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

MA Jaworski

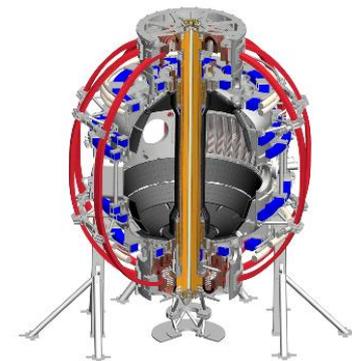
Princeton Plasma Physics Laboratory

22nd International Conference on Plasma-Surface Interactions

June 1st, 2016

Rome, Italy

*Work supported by DOE contract DE-AC02-09CH11466





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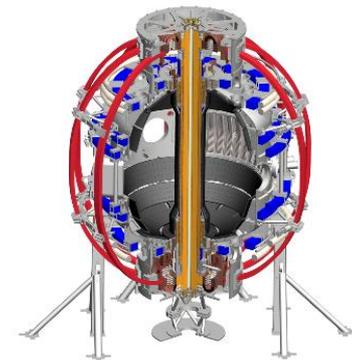
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NUF-SULI Thursday Seminar

B318 – PPPL – June 16, 2016

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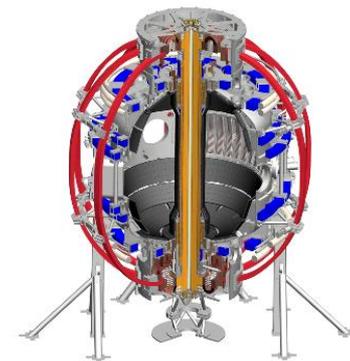
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Organization of this talk

- 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

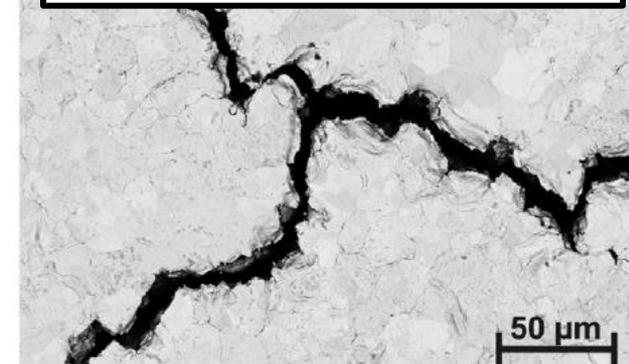
What won't be covered in this talk?

- 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

Cracking after thermal shock loading



Wirtz, et al., JNM 2013

CMOD



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

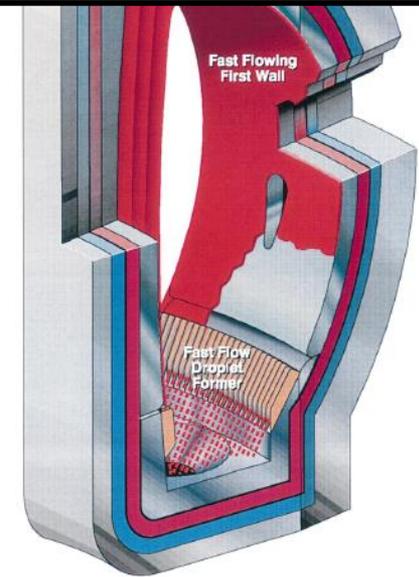
- Fast vs. slow approaches differ in maturity of physics and technology

- Fast flow: **less mature technology, less physics maturity** for surface stability

- Slow flow: **more mature technology, less physics maturity** for ablating targets

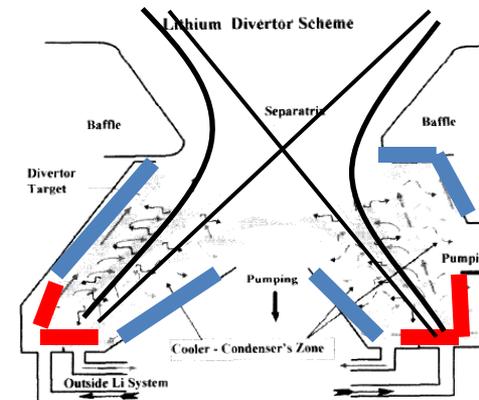
- **Reactors expected to feature large areal coverage and continuous flow**

Fast-flow, first-wall and divertor concept



Evaporation

Condensation



High-temperature, lithium divertor concept

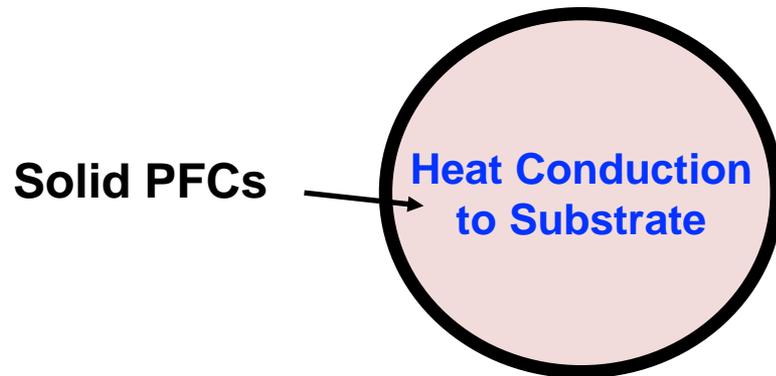
c.f. Mirnov 2009 JNM
"emitter-collector"

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

Liquid metal PFCs provide additional pathways for energy transport

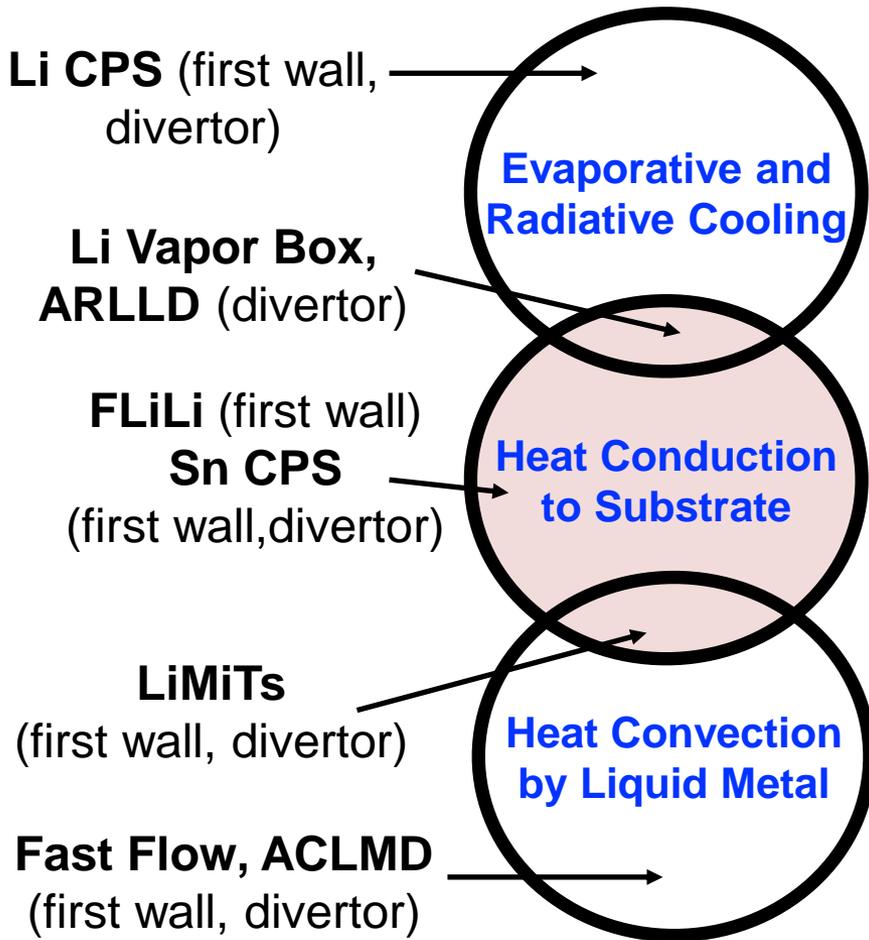
Energy Transport Mode

- Conventional, solid PFCs utilize extrinsic impurities to enhance radiation



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
- 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

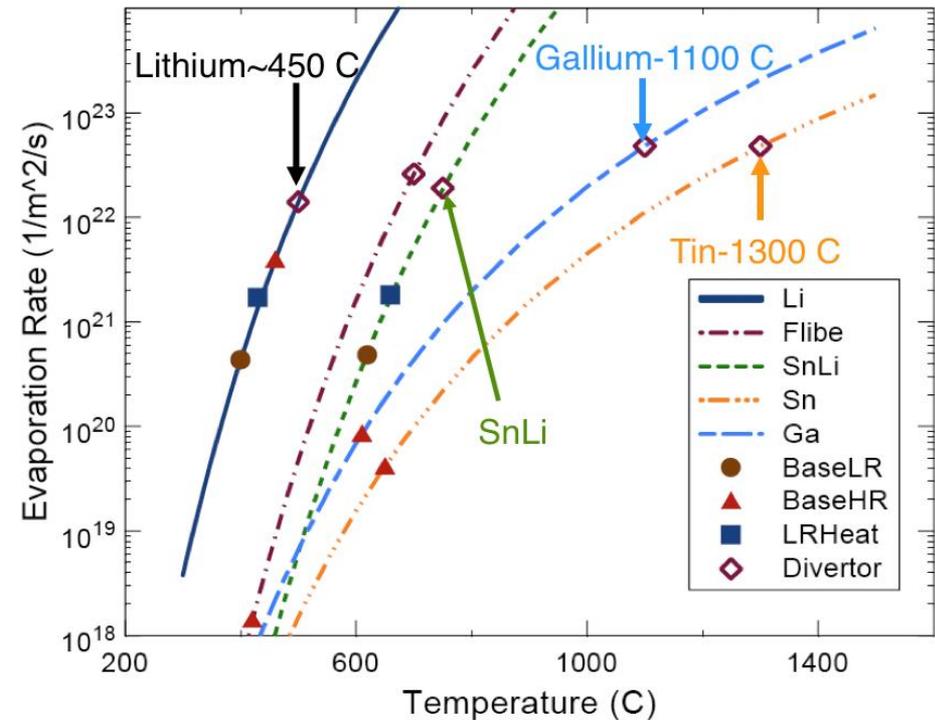
Incident heat flux vs. velocity



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

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

- 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

Solid PFCs



Liquid PFCs



Ultimate decisions comparing approaches likely to turn on economic metrics

Solid PFCs

Liquid PFCs

- Power density and transient loading



- Maintenance availability



- Capital cost (including safety)



- Demonstrated reactor scenario with all materials



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

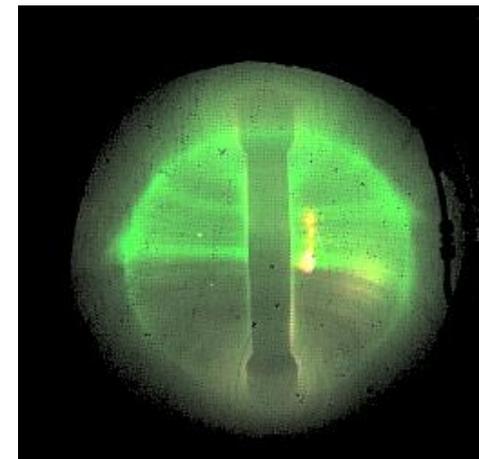
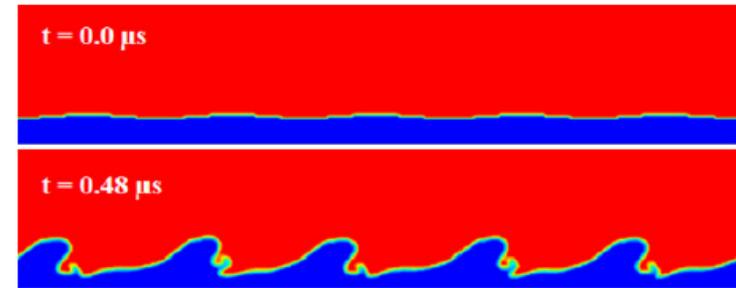
For Fusion: *an* approach that works is desired!

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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

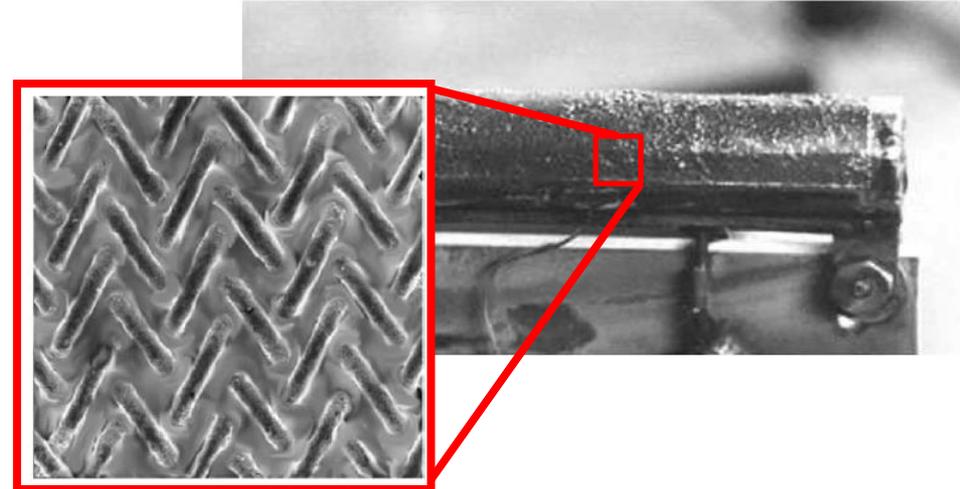


Miloshevsky, Hassanein, JNM 2011
Jaworski, et al., ISLA 2013
Mansfield, et al., FED 2010

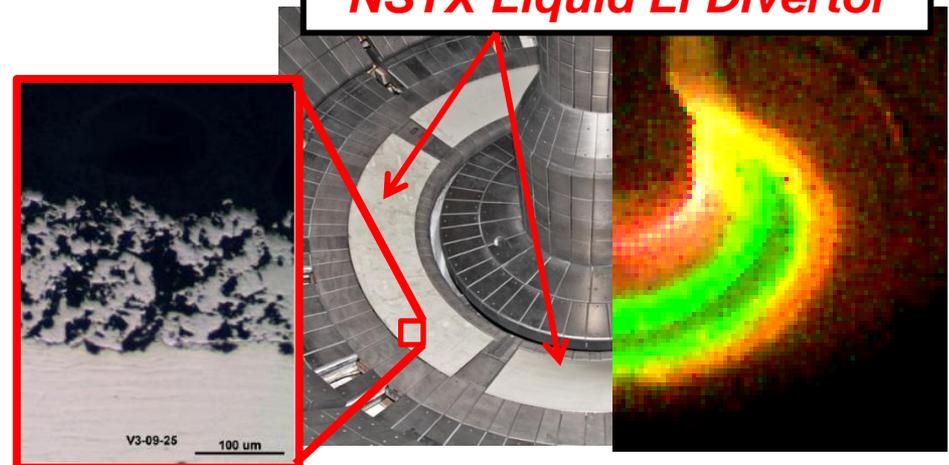
Empirical observations demonstrate stability of slow-flow, capillary systems

- 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



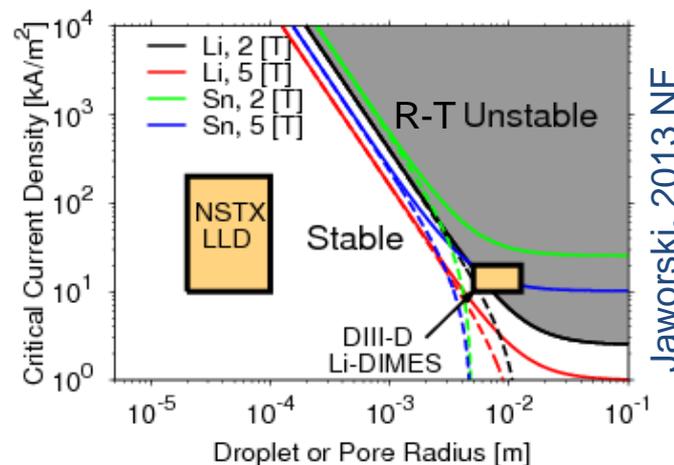
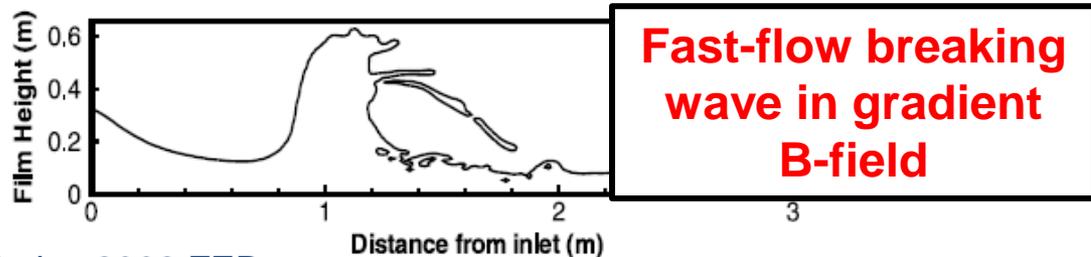
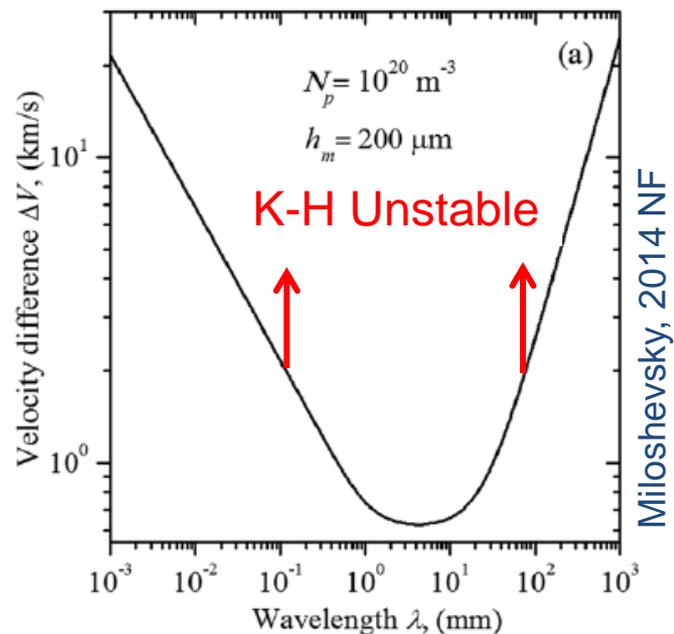
NSTX Liquid Li Divertor



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

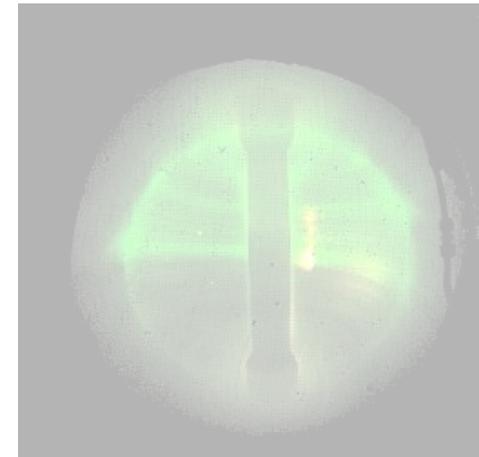
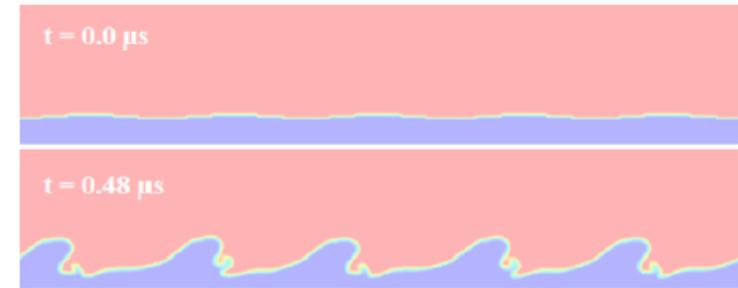
Theoretical basis for stability depends on technical approach

- 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)



Current topics impinging feasibility of liquid metal concepts

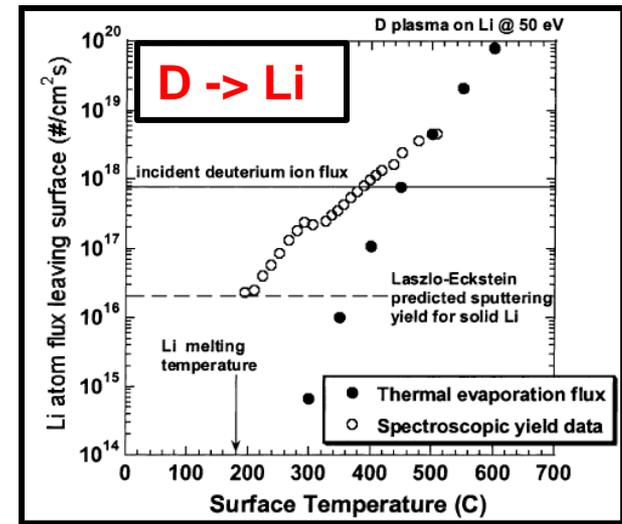
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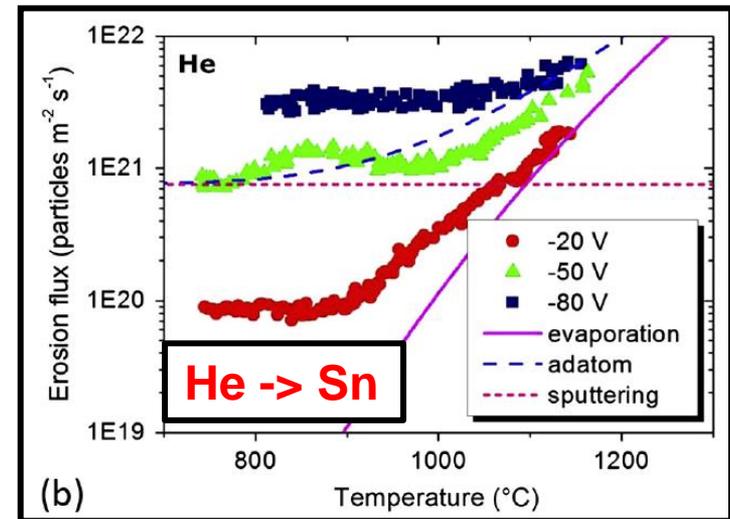
Miloshevsky, Hassanein, JNM 2011
Jaworski, et al., ISLA 2013
Mansfield, et al., FED 2010

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)



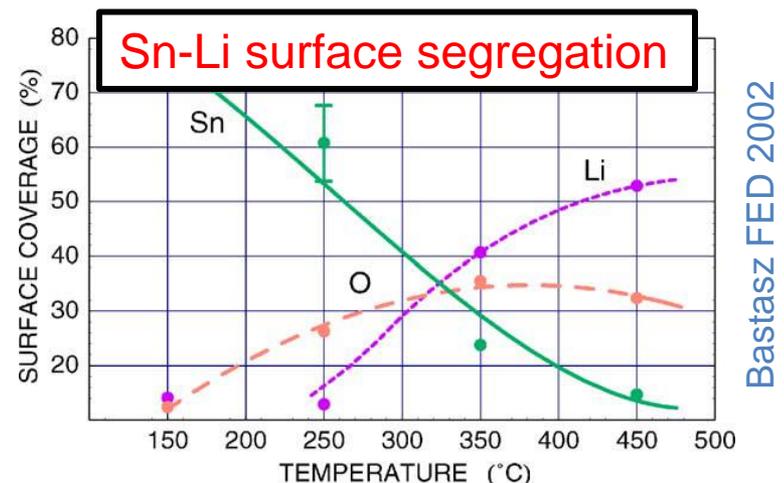
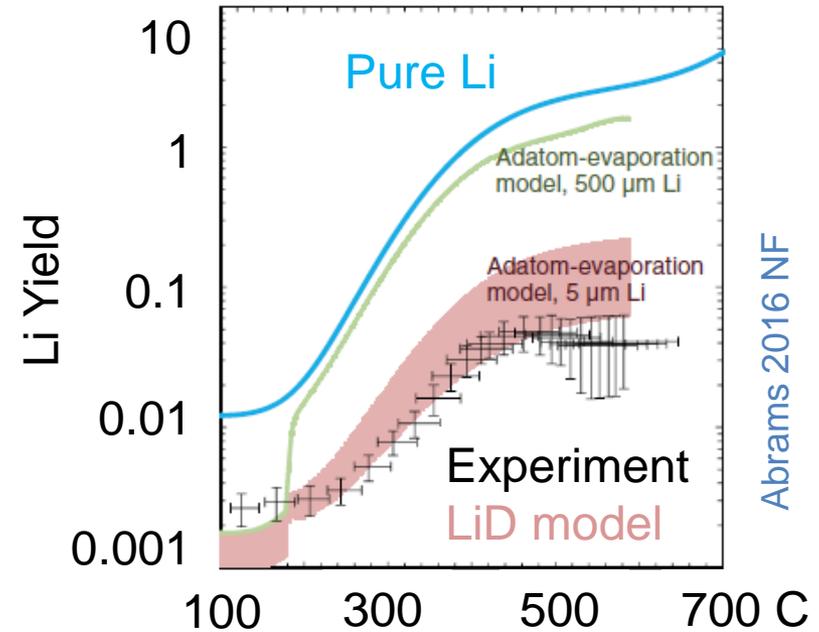
Doerner, 2001 JNM,
cf. Allain 2007 PRB



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

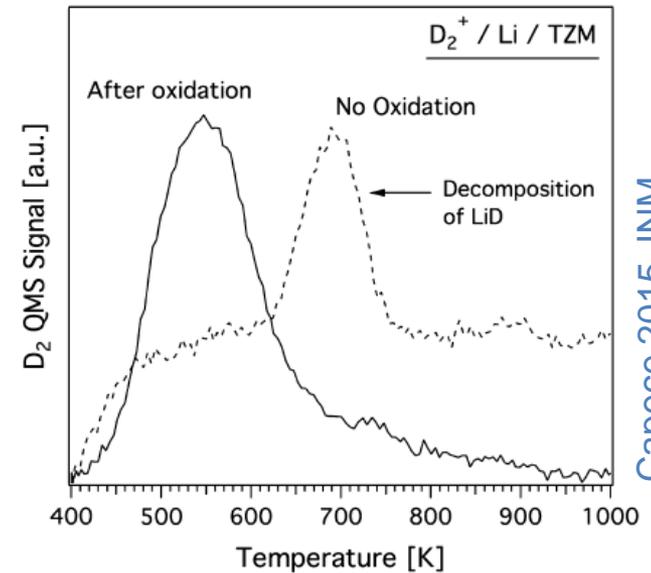
Surface composition demonstrated to vary and has strong effect on PMI

- 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)

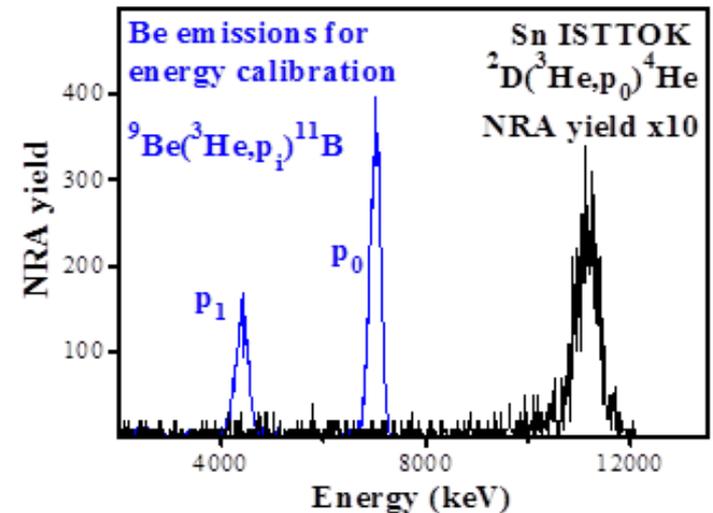


Deuterium retention in Li affected by oxides; Sn studies just beginning

- 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**
- 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



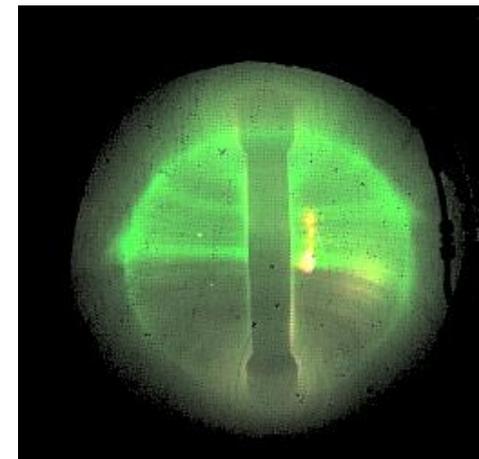
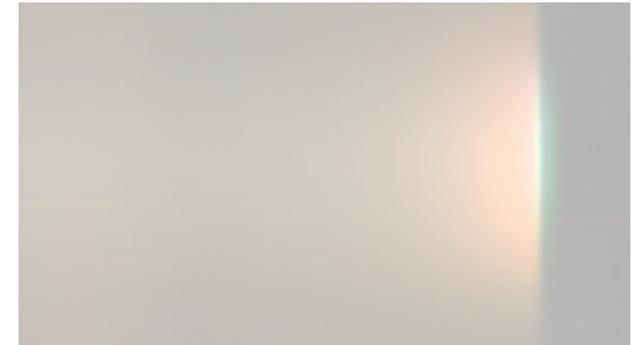
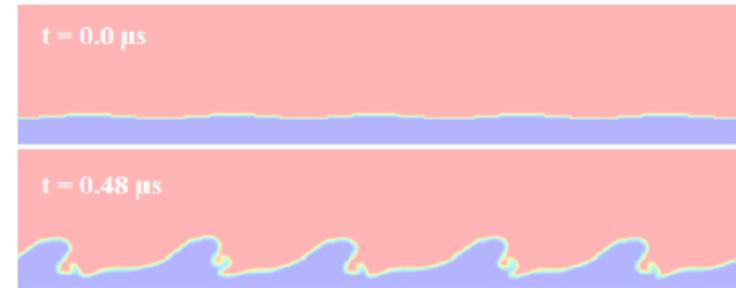
Capece 2015 JNM



Loureiro ISLA 2015

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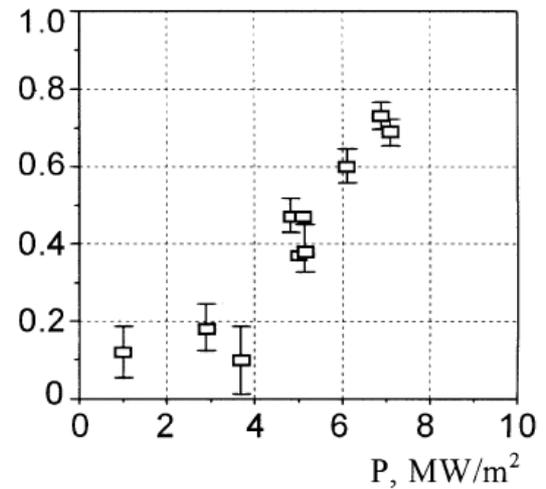


Miloshevsky, Hassanein, JNM 2011
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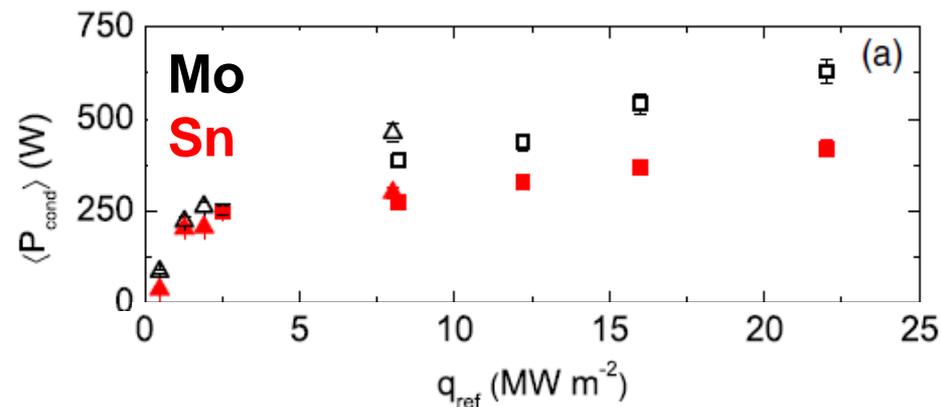
Lab and confinement device experiments show favorable initial results

- Power reduction with Li demonstrated in e-beam and pulsed plasmas
- 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)
- Li heat flux reduction in confinement devices still under study

Removed (evaporation)-to-Incident Power Ratio



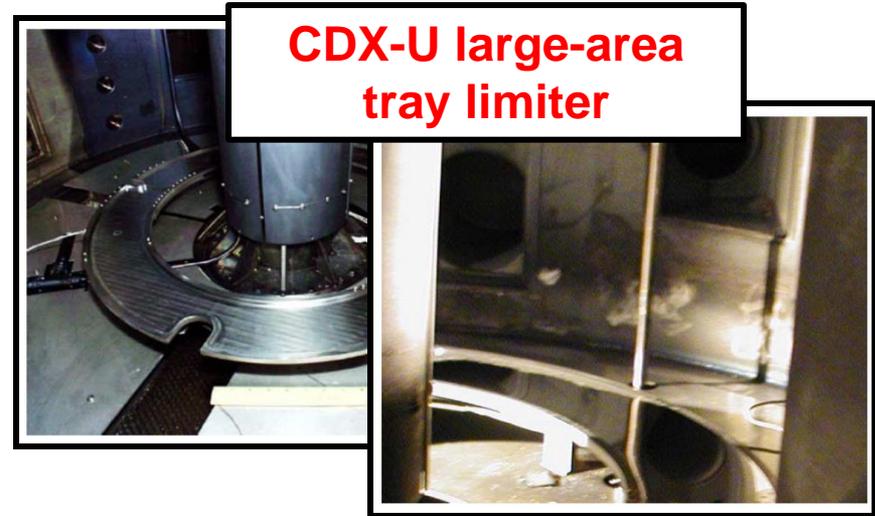
Khripunov 2003 JNM



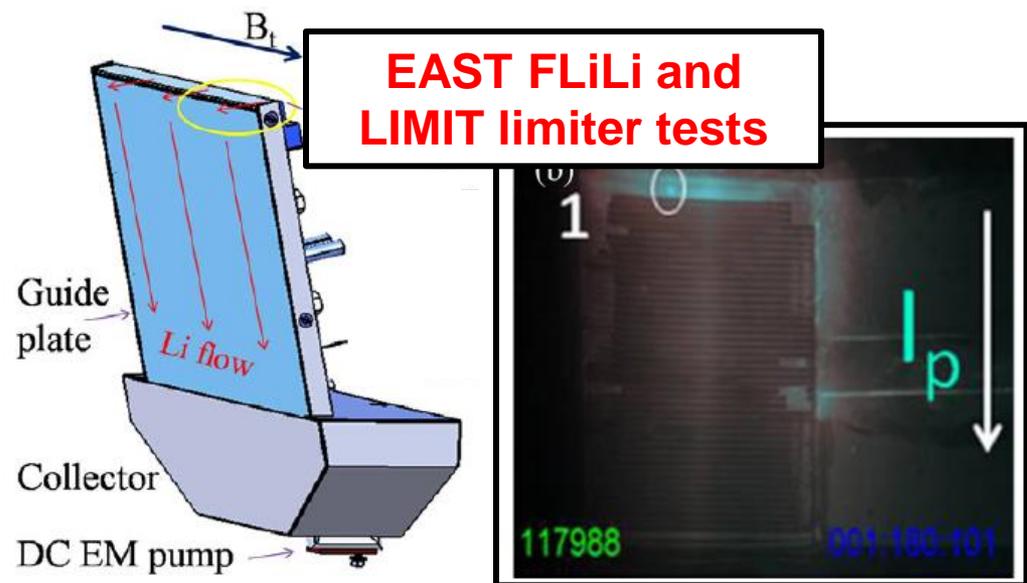
G.G. Van Eden 2016 PRL

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)



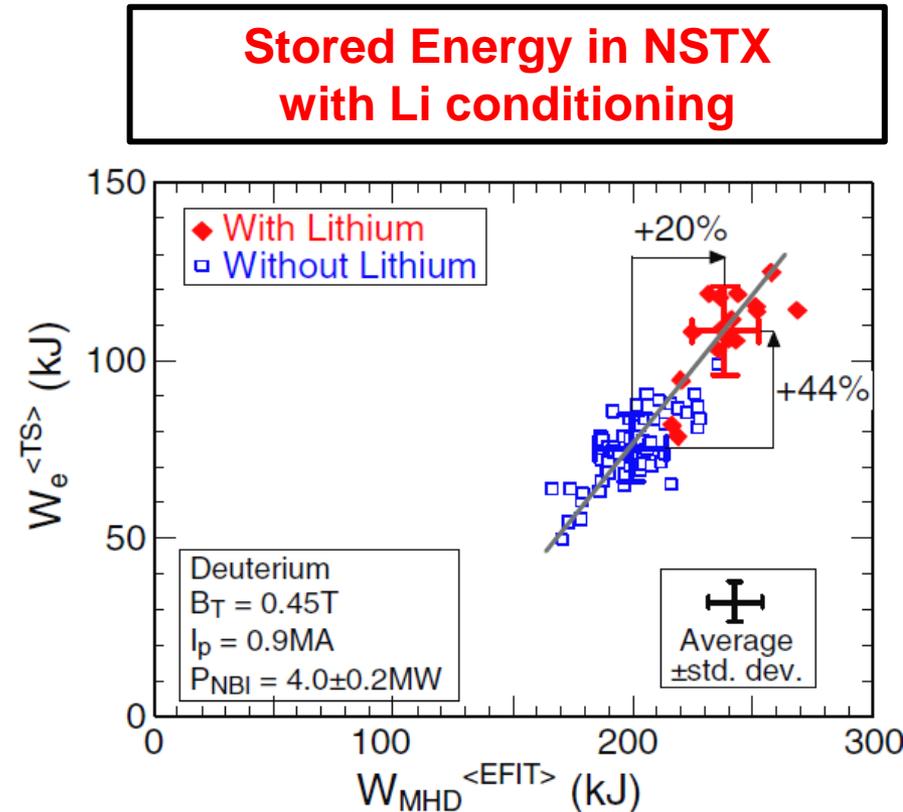
Kaita 2005 JNM



Hu 2016 NF; Ren 2016 FED

PMI complexities strongly motivate consistent experimental design

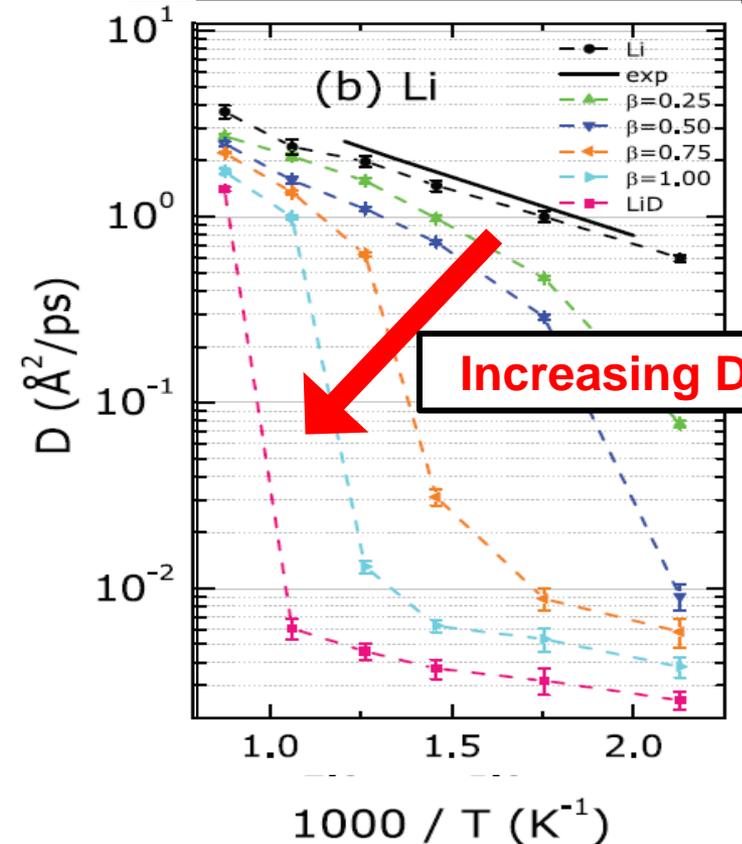
- Large amount of literature reports on evaporative wall conditioning
 - Confinement improvements
 - ELM modification/suppression
- Evaporation of Li onto graphite unlike expected LM PFCs for reactors
 - Rapid Li intercalation occurs immediately (Itou 2001 JNM)
 - Li-O-C complex shown with DFT modeling 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!



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 ($<600\text{C}$ for Li-D, $<400\text{C}$ for oxidized Li)
- Recovery demonstrated from Li at $\sim 1\text{ppm}$ 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!**

Terminator 2: Judgment Day
Director: James Cameron
Carolco Pictures, 1991

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!

But wait, there's more!

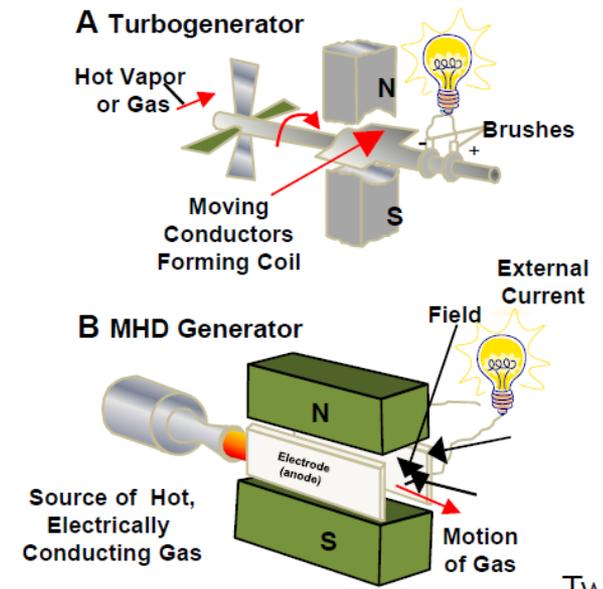
- Progress reactions - awe and tear - to liquid metals

- **Thank you for your attention!**

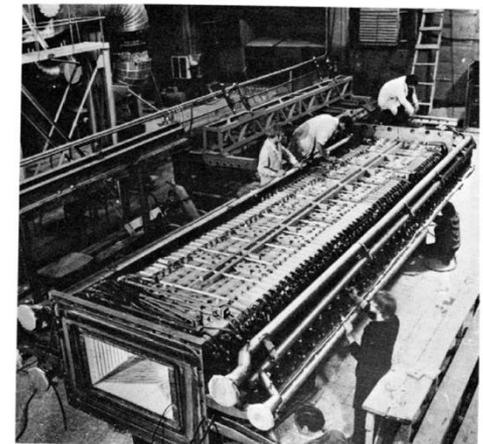
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Carolco Pictures, 1991

Fusion isn't the only application with difficult plasma-material interaction problems!

- Direct Power Extraction (DPE) is extraction of electricity with fewer intermediary steps
- MHD power gen. uses ionized gas flow through magnetic field to extract power
- Concept demonstrated in 25-75MW_{th} scale facilities into early 90s



Soviet U-25 Generator
ca. 1978



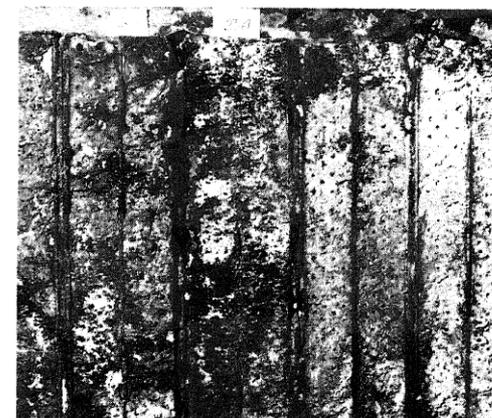
Lack of feasible electrode killed program in 90s – time to reconsider?

- DOE program closed in 90s due to technical road-blocks
- Electrode durability highlighted as major issue
- Newly restarted effort in FE to re-evaluate
 - Carbon-Capture-&-Sequestration makes this more attractive/necessary
 - Liquid electrodes proposed to solve erosion issue

U-25 Anode ~100hrs operation



cathode

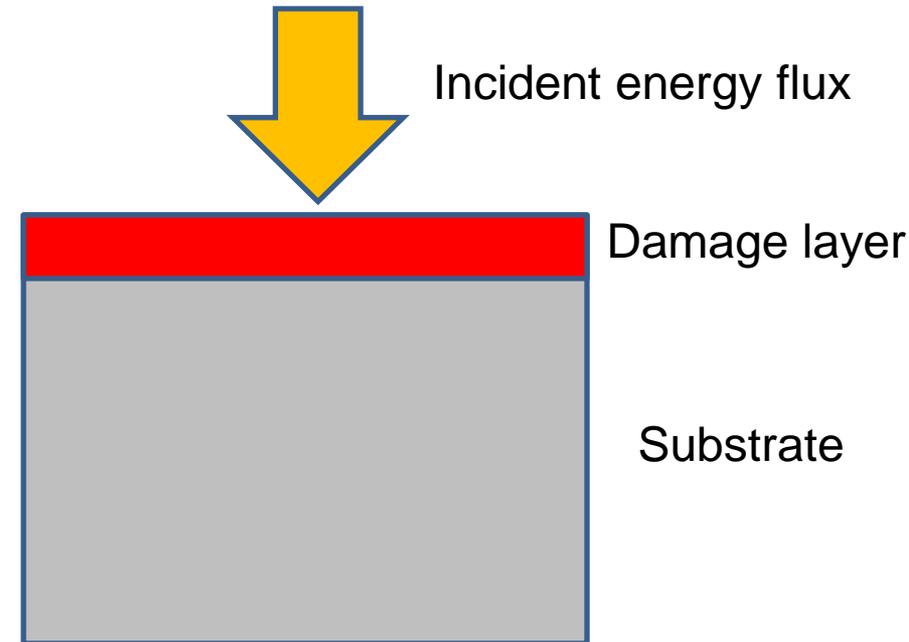


**Zirconia-based
concrete with
tungsten
needles,
cathodes
eroded 8mm in
100 hrs
(need about
800 hrs)**

Sheindlin, et al., (1976) SEAM pIV.1.1

How to estimate potential of liquid plasma-facing components?

- Begin assessing benefits of molten salts
 - Self-healing
 - Substrate exposure required for damage
 - Metals only require surface melting for damage
- Additional avenue to high-current density devices (i.e. high field)
 - Micro-arc size related to average current density in device
 - Limiting current density in scoping studies
 - High-field -> high power density -> smaller magnet volume
- Energy limit figure of merit similar to fusion component considerations



$$E_{limit} = m(c_p \Delta T_{limit} + h_{latent})$$

$$E''_{limit} = E_{limit}/A = \rho t(c_p \Delta T_{limit} + h_{latent})$$

Molten carbonate figure-of-merit exceeds tungsten for equivalent damage depth

- Some assumed parameters:
 - Thickness of 10 microns for arc damage
 - 700K initial temperature
 - Carbonate eutectic used, assume decomposition at 1273K (*n.b.* Olivares, 2012 found *no* decomposition under CO₂ atmosphere at this temperature)
- Carbonate decomposition occurs in two steps
 - M₂CO₃ → M₂O + CO₂ (decomp. energy from Janz, Molten Salt Handbook)
 - M₂O → 2M + ½ O₂ (decomp. energy from web values of enth. formation) (assumes oxide decomposition before substrate melts)

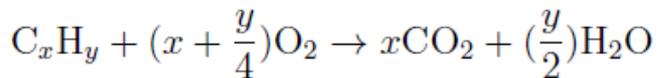
Material	T _{limit} [K]	Latent enth. [kJ/kg]	cp*dT _{lim} [kJ/kg]	E'' _{lim} [kJ/m ²]
Cu	1358	205	253.3	40.9
Pt	2045	100	178.9	59.8
W	3660	193	390.7	112.7
Mo	2894	289	550.7	86.0
ATJ graphite	4000	0	4290.0	77.6
(Li,Na,K)CO ₃ decomp.	1273	1130	991.0	45.0
(Li,Na,K)O decomp.		9983	0.0	87.2
Total Salt				132.1

$$E''_{limit} = E_{limit}/A$$

$$= \rho t (c_p \Delta T_{limit} + h_{latent})$$

Efficiency matters when decarbonizing energy

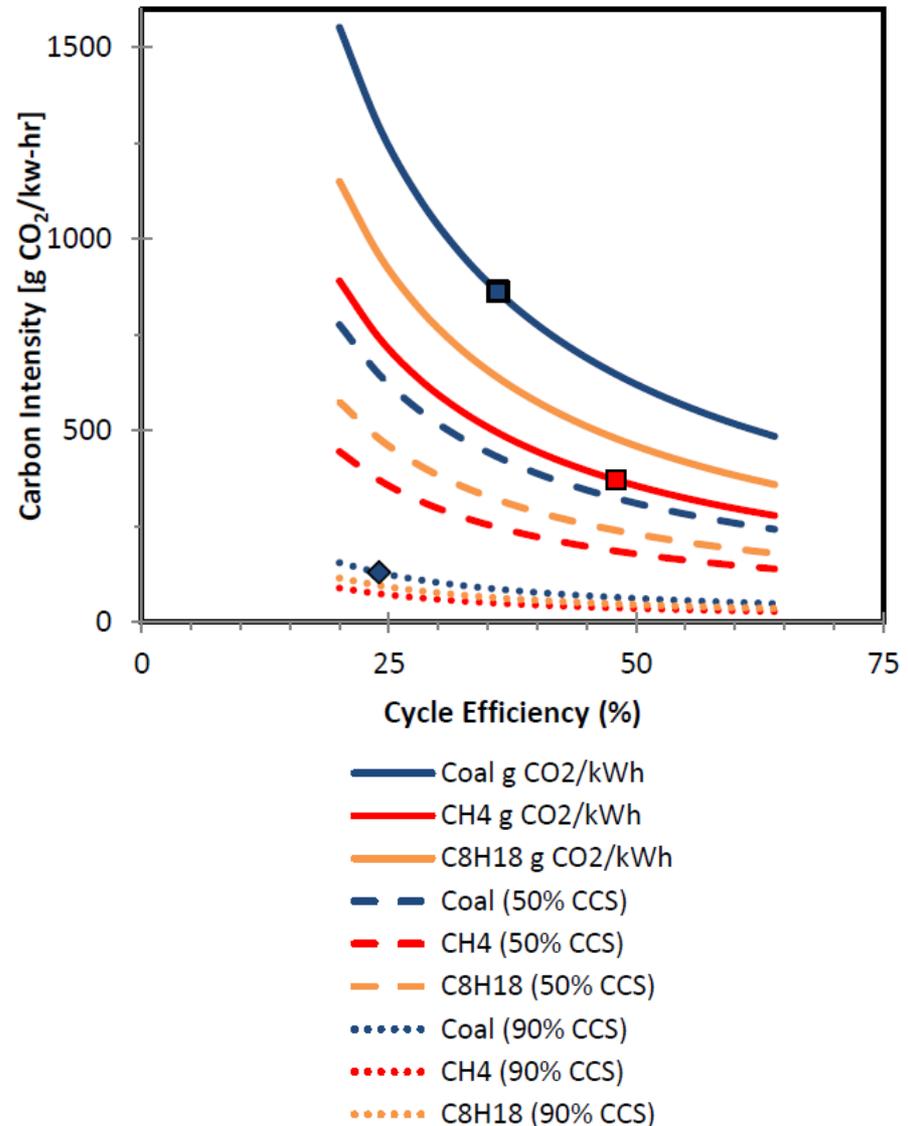
- More efficient cycles means less fuel burned per MW-hr
- More efficient cycles means less \$\$\$ paid for fuel per MW-hr



$$\Delta \bar{h}_{react} = x\bar{h}_{CO_2}^\circ + \frac{y}{2}\bar{h}_{H_2O}^\circ - \bar{h}_{C_xH_y}^\circ$$

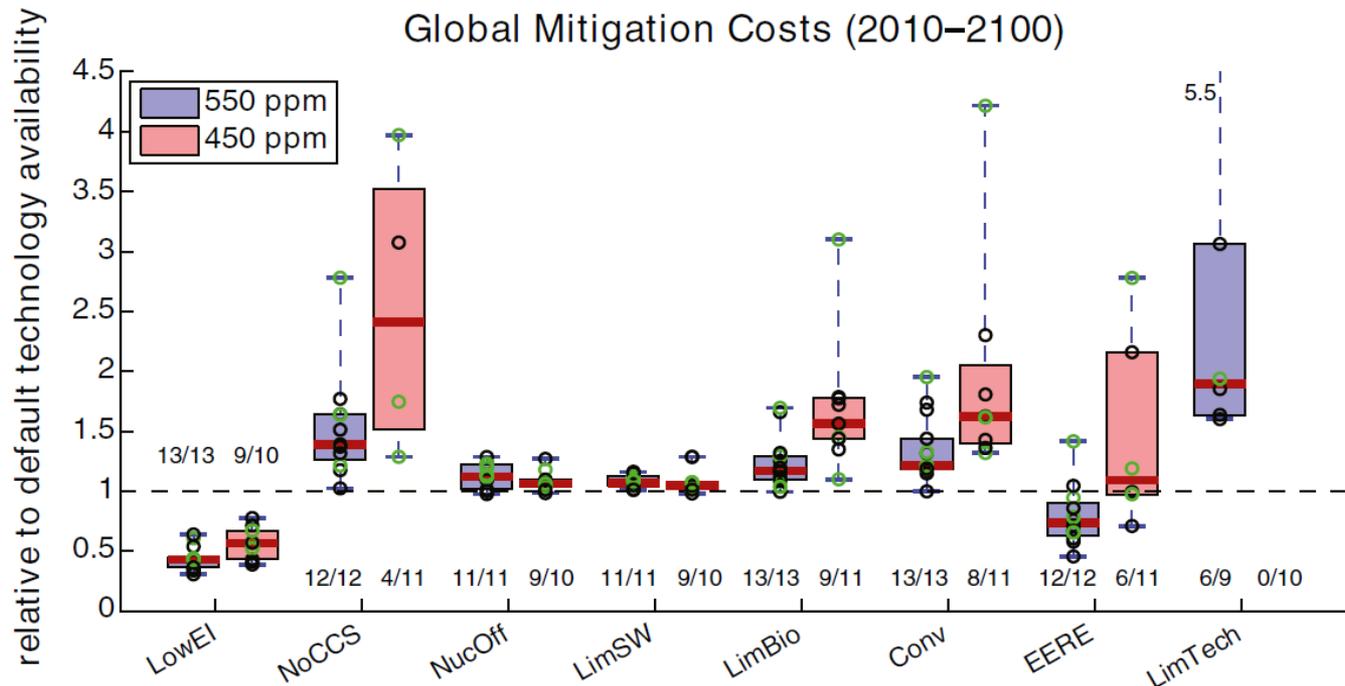
$$i_{fuel}^\circ = \frac{x \cdot 44 \frac{\text{gCO}_2}{\text{mol fuel}}}{\Delta \bar{h}_{react} \frac{\text{kJ}_{th}}{\text{mol fuel}}} \times 3600 \frac{\text{kJ}_{th}}{\text{kWh}_{th}}$$

$$i_{fuel} = \frac{i_{fuel}^\circ}{\eta_{th}} \frac{\text{gCO}_2}{\text{kWh}_e}$$



The world *needs* clean-energy options

- EMF27 (Energy Modeling Forum) studies range of macro-economic models
- Reduced technological availability impacts economics (e.g. no nuclear or no CCS)
- Lack of technological options leads to increased economic costs or no model convergence at all



Kriegler, et al., *Climate Change* **123** (2014) 353-367.

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Kriegler, et al., *Climate Change* **123** (2014) 353-367.

Final thoughts

- Liquids provide unique capabilities compared to solids
 - Self-healing, recoverable geometry is massive benefit
 - Mobility can sometimes be a liability – new challenges
- Liquid plasma-material interaction science is a rich topical area
 - Lots of new ground to explore and understand
 - Few things are going to be simple (status: it's complicated!)
- Energy options are needed *now!*
 - Energy deployment is technological *and* economic

What should you do after college? Work on Grand Challenge of Clean Energy!
