# Collaborative Research and Development of Liquid Metal Plasma Facing Components

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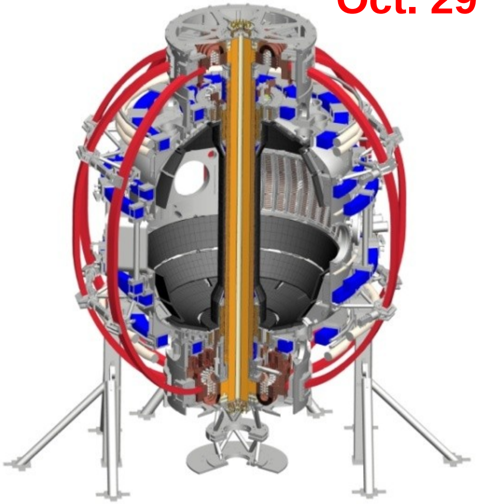
**54th American Physical Society Division of Plasma Physics Meeting, Providence, RI**
**Oct. 29th – Nov. 2nd, 2012**



*Coll of Wm & Mary*
*Columbia U*
*CompX*
*General Atomics*
*FIU*
*INL*
*Johns Hopkins U*
*LANL*
*LLNL*
*Lodestar*
*MIT*
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*Nova Photonics*
*ORNL*
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*Think Tank, Inc.*
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*U Maryland*
*U Rochester*
*U Tennessee*
*U Tulsa*
*U Washington*
*U Wisconsin*
*X Science LLC*

*Culham Sci Ctr*
*York U*
*Chubu U*
*Fukui U*
*Hiroshima U*
*Hyogo U*
*Kyoto U*
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*Kyushu Tokai U*
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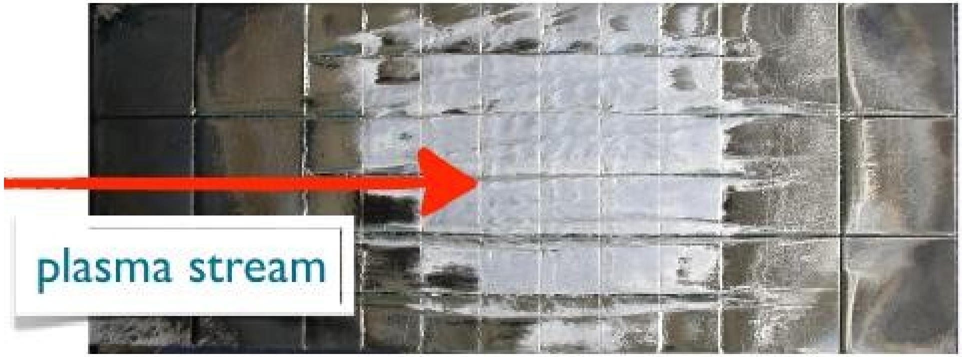
*FOM Inst DIFFER*
*ENEA, Frascati*
*CEA, Cadarache*
*IPP, Jülich*
*IPP, Garching*
*ASCR, Czech Rep*

# Why liquids? Because solids may not extrapolate

- Two major failure modes for solids that are known:
  - Melting (transient heat loads)
  - Net-reshaping (erosion, migration, redeposition)
- Some speculative failure modes:
  - Neutron-PMI synergistic effects (aside from bulk material changes)
  - Steady-state, self-regulating walls?

B. Lipschultz, et al., “Tungsten melt effects on C-MOD operation & material characteristics”, 20-PSI, Aachen, Germany, May, 2012.



Coenen, et al., “Evolution of surface melt damage, its influence on plasma performance and prospects of recoverhy”, 20-PSI, Aachen, Germany, May, 2012.
Klimov, et al., JNM **390-391** (2009) 721.

# Wall erosion/redeposition not mitigated by divertor configuration

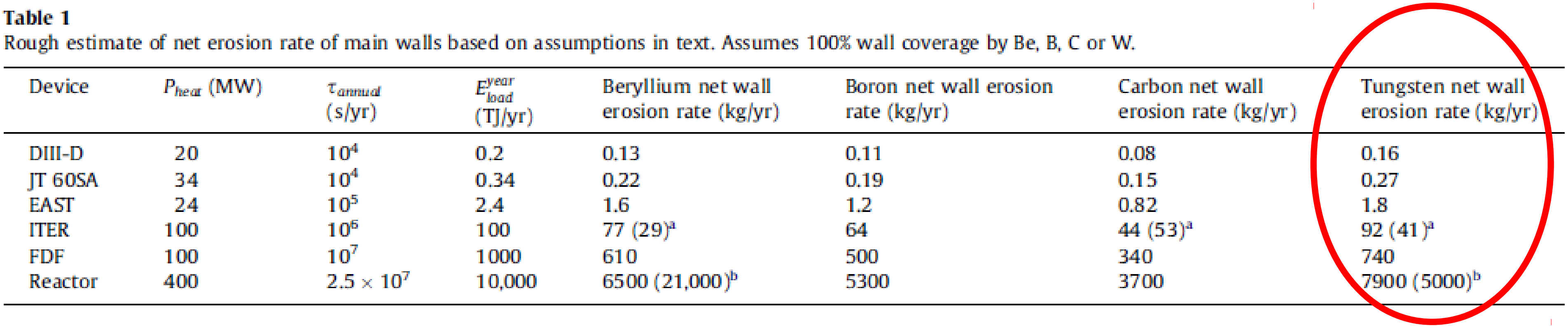


**Table 1**

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) | $\tau_{annual}$ (s/yr) | $E_{load}^{year}$ (TJ/yr) | Beryllium net wall erosion rate (kg/yr) | Boron net wall erosion rate (kg/yr) | Carbon net wall erosion rate (kg/yr) | Tungsten net wall erosion rate (kg/yr) |
|---|---|---|---|---|---|---|---|
| DIII-D | 20 | $10^4$ | 0.2 | 0.13 | 0.11 | 0.08 | 0.16 |
| JT 60SA | 34 | $10^4$ | 0.34 | 0.22 | 0.19 | 0.15 | 0.27 |
| EAST | 24 | $10^5$ | 2.4 | 1.6 | 1.2 | 0.82 | 1.8 |
| ITER | 100 | $10^6$ | 100 | 77 (29)$^a$ | 64 | 44 (53)$^a$ | 92 (41)$^a$ |
| FDF | 100 | $10^7$ | 1000 | 610 | 500 | 340 | 740 |
| Reactor | 400 | $2.5 \times 10^7$ | 10,000 | 6500 (21,000)$^b$ | 5300 | 3700 | 7900 (5000)$^b$ |

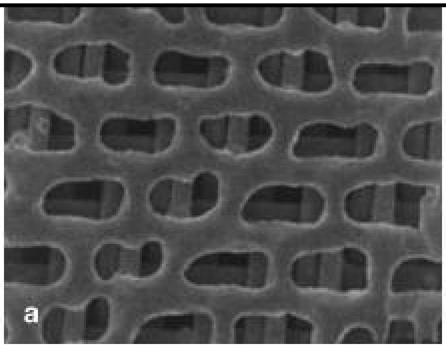
*P.C. Stangeby, et al., JNM 415 (2011) S278.*

- Charge-exchange processes create steady wall-flux
- Low density plasma at first wall reduces local redeposition
- **1000s of kgs** of eroded material migrating around tokamak vessel
- Likely to redeposit in locations where cooler plasmas exist or behind baffled areas of machine
- Do PFCs remain functional with large amounts of redeposited material?
  - Need very high duty-factor to even study the problem!

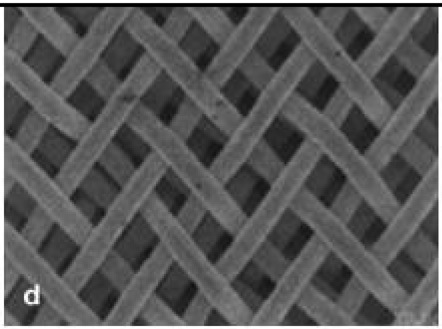
# Liquids already shown to outperform solids in some areas

- Red Star Capillary-Porous-System (CPS) long-since shown to resist melting damage – protect the substrate
  - CPS surface consists of metal mesh wicking structure (Mo mesh)
  - Capillary forces maintain liquid lithium on plasma-facing surface
- Also shown to absorb, in steady-state, 1-25 $MW/m^2$
  - Electron beam heating of the surface
  - Tests lasted between 30s-10min
- In principle, all PFCs in fully-flowing system will return to an equilibrium position (i.e. self-healing)

**Exposed w/o Li**



**Exposed w/ Li**

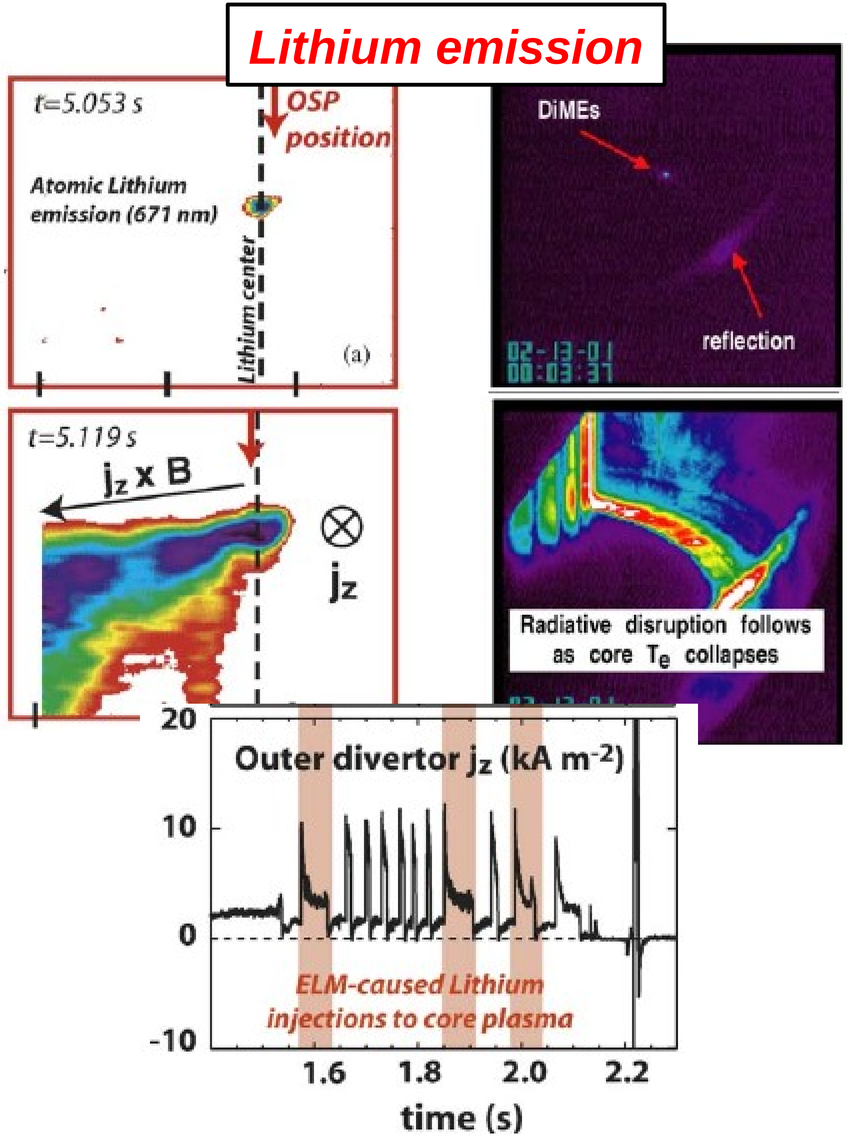


***CPS Mo meshes after plasma exposure. Top did not have lithium fill during exposure. 15-100µm pores***

Evtikhin, et al., J. Nucl. Mater. **271-272** (1999) 396.

# Stability of the free-surface LM is critical

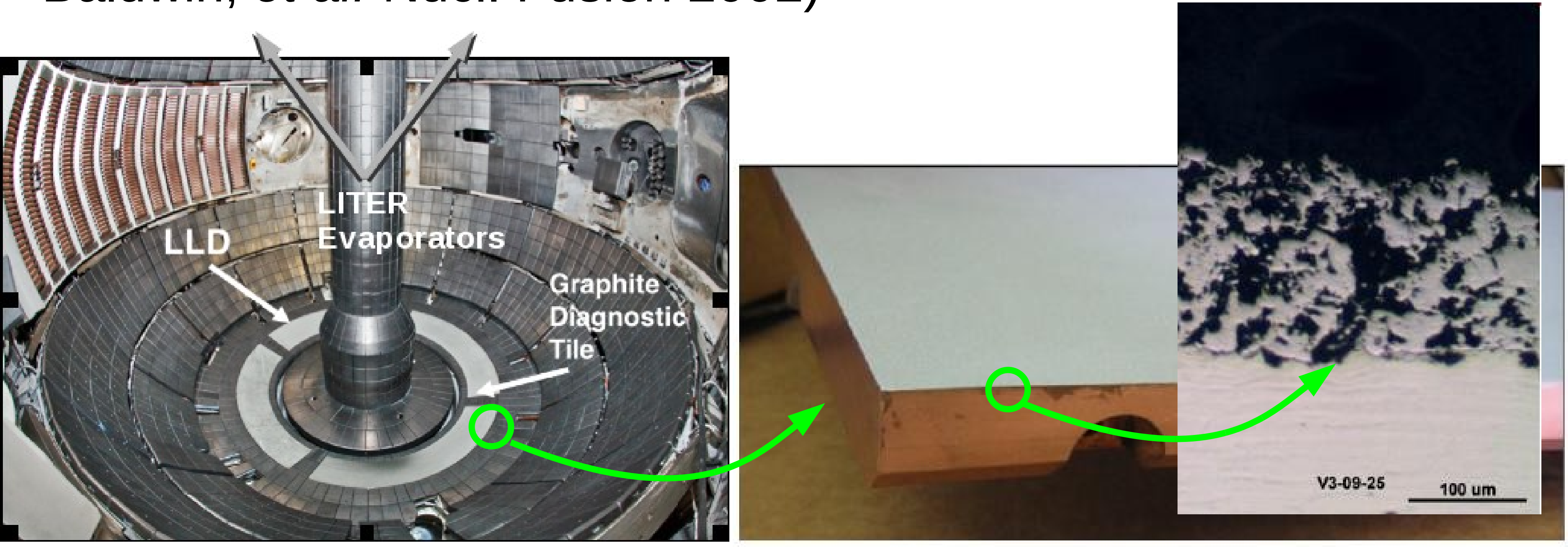
- DIII-D Li-DIMES experiments ended in plasma disruption
  - Introduced small sample of Li into divertor of DIII-D
  - Current perturbations measured up to 10 kA/m$^2$
  - Li plume observed when lithium ejected from sample holder
  - Disruption shortly follows lithium ejection
- If relying on LM to protect 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.

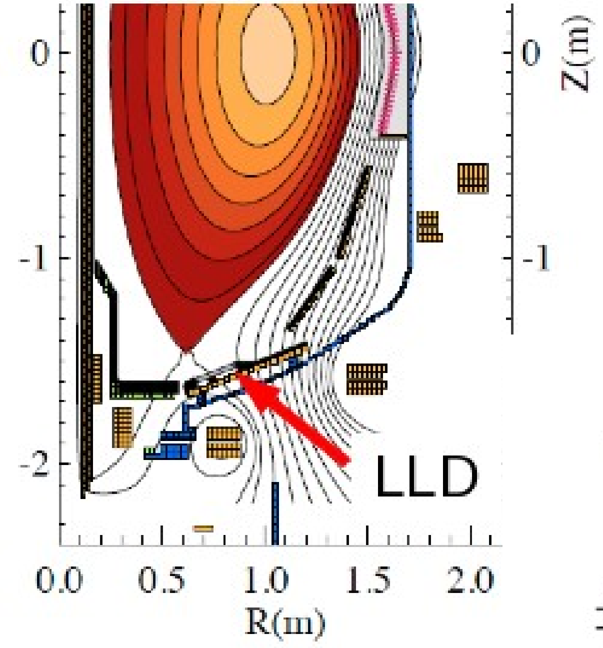
# NSTX experience with the Liquid Lithium Divertor

- Liquid lithium divertor installed for FY2010 run campaign
- 2.2cm copper substrate, 250μm SS 316, ~150μm flame-sprayed molybdenum, loaded via LITER evaporators
- 37g estimated capacity, 60g loaded by end of run campaign
- Motivated to explore liquid lithium pumping of deuterium (c.f. Baldwin, *et al.* Nucl. Fusion 2002)

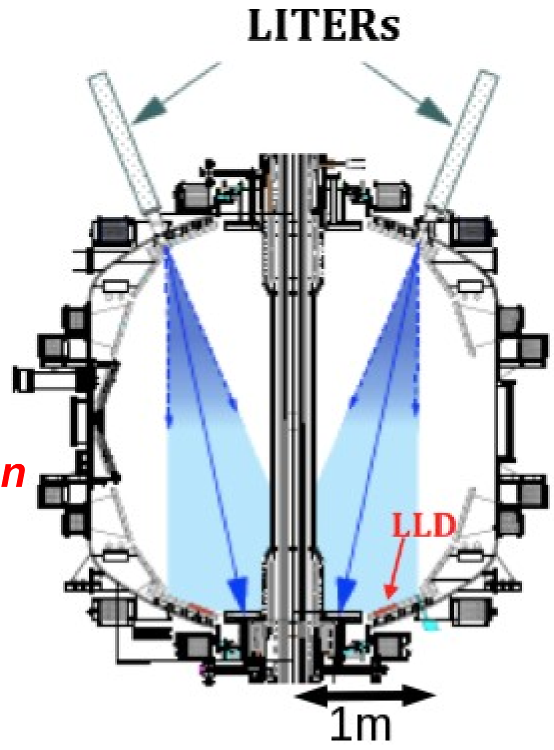


# Overview of experiments

- 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

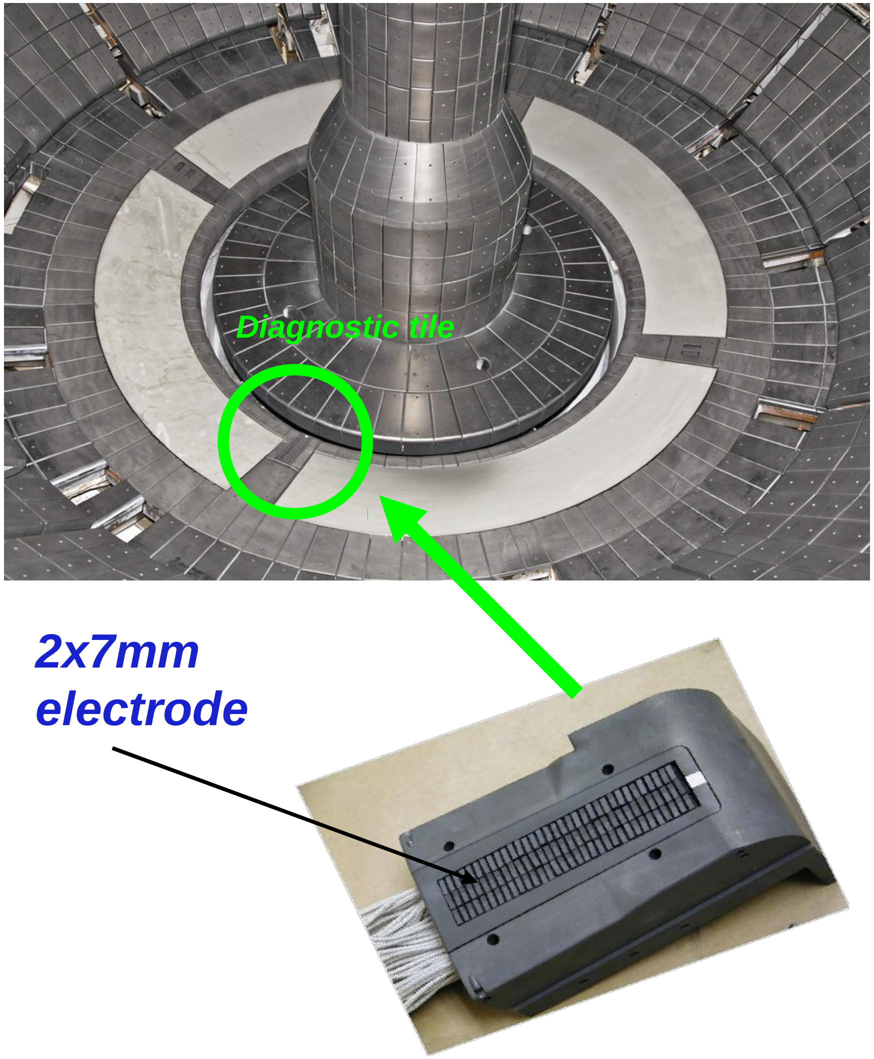


***No boronization campaign prior to lithium introduction***
***Database already starts with 60g inventory in vessel***



# High-density Langmuir probe array installed for divertor plasma characterization

- Liquid Lithium Divertor (LLD) installed to study lithium plasma-material interactions
- Probe array characterizes local plasma properties in a range of experiments
- Provides high spatial density of measurements
- Oblique incidence yields smaller effective probe size

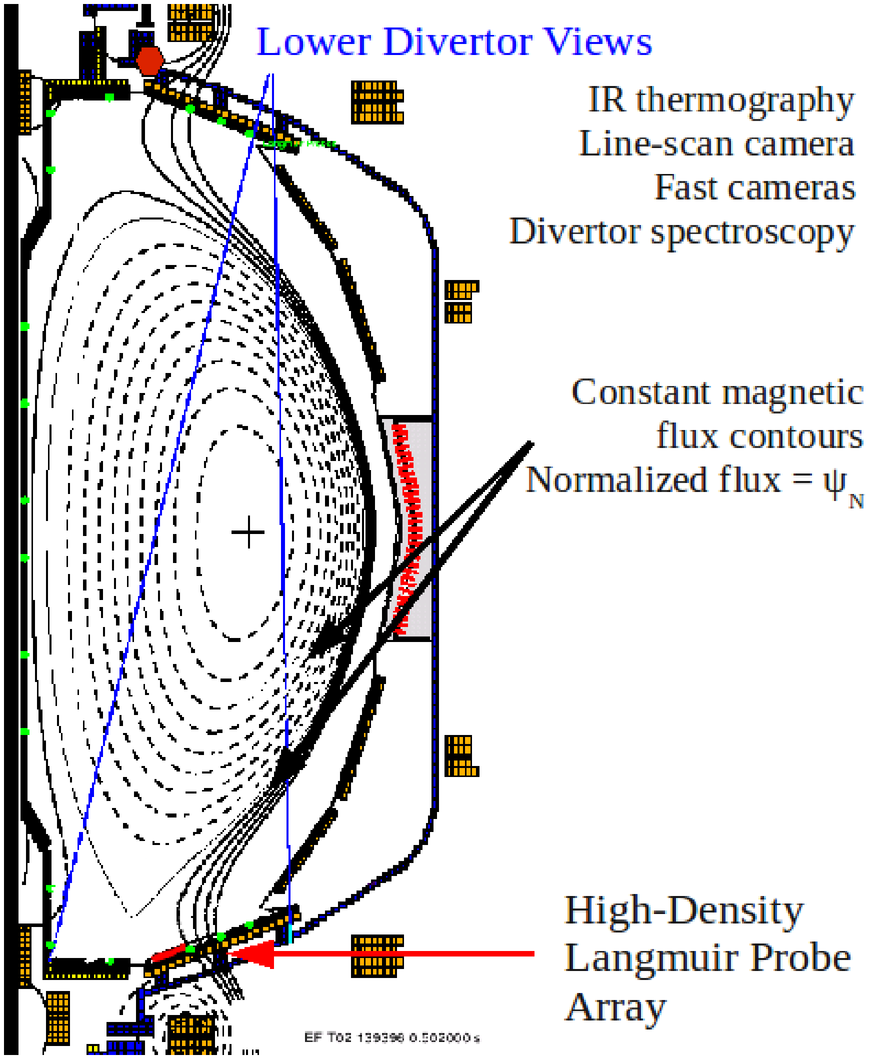


*2x7mm electrode*

*J Kallman, RSI 2010*
*MA Jaworski, RSI 2010*

# Consistency between diagnostics demonstrated with empirical plasma reconstruction framework

- Utilizes measured data points as starting point in constraining plasma models to fill the gaps between diagnostics
- Solution improves as more and more data constrains background
- OEDGE code suite used here: Onion-Skin Method (OSM2)+EIRENE+DIVIMP
  - OSM2 solves plasma fluid equations
  - EIRENE performs Monte Carlo neutral hydrogen transport, iteratively coupled to OSM2
  - DIVIMP performs Monte Carlo impurity transport
- Utilized here to compare probe interpretation methods against other diagnostics



Lower Divertor Views

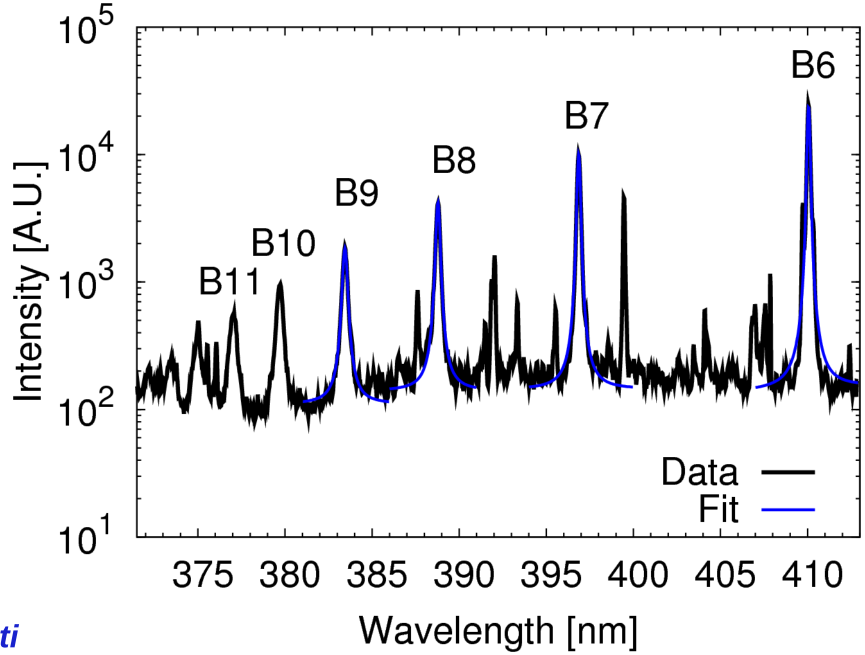
IR thermography
Line-scan camera
Fast cameras
Divertor spectroscopy

Constant magnetic flux contours
Normalized flux = $\psi_N$

High-Density Langmuir Probe Array

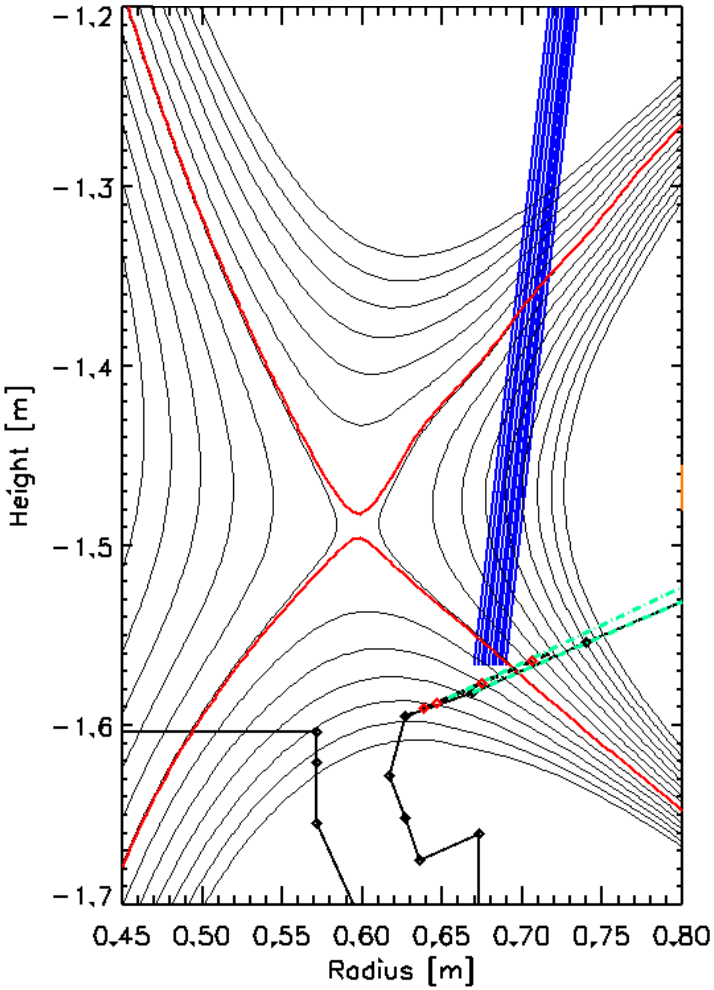
# Density measurement from spectroscopy confirm kinetic probe interpretation

- Divertor spectrometer viewing strike-point region during discharge
- Deuterium Balmer lines shown in spectra
- Pressure broadening analysis indicates dneisty of 3.6e20 m$^{-3}$
  - Existence of high-n Balmer lines indicates low temperature



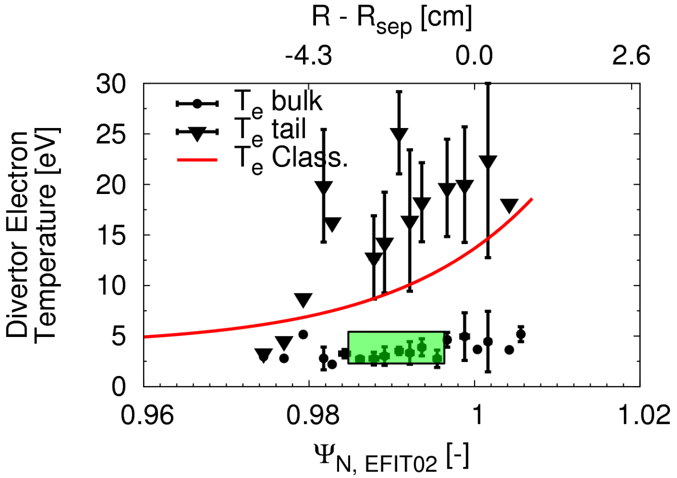
**F. Scotti**

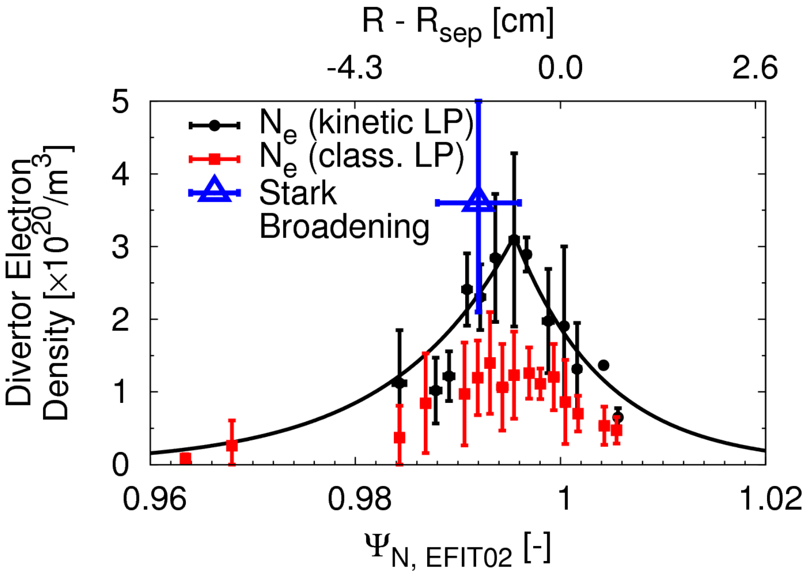
***Divertor spectrometer view***



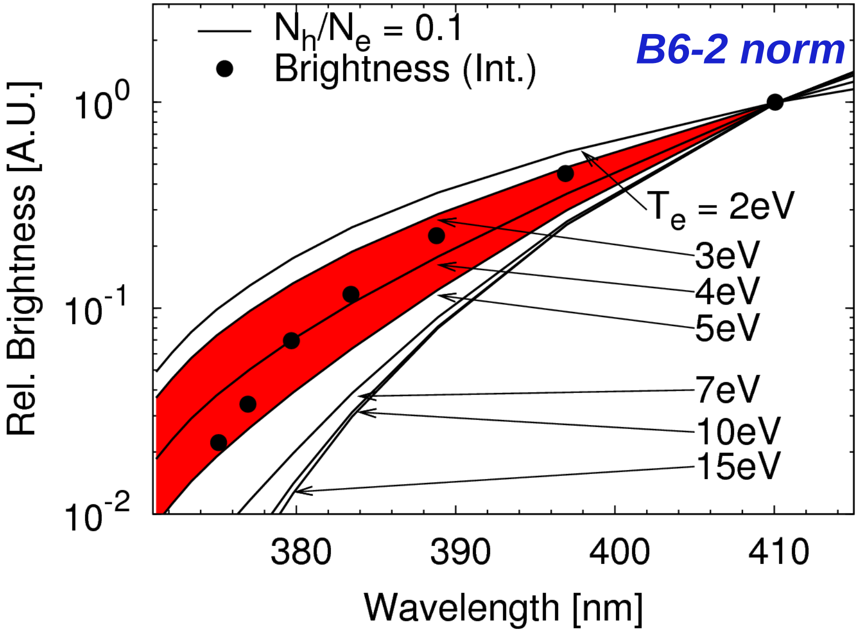
# Broadening measurement and modeling of hydrogen spectrum consistent with kinetic probe interpretation

- Pressure broadening yields density
- OEDGE plasma+neutral solution provides local parameters
- Collisional-radiative model by D. Stotler calculates excited state populations
- Brightness ratios normalized to B6-2 consistent with $3<T_e<5$eV





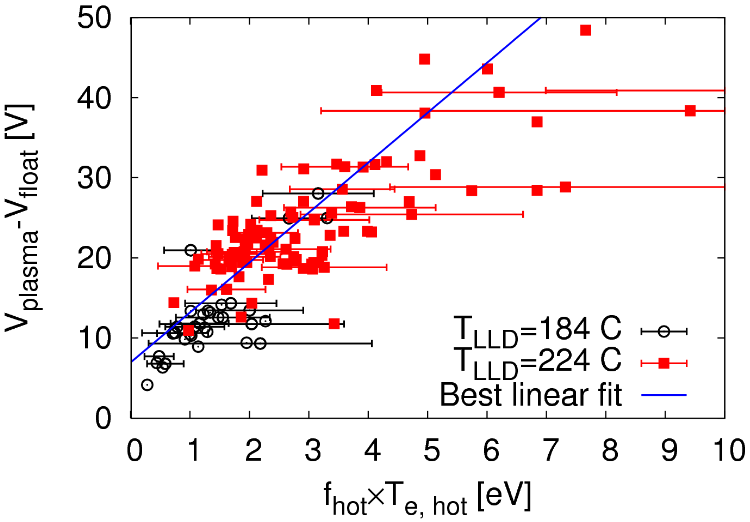
*Balmer-Series Brightness Ratios*



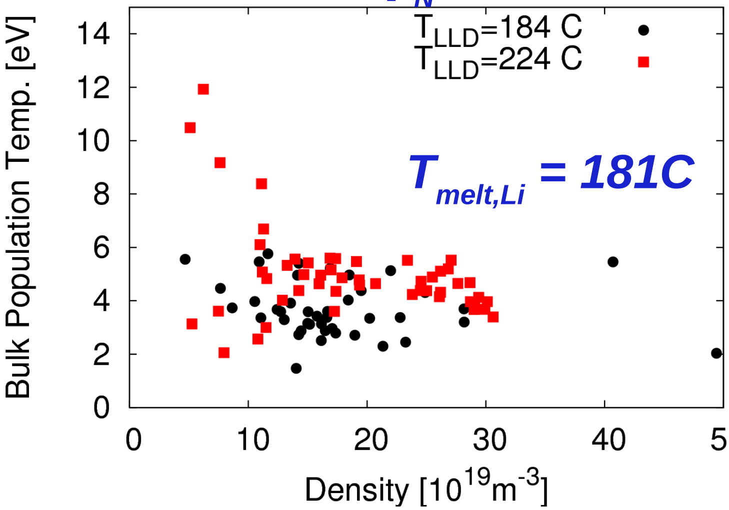
*Jaworski, et al., 20th PSI, Aachen, Germany, June 2012.*

# Distribution function analysis indicates some local changes in plasma conditions on plasma-heated LLD

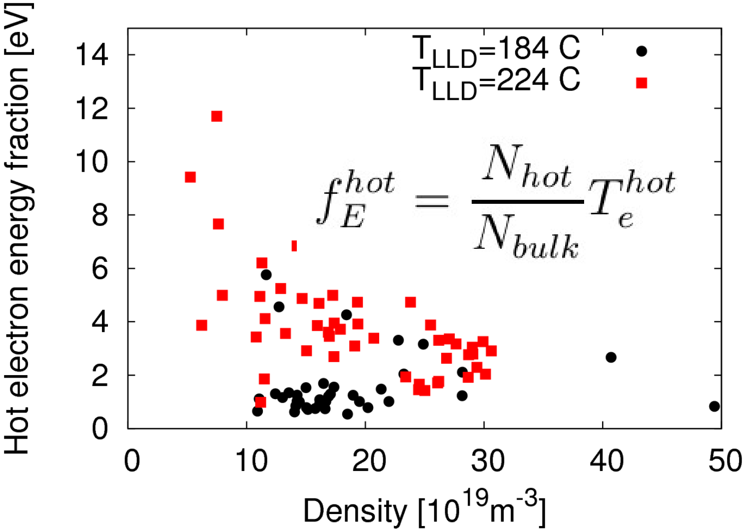
- Discharge sequence repeatedly heated and plasma-conditioned the LLD surface
- Local plasma temperatures elevated with hotter LLD surface temperature ($T_{LLD} > T_{melt,Li}$)
- Increase in plasma temperatures correlated with increase in $V_p$-$V_f$ potential difference[1]
- **Local changes raise the question whether large-scale global changes are also observed...**



*Comparisons made on identical $\psi_N$ locations*



$T_{melt,Li}$ = 181C

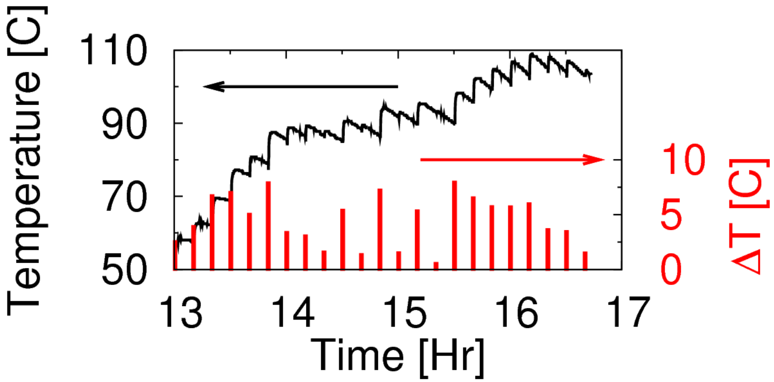


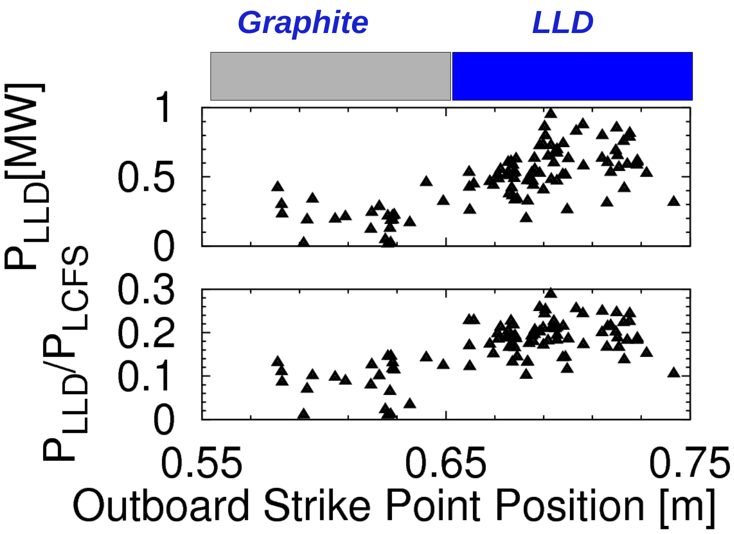
$$f_E^{hot} = \frac{N_{hot}}{N_{bulk}} T_e^{hot}$$

[1] *Jaworski et al., Fusion Eng. Des. 87 (2012) 1711.*

# Significant power onto LLD measured

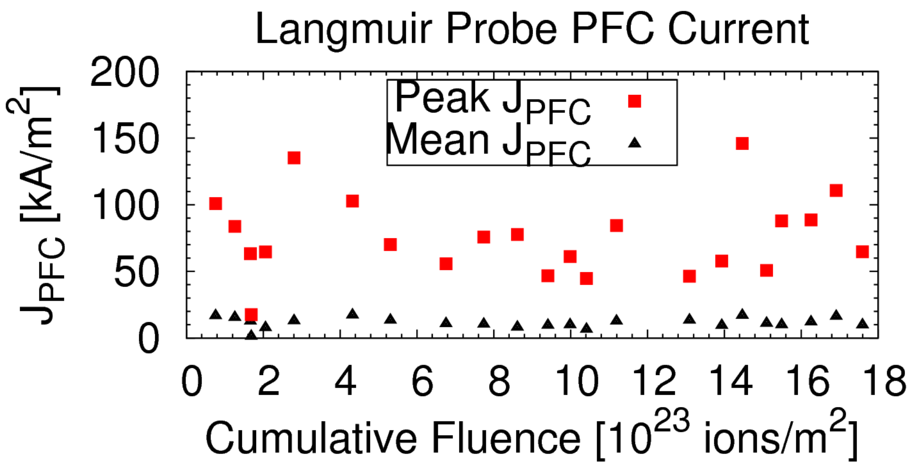
- Embedded thermocouples provide measure of temperature changes from before and after discharge
- Each plate is 43kg of copper
  - $\Delta E = mc_p \Delta T$ per plate
  - $P_{LLD} \sim 4\Delta E / \tau_{pulse}$
  - $P_{LCFS} = P_{NBI} + P_{OHM} - P_{RAD} - dW/dt$
- LLD absorbing about 25% of exhaust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

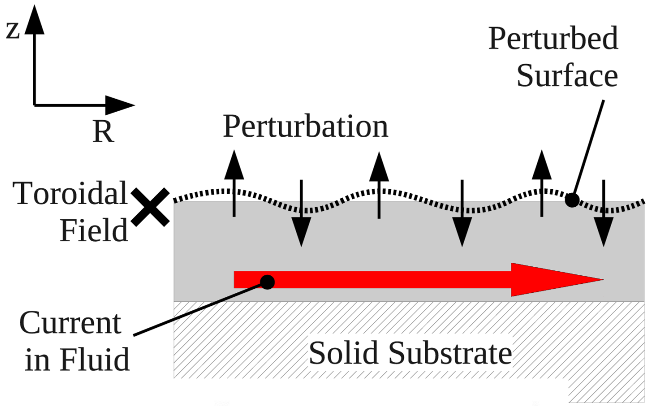




Jaworski, et al., IAEA FEC 2012

# No macroscopic ejection of lithium observed; Demonstration of Stable Operation of LM PFC in Divertor Configuration





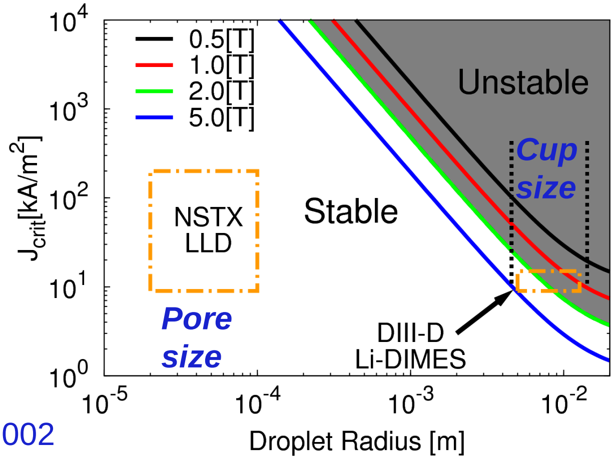
$$\exp(ik_x x + ik_y y + nt)$$

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

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

***For the fastest growing modes***

- Large transient currents measured with Langmuir probes
- Magnetized Raleigh-Taylor analysis provides stability curves
- Indicates strong stabilization expected with small feature sizes
- CPS tests also reduced droplet ejection with smaller pore sizes*



Jaworski **JNM** 2011, Jaworski IAEA FEC 2012, Whyte **FED** 2004, *Evtikhin **JNM** 2002

# Surface contamination indicates this was not a “fair” test of a liquid lithium PFC

- Divertor filterscopes provide indicator of impurities
  - Relative fraction of impurity should be reflected in sputter yield
  - Particle flux proportional to power
- Normalization against flux indicates no difference diverted onto the LLD
- Plasma cleaning in PISCES-B did show oxygen reduction*
  - 400s, T>600K
  - LLD transiently exceeded these temperatures, but not steady
- $\tau_{intershot} \sim \tau_{oxidize}$ indicates oxidation likely (see GO6.008, A. Capece)

$$\epsilon_{imp} \propto N_{imp} \propto Y_{imp} J_{sat}$$

$$Y_{imp} \propto Y^{0}_{imp} \theta_{imp}$$

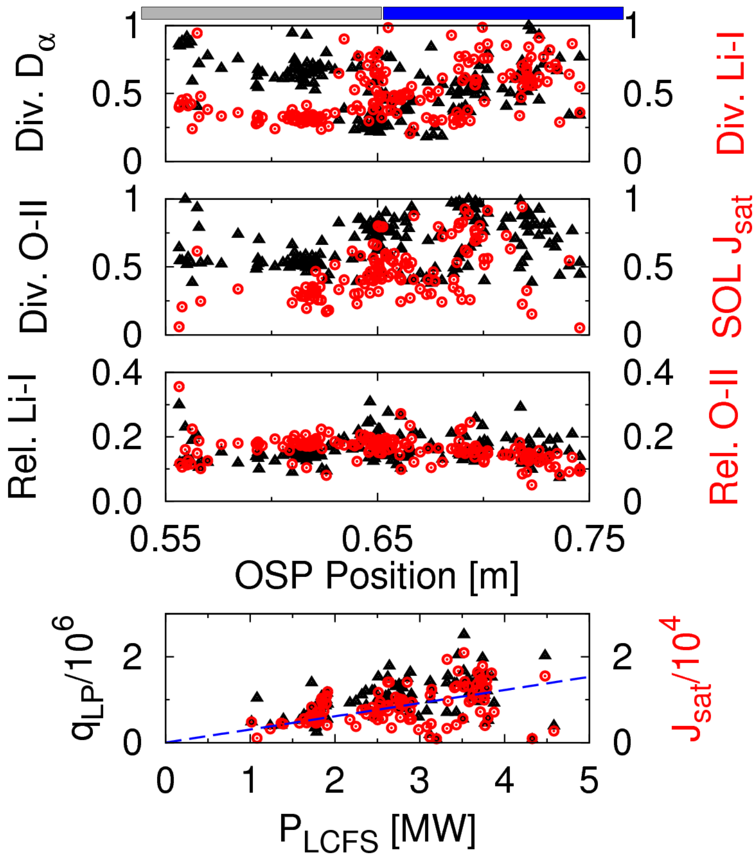
$$P \propto \gamma J_{sat} T_{e}$$

$$\theta_{imp} \propto \frac{\epsilon_{imp}}{P}$$

***Emission ϵ***

***Coverage θ***

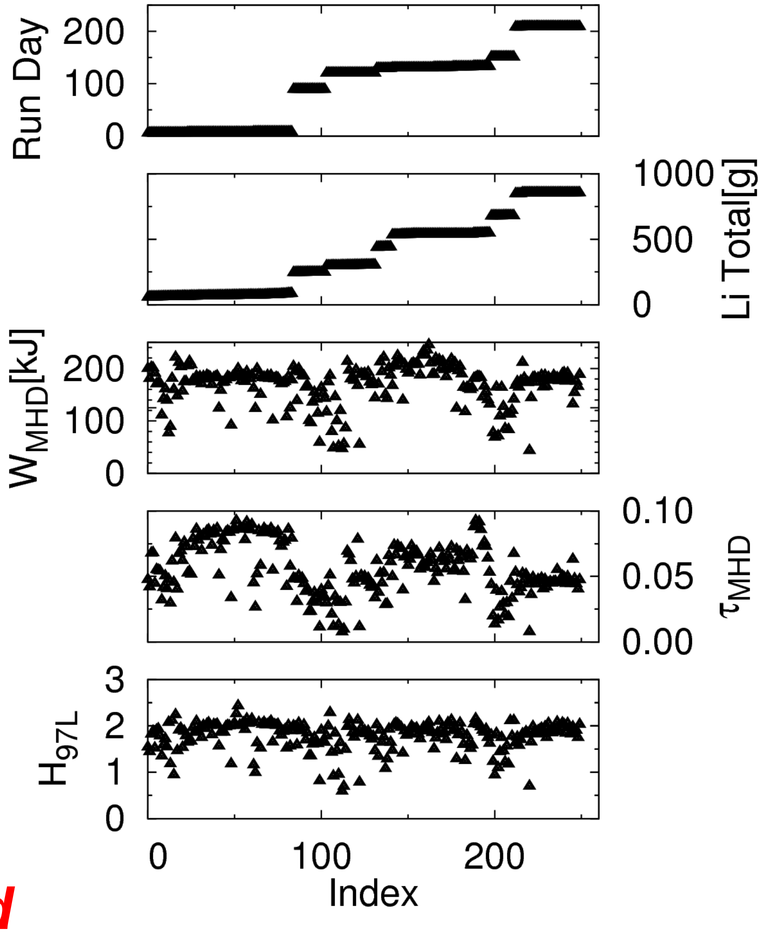
***Divertor Power P***



Jaworski IAEA FEC 2012, *Baldwin **NF** 2002.

# 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

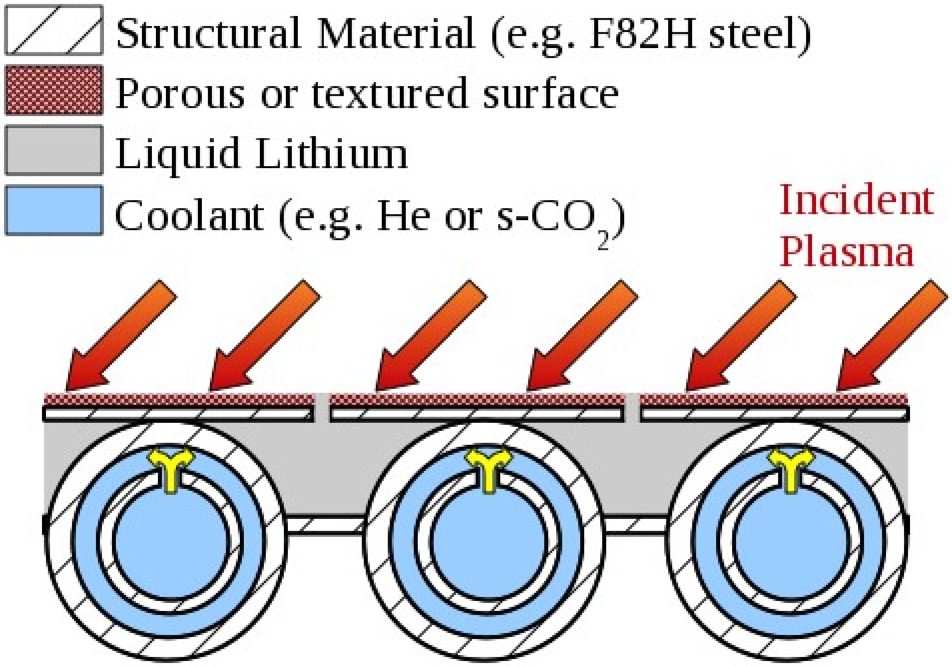


***Fully-flowing PFC can provide a means of sweeping away gettered material and creating "stationary" surface conditions.***

Jaworski, et al., IAEA FEC 2012

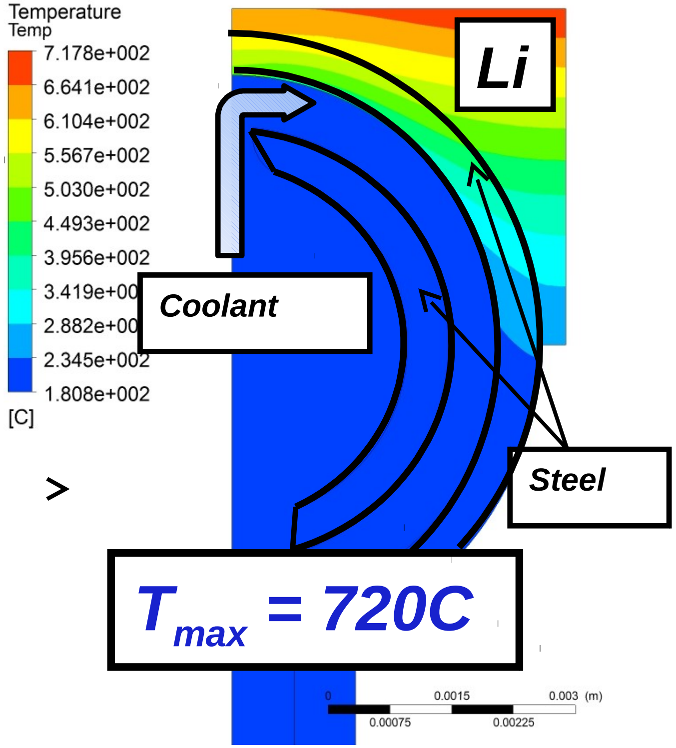
# Active supply, capillary-restrained systems (PPPL)

- Hybrid approach to join flow-thru loop with active cooling
  - Leverage numerous results an experience with thin, capillary-restrained concepts
  - Maintain thin structures (as thin as possible) to maximize heat transfer to coolant
- Modular approach considered to provide optimization space
  - T-tube concept shown, other gas cooling schemes available (e.g. SOFIT, vapor-box/heat pipes)
  - Surface could be flame-sprayed or other scheme (e.g. laser textured)



# Current work-in-progress: steel with low-Z lithium coating

- T-tube size reduced to minimize wall thickness, supercritical-CO2 coolant
- F82H steel properties with liquid lithium used in design
  - Liquid lithium evaporative cooling included
  - 10 MW/m$^2$ heat flux simulated, no nuclear heat
  - No provision for plasma cooling and shielding
- Steel structure maintained below ~650C, close to range for ODS-steel operation*



$T_{max}$ = 720C

**Still optimizing/developing 3D solution, 720C might be too hot****

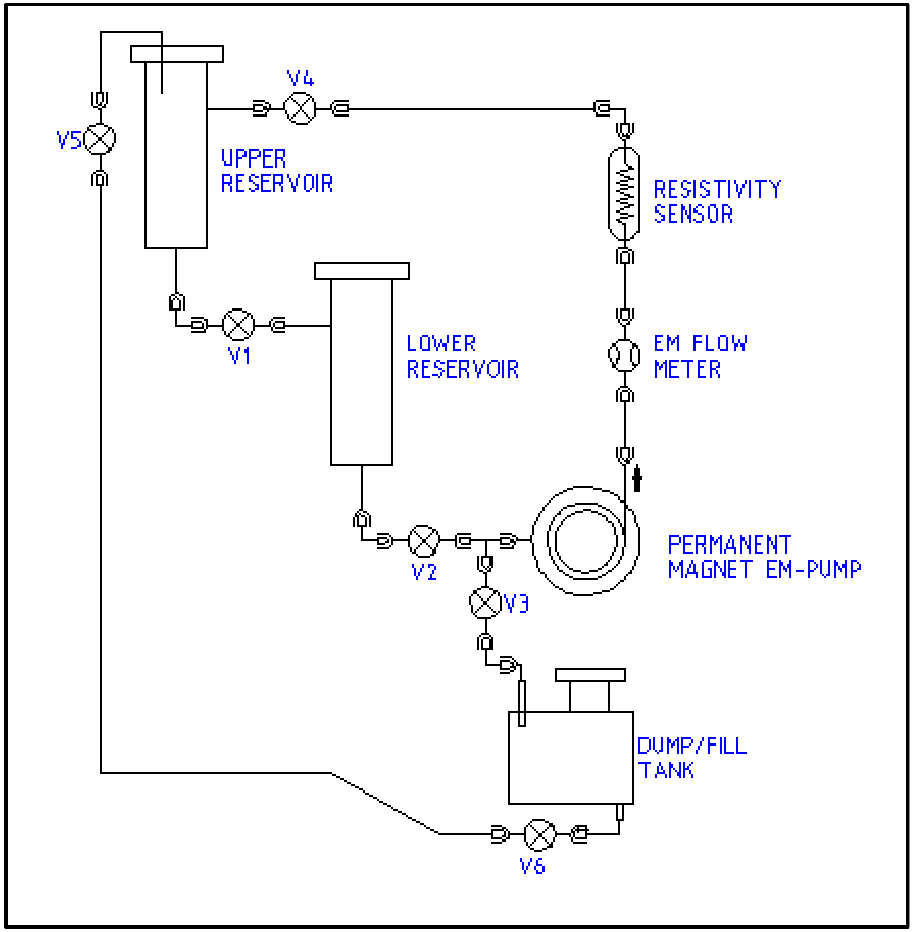
*Zinkle,, Ghoniem, Fusion Eng. Des. **51-52** (2000) 55.

**Apiccella, et al., PPCF **54** (2011) 035001.

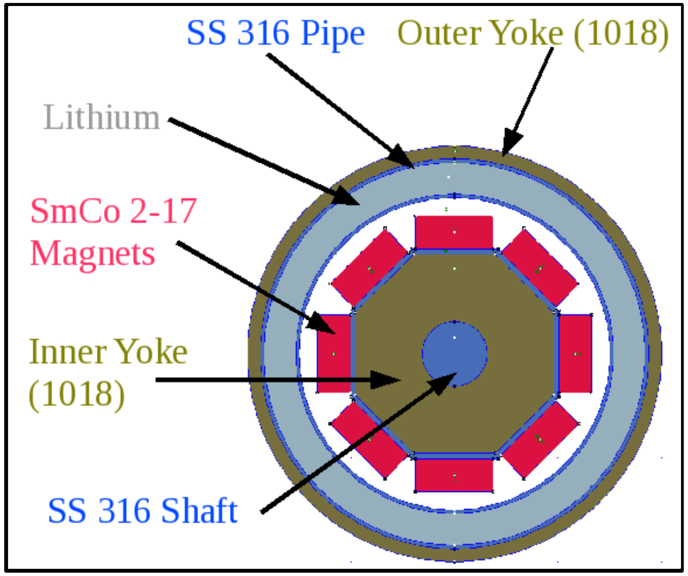
# Experiment construction underway to provide testbed for PFCs and demonstration of necessary technologies

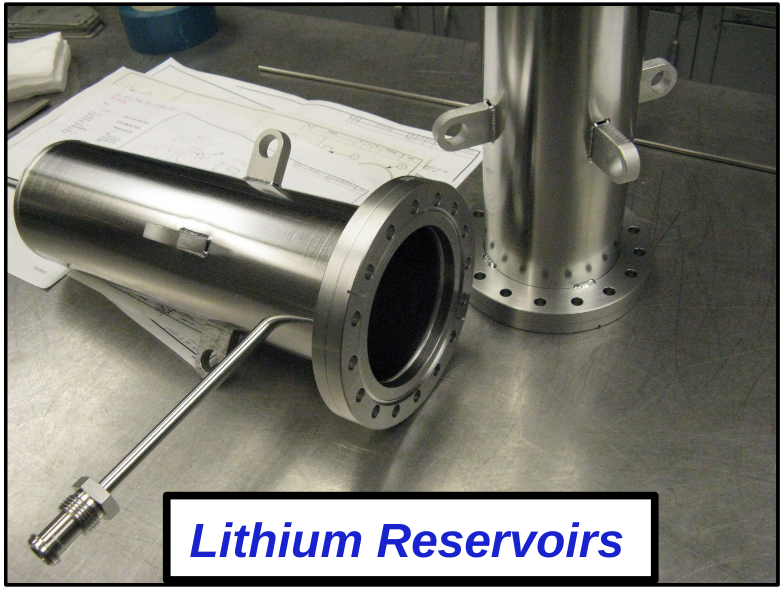
- Liquid lithium loop for demonstration of:
  - Safe operation of loop
  - Robust operation and maintainability
  - Develop control systems, handling procedures
  - And expertise for integration with tokamak systems
- PFC proof-of-principle tests
  - Couple to vacuum system
  - Demonstrate LM concepts in relevant vacuum environment

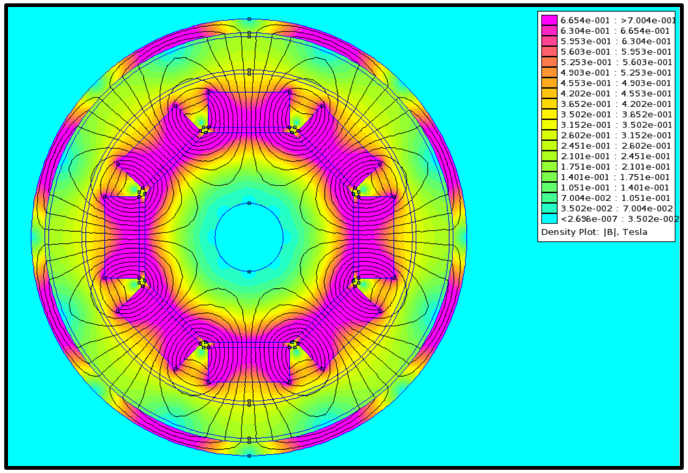
***Liquid Lithium Test Stand Loop Diagram***



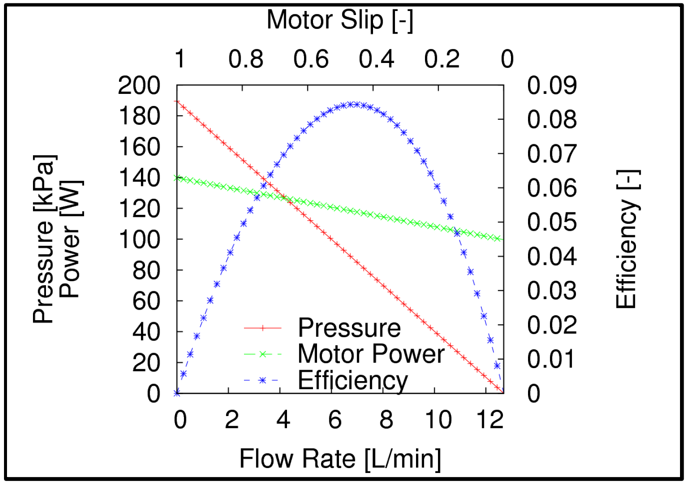
# EM pump designed, hardware currently being fabricated




**Lithium Reservoirs**



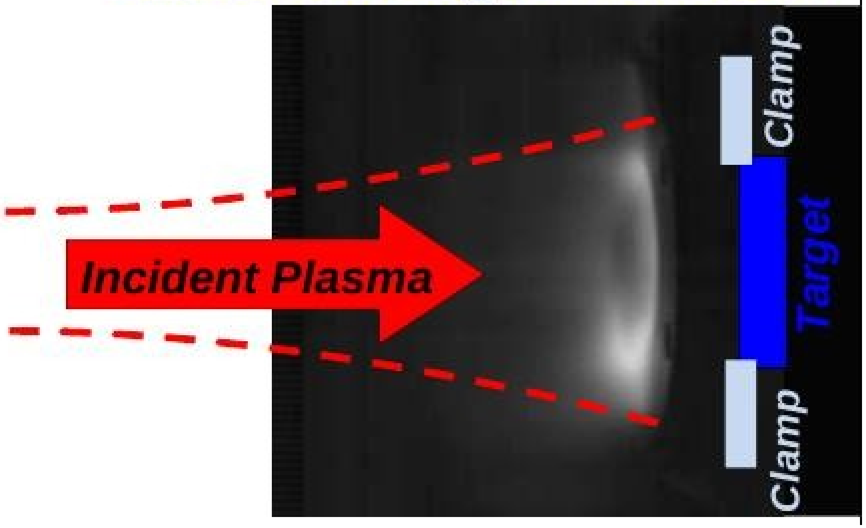
**Magnetic field simulation**



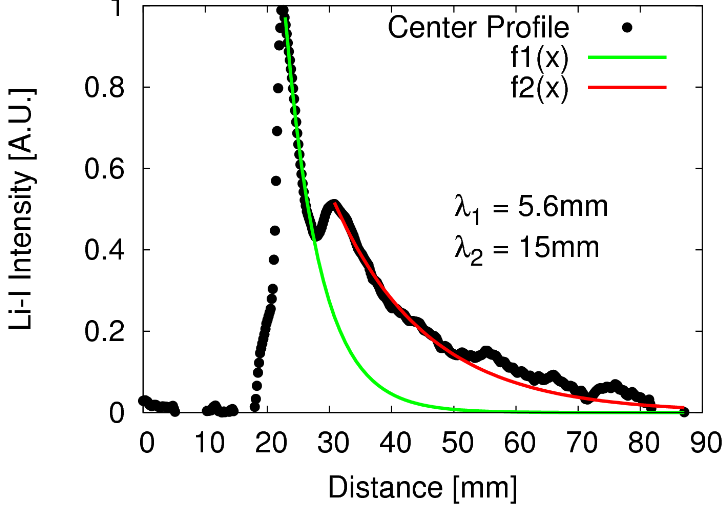
**Predicted Pump Performance**

# Initial lithium experiments at Magnum-PSI examining lithium material migration and oxide removal

***Fast-camera Image Li-I Emission***



***Li-I Emission Profile***



- Magnum-PSI
  - Linear plasma device
  - Divertor plasma simulator – density and temperature similar to NSTX divertor
  - Lithium evaporator commissioned for these experiments
  - Well-diagnosed
- Initial experiments on NSTX-U candidate PFC materials
  - ATJ graphite, TZM, W
  - Examine behavior of coatings under 5s discharges over range of Ne and Te

***See also T. Abrams PP8.00033 NEXT POSTER***

# Magnum-PSI plasmas similar to NSTX divertor conditions

| Parameter | Magnum-PSI | NSTX discharges with heavy lithium (Liquid Lithium Divertor) |
|---|---|---|
| Power [kW] | 60 | 4 MW NBI **(15MW NSTX-U)** |
| Pressure source [Pa] | $10^4$ | N/A |
| Pressure target [Pa] | <3 | ~0.1-1 (OEDGE modeling) |
| Ti target [eV] | 0.1-10 | 1-50? |
| Te target [eV] | 0.1-10 | 1-15 (non-Maxwellian) |
| Ni target [$m^{-3}$] | $10^{20}$-$10^{21}$ | $5\times10^{20}$ at SP |
| Ion flux target [$m^{-2}s^{-1}$] | $10^{24}$-$10^{25}$ | $2\times10^{23}$ at SP |
| Power flux [MW $m^{-2}$] | 10 | 2-5 at ~5 deg. Incl. **(25 unmit.)** |
| B [T] | 1.9 | 0.6 **(1T NSTX-U)** |
| Beam diameter [cm] | 10-1.5 | ~4cm FWHM |
| Pulse length [s] | 12-110 | 1s **(5s-10s)** |
| Target size [cm] | 3cm – 60x12 | Order~10cm |
| Bias [V] | $-100 < V_{target} < 0$ | $-20 < V_{floating} < 20$ |

# Simple transport models under development to understand local material transport

- Quasi-2D transport model developed
  - 1D mass continuity in x
  - 1D profile variation in r
- Emission simulated using ADAS rate coefficients
- **Next-steps: include ion fluid and recombination emission**

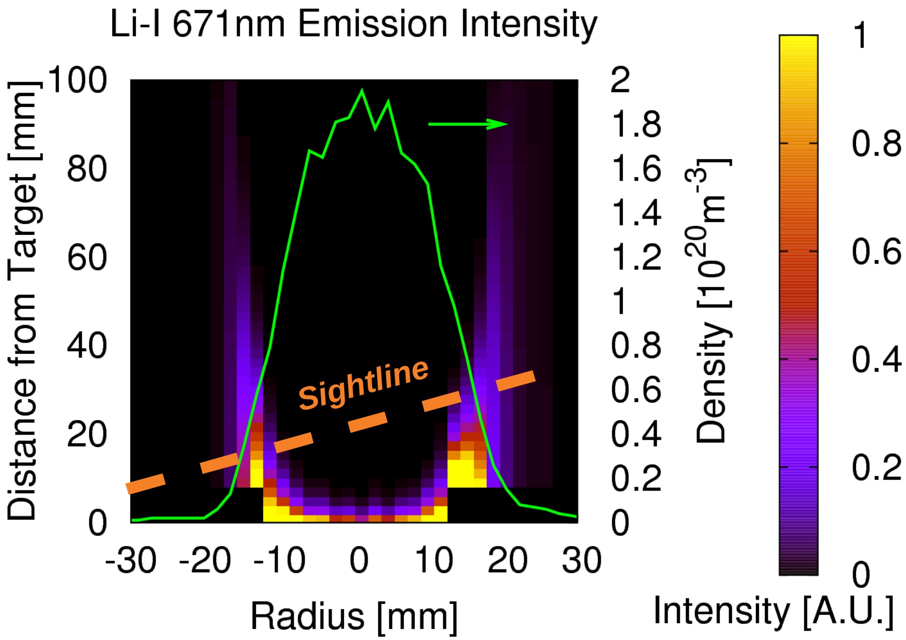
$$\frac{\partial N(r)}{\partial t}+\nabla\cdot(v N(r))=S_{iz}+S_{rec}$$

$$N(x,r)=N_0(r)\exp\left(\frac{-x}{\lambda_{iz}(r)}\right)$$

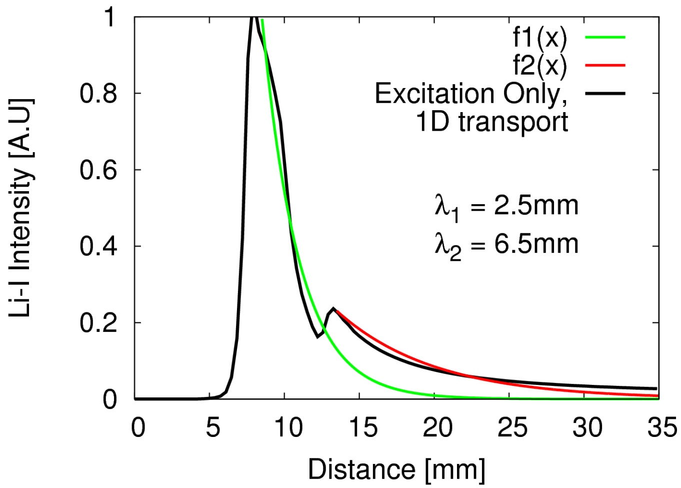
$$\lambda_{iz}(r)=\frac{v_{Li}}{N_e S_{eff}^{iz}(N_e(r),T_e(r))}$$

$$\Gamma^{Li}_{sputt.}=Y_{D\to Li}\Gamma^{D}_{inc.}=Y_{D\to Li}N_D(r)c_s(r)$$

$$N_0(r)=Y_{D\to Li}N_D(r)\frac{c_s(r)}{v_{Li}}$$



## *Simulated Diagnostic View*

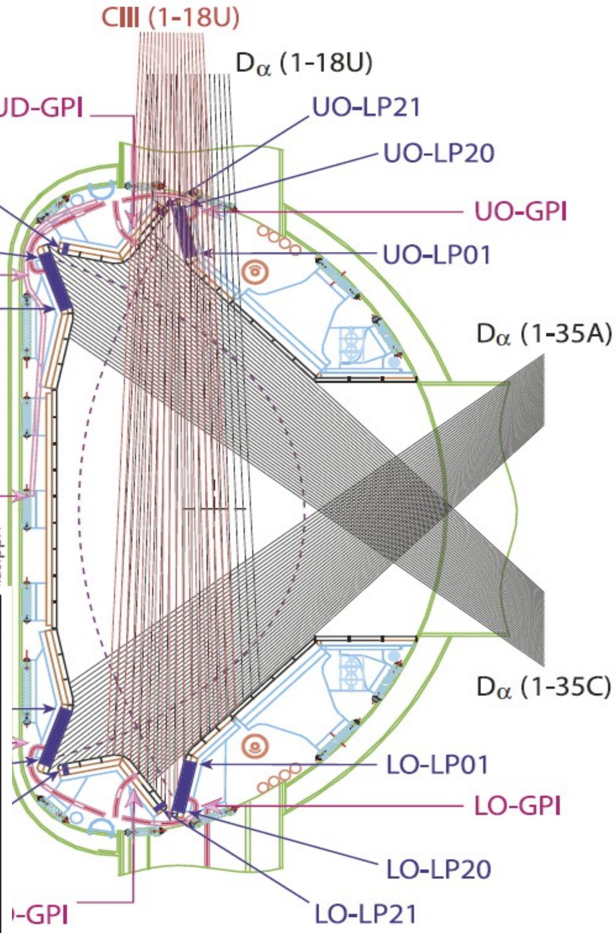


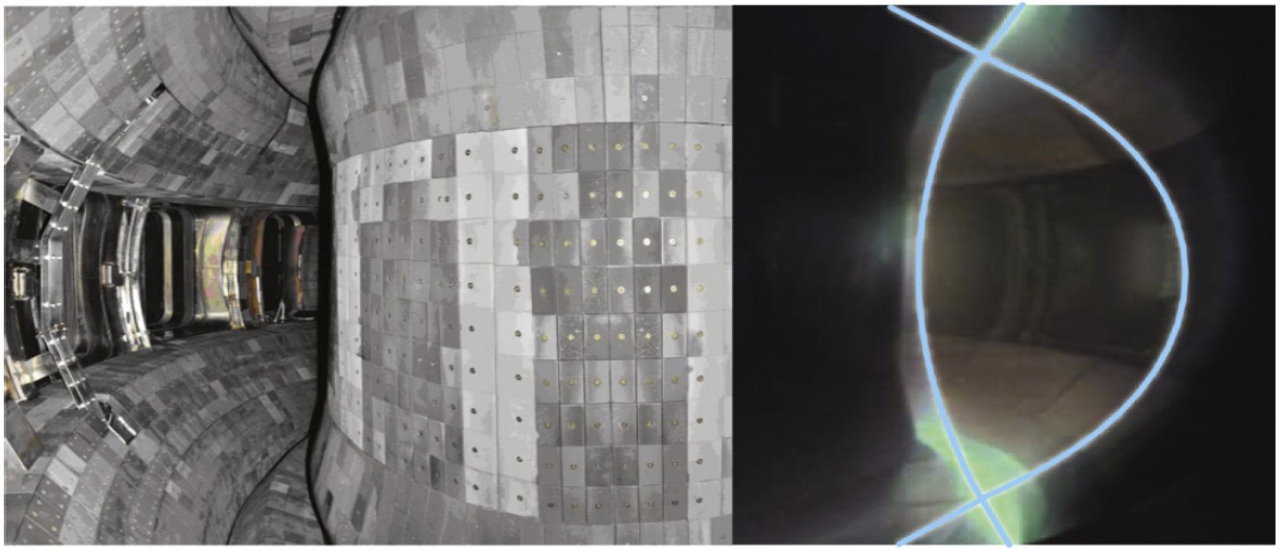
# Reprints

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

# Deposited lithium lifetime also explored on EAST

- ASIPP long-pulse device: EAST
  - Superconducting, lithium wall conditioning
  - Excellent diagnostic coverage
- Transient fueling with SMBI
  - Supersonic Molecular Beam Injector
  - Feed-back density control





*H. Guo, et al., J. Nucl. Mater. (2011)*

# SMBI provides pump-out measurement, diagnosed with divertor Langmuir probes

- Characteristic pump-out times related to local recycling
  - Source-free times between gas puffs
  - Analyze probe $I_{sat}$ signal while SMBI used for core-density feedback
- Local recycling affects pump-out
  - More recycling lengthens the characteristic time-constant
  - Limit of no recycling is the ion transit time in a flux-tube
- Same time response seen on filter-scope signals

$$V\frac{dn}{dt}=\Gamma A+S_0$$

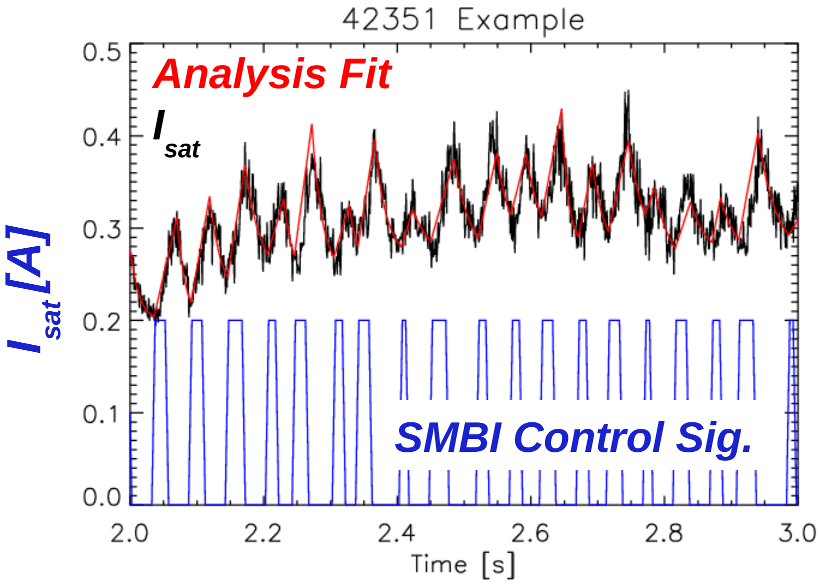
$$\Gamma=\Gamma_{out}-\Gamma_{\mathrm{in}}=(1-R)\Gamma_{out}$$

$$\Gamma_{out}A=I_{sat}\propto n c_s$$

$$\frac{dn}{n}=\frac{(1-R)c_s}{L_{char}}dt$$

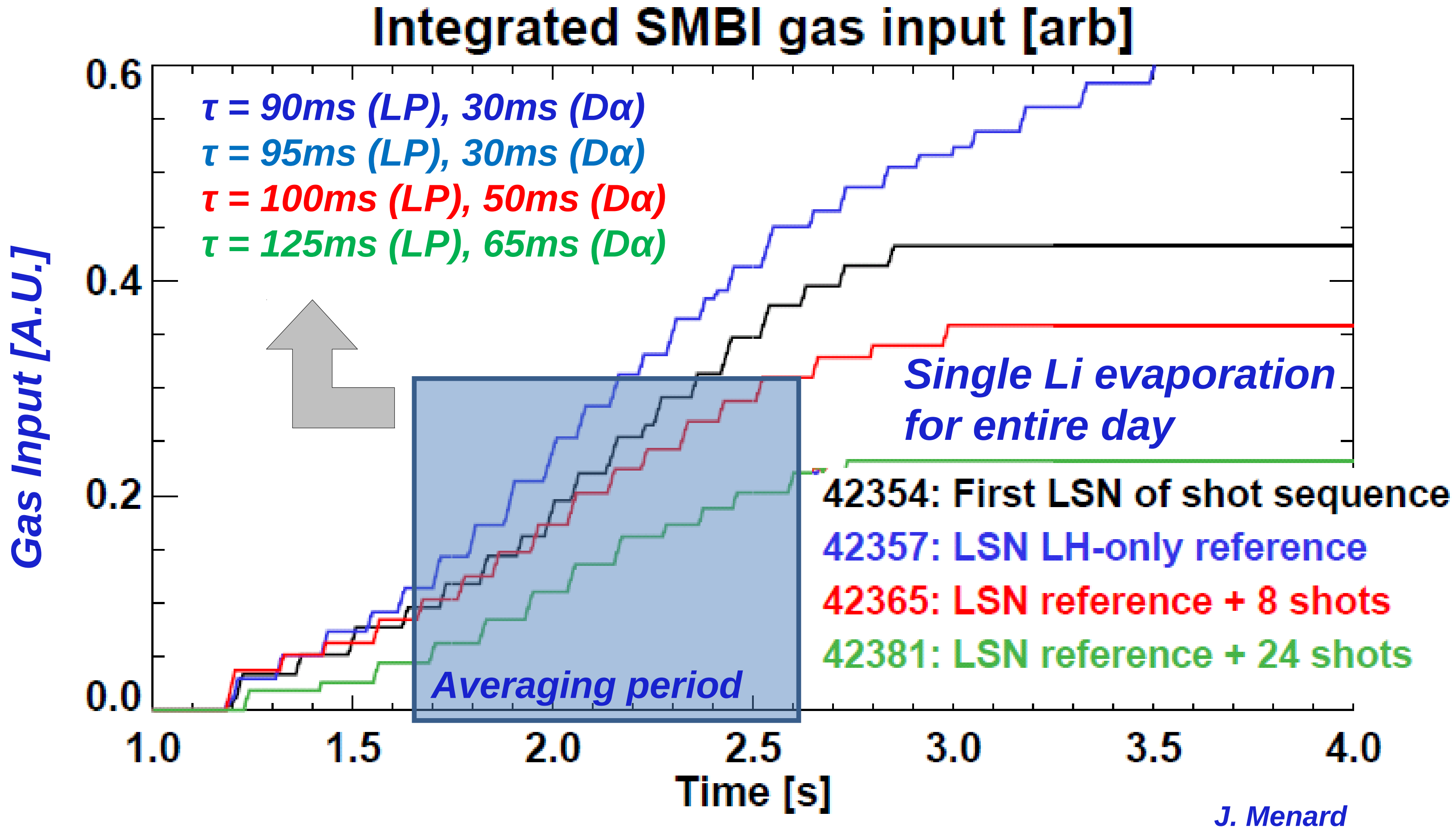
$$n(t)=n_0\exp\left(\frac{(1-R)c_s}{L_{char}}t\right)$$

$$\tau=\frac{L_{char}}{(1-R)c_s}$$



# Probe characteristic times vary in consistent manner with discharge fueling requirements

- Higher fueling requirements (integrated SMBI signal) correspond to shorter pump-out times implying lower recycling
- Discharge sequence implies Lithium coating efficacy decreasing w/ shot#



J. Menard

# NSTX-U lithium research proceeding through numerous collaborations during the upgrade period

- Liquid Lithium Divertor research has produced important results for NSTX-U
  - Capillary-restrained liquid metal PFC system demonstrated in divertor configuration
  - Oxygen impurities complicate test of lithium PFCs
  - Motivates *flowing system* development
- Magnum-PSI linear test-stand experiments exploring local material transport and compositional variations
  - Similar plasmas as observed in NSTX divertor
  - Ability to test candidate NSTX-U PFC materials
- EAST collaboration providing insight into lithium lifetime including fueling, diagnostic methods and analysis