NSTX-U

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Liquid metal plasma-facing component research on the NSTX

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and the NSTX Research Team

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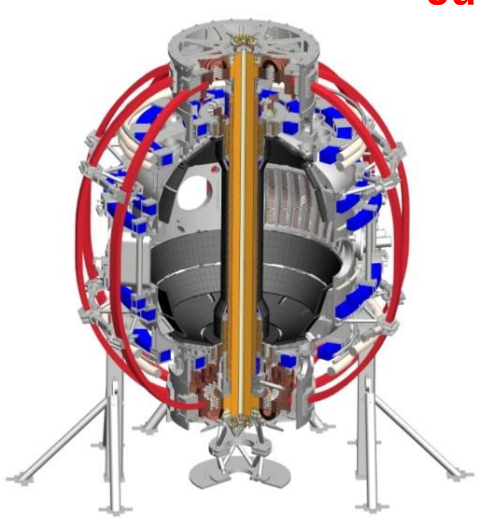

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Clever application of liquid metals can aid in overcoming adverse (even hostile) situations

http://en.wikipedia.org/wiki/Bellerophon

Solid plasma-facing components may not extrapolate to future devices

- Tungsten components still subject to melting
  - Transient loading results in melt and motion
  - Repair of components requires…
- Wall erosion induces net reshaping of components even in steady state
  - Charge-exchange fluxes erode first-wall components
  - Rough estimates for a reactor-scale device indicates redistribution of **1000s of kgs**[1]

Coenen, et al., JNM 2013

$$\Gamma^{Gross}_{sputt.} \approx Y_{sputt,cx} \frac{P_{cx}/E_{cx}}{S_{plasma}}$$

Machine	P_{max}/S [MW/m^2]	τ_{annual} [s]	Yield [kg/yr]
DIII-D[1]	0.4	10^4	0.08 (C)
NSTX	0.2	3×10^3	0.012 (C)
NSTX-U	0.5	10^4	0.1 (C)
ITER[1]	0.15	10^6	92 (W)
ST-Pilot	0.98	10^7	1800 (W)
ARIES-AT	0.98	3×10^7	8000 (W)

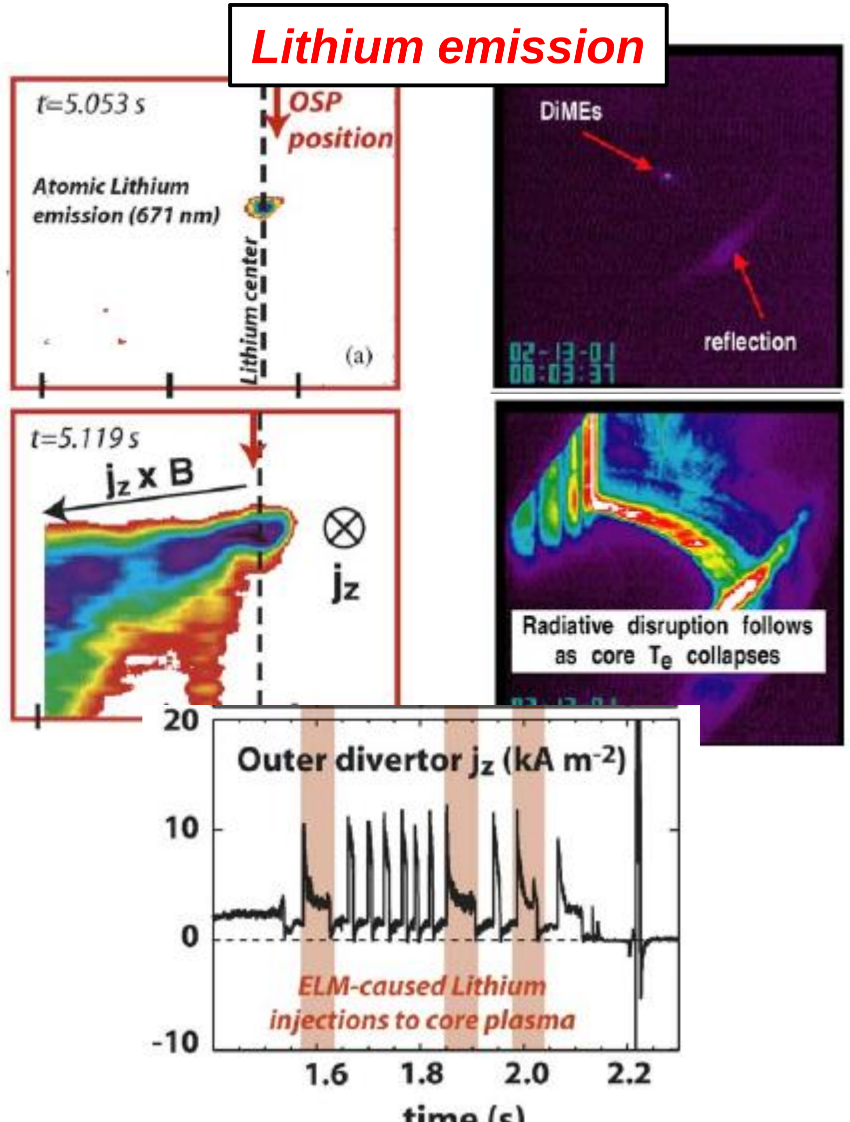
[1] Stangeby, JNM 2011

Outline of material

- Questions facing the implementation of liquid metal PFCs
  - Free-surface stability
  - Mass transport
  - Temperature limits/core compatibility
- NSTX Liquid Lithium Divertor
  - Physical construction
  - Divertor conditions
  - Raleigh-Taylor linear stability analysis
- Surface impurities and contamination
  - Spectroscopic emission
  - Laboratory gettering studies
- PFC design studies and future directions
  - LM concept overview
  - Implications of present-day cooling technologies
- Summary

Stability of the free-surface LM is critical

- DIII-D Li-DIMES experiments ended in plasma disruption
  - Introduced small sample of Li into divertor of DIII-D
  - Current perturbations measured up to 10 kA/m^2
  - Li plume observed when lithium ejected from sample holder
  - Disruption shortly follows lithium ejection
- If relying on LM to protect substrate, need robust solution
  - Protect against steady-state and transient events
  - **We show NSTX LLD exhibits stability in the divertor**



Whyte, et al., Fusion Eng. Des. **72** (2004) 133.

Key research challenges before liquid-metal plasma-facing components

- Stable operation of a free-surface, liquid-metal on the first-wall and divertor of the fusion device
- Mass transport and material inventory control of the liquid metal (and absorbed material)
- Establishing the operating temperatures of the liquid-metal plasma-facing components (PFCs) consistent with good core performance (i.e. an integrated scenario)

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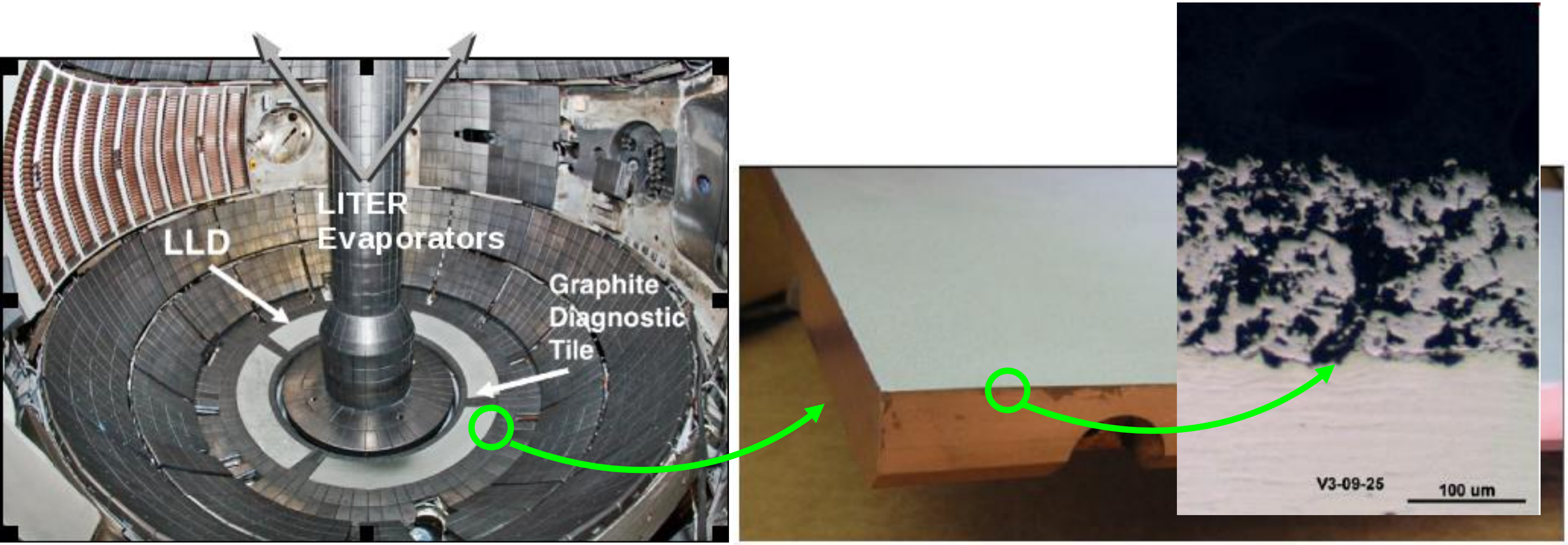
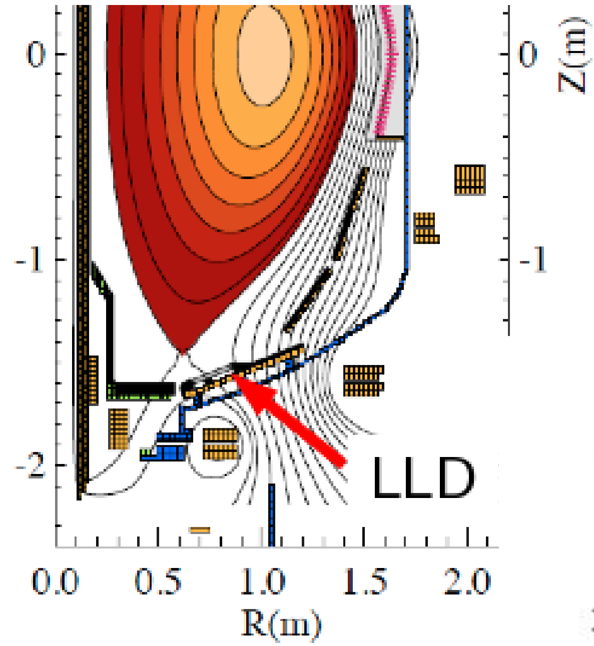
NSTX performed liquid-metal PFC experiments with the Liquid Lithium Divertor (LLD)

- Liquid lithium divertor installed for FY2010 run campaign
- 2.2cm copper substrate, 250um SS 316, ~150um flame-sprayed molybdenum porous layer; LITER loaded
- 37g estimated capacity, 60g loaded by end of run

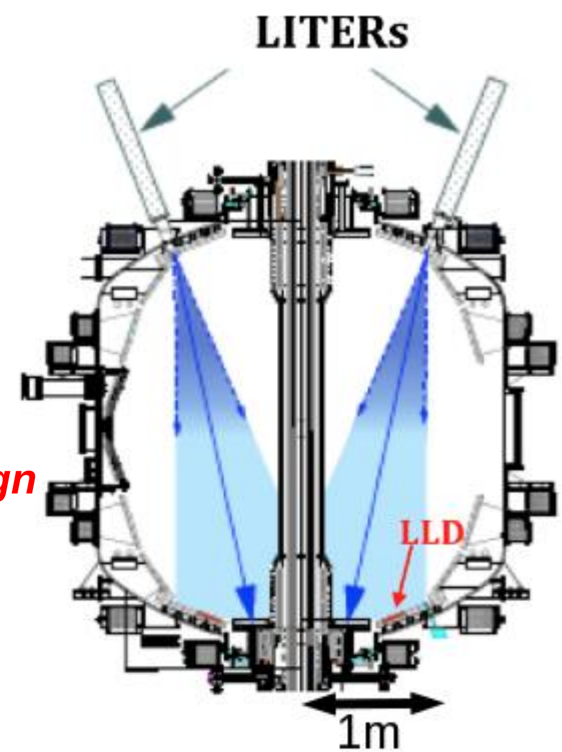


Overview of experiments

- Experiments diverting onto the LLD occurred throughout run campaign
- Either diverted onto LLD or just inboard on ATJ graphite
- LITER only available filling method for the LLD
  - 7% filling efficiency estimated
  - Always coating entire lower divertor in addition to LLD
- Database of shots taken throughout run year

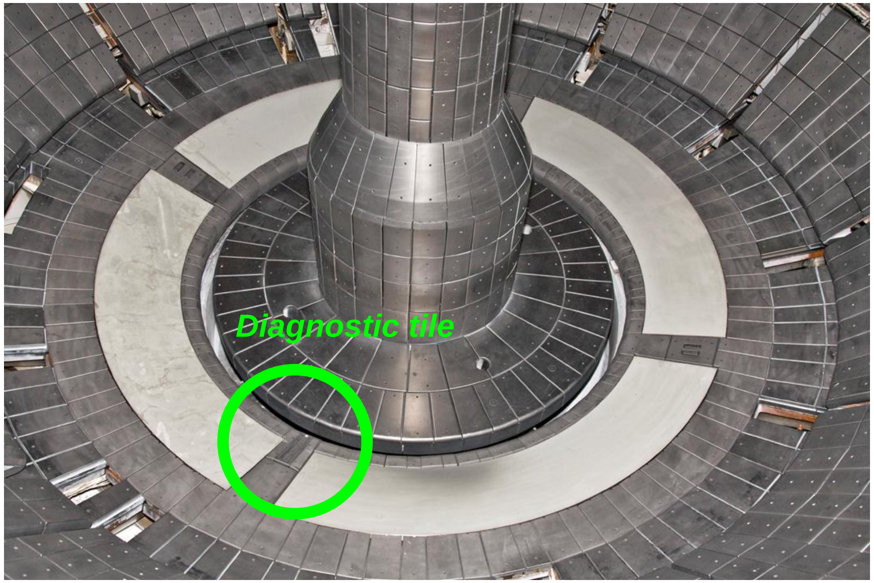


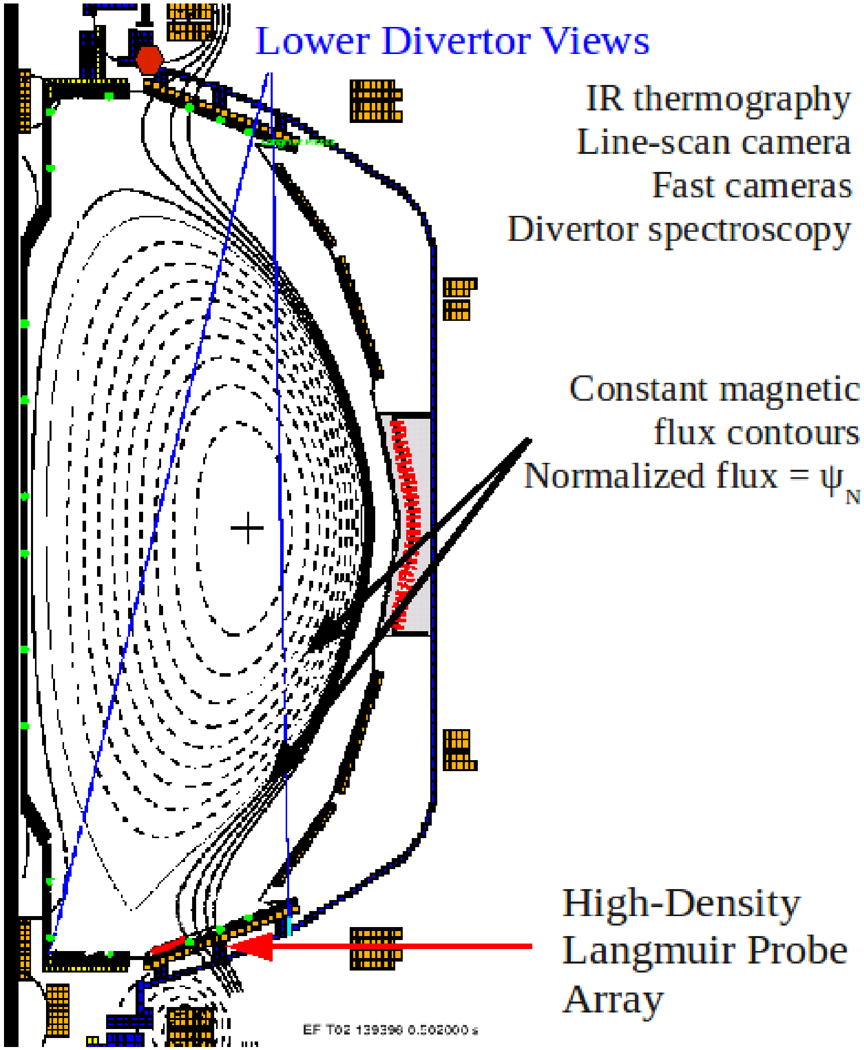
No boronization campaign prior to lithium introduction
Database already starts with 60g inventory in vessel



Array of plasma diagnostics utilized during experiments

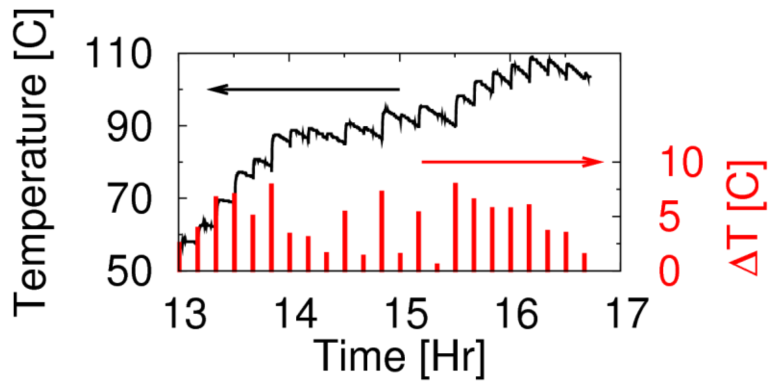
- Local plasma conditions and PFC currents measured with Langmuir probe system
- 2D fast-cameras provide nearly full toroidal coverage of divertor

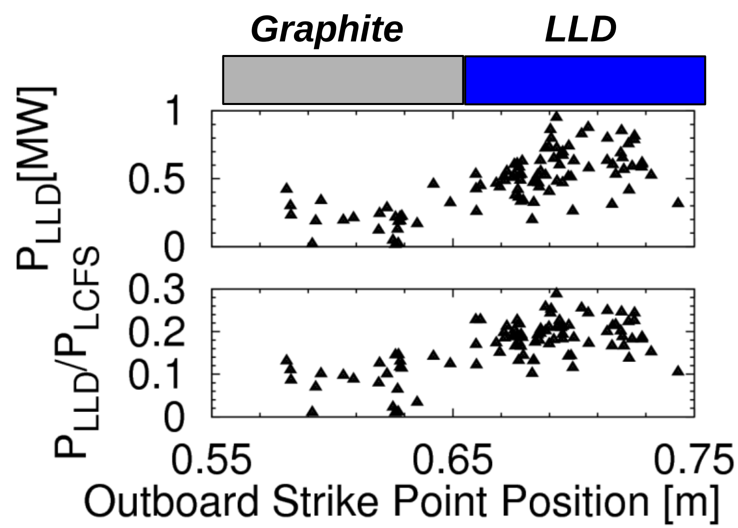




Significant power deposited on LLD measured

- Embedded thermocouples provide measure of temperature changes from before and after discharge
- Each plate is 43kg of copper
  - $\Delta E = mc_p\Delta T$ per plate
  - $P_{LLD} \sim 4\Delta E / \tau_{pulse}$
  - $P_{LCFS} = P_{NBI}+P_{OHM}-P_{RAD}-dW/dt$
- LLD absorbing about 25% of exhaust power (P_{LCFS})
  - ~1MW in some cases
- No molybdenum observed in the plasma after Li melt temperatures reached (Soukhanovskii, **RSI**, 2010)

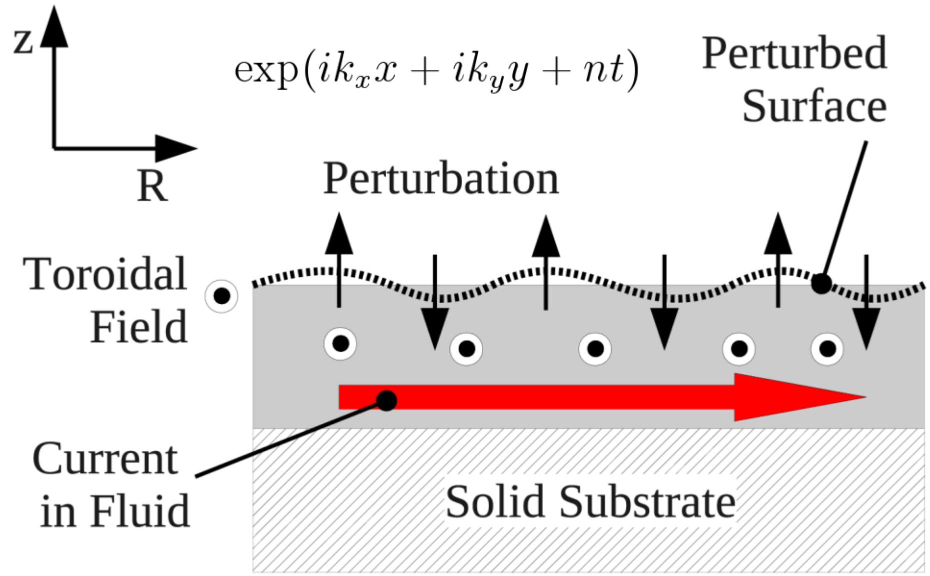




Jaworski, et al., IAEA FEC 2012

Vertical body forces can destabilize free surface…

- Net result of radial currents is to produce vertical forces
  - Currents in SOL that close in the PFC (DIII-D reported J_{PFC})
  - Disruption eddy currents



- Net body force upward has the potential to create Raleigh-Taylor instability
  - Must overcome gravity and surface tension
  - Must overcome magnetic tension (depending on orientation)

$$\frac{\partial u_i}{\partial x_i} = 0$$

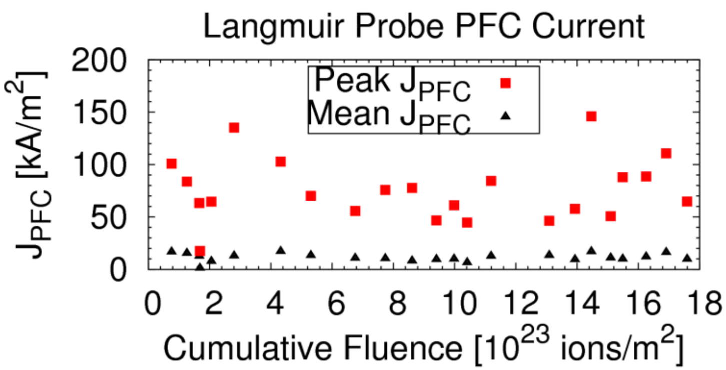
$$\rho\left(\frac{\partial u_i}{\partial t} + u_j \frac{\partial u_i}{\partial x_j}\right) = \rho X_i - \frac{\partial p}{\partial x_i} + \mu \nabla^2 u_i$$

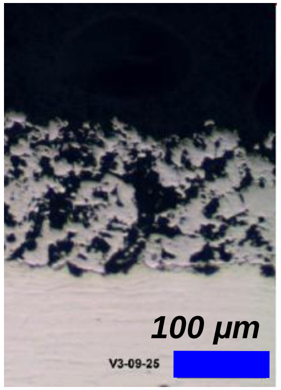
$$n^2 = k(jB/\rho - g)\left[1 - \frac{k^2\Sigma}{(jB/\rho - g)\rho} - \frac{B^2 k_x^2}{2\pi\mu_0 (jB/\rho - g)\rho k}\right]$$

Jaworski JNM 2011, Jaworski NF submitted

…but stable liquid metal PFC operation demonstrated with NSTX LLD

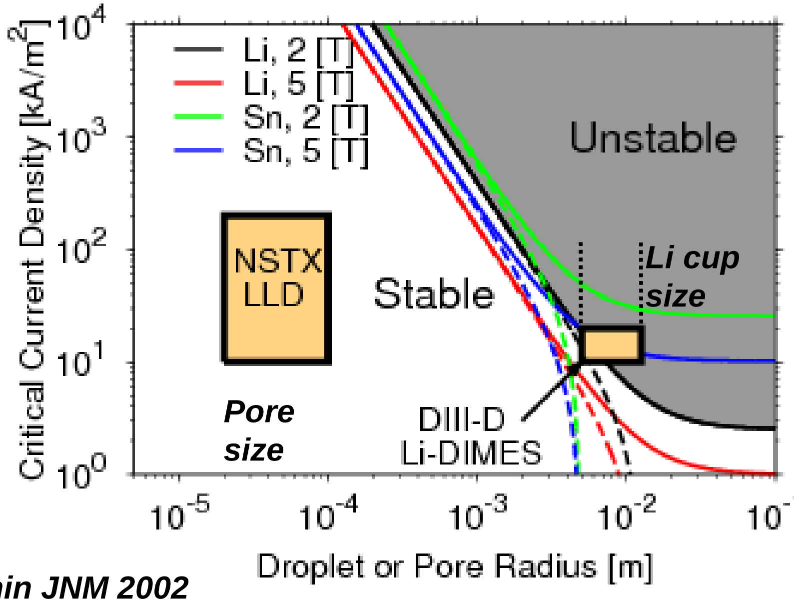
- Large transient currents measured with Langmuir probes, LLD porous geometry limits wavelength
- Raleigh-Taylor analysis provides marginal stability curves; NSTX LLD stable
- CPS tests also reduced droplet ejection with smaller pore sizes*





$$k_{Cr} = \sqrt{\frac{jB - \rho g}{\Sigma}}$$

For the fastest growing modes

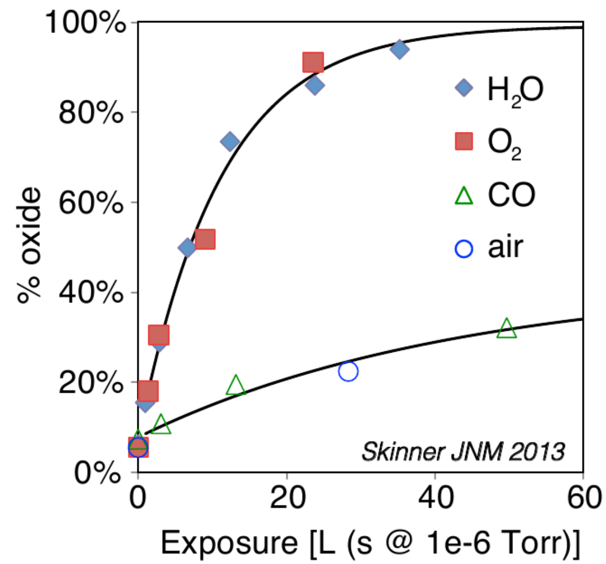


Jaworski JNM 2011, Jaworski NF submitted, Whyte FED 2004, *Evtikhin JNM 2002

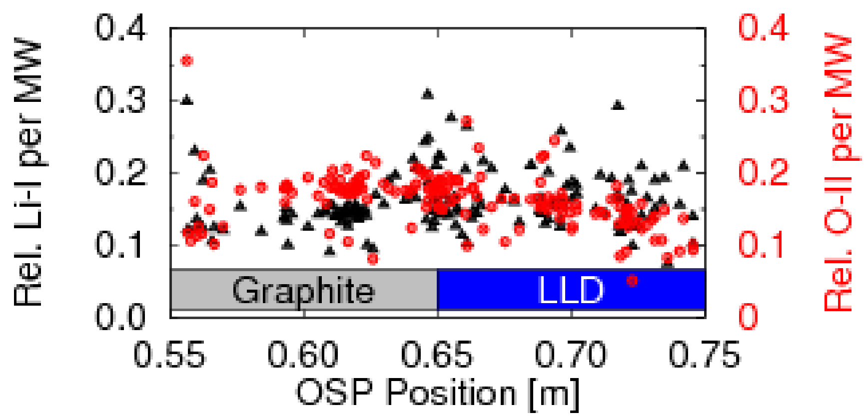
Oxygen recently identified as important to lithium chemistry and sputtering

- Oxygen uptake by lithium films quantified in laboratory experiments
  - Oxide layer formation in ~200s in NSTX (~600s inter-shot time)
  - Consistent with Liquid Lithium Divertor (LLD) results showing little change in impurity emission
- Influence of oxygen contaminants under investigation
  - Molecular dynamics simulations of Li-C-O show increased D uptake (Krstic, PRL 2013)
  - Non-zero **oxygen** sputter yield from contaminated surfaces

Oxygen uptake by Li coating on Mo



NSTX whole-divertor impurity emission

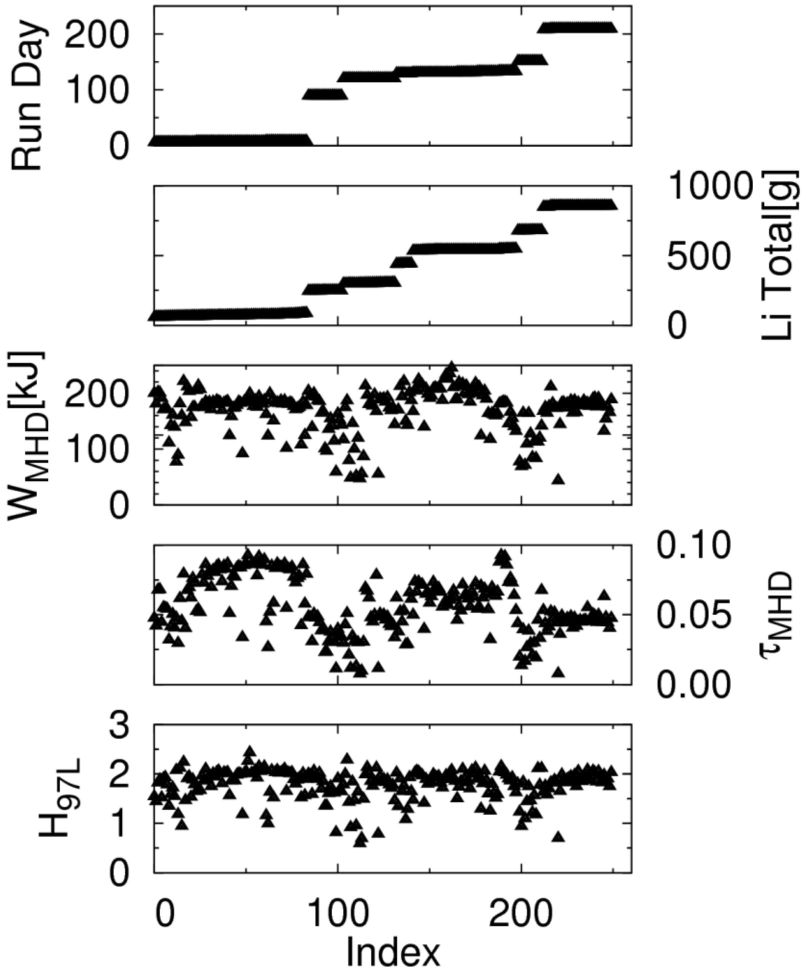


Jaworski IAEA FEC 2012

Performance should be independent of lithium quantity *if* surface contamination is key variable

- FY2010 LLD experimental set
  - Experiments span 60g to nearly 1kg of deposited lithium
  - Includes 75hr deposition at mid-year
  - Calculate ITER 97L H-factor *average* from 400-600ms for each discharge
- Discharges look about the same between start and end of run
  - Consistent with surface contamination hypothesis

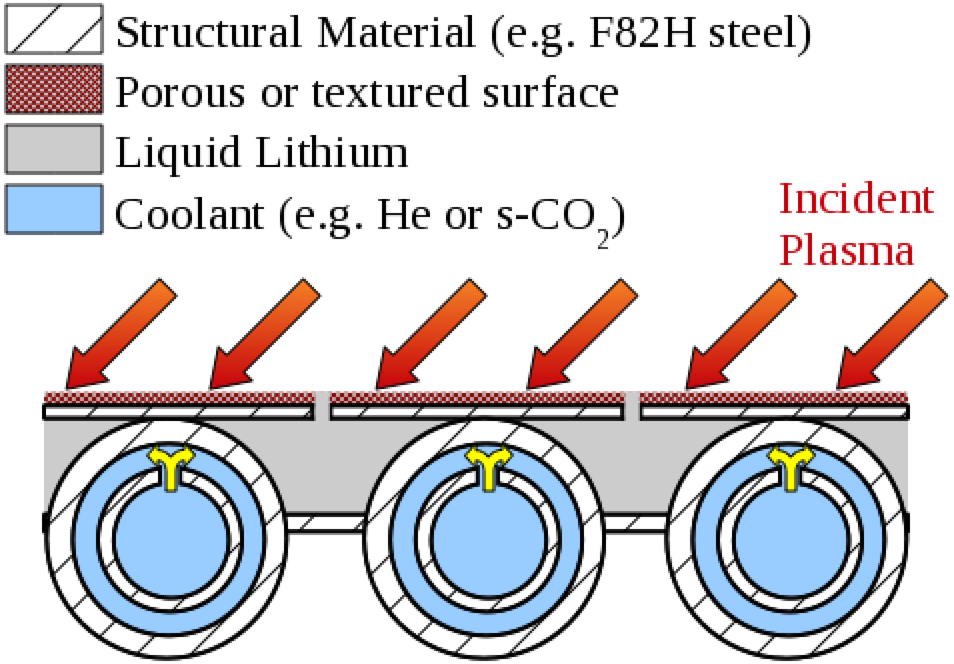
Fully-flowing PFC can provide a means of sweeping away gettered material and creating "stationary" surface conditions.



Jaworski, et al., IAEA FEC 2012

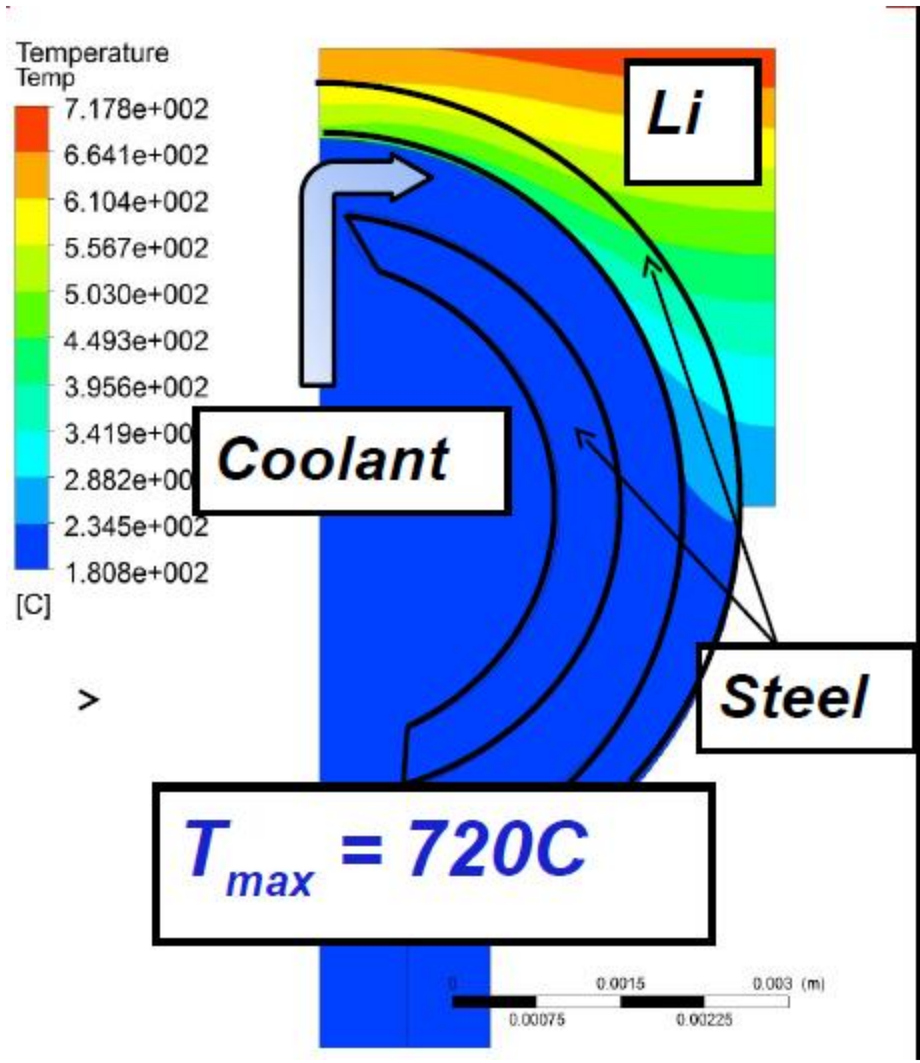
An approach to a liquid-metal PFC: Actively-supplied, capillary-restrained systems

- Closely connected primary coolant and liquid lithium reservoir/supply structure
- Continuous flow to the surface to flush gettered material and maintain wetted surfaces (substrate protection)
- Multiple coolant options exist (T-tube impinging jets shown as example)



Advanced cooling techniques can be optimized for LM-PFCs

- T-tube[1] uses impinging gas jets to increase local heat transfer coefficient
- Helium jet peak heat transfer is near ~40 kW/m^2/K in original T-tube design
- Altered T-tube for these simulations to have:
  - Smaller radius
  - Steel structure, s-CO2 coolant **(No tungsten)**
  - 10 MW/m^2 incident



[1]*Abdel-Khalik FST 2008.*

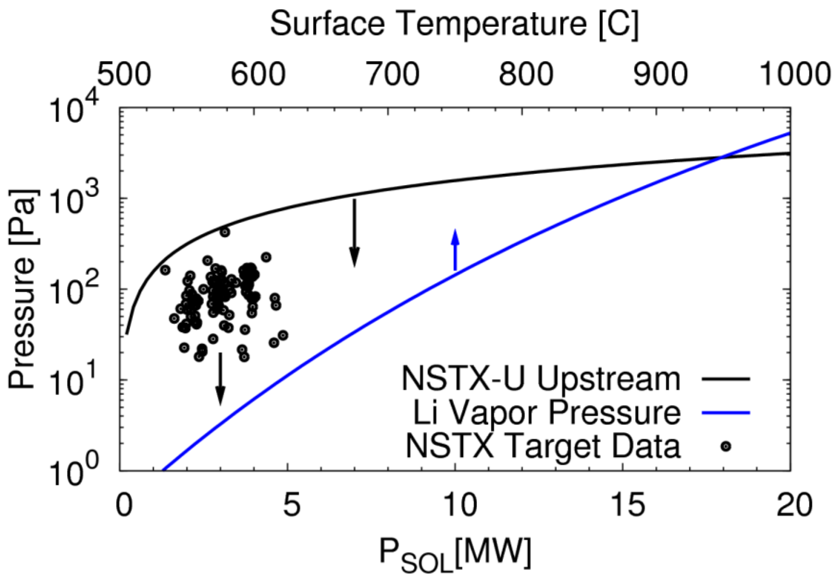
High temperature lithium surface may be able to provide a self-healing surface and intrinsic low-Z impurity radiation source

- Lithium vapor cloud can potentially provide effective power and pressure loss
  - Non-coronal Li radiation
  - Li vapor pressure vs. plasma pressure
- Capillary-Porous System(CPS) targets have dissipated large incident heat fluxes: e-beam tested to 25MW/m^2 limited by Li inventory (Evtikhin JNM 2002)
- CPS limiter in FTU able to operate above 550C (Apicella PPCF 2012)
- **What is $T_{max,surf}$ for a lithium PFC in the divertor?**
- Preliminary experiments being performed on Magnum-PSI plasma device

$$p_u = p_t(1 + M_t^2) + p_{Li}$$

$$q_t^{plasma} = \gamma \Gamma_{sat}^{+} T_e = \gamma n_{es} c_s T_e = \gamma c_s p_t$$

$$P_{SOL} = 4\pi^2 R_0 a \kappa^{1/2} \frac{\chi_\perp}{\lambda_T} n_u T_u = 4\pi^2 R_0 a \kappa^{1/2} \frac{\chi_\perp}{\lambda_T} p_u$$



Summary and Future Work

- Liquid metal PFCs may provide key advantages over solids, particularly by eliminating net reshaping
- Key issues still face the usage of liquids but the NSTX LLD demonstrates stable operation in the diverted configuration
- Oxygen contamination prevented the LLD from providing a pure lithium surface and motivates flowing systems
- Present state-of-the-art gaseous cooling technologies are still expected to result in elevated surface temperatures under 10 MW/m^2 incident heat fluxes
- A liquid lithium PFC at such temperatures could lead to a continuously vapor-shielded target and will be studied in linear plasma devices and the NSTX-U
  - Mass transport and compatibility with integrated scenarios will also be assessed

Thank you for your attention

Bellerophon and the Chimera

http://en.wikipedia.org/wiki/Bellerophon

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