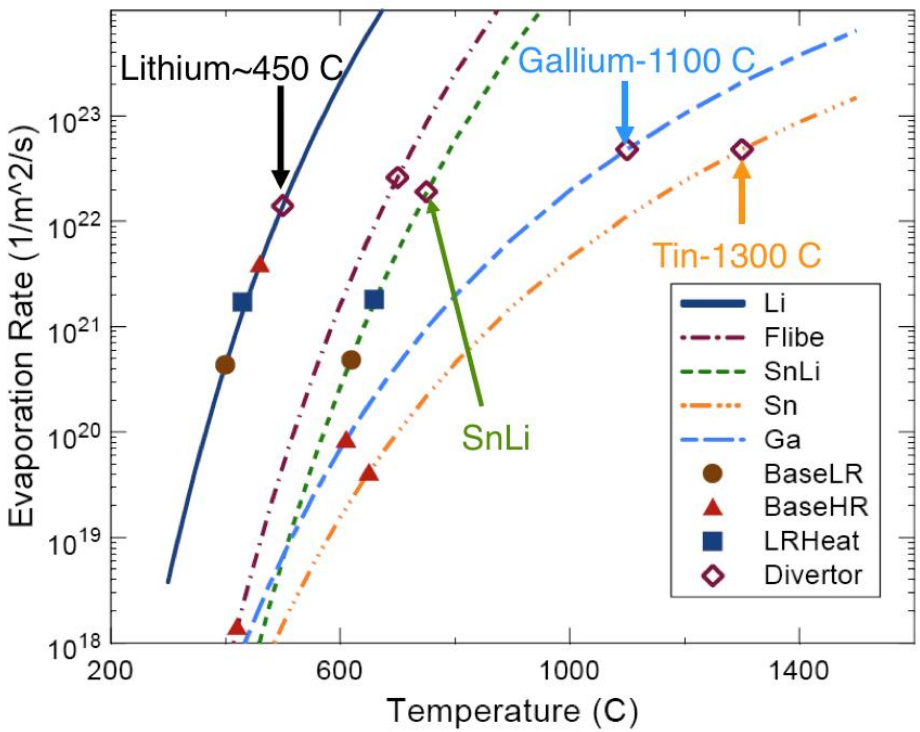



$$q_0 = \frac{\Delta T_{Lim} k}{2} \sqrt{\frac{\pi v_{LM}}{\alpha L_{char}}}$$



# 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

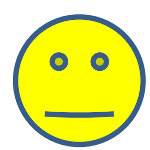



Majeski, PPPL-4480, Jan. 2010

# 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 (including 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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  - PMI processes and complications
  - Liquid metal impact on the plasma
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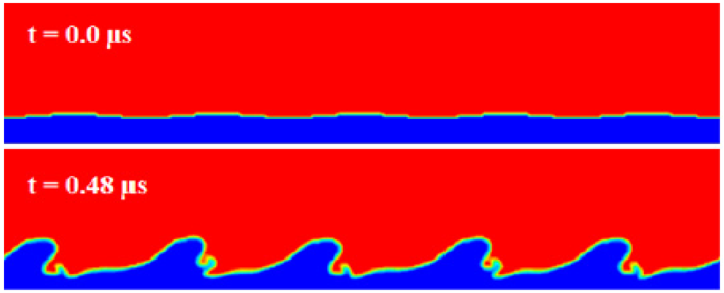
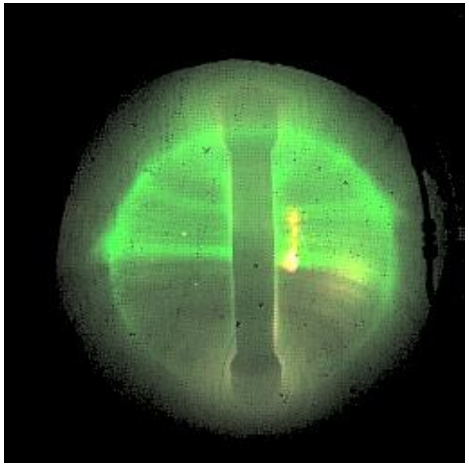
# Current topics impinging feasibility of liquid metal concepts




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

- PMI processes complicated by temperature and mixed material effects

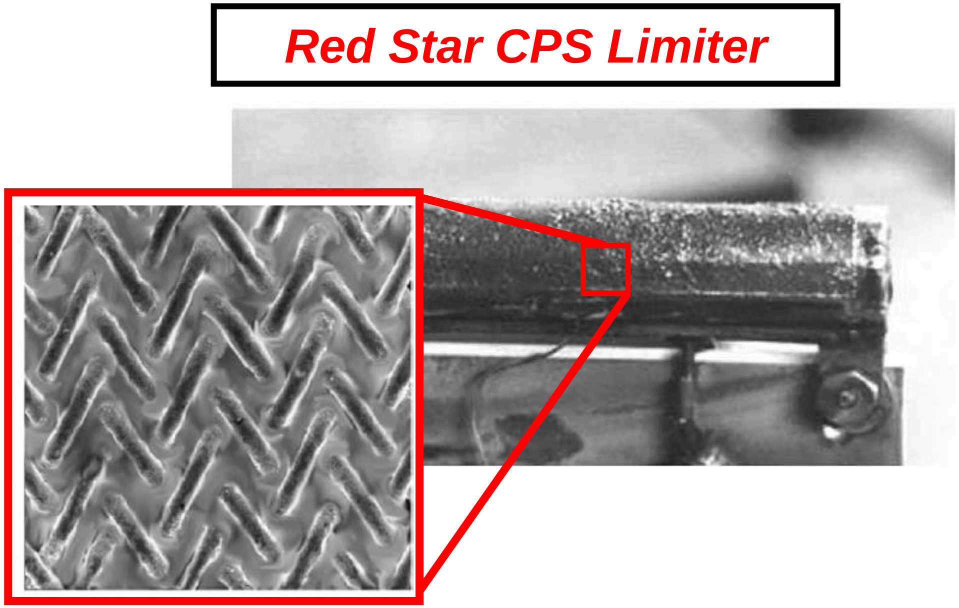


- Some positive results with use of liquid metals but obscured by complex PMI processes

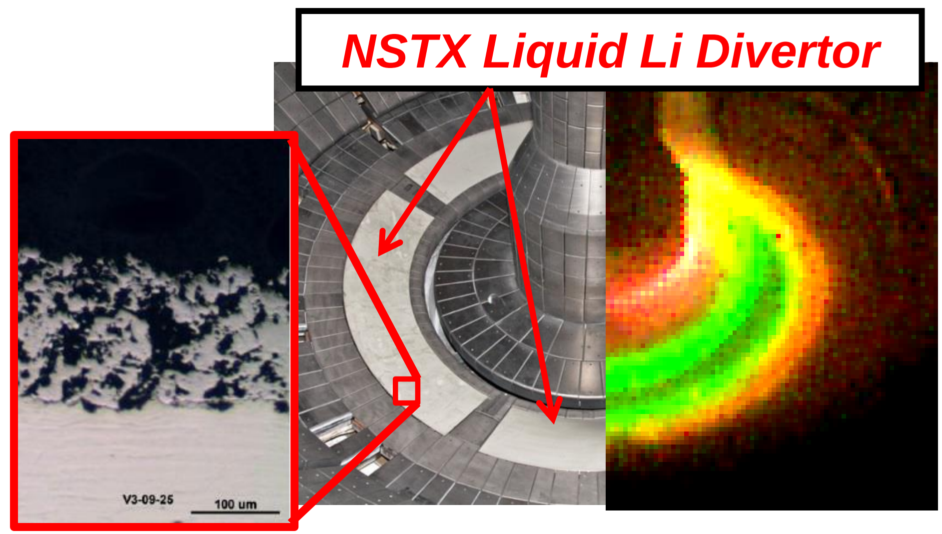
Miloshevsky, Hassanein, JNM 2011
Jaworski, et al., ISLA 2013
Mansfield, et al., FED 2010

# 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)



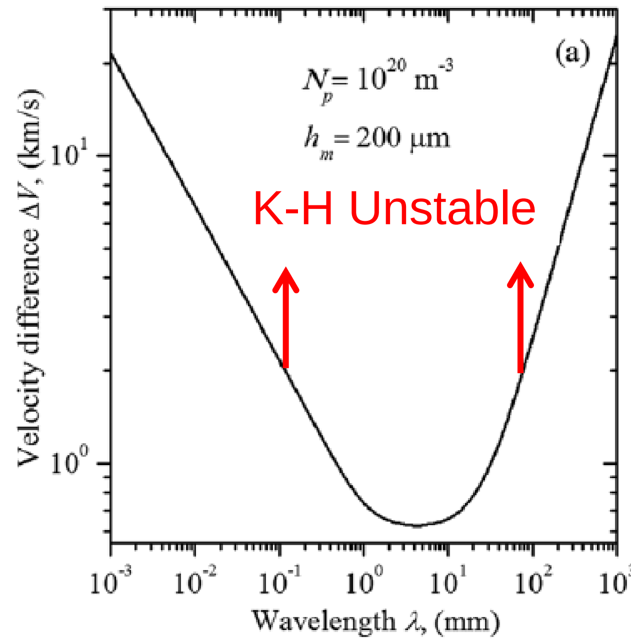

- Micro-scale droplet emission sometimes still observed and subject of on-going investigation



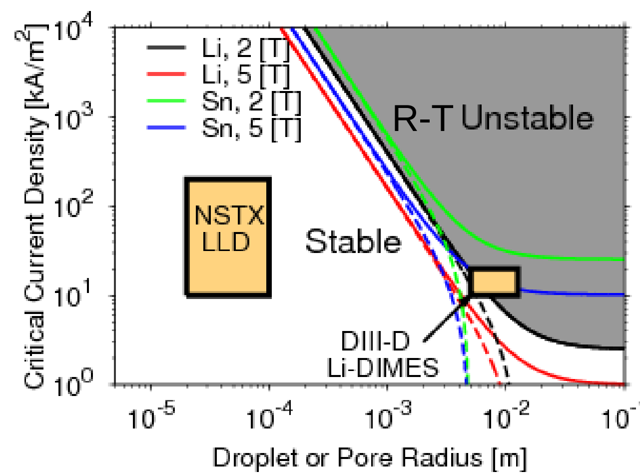

Lyublinski, et al., Plasma Dev. Ops. 2009;
Jaworski, et al., PPCF 2013

# Theoretical basis for stability depends on technical approach

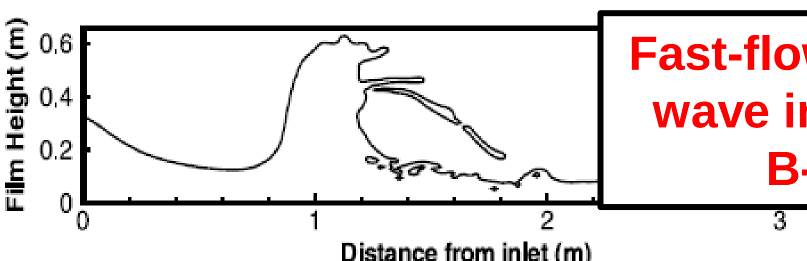
- Rayleigh-Taylor and Kelvin-Helmholtz instabilities both recently re-analyzed
  - K-H stable up to critical flow velocity depending on wavelength and fields (Miloshevsky 2014 NF)
  - R-T stable in porous target depending on field and currents (Jaworski 2013 NF)
- Fast-flow systems take various approaches 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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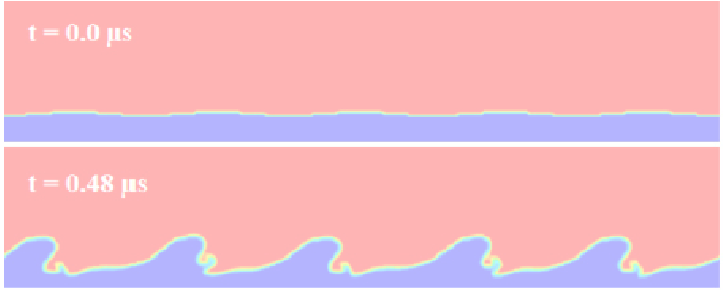


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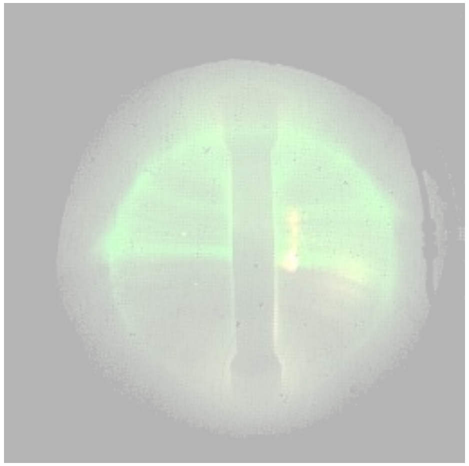
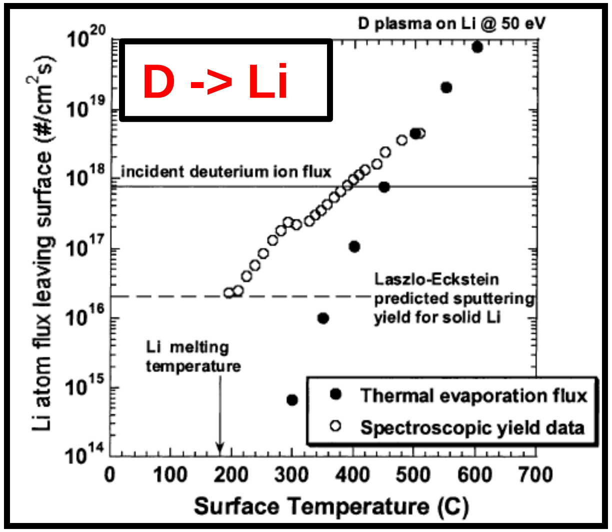
- Some positive results with use of liquid metals but obscured by complex PMI processes



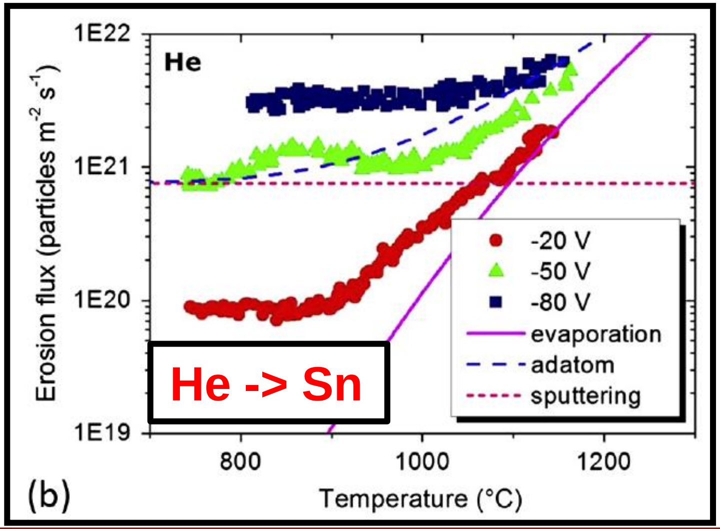
Miloshevsky, Hassanein, JNM 2011
Jaworski, et al., ISLA 2013
Mansfield, et al., FED 2010

# 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)



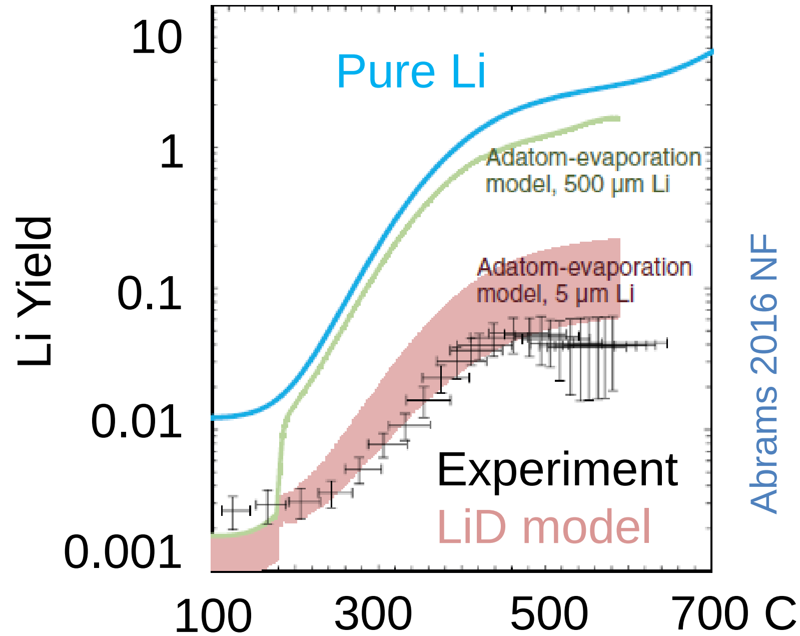

Doerner, 2001 JNM, cf. Allain 2007 PRB

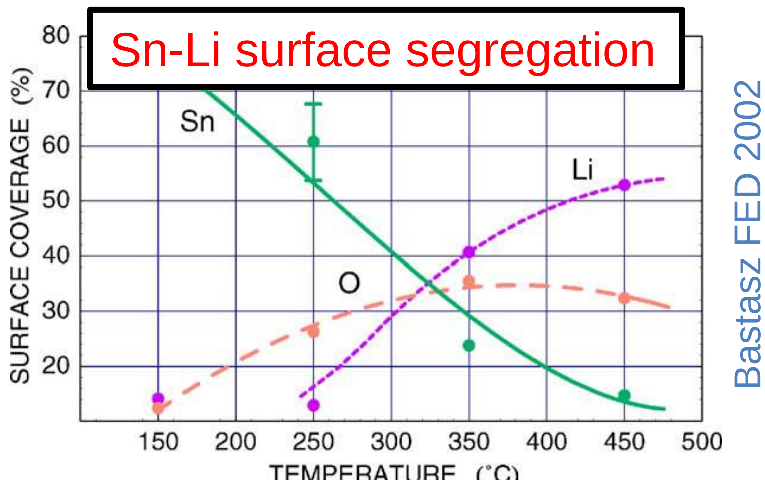



Morgan, 2015 JNM; cf. Coenen 2014 Phys. Scr.

# Surface composition demonstrated to vary and has strong effect on PMI

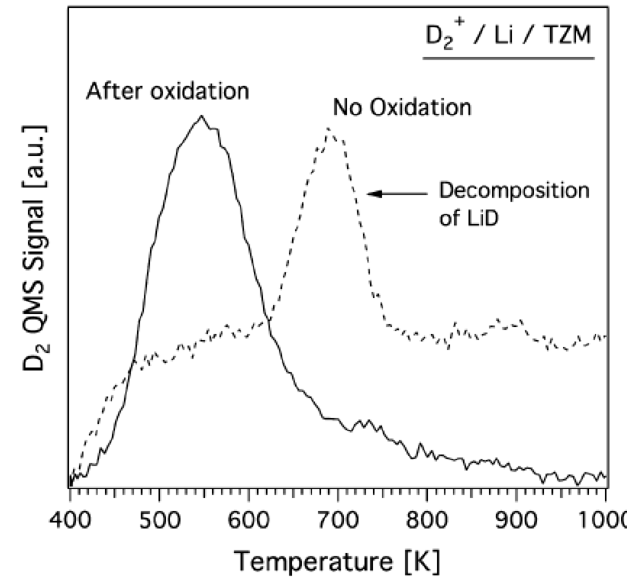
- Strong effect of LiD-Li mixed material during high-flux experiments (divertor-like) (Abrams NF 2016; Chen NF 2016)
- Indications of chemical interactions in high-flux tin experiments (Morgan JNM 2015)
- Surface composition of alloy known to depend on temperature and constituents (Bastasz FED 2004)



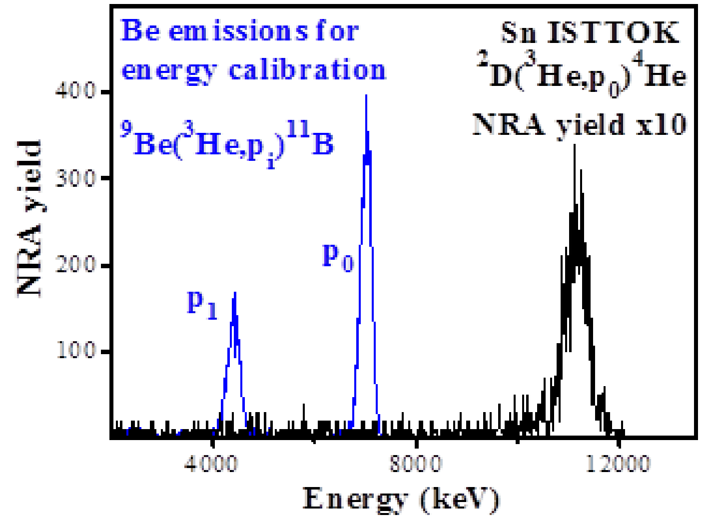
# Deuterium retention in Li affected by oxides; Sn studies just beginning

- 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

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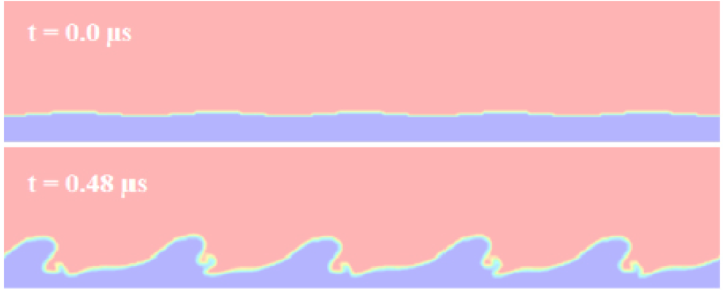


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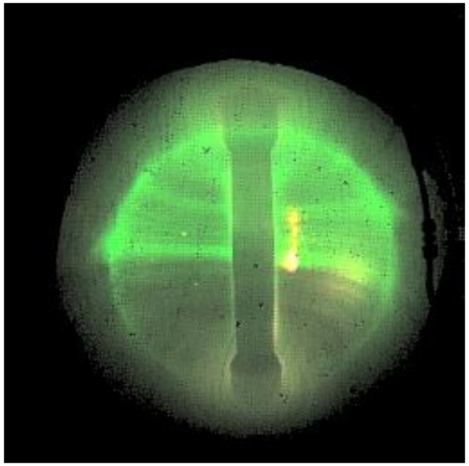

Miloshevsky, Hassanein, JNM 2011
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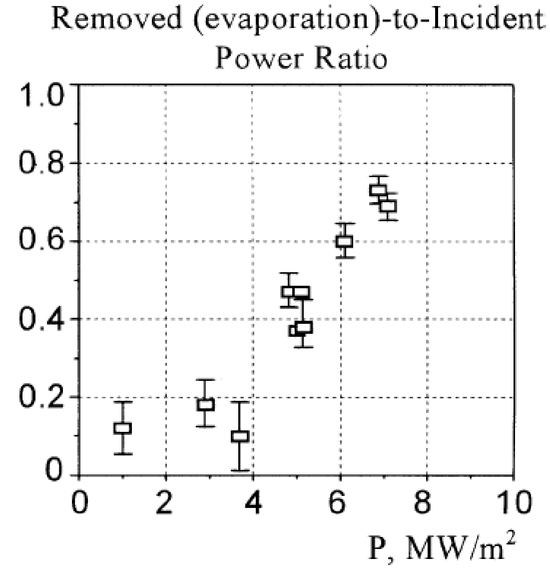
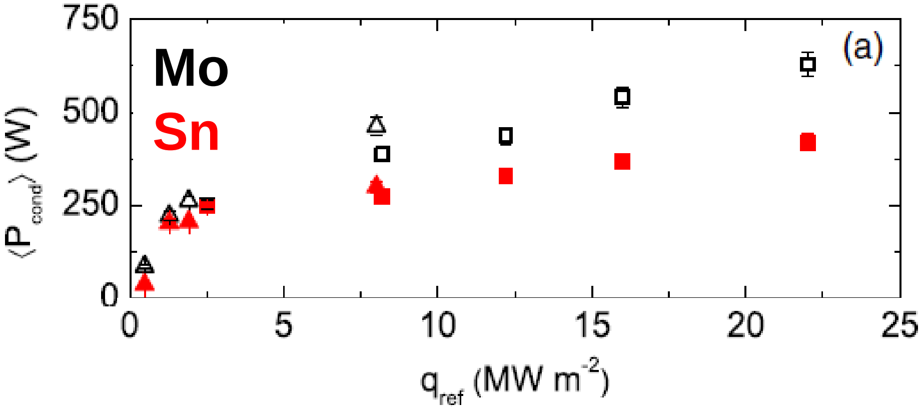
# Lab and confinement device experiments show favorable initial results

- 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)
  - No heat flux reduction with Li yet reported (Martin-Rojo ISLA 2015, Jaworski ISLA 2013)

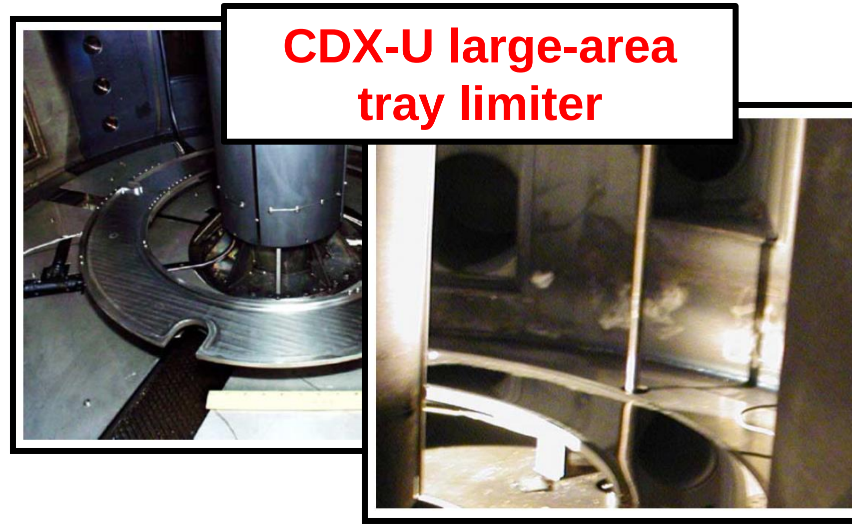



G.G. Van Eden 2016 PRL

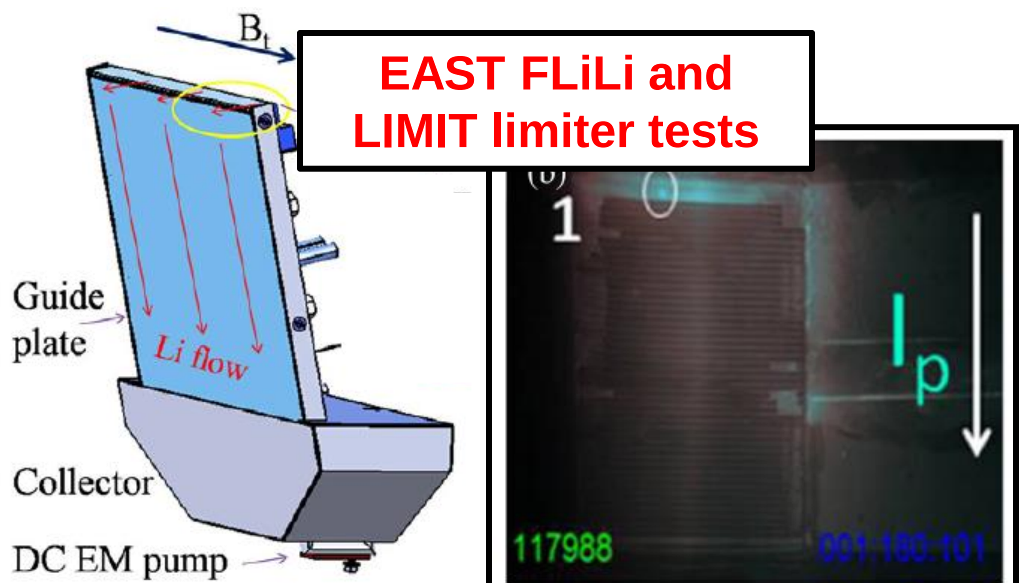
- Li heat flux reduction in confinement devices still under study (e.g. Mazzitelli, PSI 2016)

# 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)




Kaita 2005 JNM




Hu 2016 NF; Ren 2016 FED

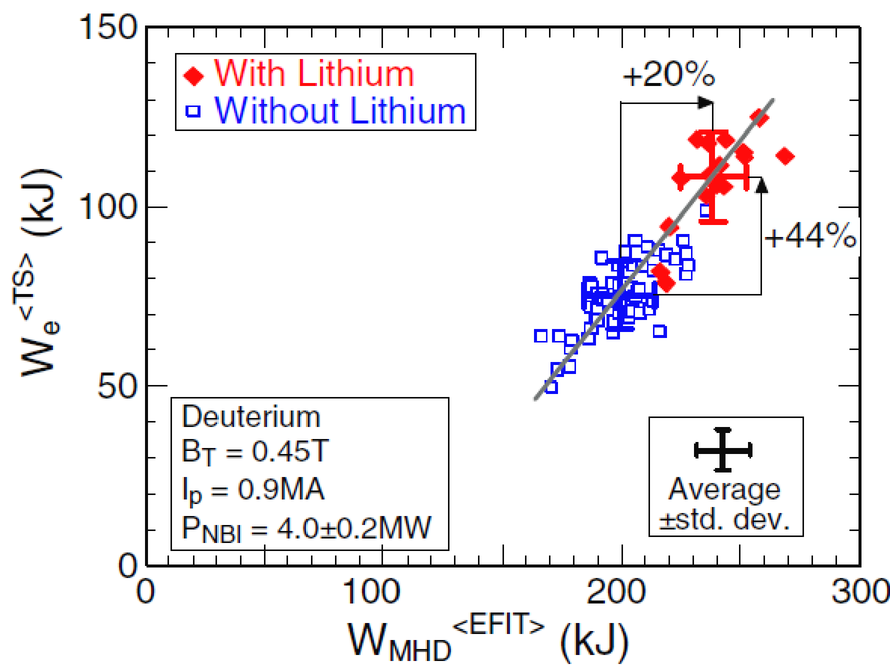
# PMI complexities strongly motivate consistent experimental design

- 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**

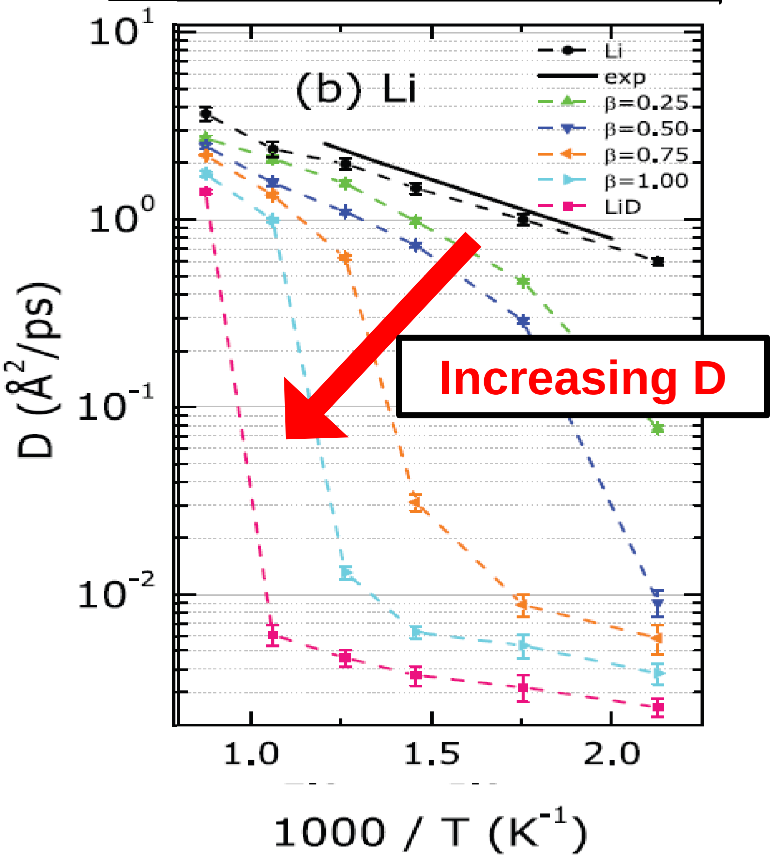



Bell 2009 PPCF

# 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
  - 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

# Advances are being made by numerous research groups around the world

- Mechanism studies, controlled impurity effects, concept development focus of laboratory studies
  - NIFS (JPN), Princeton Univ. (US), U-Illinois (US), CIEMAT (EU), Moscow Univ. (RF)

- Component-level testing and high-power, high-density plasma bombardment focus of plasma devices
  - FOM-DIFFER (EU), U-Illinois (US), Sichuan University (CN)

- Confinement device testing continues to aspire to integrated scenario demonstration
  - NSTX-U (US), TJ-II (EU), FTU (EU), EAST (CN), ISTTOK (EU), T-11M (RF)

# Increased attention to safety and reliability needed as experiments go forward

- Lithium work particularly sensitive as even 1kg of Li can release significant energy
- Current experience in fusion is on experimental devices: low availability and limited life
- IFMIF lithium system an “industrial scale” example in fusion context for handling >1000kg Li
- External communities should be considered resources for engineering issues (e.g. sodium fast-breeder reactors or liquid heavy-metal accelerator targets)
- Prospects of handling tritiated liquid metal streams may require significant engineering investment as scientific basis matures