NSTX-U

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NSTX-U 5-Year Plan for Materials and Plasma Facing Components

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and D.P. Stotler

NSTX-U PAC-33 Meeting
PPPL – B318
February 19-21, 2013

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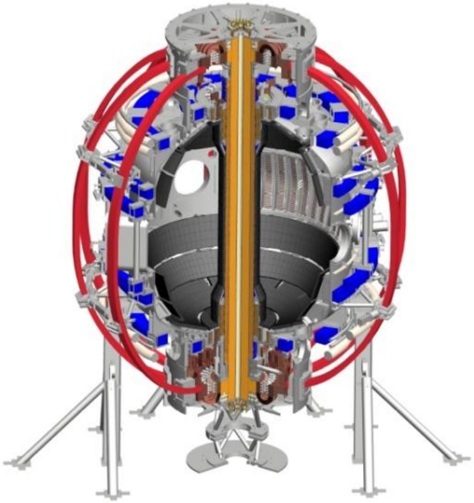

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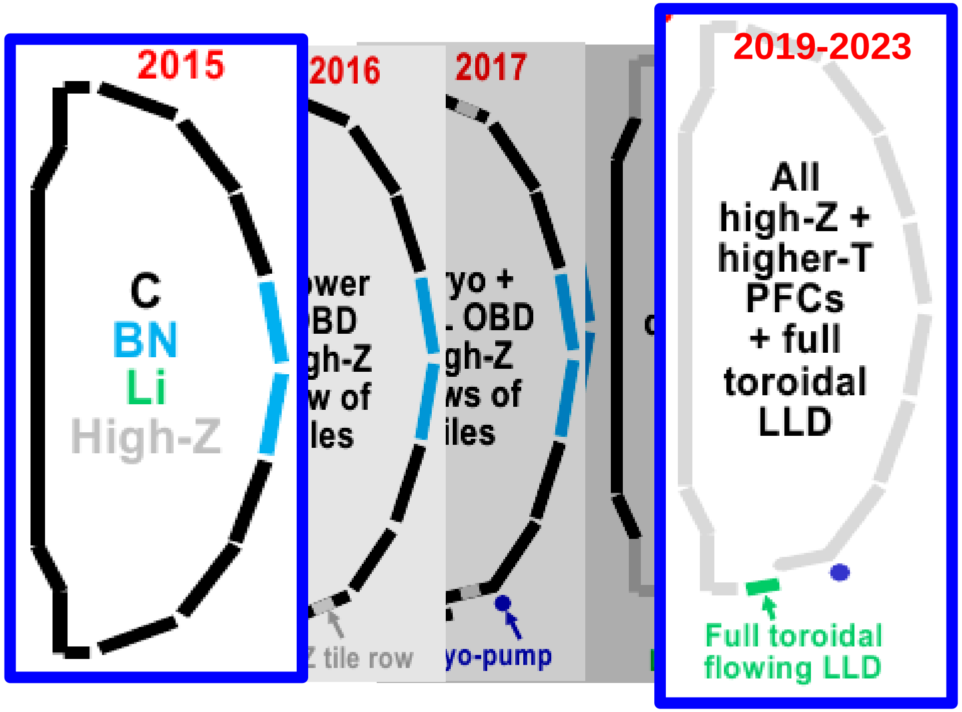
High-level goals for NSTX-U 5 year plan
(see Program Overview Talk)

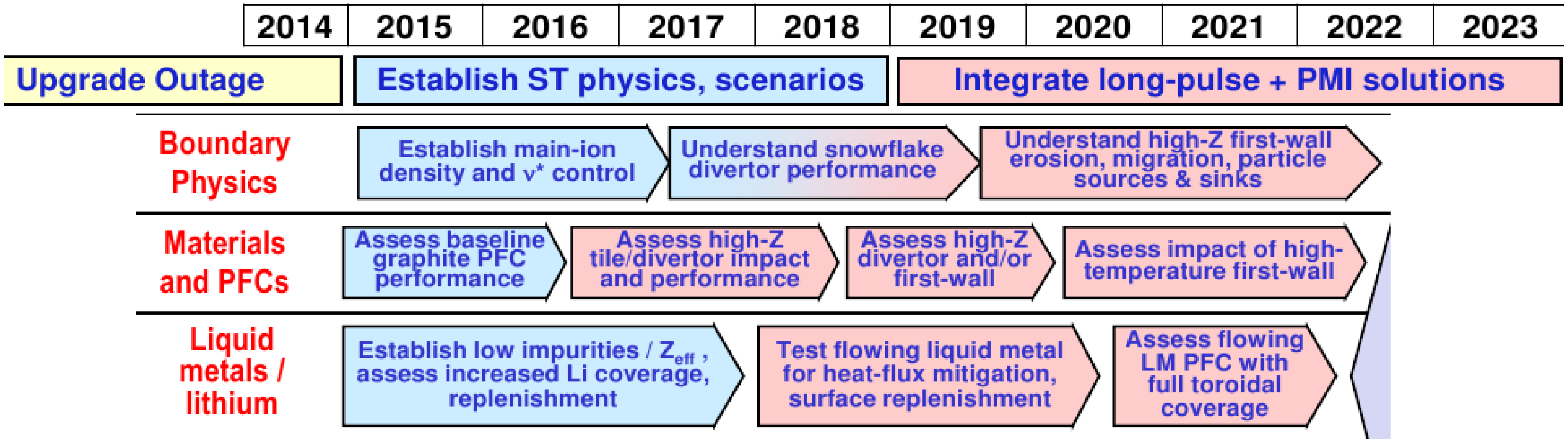
1. Demonstrate stationary 100% non-inductive at performance that extrapolates to ≥ $1 MW/m^2$ neutron wall loading in FNSF
   - Note: Non-inductive goal also supports ST-based PMI facility application
2. Access reduced ν^* and high-β combined with ability to vary q & rotation to dramatically extend ST plasma understanding
3. Develop and understand non-inductive start-up/ramp-up to project to ST-FNSF operation with small or no solenoid
   - Note: ST-based PMI facility could have solenoid for start-up/ramp-up
4. Develop and utilize high-flux-expansion "snowflake" divertor and radiative detachment for mitigating very high heat fluxes
5. Begin to assess high-Z PFCs + liquid lithium to develop high-duty-factor integrated PMI solution for SS-PMI, FNSF, beyond

NSTX-U long-term objective is to perform comparative assessment of high-Z and liquid metal PFCs (see Maingi talk)

- Conversion to all-metal PFCs provides opportunity to to examine role of PFCs (including liquids) on integrated scenarios with good core, pedestal, div.

- NSTX-U has two emphases for addressing power exhaust and PMI issues for next step devices
    - Magnetic topology and divertor configuration
    - **Self-healing/replenishable materials (e.g. liquids)**





2014 2015 2016 2017 2018 2019 2020 2021 2022 2023

Upgrade Outage | Establish ST physics, scenarios | Integrate long-pulse + PMI solutions

Boundary Physics: Establish main-ion density and ν* control → Understand snowflake divertor performance → Understand high-Z first-wall erosion, migration, particle sources & sinks

Materials and PFCs: Assess baseline graphite PFC performance → Assess high-Z tile/divertor impact and performance → Assess high-Z divertor and/or first-wall → Assess impact of high-temperature first-wall

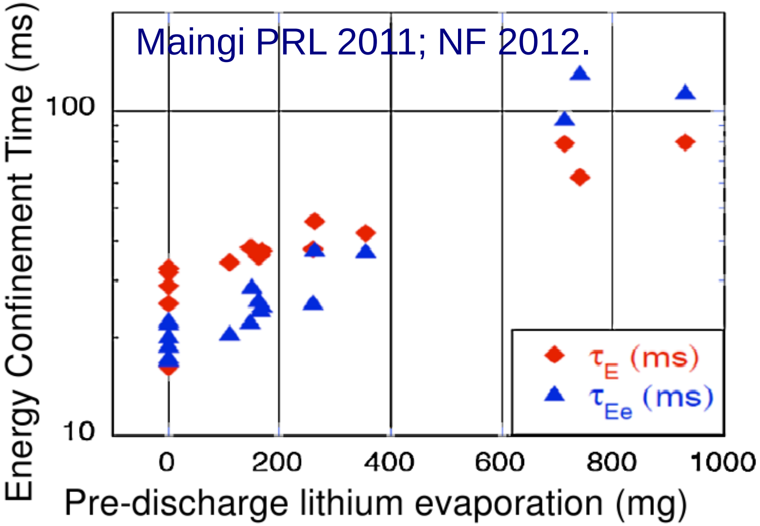
Liquid metals / lithium: Establish low impurities / Z_{eff}, assess increased Li coverage, replenishment → Test flowing liquid metal for heat-flux mitigation, surface replenishment → Assess flowing LM PFC with full toroidal coverage

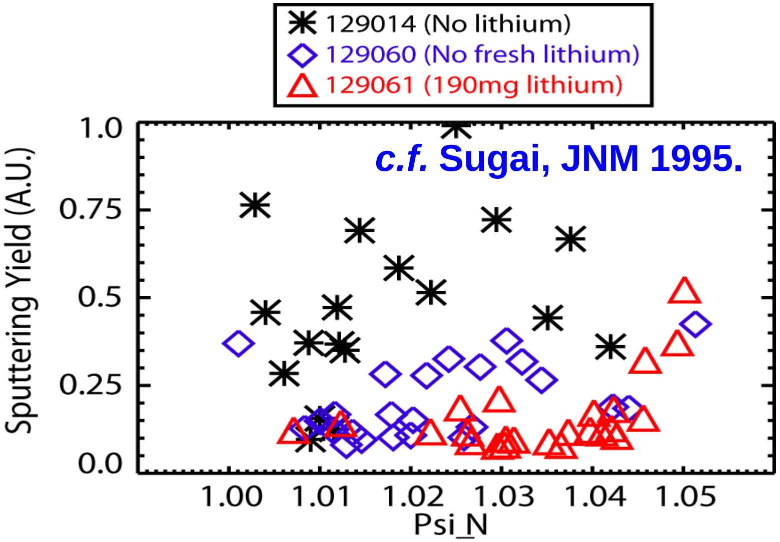
M&P research will develop understanding of material migration and heat-flux handling of high-Z and liquid Li PFCs

- Understand lithium surface-science for long-pulse PFCs
  - Assess impact of more complete Li coverage
  - Use the new Material Analysis and Particle Probe (MAPP) and laboratory studies to link tokamak performance to PFC surface composition
- Unravel the physics of tokamak-induced material migration and evolution
  - Confirm erosion scalings and evaluate extrapolations
  - Determine migration patterns to optimize technical solution
- Establish the science of continuous vapor-shielding
  - Determine the existence and viability of stable, vapor-shielded divertor configurations
  - Determine core compatibility and extrapolations for extended durations and next-step devices

Li wall conditioning results in confinement improvements and reduction in divertor carbon source

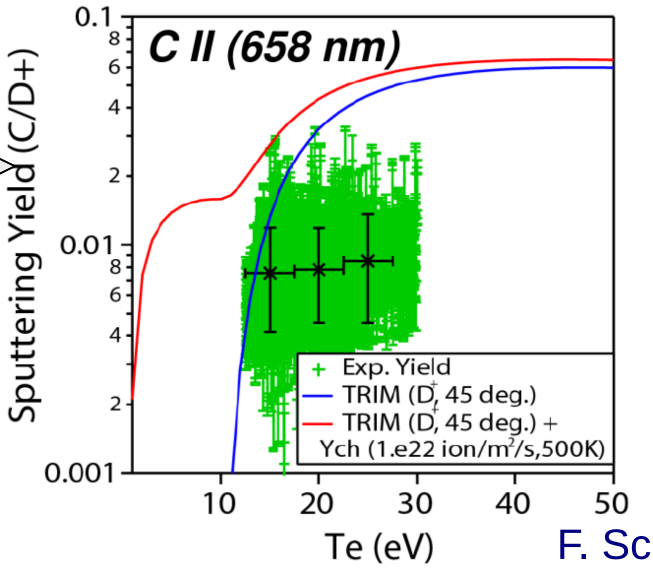
- Confinement increases continually with pre-discharge lithium application
    - Deuterium inventory stationary (see J. Canik talk)
    - ELM elimination results in core carbon accumulation (see J. Canik talk)
- Carbon influx in divertor reduced after application of lithium conditioning





Plasma spectroscopy and target Langmuir probes provide gross yield

Carbon sputtering yield with lithium

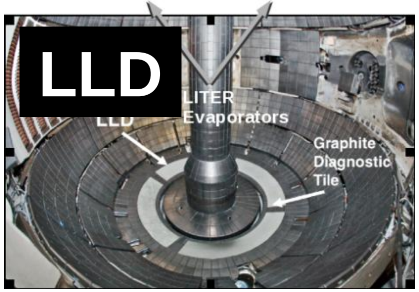


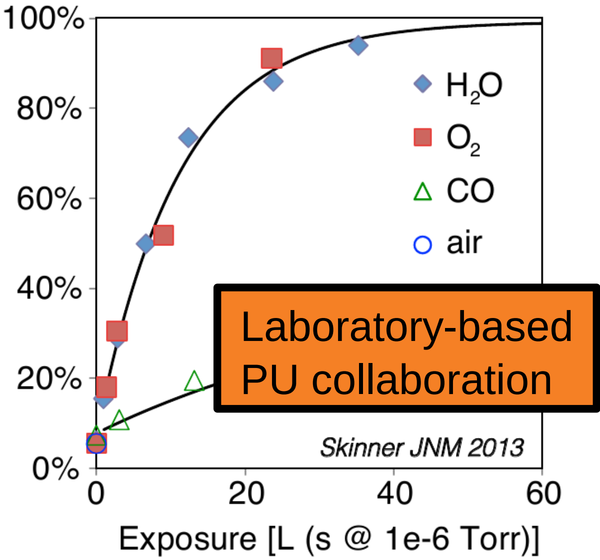
F. Scotti

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 being investigated in laboratory
    - Molecular dynamics simulations of Li-C-O show increased D uptake (Krstic, PRL 2013)
    - Non-zero **oxygen** sputter yield from contaminated surfaces
    - No indications of O degrading plasma performance (so far)
    - Motivates flowing system to control impurity accumulation

Oxygen uptake by Li coating on Mo

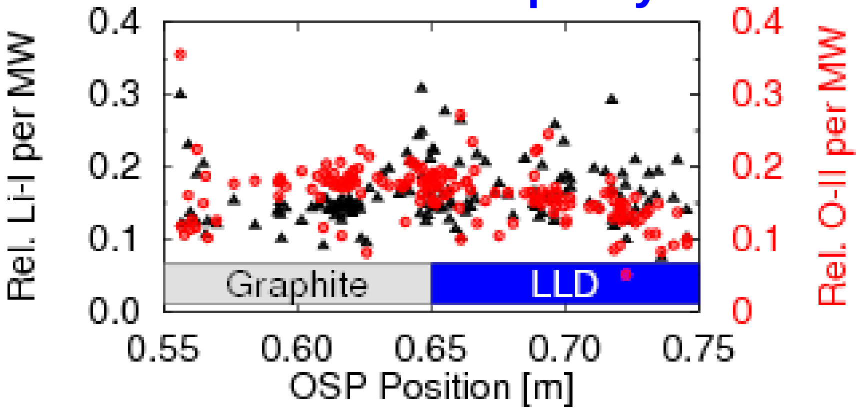




Laboratory-based PU collaboration

Skinner JNM 2013

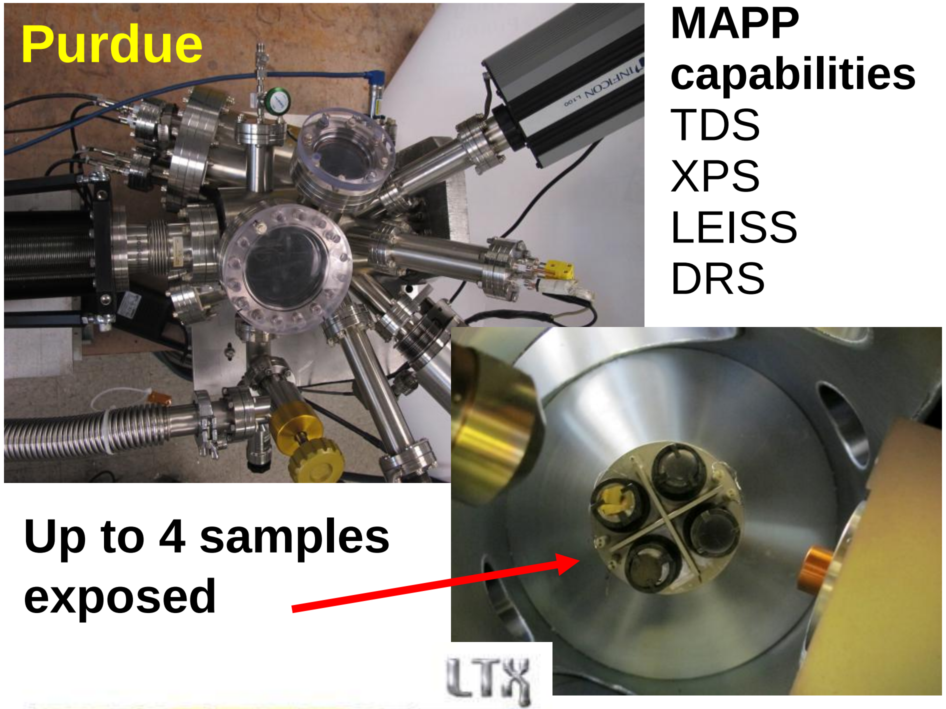
NSTX whole-divertor impurity emission



Jaworski, IAEA 2012

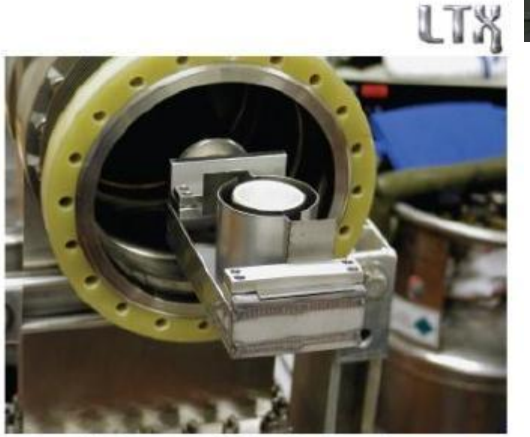
MAPP will be a key diagnostic for bridging the gap between discharge performance and lab-based surface science

- Determine material composition and surface chemistry inside tokamak
  - Exploit MAPP capabilities to link with surface science labs at PPPL, Purdue, U-Illinois
  - Identify role of contaminants in Li PMI
  - Being prepped for use in LTX this year
- Optimize areal coverage of wall conditioning techniques
  - Diffusive evaporations and upward-facing evaporators
  - Examine energy confinement, impurity production, particle control...



MAPP capabilities
TDS
XPS
LEISS
DRS

Up to 4 samples exposed



Y_2O_3 crucible, Ta heater
➤Tested to 700 °C

Upward evaporator under development for NSTX-U

Thrust 1 research plan makes use of multiple tools to unravel lithium surface-science during transition to high-Z PFCs

- FY14 – Surface science laboratory and LTX experiments
  - Utilization of MAPP to examine high-Z substrates in LTX
  - Measurements of deuterium retention in lithium on high-Z substrates in laboratory experiments (PU collaboration)
- FY15 – Comparison of boronization with more complete PFC coverage by Li, establish baseline performance data sets
  - Diffusive evaporation and MAPP to identify surface chemistry changes during transition to lithium wall conditioning
  - Prepare high- and low-triangularity discharges to prep for high-Z tiles
- FY16 – High-Z tile installation, upward evaporation
  - Examine role of evaporation *rate* on Li efficacy
  - Determine how high-Z substrate affects coating performance
- FY17-18 – High-Z tiles and vapor shielding
  - Determine high-temperature (T>500C via plasma heating), coated PFC performance and role of impurities in lithium PMI throughout machine

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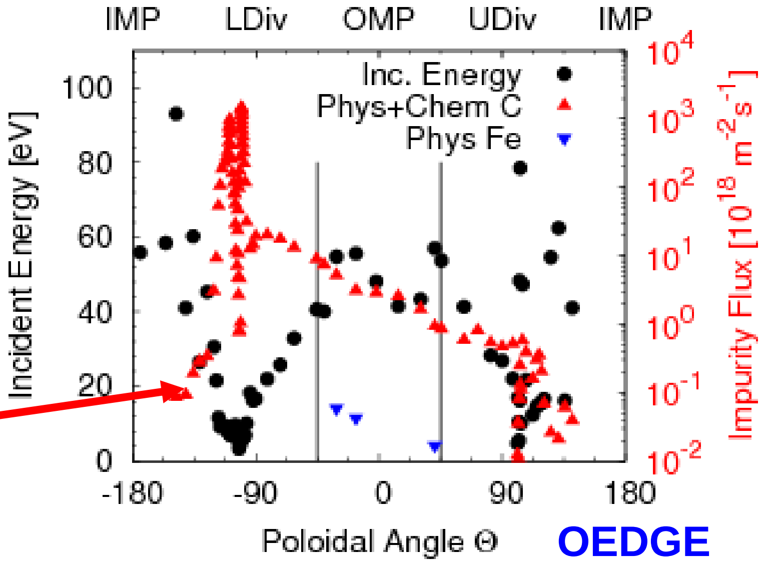
NSTX discharges already indicate significant first-wall erosion and NSTX-U will extend this erosion by factor of 10

- Simplified estimates indicate large amounts of wall erosion in next-step devices
  - Estimates based on charge-exchange neutrals at the edge
  - Several simplifications (e.g no neutral pressure dep., poloidal uniformity)
- Plasma + neutral transport codes enable modeling of these processes
  - Fluid codes: UEDGE, SOLPS, OEDGE; Neutral codes: EIRENE, DEGAS2; impurity codes: DIVIMP
  - Mean neutral energies in NSTX discharge 40-90eV
  - Flux to walls poloidally non-uniform (peaked near outboard LSN)
  - ~20% of carbon flux from first wall

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

$$\approx Y_{sputt,cx}\frac{f_{cx}P_{heat}/E_{cx}}{S_{plasma}}$$

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)



OEDGE

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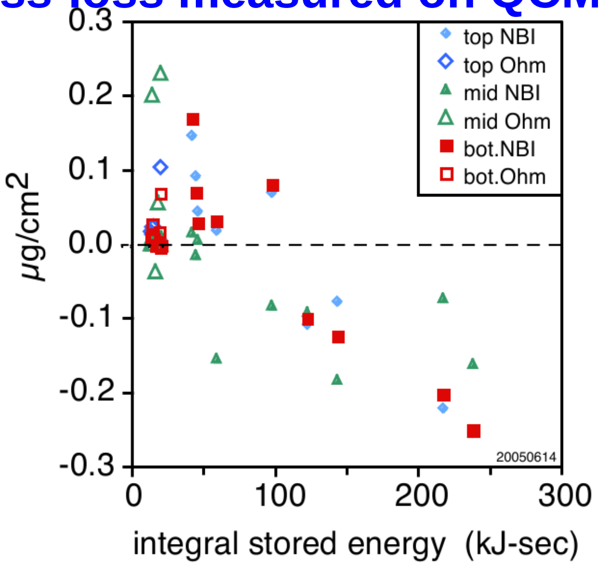
[1] P.C. Stangeby, JNM 2011.

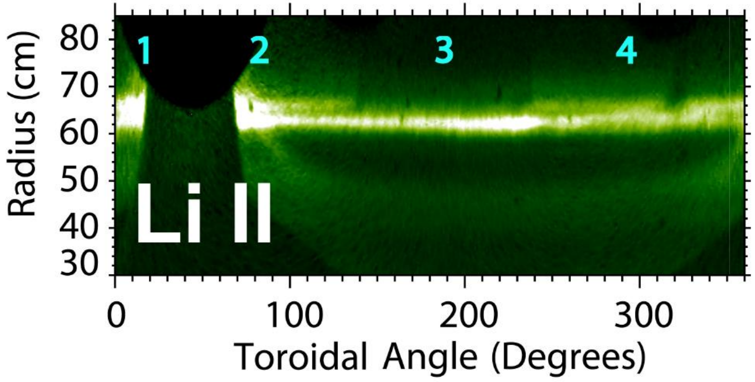
Complementary erosion diagnostics will enable identification of erosion/redeposition patterns

- NSTX-U will expand coverage of erosion diagnostics
    - QCMs and witness samples at multiple first-wall locations (4x poloidal locations, 20 witness plates in NSTX)
    - Marker tiles will be used in high-heat flux regions
    - MAPP to be upgraded with QCM allowing simultaneous mass/composition measurements
    - **Net erosion** diagnosed with mixture of inter-shot and campaign-integrated diagnostics
- Expanded suite of plasma diagnostics to constrain plasma models
    - Langmuir probes for local n_e, T_e, potential (Div. Thomson incremental)
    - **Gross erosion** via plasma spectroscopy

Mass-loss measured on QCMs



Full-toroidal camera coverage



Skinner, JNM 2007 Scotti, RSI 2012

Thrust 2 research will quantify material erosion/migration on first-wall and in divertor for both high-Z and low-Z surfaces

- FY14 – Data analysis and test-stand experiments to prepare for tokamak experiments
  - Continue analysis of NSTX discharges to optimize diagnostics
  - Magnum-PSI experiments to measure gross and net erosion at high Temp.
- FY15 – Make initial assessment of material erosion and migration in NSTX-U discharges, compare B vs. Li discharge conditions
  - Utilize MAPP to measure composition of films, compare to Magnum-PSI material evolution data and models; measure gross and net erosion
  - Prepare for high-Z tile upgrade with low- and high-triangularity data sets
- FY16 – Establish first-wall erosion scalings, protection of high-Z substrate and compatibility with high-performance discharges (e,g. high-Z impurity accum.)
  - Examine dependence on edge neutral pressure, input power, pulse length
  - Determine impact of synergistic operations on material migration (e.g. impurity seeded divertors, snowflake configuration)
- FY17-18 – Determine impact of upper divertor high-Z tiles and the impact of vapor-shielded regime on material migration

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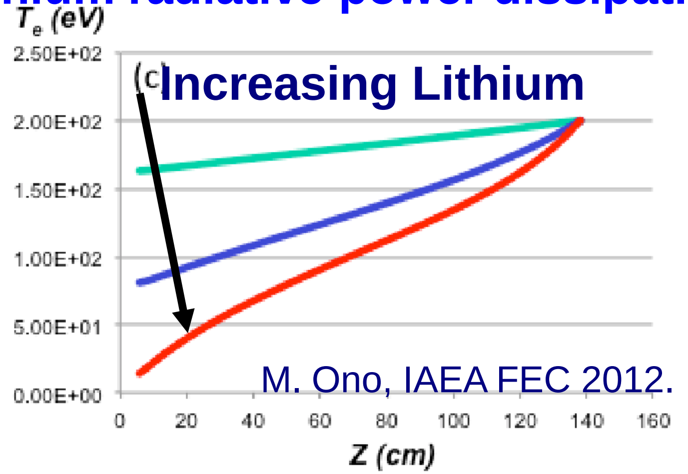
High temperature lithium surface may be able to provide a self-healing surface and intrinsic low-Z impurity radiation source

- Lithium vapor cloud can potentially provide effective power and pressure loss at divertor target
  - Non-coronal Li radiation
  - Li vapor pressure vs. plasma press.
- Capillary-Porous System targets have dissipated large incident heat fluxes - tested to 25MW/m^2 limited by Li inventory (Evtikhin JNM 2002)
- Diagnosis in NSTX-U via complementary diagnostics
  - Langmuir probes for target pressure, n_e, T_e
  - Optical, VUV emission and bolometry for P_{rad}
  - DBIR thermography and TCs for heat flux and energy deposited

FTU CPS

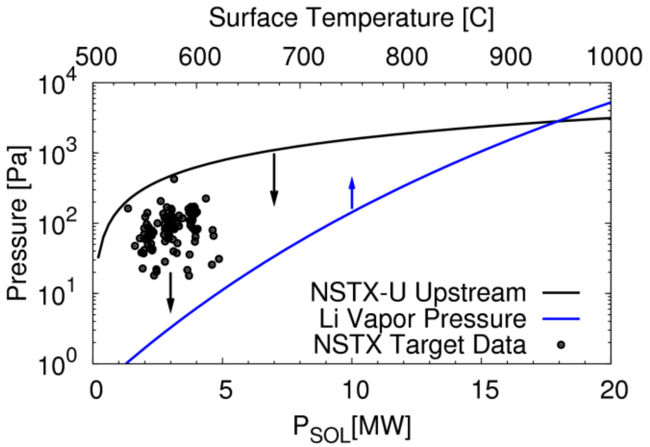
Lithium radiative power dissipation



M. Ono, IAEA FEC 2012.

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

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



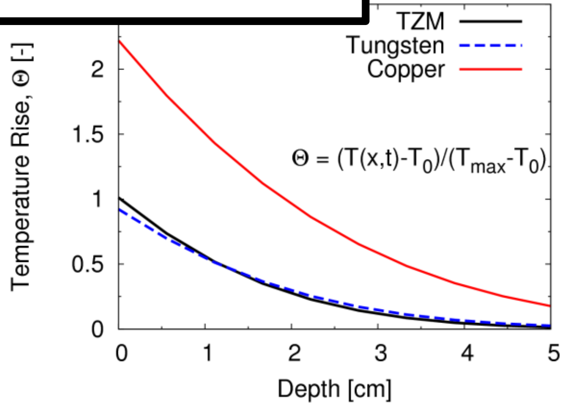
Thrust 3 will establish the existence of vapor-shielded regime and assess compatibility with high-performance discharges

- FY14-15 – Assess the high Li influx regime (w/ Thrust 2)
  - Complete high-Z tile design for installation in year 3
  - Conduct high temperature experiments on Magnum-PSI
  - Validate plasma transport and atomic physics data bases for high-density, high-Li fraction plasmas
- FY16 – Validate high-Z substrate design and reference performance
  - Boron vs. Lithium experiments diverted directly onto high-Z tiles
  - Assess power and pressure balance in the NSTX-U SOL
- FY17 – Extend operational space of vapor-shielded regime
  - Determine core compatibility with vapor-shielded divertor plasmas
  - Determine vapor-shield performance with varying SOL pressures, input powers, connection length
  - Assess transient loading response (ELM loads)
- FY18 – Determine flowing-system replenishment needs due to net erosion to extend vapor-shielding regime beyond 1s tests

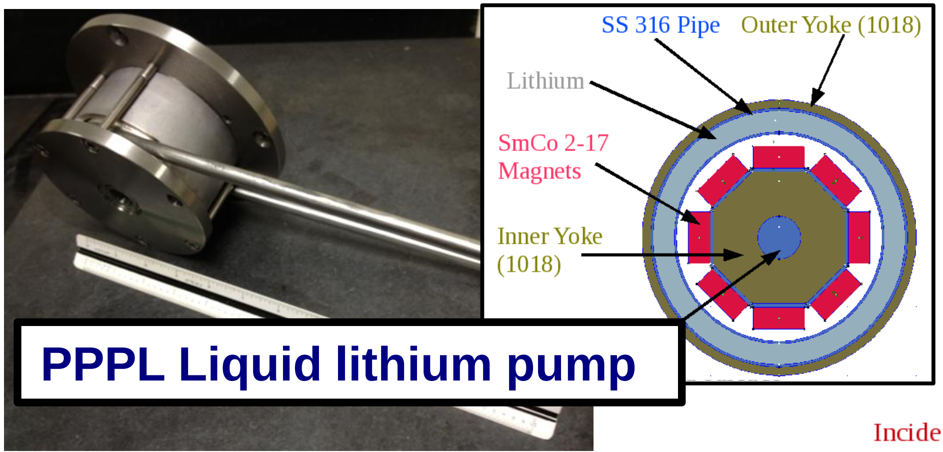
Parallel plasma-facing component research and development to support high-Z tile upgrade and vapor-shielding studies

- High-Z PFC assessment
  - Lamellae used on other machines (e.g. JET-ILW, CMOD) to reduce stress
  - Both compatible with Li
- Flowing liquid lithium PFC development underway
  - Conceptual design and initial engineering assessment of long-pulse, LM-PFCs underway
  - Basic liquid-metal loop technologies being assembled for testing

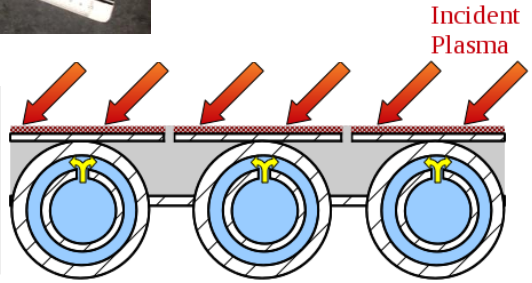
Recrystallization limits



Const. Surface q_0 $10MW/m^2$ for 5s



PPPL Liquid lithium pump



Actively-supplied, capillary-restrained, gas-cooled LM-PFC

NSTX-U Five-year plan will begin assessment of a high-Z PFC and liquid lithium integrated PMI solutions for next steps

- M&P research will contribute to the understanding of material migration and evolution to prepare for next-step devices
  - Study mixed material issues with Li, C, O and high-Z studies
  - Examine whole machine material erosion, migration, re-deposition
  - Begin assessment of high-Z PFCs with low-Z coatings

- M&P research will advance liquid metal PFCs as an innovative solution to handling fusion exhaust power and particle loads
  - Establish the science of continuous vapor shielding with high-temperature, liquid lithium PFCs and determine the compatibility with high-performance discharges
  - Perform side-by-side comparison of a high-Z PFC vs. a liquid metal PFC to inform next-step devices

Backup

PAC-31 response slide 1

- Diagnostic priorities for M&P research plan (divertor)
  - Top priority: divertor Langmuir probe array, divertor spectroscopy (cameras+spectrometers), DBIR thermography, MAPP, QCMs, marker tiles, witness samples, divertor bolometry
  - Highly desirable: SOL flow measurements (e.g. Mach probes), remote material analysis (e.g. LIBS), spectrally and spatially resolved VUV spectroscopy, hydrogen sensors, time-resolved pressure gauges

PAC-31 Response slide 2

- PAC 31-8: The PAC suggests that a much clearer plan is needed to better clarify the evolution from carbon to all-metal walls. Effects of the high-Z wall on the PWI and plasma performance should be determined without influence of Li layers, i.e., prior to Li studies on the metal walls...
  - This is explicitly included in the 5-yr plan which makes use of multiple years examining the transition from boronized wall conditions to lithiated conditions. The timing of a bare-wall run campaign is still being debated and will depend on run-time allocation for such an endeavour.

PAC 31 response slide 3

- PAC 31-13: ...The NSTX-U team needs to address the engineering issues of high-Z tile edge design and configuration, especially leading edges that intercept parallel plasma flow along the magnetic field, B. This is an important issue to reduce erosion and melting, in particular, for the snowflake divertor...
    - The plan for high-Z tile implementation, at present, is to limit the installed tiles to the outer divertor to mitigate risk. In these locations, the angle of incidence is higher which alleviates leading edge effects, but still carries large incident power fluxes when diverted in this region of the device. Examining erosion of the high-Z tiles is a central element of the M&P program and will be used to inform design decisions for high-Z PFCs to be implemented in the inner divertor.

PAC 31 response slide 4

- PAC 31-19: The reduction of peak heat flux with Li deposition was documented, as well as the narrowing of the heat-flux radial profile for the same power as no-Li discharges. Just where the remaining power went is not well understood, though likely it is distributed via impurity radiation...
  - Examining the usage of lithium impurities as a radiator is the focus of Thrust 3 in M&P TSG. Analysis of the discharges in question is ongoing, but made difficult by diagnostic coverage present in NSTX (e.g. sparse probe and bolometer coverage). Diagnostic coverage in NSTX-U will be improved to better understand the physics involved.

PAC 31 response slide 5

- PAC 31-21: Hydrogenic and impurity particle recycling & transport in the inboard divertor and wall can contribute to the overall sources of these particles, and it is thus important to understand such processes in this region when designing PFCs appropriate for ST tokamaks. Simulation and experiment studies such as local Li coating and divertor pumping from the private region will help evaluate their influence on divertor and core plasmas. It is also important to measure influx profiles of intrinsic D and Li, and seeded impurities.
  - A broader analysis of NSTX discharges is planned in the years leading up to NSTX-U operations. Improved diagnostic coverage will improve confidence in the accuracy of plasma reconstructions and fluid models as an aid to interpreting the experimental measurements.

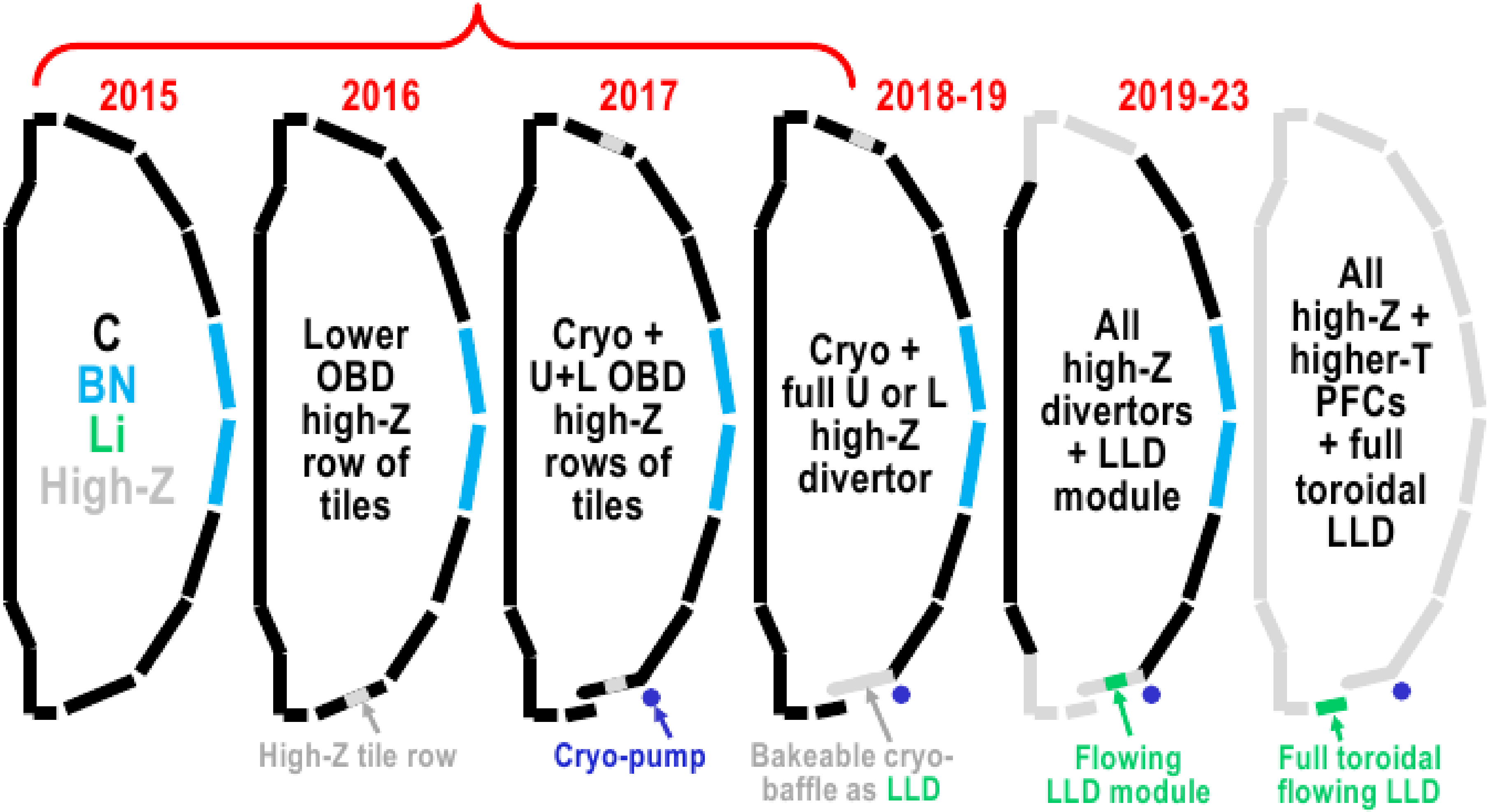
PAC 31 response slide 6

- PAC 31-28: Compatibility of impurity seeding with Li layers (impurity retention and Li erosion) and the feedback system should be investigated at this stage
  - Noble gas elements are chemically compatible with lithium and the measurement of erosion rates is a central thrust of this TSG. The existence of boronization campaigns and end-of-run experiments may permit the use of chemically reacting impurities such as nitrogen and will be considered.

NSTX-U 5YP PMI goal: implement cryo-pumping and *begin* transition to metallic PFCs to support PMI/FNSF next-steps

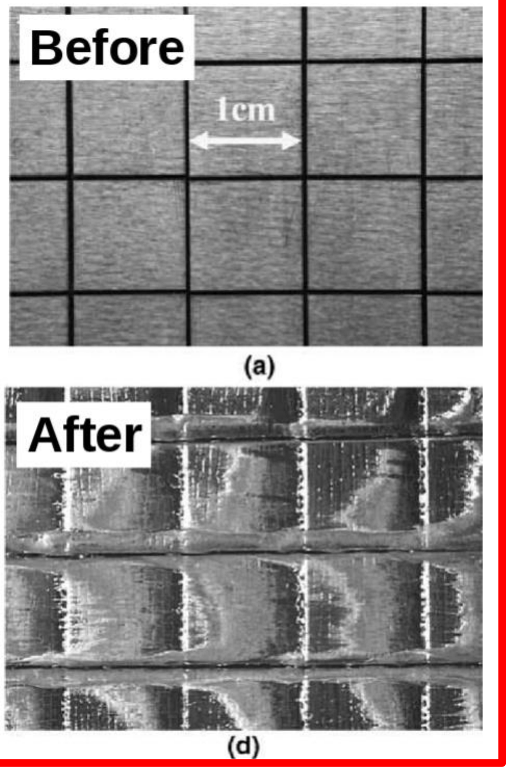
- Long-term goal: assess compatibility of high τ_E and β + 100% NICD with metallic PFCs

Nominal 2014-18 5 year plan steps for implementation of cryo-pump + high-Z PFCs + LLD

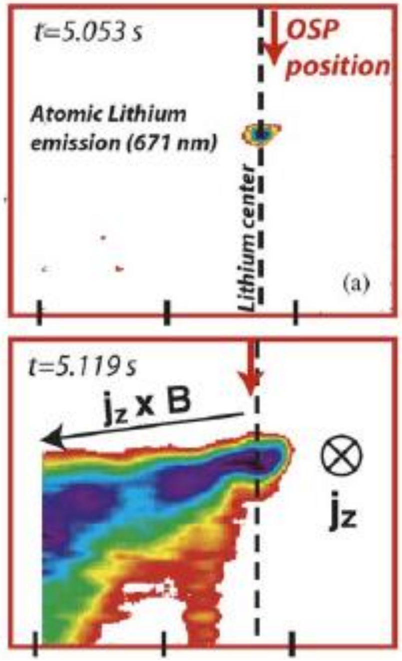


Taming the plasma-material interface is a grand-challenge for magnetic fusion energy

- Creation of economical fusion energy depends on component lifetime
- Significant uncertainty in how existing PFC candidates will extrapolate
  - Solids look promising but...
  - Liquids look promising but...
- PMI challenge must be met to enable a high-power-density, long-pulse facility such as FNSF



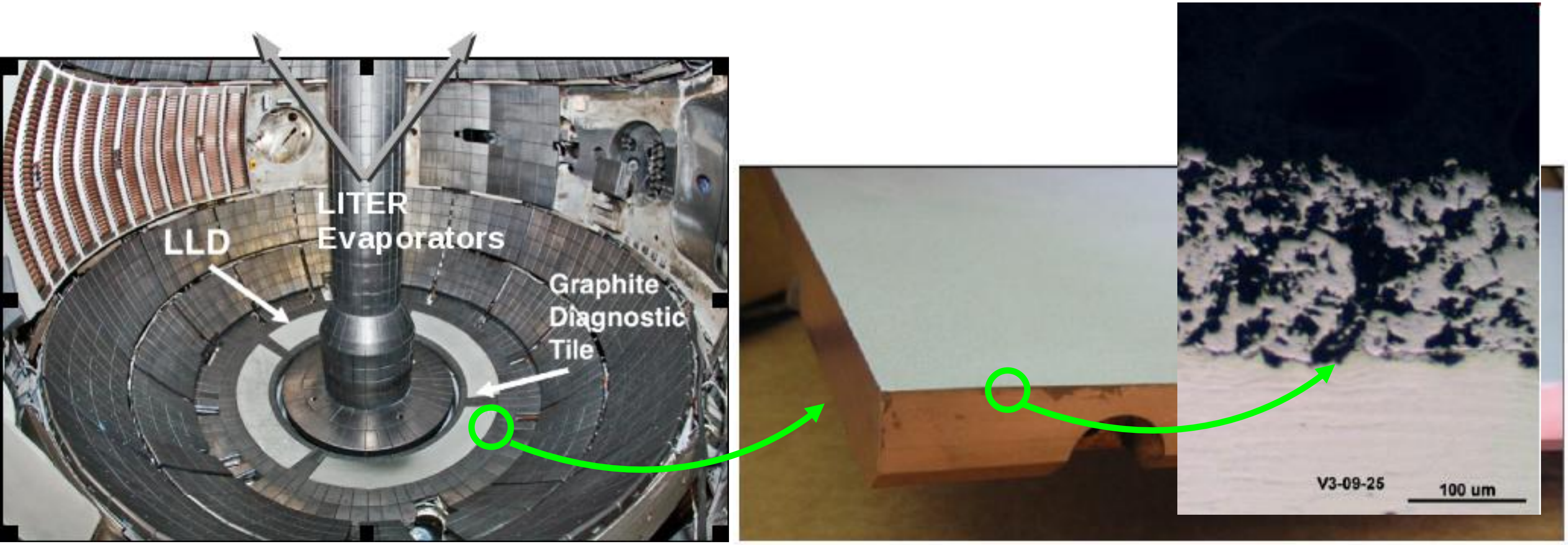
Tungsten melting under ELM-like bombardment (Federici, JNM 2005)



Lithium ejection in DIII-D (Whyte, FED 2004)

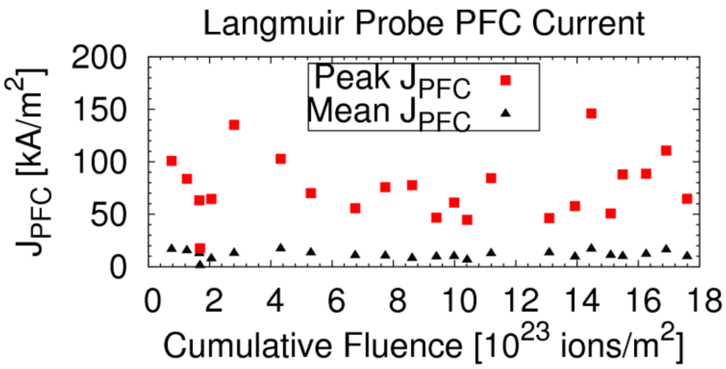
NSTX performed liquid-metal PFC experiments with the Liquid Lithium Divertor (LLD)...

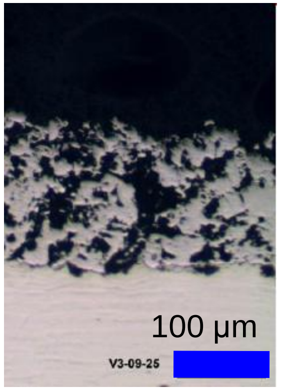
- Liquid lithium divertor installed for FY2010 run campaign
- 2.2cm copper substrate, 250um SS 316, ~150um flame-sprayed molybdenum porous layer; LITER loaded
- 37g estimated capacity, 60g loaded by end of run



...and demonstrated stable liquid metal PFC operation in a diverted tokamak

- Large transient currents measured with Langmuir probes, LLD porous geometry limits wavelength

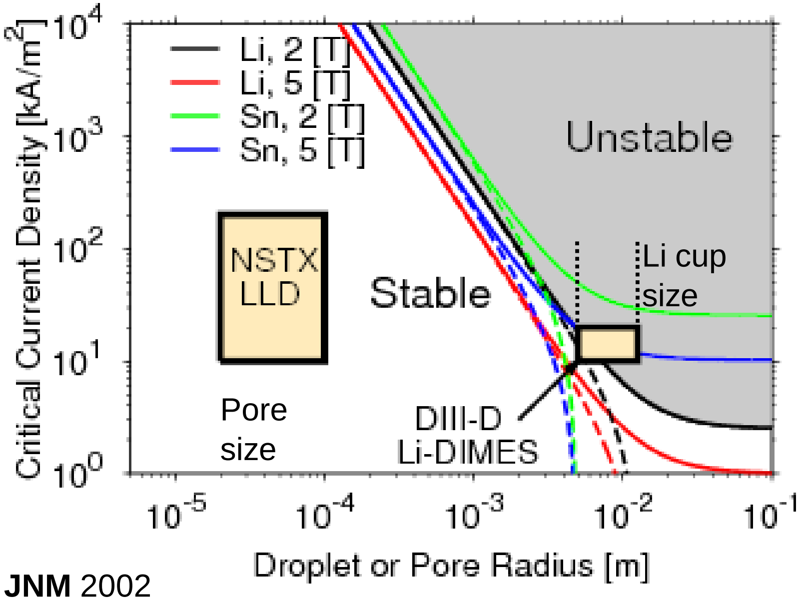




- Raleigh-Taylor analysis provides marginal stability curves; NSTX LLD stable

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

For the fastest growing modes



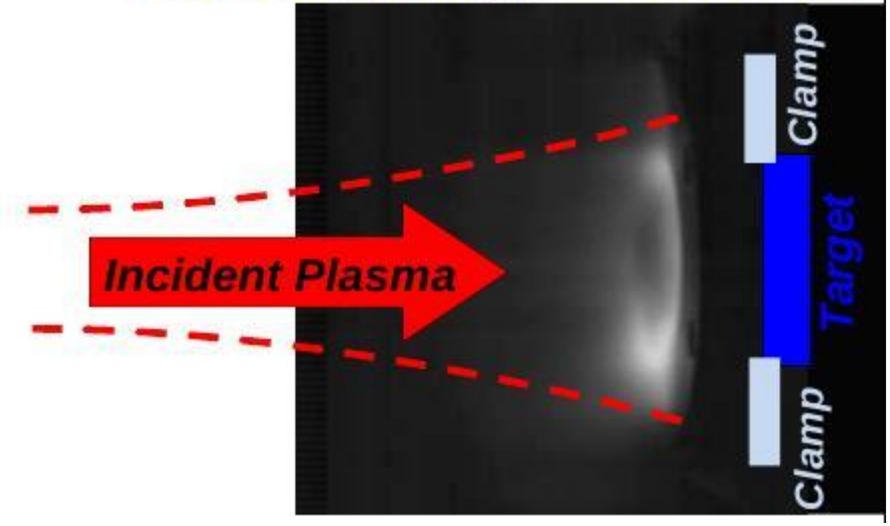
- CPS tests also reduced droplet ejection with smaller pore sizes*

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

Local erosion and redeposition already being studied in linear device and will be extended to NSTX-U divertor

- Magnum-PSI linear test-stand provides divertor-relevant plasmas (FOM-DIFFER/PPPL collab.)
  - 1.4T (upgrade to 2.5T)
  - >10 MW/m^2 inc. heat flux
  - Tilting target for obl. inc.
  - Extensive diagnostics
- Initial experiments already indicate large redeposition fraction of lithium
  - In-situ deposition of lithium films w/ evaporator
  - Evolution of surface impurities observed and may provide means of discharge cleaning Li

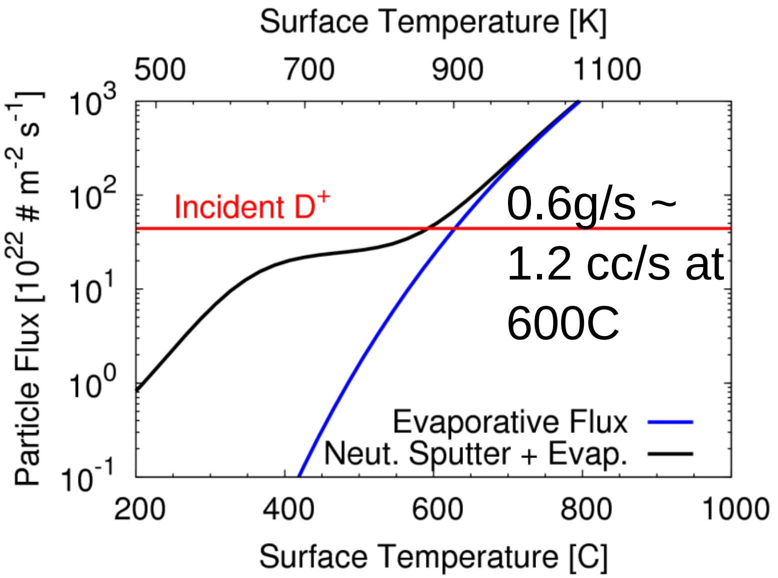
Fast-camera Image Li-I Emission



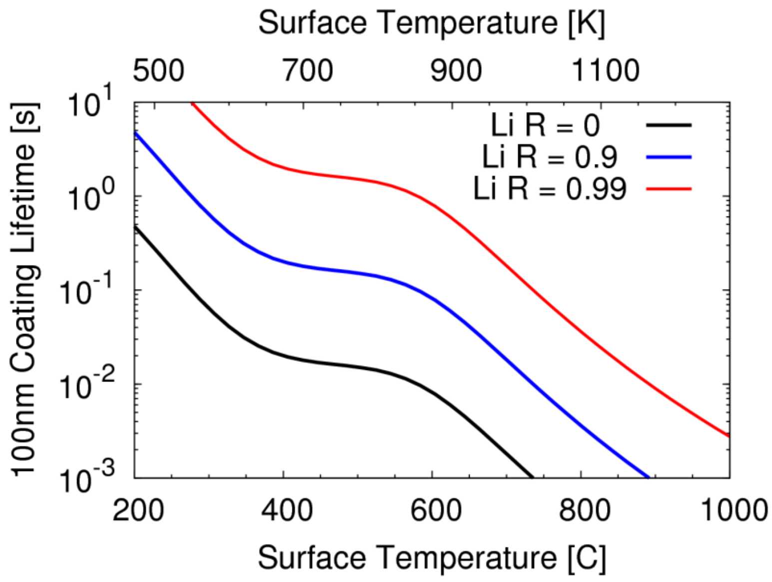
Parameter	Value
Discharge time	8x 5s (40s total)
Typical T_e, N_e	1eV, 1.4e20 m^{-3}
Gross Li yield (TRIM est.)	0.52 mg m^{-2}
Total deposited (max Net)	0.05 mg m^{-2}
Redeposition (if max Net)	0.9

Thin coatings can provide protection of high-Z substrates

- Ion penetration depth of ~10nm means plasma will only interact with coating material
- Lithium erosion rate is large and highly temperature dependent
  - Erosive fluxes could quickly remove protective layers
  - No experimental data of erosion yield above ~500C, at these fluxes[1,2]
- Coating lifetime is extended by redeposition fraction
  - Motivates flowing systems to replenish coating
  - No temperature dependence in boron sputter yield[3], τ~2s at R=0



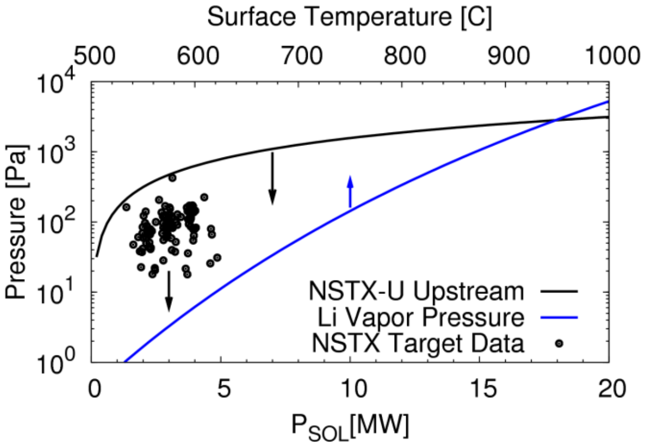
0.6g/s ~ 1.2 cc/s at 600C



[1] Doerner, JNM 2001. [2] Allain, JNM 2003. [3] Hechtl, JNM 1992

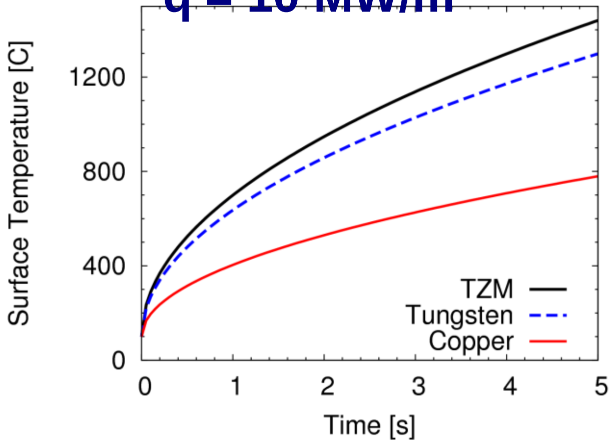
Vapor shielding regime should be identifiable through target plasma parameters, surface temperature and bolometry

- Large lithium erosion rates should provide several indicators of vapor shielding
    - Target plasma pressure loss due to Li vapor pressure
    - Target electron temperature reduction by plasma radiation
    - Optical emission, total radiation from near target
    - Reduced PFC temperature rise measured via DBIR thermography, PFC calorimetry
- Transient testing length will be determined by lithium lifetime
    - Assessed in Thrust 2 plan
    - Motivates long-pulse flowing PFC



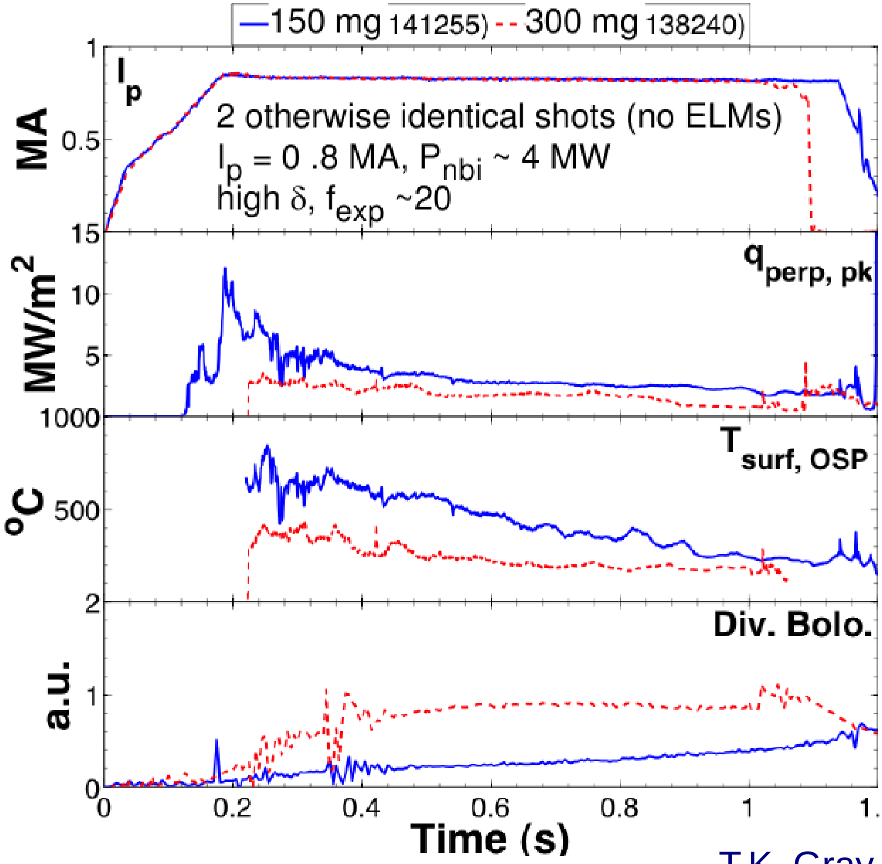
$$q_t = \gamma \Gamma^{+}_{sat} T_e = \gamma n_{es} c_s T_e = \gamma c_s p_t$$

Unmitigated temperature rise
q = 10 MW/m²



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

- NSTX indicates reduced surface heat flux with elevated lithium deposition
- Capillary-Porous System targets have dissipated large incident heat fluxes at high temperatures
    - E-beam tested to 25MW/m^2 for 5-10 min
    - QSPA plasma disruption tested up to 60 MJ/m^2
- Diagnosis in NSTX-U via complementary diagnostics
    - Langmuir probes for target pressure, n_e, T_e
    - Optical, VUV emission and bolometry for P_{rad}
    - DBIR thermography and TCs for heat flux an energy deposited



T.K. Gray, IAEA FEC 2012.

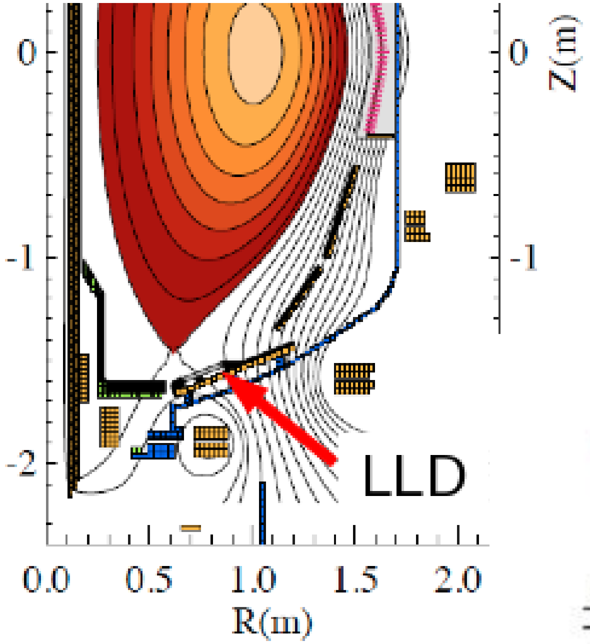
$$p_u = p_t(1+M_t^2) + p_{Li}$$

$$p_t = \frac{p_u - p_{Li}}{2}$$

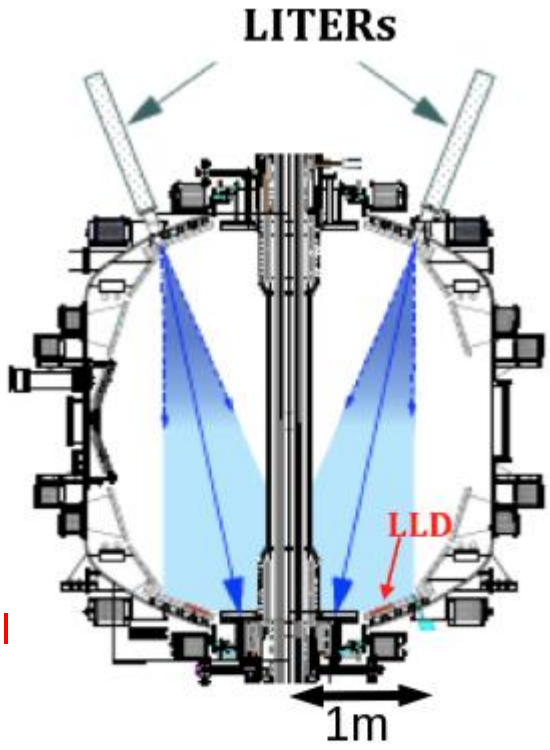
$$q_t = \gamma\Gamma^+_{sat}T_e = \gamma n_{es}c_sT_e = \gamma c_s p_t$$

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

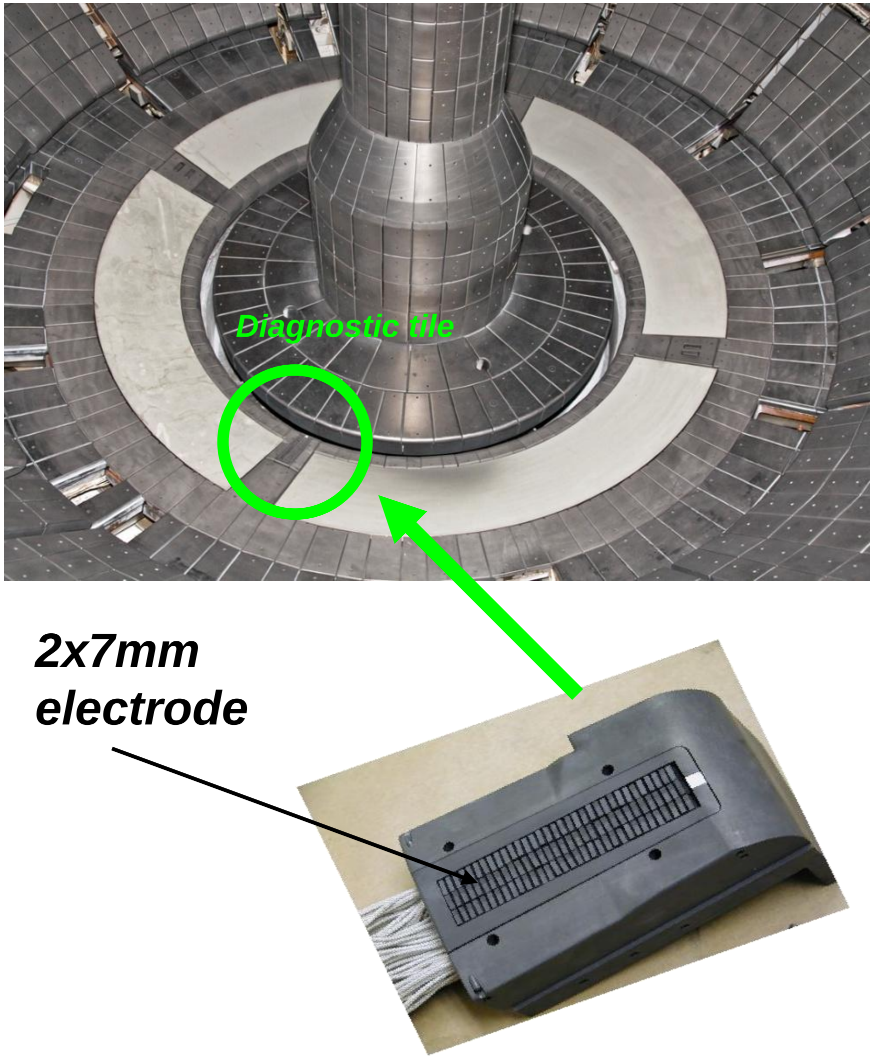


No boronization campaign prior to lithium introduction
Database already starts with 60g inventory in vessel



High-density Langmuir probe array installed for divertor plasma characterization

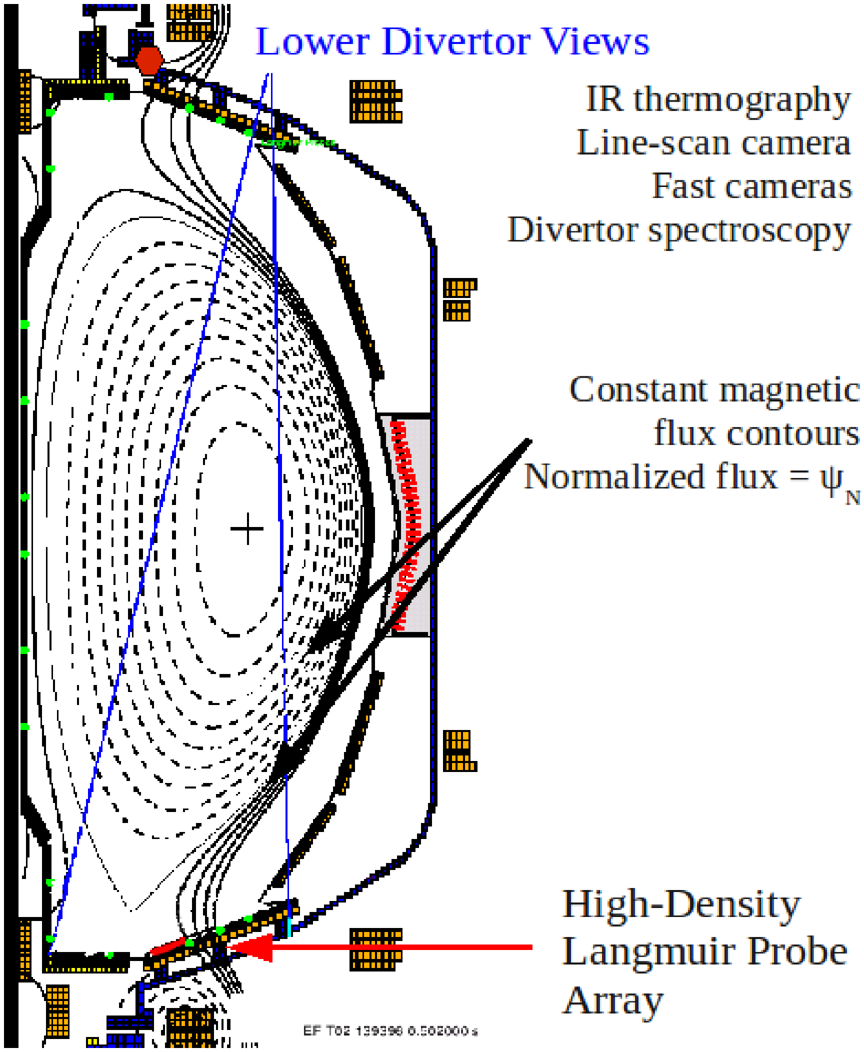
- Liquid Lithium Divertor (LLD) installed to study lithium plasma-material interactions
- Probe array characterizes local plasma properties in a range of experiments
- Provides high spatial density of measurements
- Oblique incidence yields smaller effective probe size



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

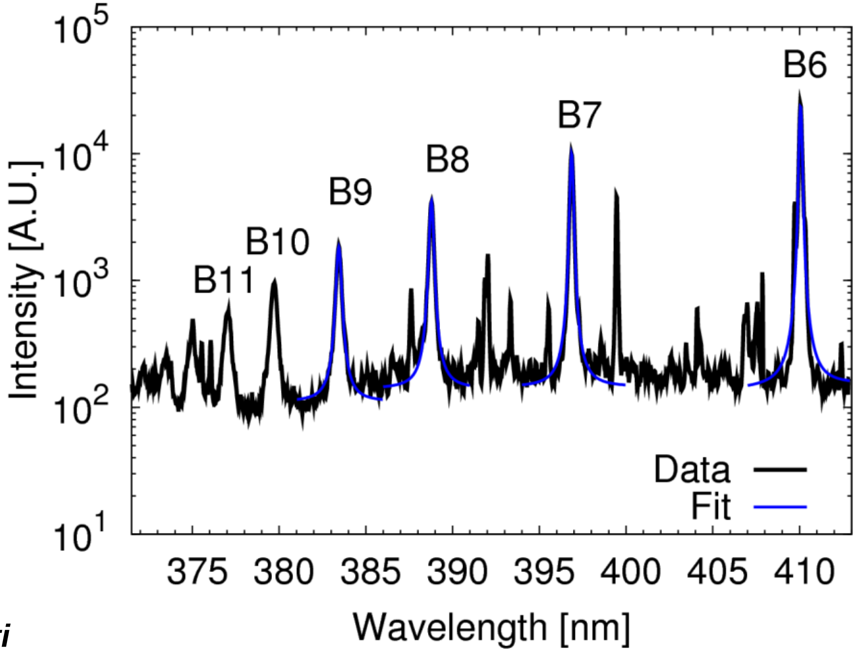
IR thermography
Line-scan camera
Fast cameras
Divertor spectroscopy

Constant magnetic flux contours
Normalized flux = ψ_N

High-Density Langmuir Probe Array

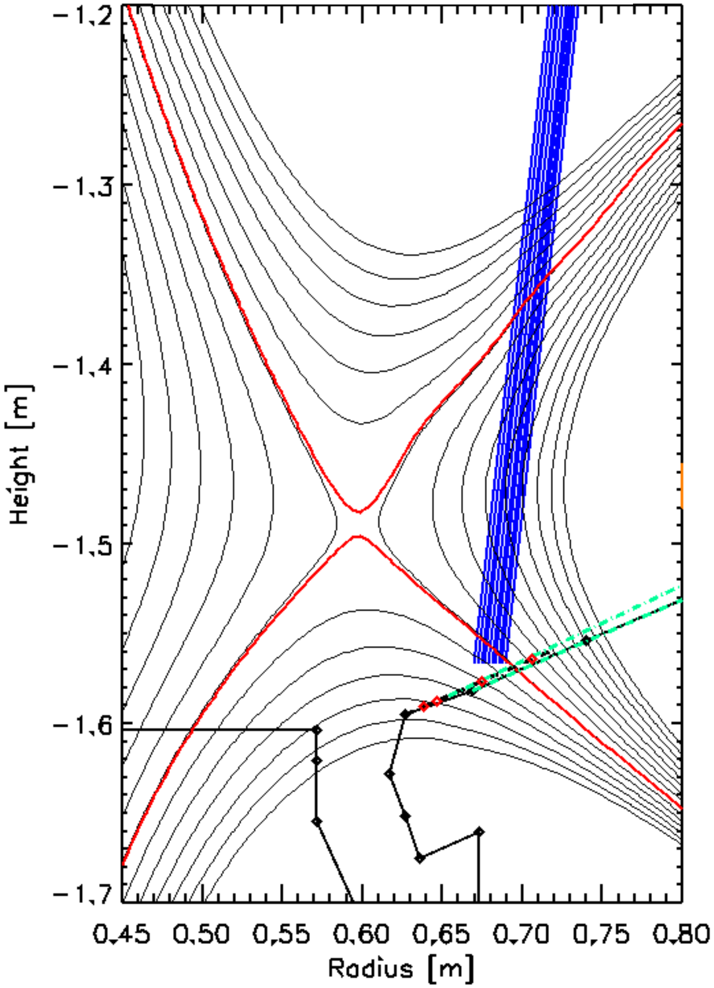
Density measurement from spectroscopy confirm kinetic probe interpretation

- 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



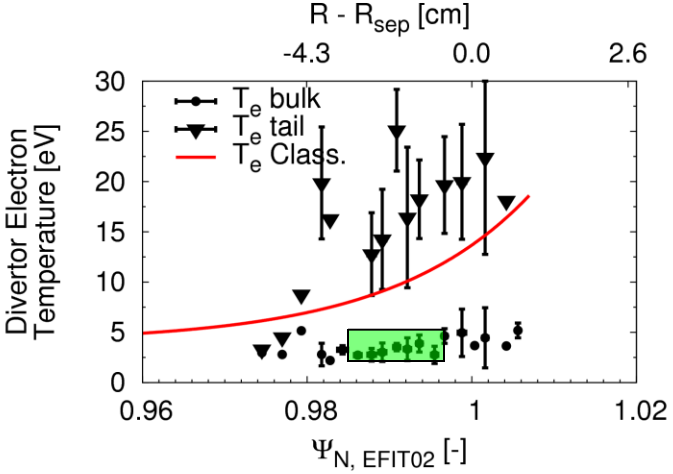
F. Scotti

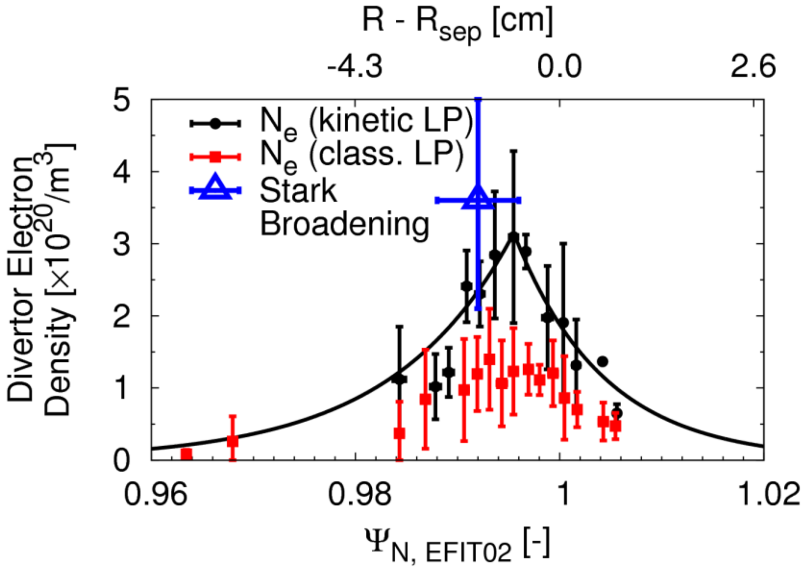
Divertor spectrometer view

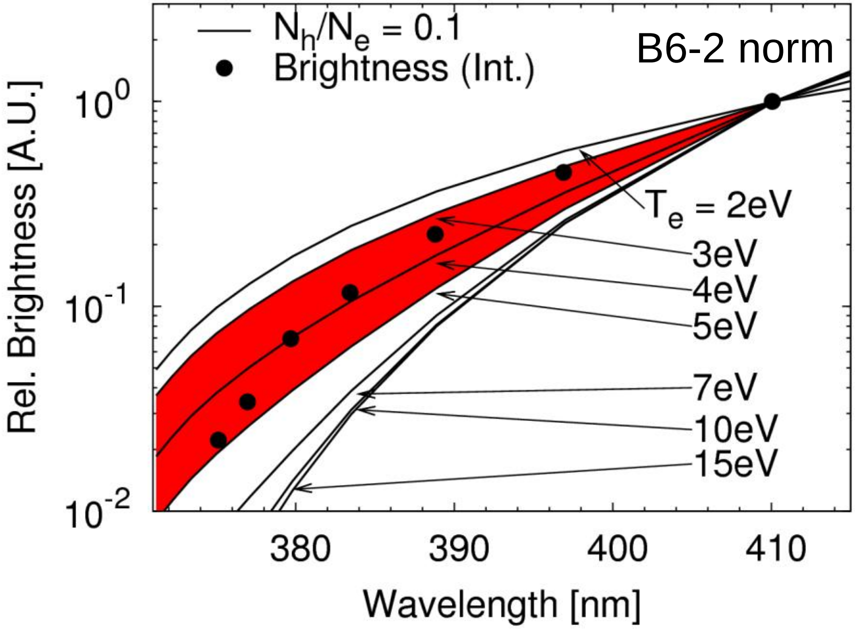


Broadening measurement and modeling of hydrogen spectrum consistent with kinetic probe interpretation

- 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





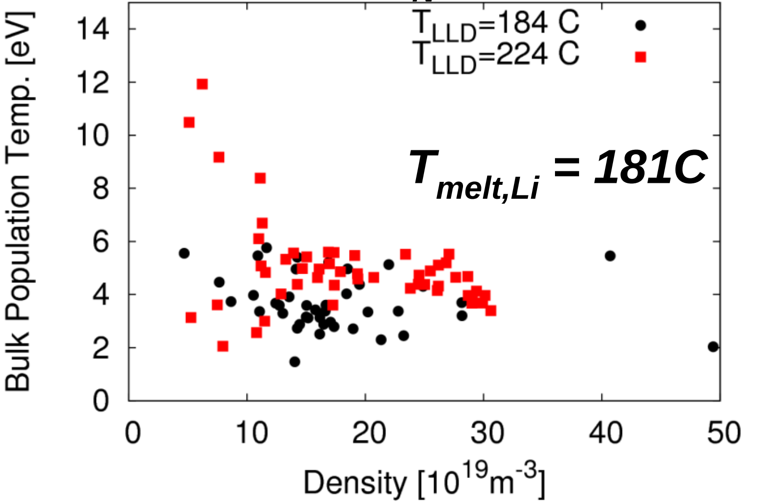

Balmer-Series Brightness Ratios

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

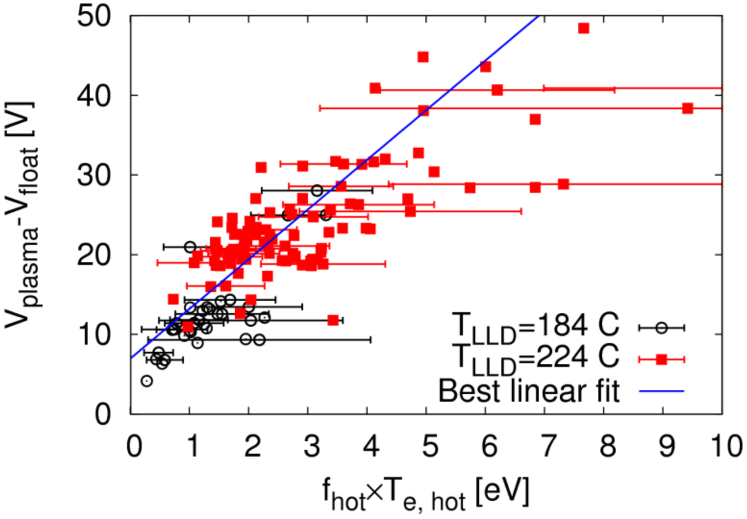
Distribution function analysis indicates some local changes in plasma conditions on plasma-heated LLD

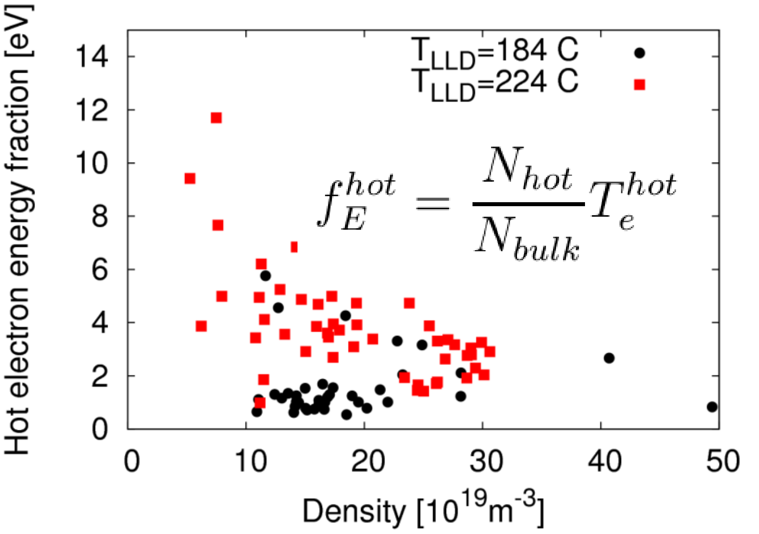
- Discharge sequence repeatedly heated and plasma-conditioned the LLD surface
- Local plasma temperatures elevated with hotter LLD surface temperature ($T_{LLD} > T_{melt,Li}$)
- Increase in plasma temperatures correlated with increase in V_p-V_f potential difference[1]
- **Local changes raise the question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

Comparisons made on identical ψ_N locations



$T_{melt,Li}$ = 181C





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

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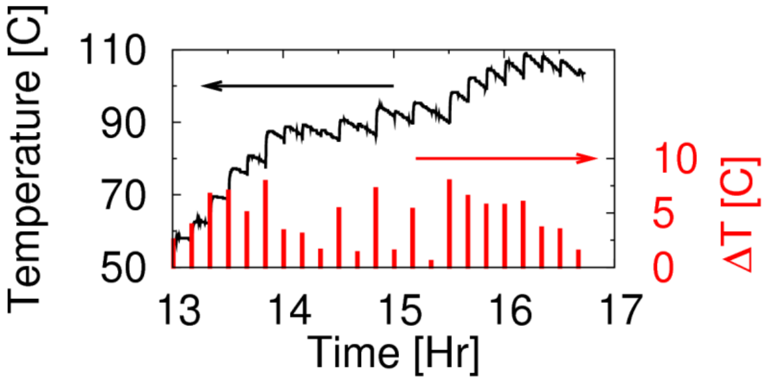
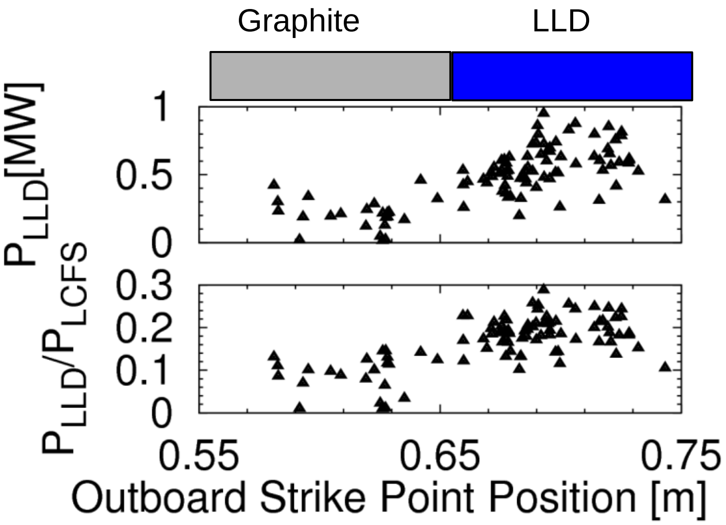
[1] ***Jaworski et al., Fusion Eng. Des. 87 (2012) 1711.***

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

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)

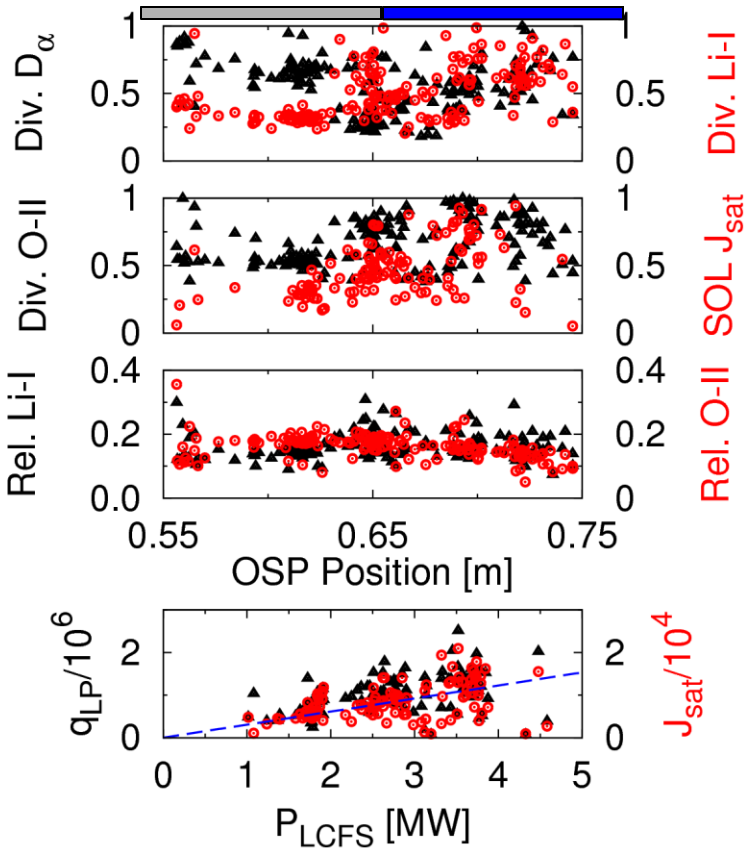
$$\varepsilon_{imp} \propto N_{imp} \propto Y_{imp} J_{sat}$$

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

$$P \propto \gamma J_{sat} T_e$$

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

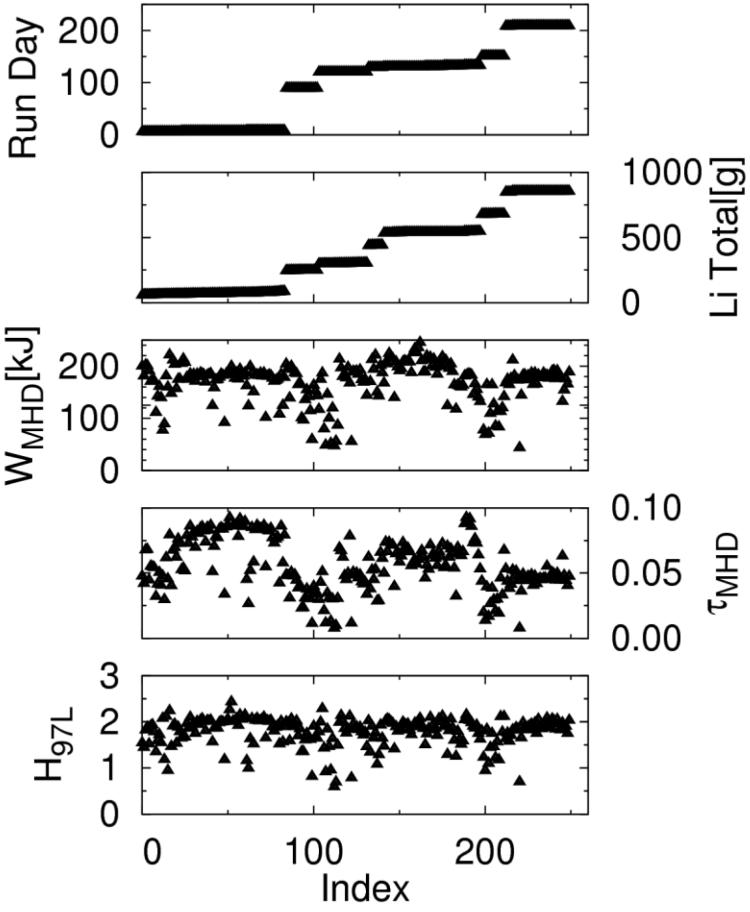
Emission ε
Coverage θ
Divertor Power P



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



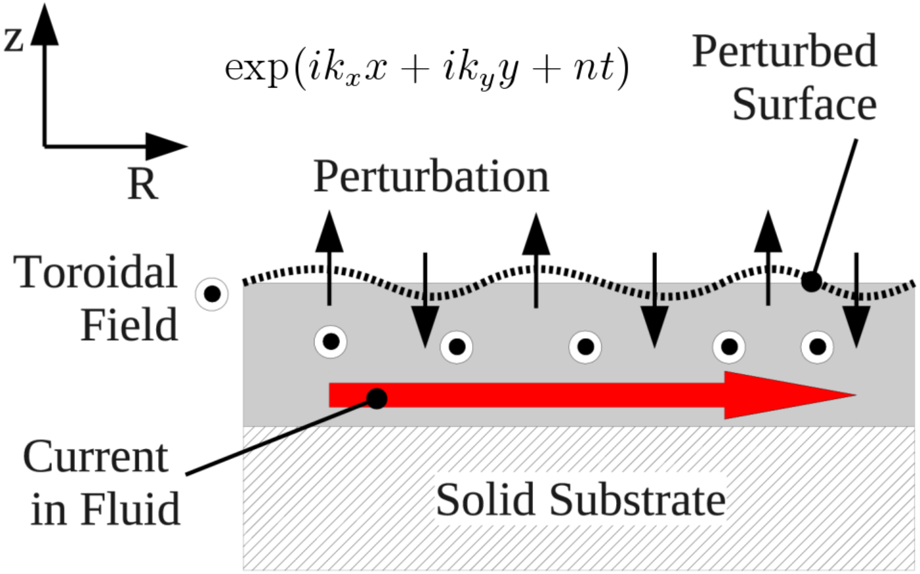
Fully-flowing PFC can provide a means of sweeping away gettered material and creating "stationary" surface conditions.

Jaworski, et al., IAEA FEC 2012

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
  - 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

Porous-MHD effects alter liquid-metal wicking

- Wicking into porous material described with Darcy Eqn.
  - Pressure head provided by capillary pressure

$$u=\frac{k\,\Delta P}{\mu L} \qquad P_c=\frac{2\Sigma\cos\alpha}{r_p}$$

- Addition of MHD pressure losses and rearrangement creates porous-MHD version of the Lucas-Washburn eqn.

$$Lu=L\frac{dL}{dt}=\frac{2\Sigma\cos\alpha}{r_p}\cdot\frac{1}{\mu/k+\sigma B^2}$$

$$=\frac{2\Sigma r_p\cos\alpha}{\mu\left(r_p^2/k+Ha^2\right)}$$

- Solution yields “sorptivity”, S, of porous material including MHD effects

$$L(t)=\left(\frac{4\Sigma r_p\cos\alpha}{\mu\left(r_p^2/k+Ha^2\right)}t\right)^{1/2}=S\sqrt{t}$$

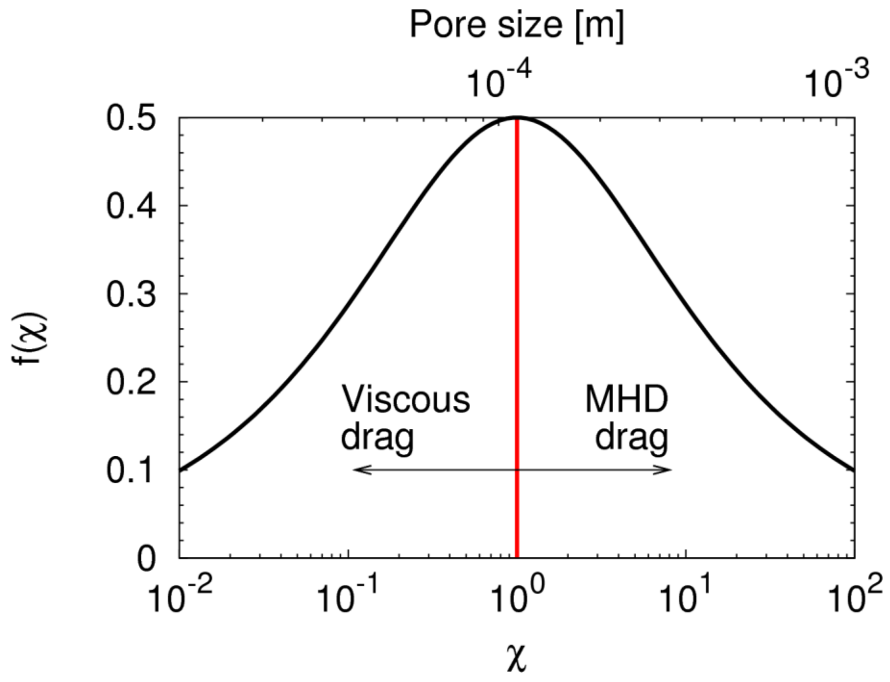
Wicking into material can be optimized with pore size

- Re-arrangement provides permeability-enhanced Hartmann parameter
  - Permeability of packed-bed used for illustration[1]
  - Liquid lithium material properties in 1T field yield 130μm pore

- Sorptivity no longer isotropic as in many hydrodynamic systems
  - $S^2/2 = 8,\ 19\ \mathrm{cm^2/s}$ (perp, para) Li, $r_{p,opt}$=130μm
  - $S^2/2 = 6,\ 20\ \mathrm{cm^2/s}$ (perp, para) Sn, $r_{p,opt}$=290μm

$$L\frac{dL}{dt}=\left(\frac{2\,\Sigma\cos\alpha}{B\sqrt{\sigma\,\mu}}\right)\left[\frac{\epsilon^3}{45(1-\epsilon)^2}\right]^{1/2}\frac{\sqrt{\chi}}{1+\chi}$$

$$\chi=\frac{k}{r_p^2}Ha^2 \qquad r_{p,opt}=\left[45\frac{(1-\epsilon)^2}{\epsilon^3}\cdot\frac{\mu}{\sigma B^2}\right]^{1/2}$$



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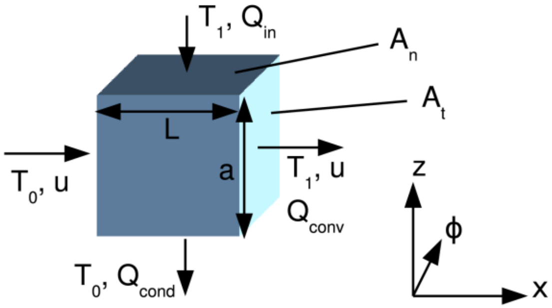
[1] *Scheidegger, A.E. The physics of flow through porous media, University of Toronto Press, Toronto, Canada, 3rd ed. 1974.*

Conduction dominated thermal transport makes conventional cooling relevant

- Control-volume analysis illustrates relevant thermal transport regime[1]

- Thin, slowly-moving liquid metal can be considered a solid in thermal anaysis

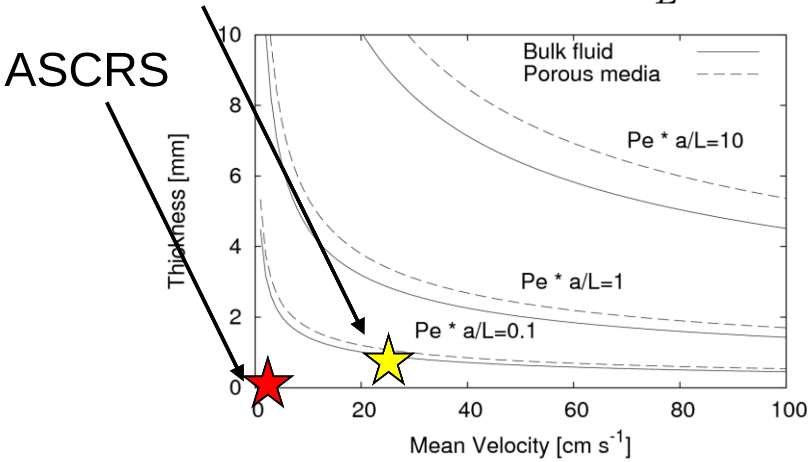
- Conventional gas cooling techniques applicable to these types of LM-PFCs



$$Q_{in} = Q_{cond,l} + Q_{cond,s} + Q_{conv}$$

$$\begin{aligned}\frac{q_{in}}{k_{\text{eff}}\Delta T/a} &= 1 + \frac{f\rho_l c_{p,l}}{k_{\text{eff}}}\frac{a^2 u}{L} \\ &= 1 + \frac{au}{\alpha_{eff}} \cdot \frac{a}{L} \\ &= 1 + \mathbf{Pe}\frac{a}{L}\end{aligned}$$

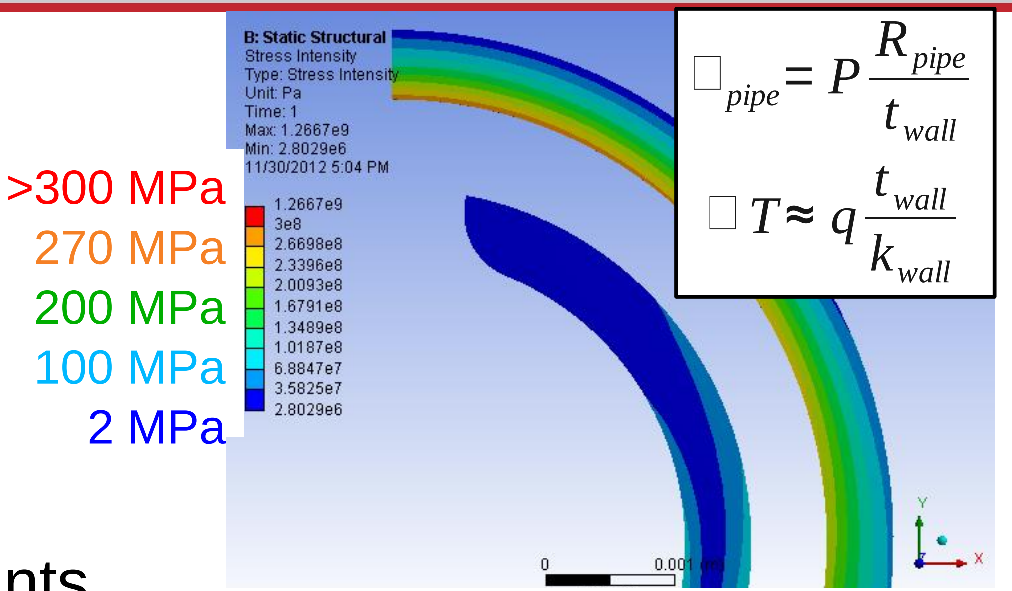
LIMIT[2]



[1]Jaworski, et al., **JNM** 2009, [2]Ruzic, et al., NF 2011.

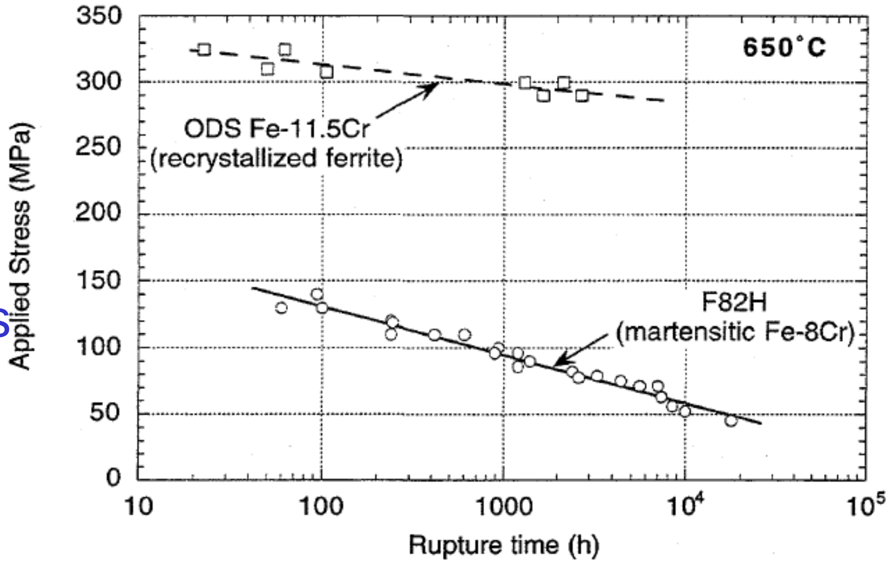
Reduced sizes can benefit power extraction

- At constant stress, radius reduction can reduce pipe-wall thickness
  - Rely on liquid metal protection of substrate
  - Manufacturing challenges...
- Yield stress and creep deformation provide design points
- ODS-RAFM should avoid rupture for >2yrs
  - $T_{max,steel}$~610C
  - Highest stress at lowest temperatures (500-550C)
  - Further optimization to be done in 3D to address margins of safety, etc.



$$\square_{pipe} = P\frac{R_{pipe}}{t_{wall}}$$

$$\square T \approx q\frac{t_{wall}}{k_{wall}}$$



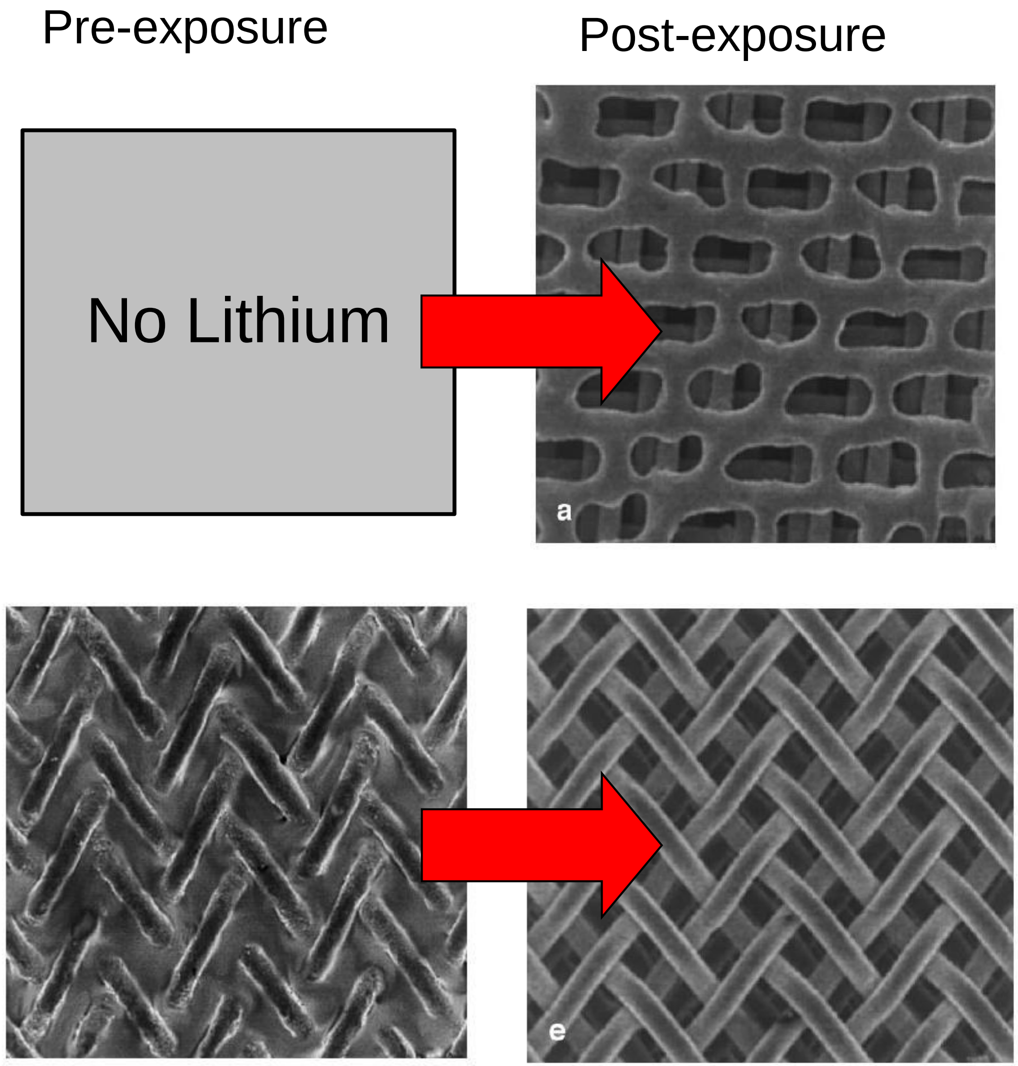
Zinkle, et al., Fusion Materials Report, June 1998, p.135.

Liquid lithium demonstrated to protect fragile substrate

- Red Star Capillary-Porous-System (CPS) long-since shown to substrate damage under ELM-like disruptions (5MJ/m^2, 0.5ms in QSPA)

- Able to withstand 25MW/m^2 heat fluxes via strong evaporation and vapor shield

- In principle, all PFCs in fully-flowing system will return to an equilibrium position (i.e. self-healing)



Pre-exposure

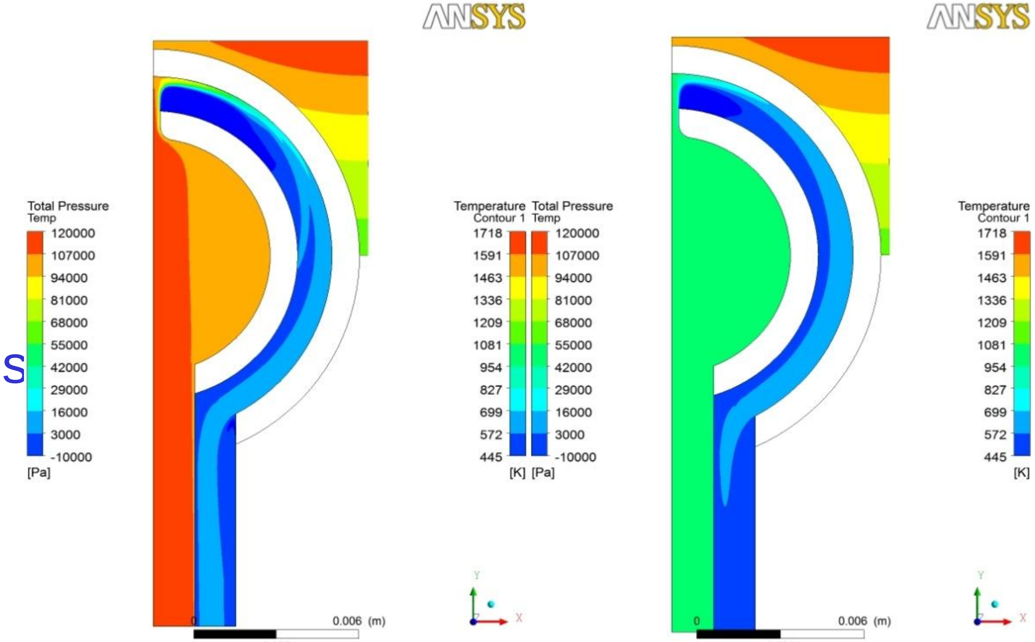
Post-exposure

No Lithium

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

Supercritical CO2 is a more effective coolant than helium

- Replacement of He with s-CO2 in base T-tube design reduces pumping power by 30%
  - Identical front-face temperatures
  - 2x pressure drop, 1/3 required flow
- Better thermal efficiency at lower temperatures than He Brayton cycle[1]
  - S-CO2 w/ 550C turbine inlet has 45% thermal efficiency
  - He w/ 700C turb. inlet had 43% (ARIES-CS)[2]



s-CO2

$T_{inlet} = 600$ C

$T_{outlet} = 647$ K

$V_{inlet} = 8$ m/s

$\Delta P = 108$ kPa

Helium

$T_{inlet} = 600$ C

$T_{outlet} = 677$ K

$V_{inlet} = 24$ m/s

$\Delta P = 50$ kPa

$$W_{pump} = Q\Delta\Delta \rightarrow \frac{W_{CO2}}{W_{He}} \approx \frac{8\times108}{24\times50} \approx \frac{2}{3}$$

[1] Dostal, et al., Tech. Report MIT-ANP-TR-100, MIT, March, 2004.

[2] Raffray, et al., **FST** 2008.

Material compatibility determines substrate

- Liquid surface absorbs incident plasma, substrate material absorbs neutrons

- Liquid lithium compatible with steel, vanadium alloys, refractory metals[1]

- Liquid tin compatible with refractories, not compatible with steel above 400C (unknown compatibility with vanadium alloys)[1]

- Porous structure can be produced by various methods (e.g. laser texturing[2], flame-spraying[3], foam CVD[4])

[1] Zinkle and Ghoniem, **FED** 2000. [2] Lin, et al., **JNM** 2013. 3 Kugel, et al., **FED** 2011, [4] Jaworski, et al., **JNM** 2008.

More advanced options could exist

- T-tube first example considered with well documented design for extension and modification
  - Still requires significant absolute pressure and wall thicknesses
  - Continued size reduction becomes difficult to manufacture
  - ~10 MW/m^2 may be the limit with steel structures
  - Integrated PFC-power cycle analysis is on-going work...

- Liquid metal heat-pipes another option being pursued
  - Reduces pressure at the target front-face allowing thinner structures and lower stress levels (may not need ODS)
  - Can effectively spread heat-flux over larger area reducing requirements on gaseous cooling
  - Porous-MHD issues already under study with free-surface work

Other open issues

- Tritium processing and closing the liquid lithium loop
  - Requires confinement device experiments to demonstrate re-capture of migrating materials
  - Could prove to be lithium “Achilles heel” due to on-site inventory[1]
- Liquid metal protection of substrate material requires demonstration
  - Thin walls for better heat transfer rely on sacrificial liquid layer
  - Runaway electron beams? Other disruption events?
- Integrated core performance with high-temperature, liquid-metal PFCs
  - High-temperature, high evaporation/erosion lithium not demonstrated in divertor (encouraging results with limiter on FTU[2])
  - High-temperature liquid tin PFCs never tested to date
- Plasma modeling...

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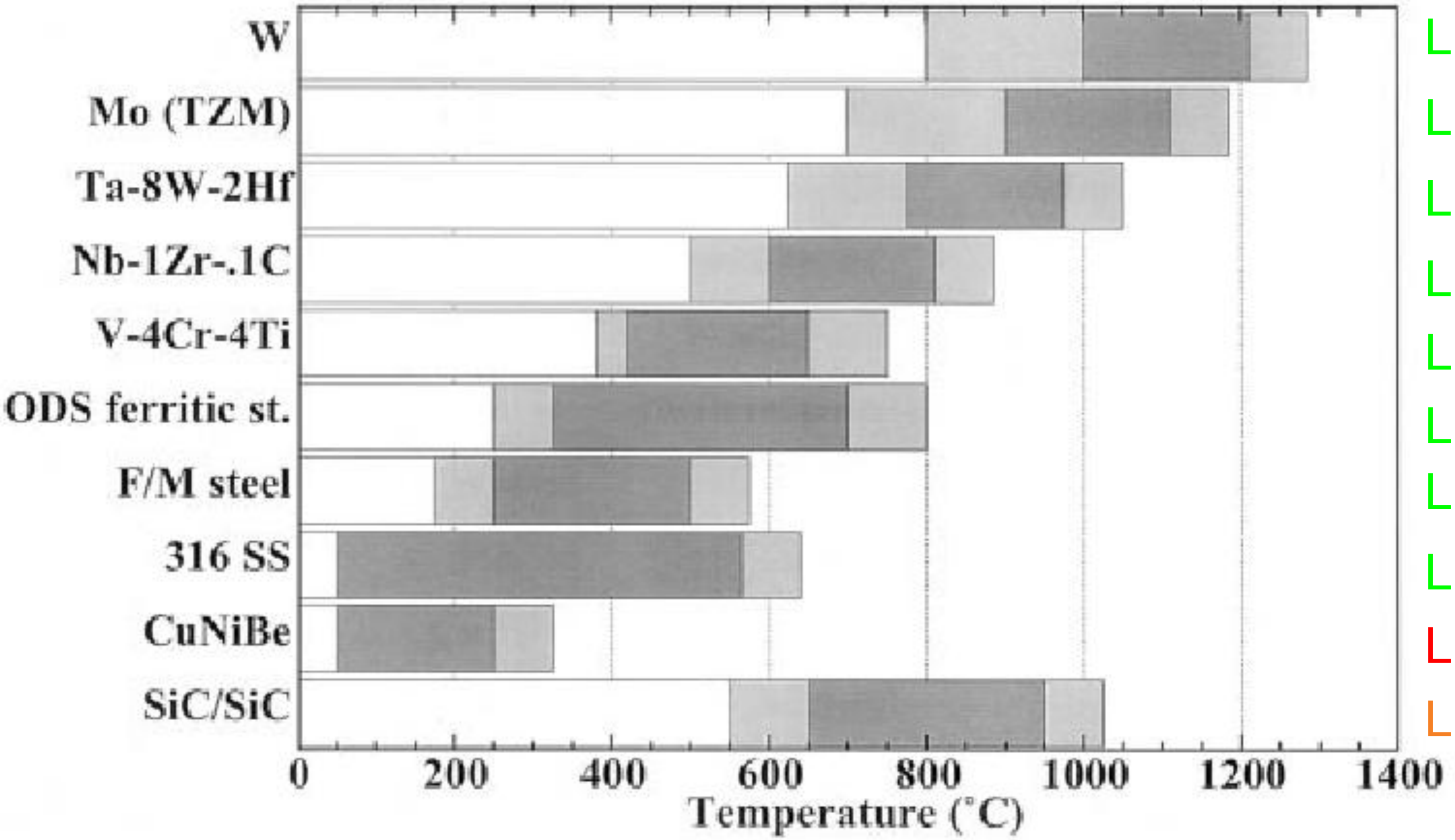
[1] M. Nishikawa, “Tritium in a fusion reactor (effect of Li system on tritium)” Presentation at PPPL ST tokamak discussion, March 27, 2012.

[2] M.L. Apicella, et al., Plasma Phys. Control. Fusion 54 (2012) 035001.

DEMO challenges considerable but progress is being made to determine if a technically feasible LM-PFC option exists

- For 10MW/m^2 peak divertor heat loads incident on target in "Pilot-plant" ST- and AT-DEMOs
  - Actively-supplied, capillary-restrained system prevents ejection
  - Liquid lithium on ODS-RAFM structure with s-CO2 cooling looks encouraging ***(eliminates net-reshaping of PFC)***
  - Some additional optimization to be done with full 3D design
  - Need data with high temperature lithium surface in divertor-like plasma
- Experimental demonstration and additional analysis will address open issues over coming years
  - @PPPL – internal lab funding, NSTX-U base program, other sources pending
  - Collaboration underway with Magnum-PSI, NSTX-U, and EAST
- Still several open issues forcing talk titles with the word "possible" but progress is being made; your input is welcome!

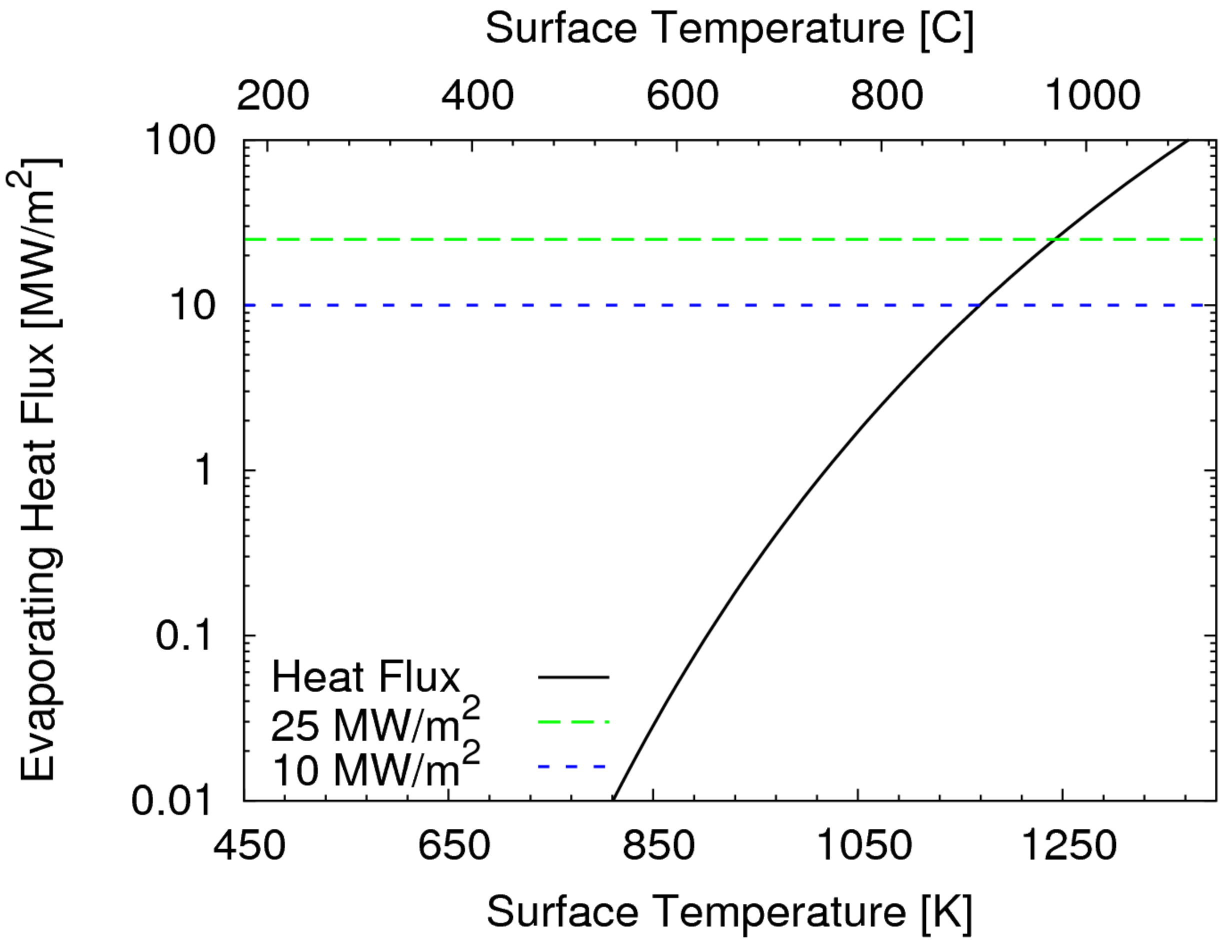
Liquid metal-structural compatibility



Li, Sn, Ga
Li, Sn, Ga
Li, Sn, Ga?
Li, Sn, Ga?
Li, Sn?, Ga?
Li, Sn, Ga
Li, Sn, Ga
Li, Sn, Ga
Li, Sn, Ga
Li?, Sn, Ga

Zinkle and Ghoniem, **FED** 2000. (Sn and Sn-Li used interchangeably)
“The Liquid Metal Handbook” Liquid-metals handbook”, United States Office of Naval Research. U.S. Govt. Print. Off. 1950. (Gallium estimates)

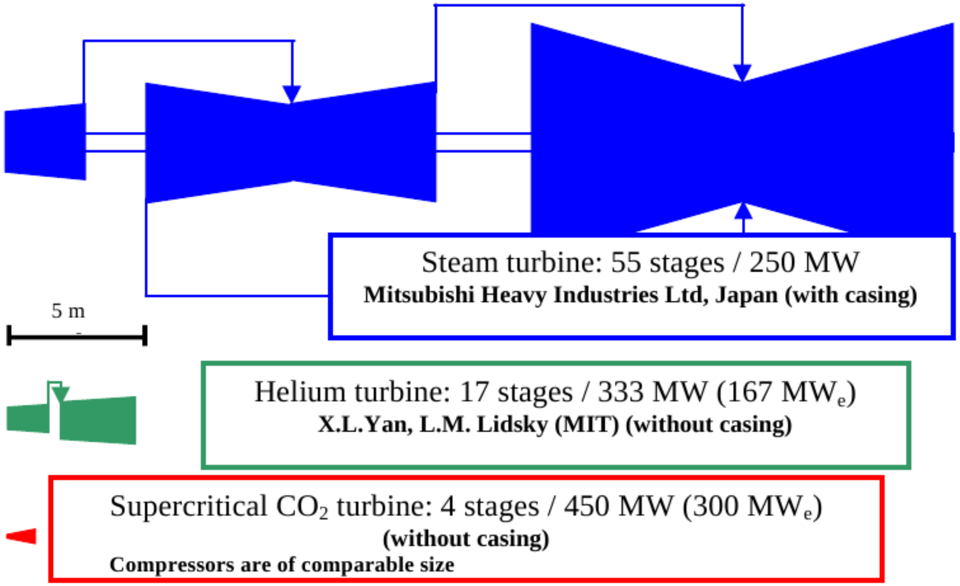
Evaporative self-cooling by Lithium



Supercritical CO2 power cycle provides higher thermal efficiency at lower temperatures than He Brayton

- *Real gas* properties of CO2 reduce power required at compression
- Dostal, et al. found that above 550C, s-CO2 recompression cycle better than He Brayton cycle (2 inter. no reheat)[1]
  - 45% thermal efficiency w/ 550C turbine inlet
  - 49.5% thermal efficiency w/ 650C turbine inlet
  - c.f. 43% helium cycle w/ 700C turbine inlet in ARIES-CS[2]

Turbo-machinery size comparison[1]

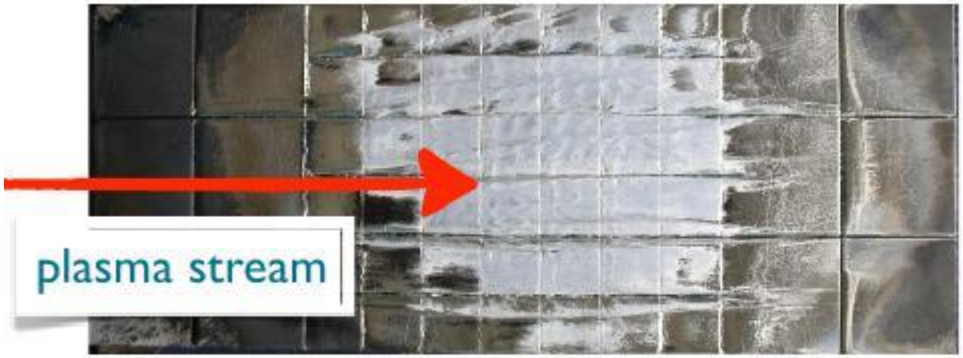


[1] Dostal, et al., Tech. Report MIT-ANP-TR-100, MIT, March, 2004.
[2] Raffray, et al., **FST** 2008.

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

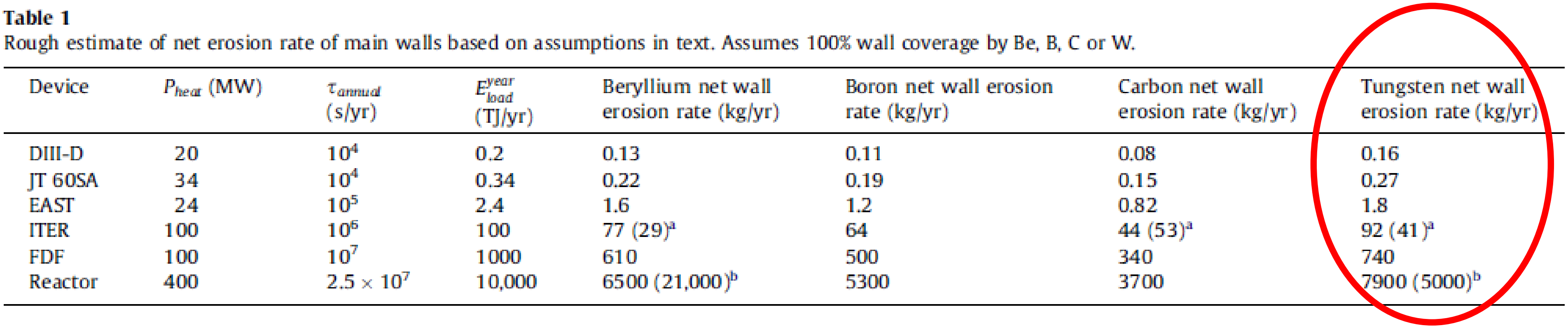


Table 1

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)	τ_{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	2.5×10^7	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!

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}	5×10^{20} at SP
Ion flux target [$m^{-2}s^{-1}$]	10^{24}-10^{25}	2×10^{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**

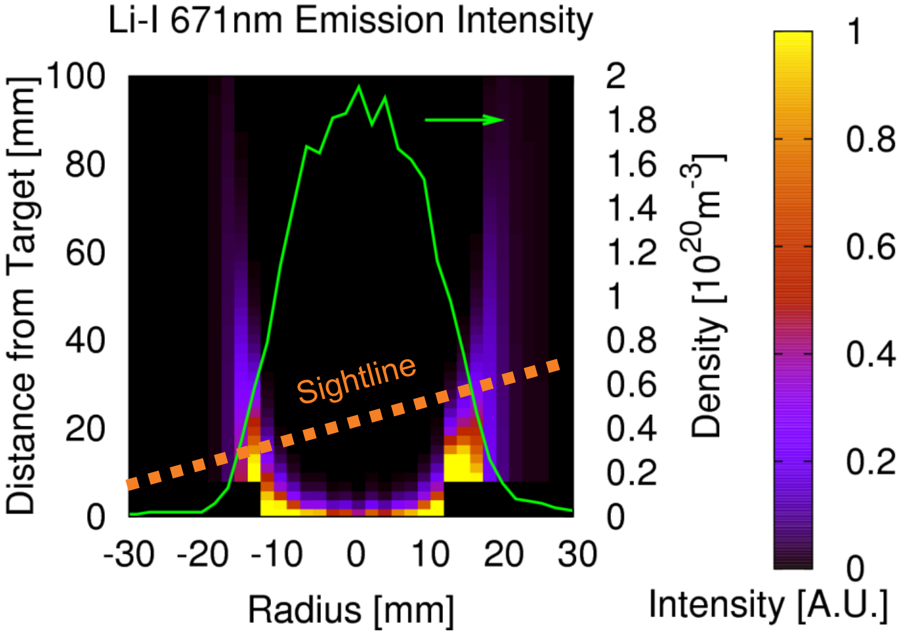
$$\frac{\partial N(r)}{\partial t} + \nabla \cdot (vN(r)) = S_{iz} + S_{rec}$$

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

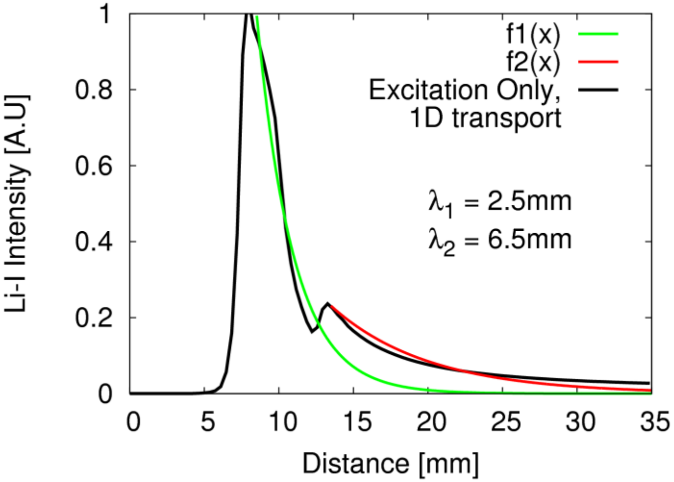
$$\lambda_{iz}(r) = \frac{v_{Li}}{N_e S_{eff}^{iz}(N_e(r), T_e(r))}$$

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

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



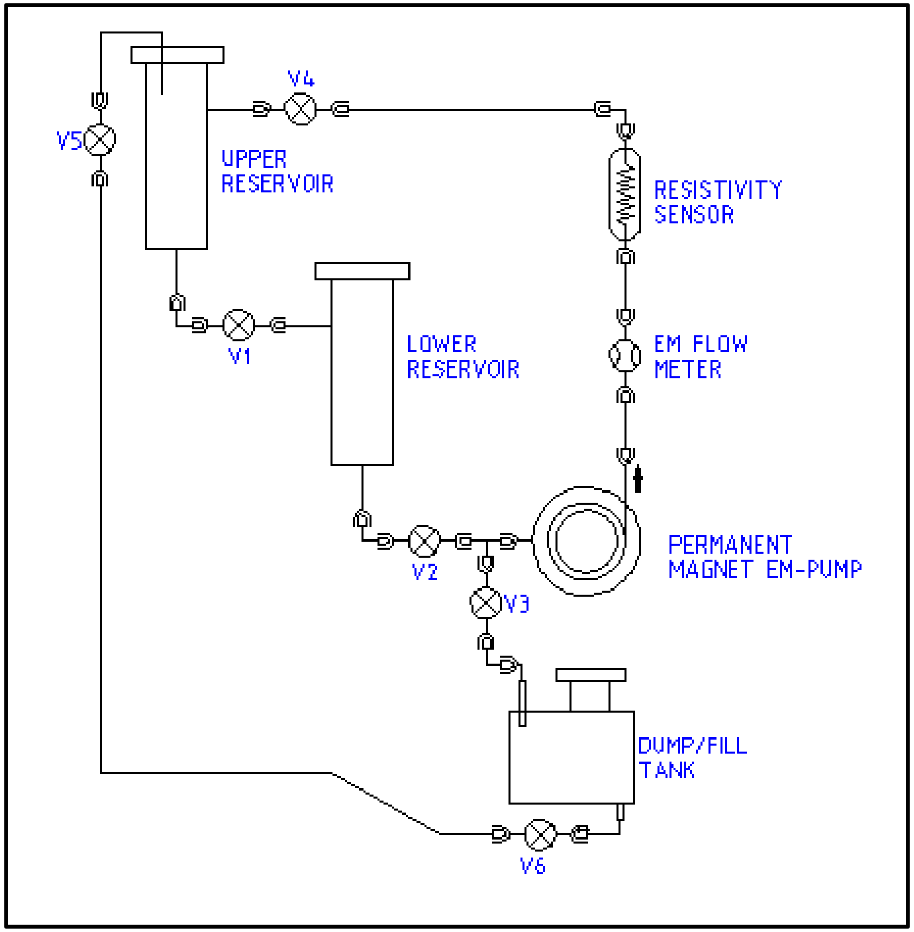
Simulated Diagnostic View



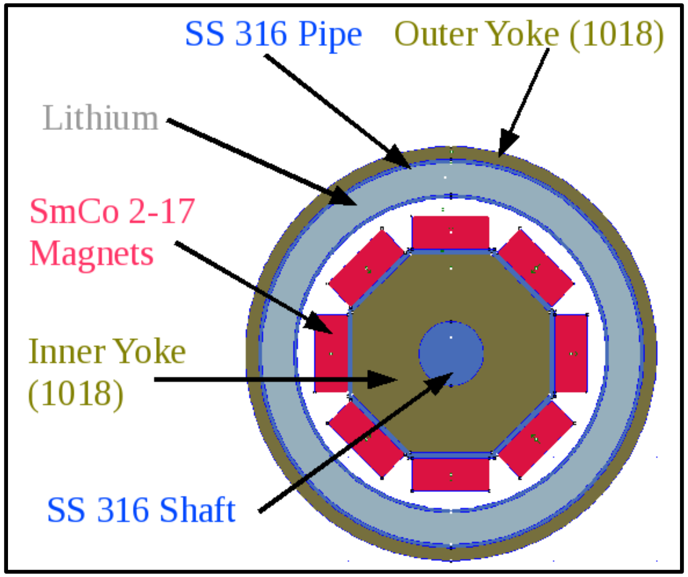
Experiment construction underway to provide testbed for PFCs and demonstration of necessary technologies

- 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

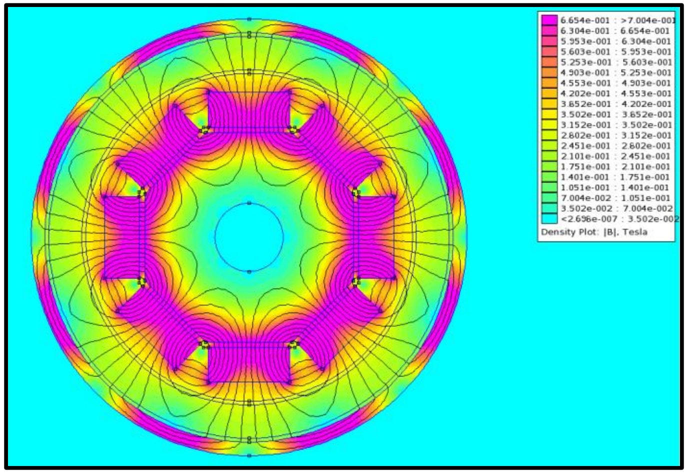
Liquid Lithium Test Stand Loop Diagram



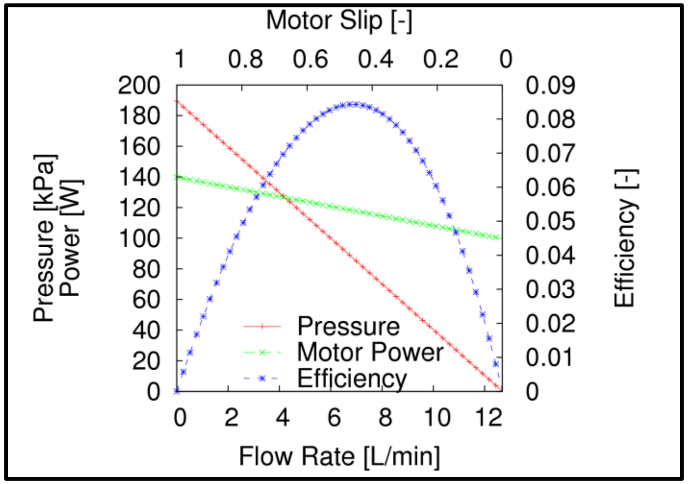
EM pump designed, hardware currently being fabricated




Lithium Reservoirs



Magnetic field simulation



Predicted Pump Performance

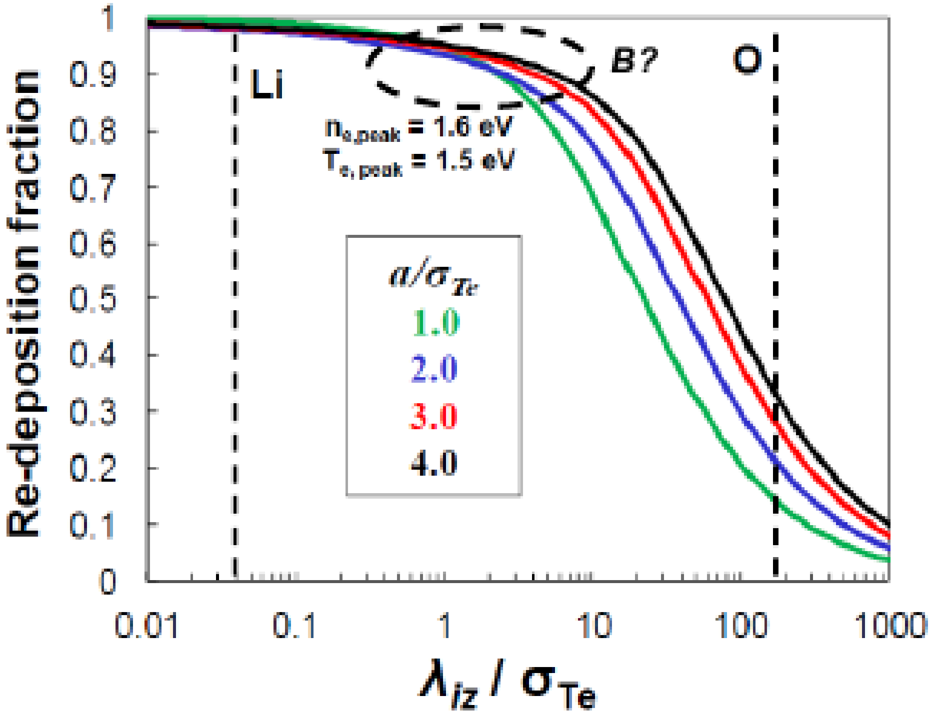
Re-deposition fraction calculations

$$R = \Gamma_{\text{redep}} / (\Gamma_{\text{sputt}} + \Gamma_{\text{evap}} + \Gamma_{\text{diff}})$$

- Set initial conditions:
  - Maxwellian T_e and n_e
  - Flat areal density $\rho(r,t=0) = \rho_0$ for r < a
- Define a surface-averaged re-deposition fraction

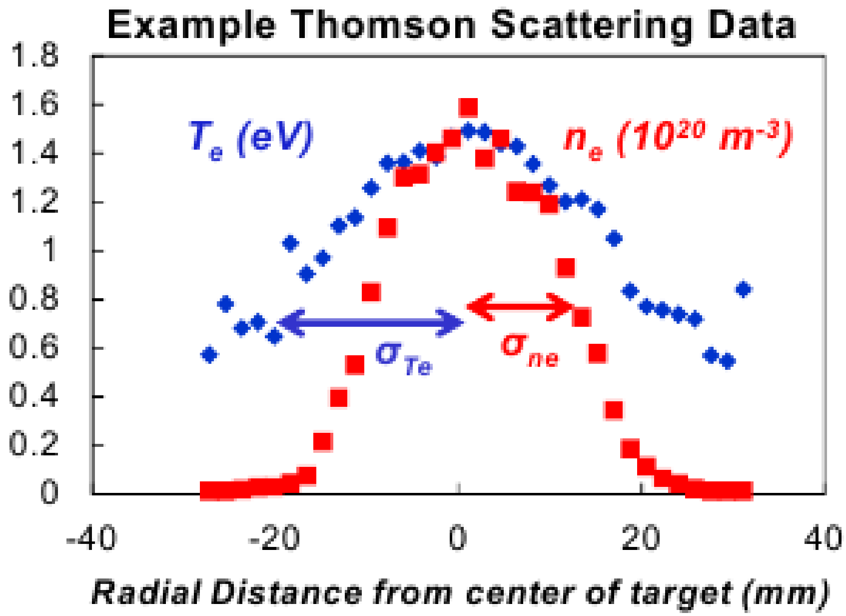
$$\langle R \rangle = \int_0^a R(r',t)\, dr'$$

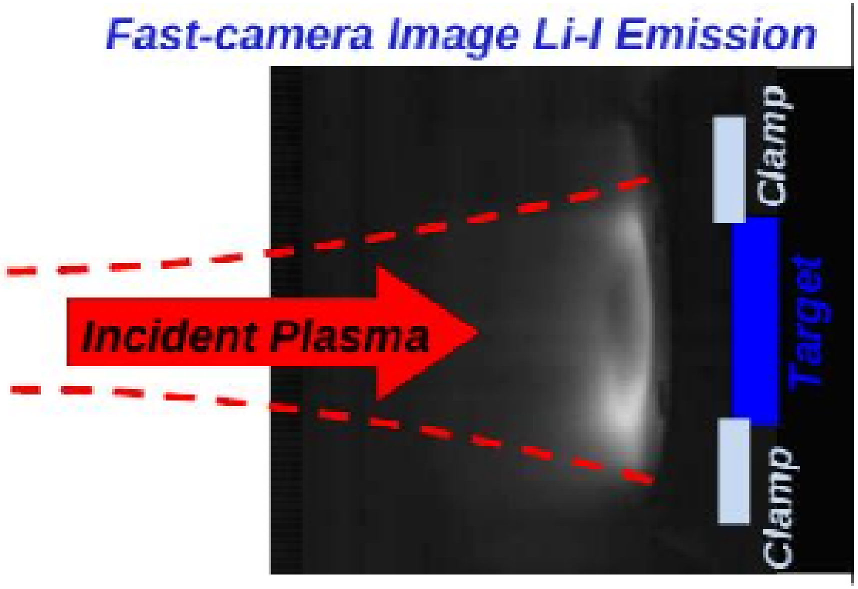
- Li atoms are trapped near the surface due to ionization
  - Electric forces draw them back
- O atoms do not ionize near the surface and are lost



Diagnostics on Magnum-PSI

- Thomson Scattering provides $n_e(r)$, $T_e(r)$
  - Single chord 2 cm from target, 1.8 mm resolution
- Visible Spectroscopy gives line intensities
  - 350 nm < λ < 800 nm, 0.2 nm, 5-10 Hz resolution
- Fast camera w/ Li-I (671 nm) filter gives $I_{Li}(r,t)$
  - 0.285 mm x 0.285 m, ~2 kHz resolution





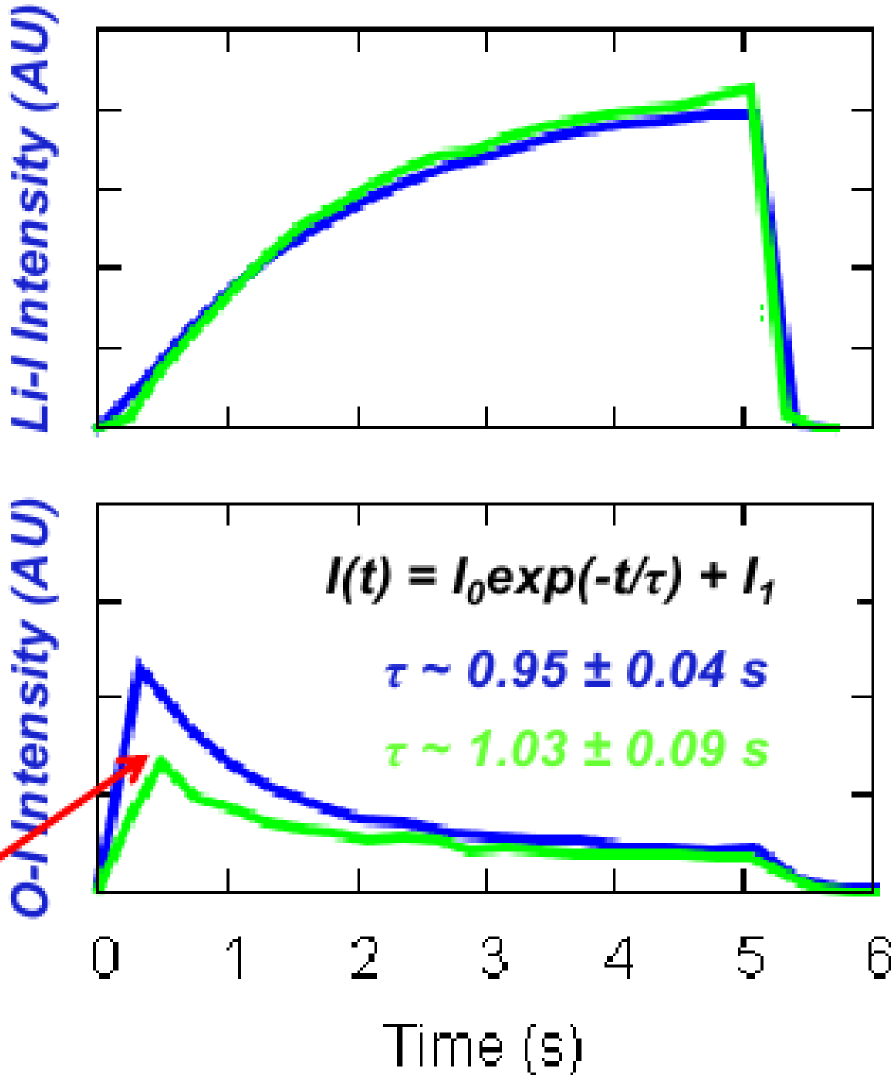
M.A. Jaworski

Li-I intensity continuously increased throughout discharge, while O-I intensity decays exponentially

T_e =1.5 eV
n_e= 1.5*10^{20} m^{-3}
t_0
100 nm in-situ Li
coating on TZM Mo

T_e =1.6 eV
n_e= 1.9*10^{20} m^{-3}
t_0 + 9 min
100 nm in-situ Li
coating on TZM Mo

O-I intensity also decreases by ~40% in second discharge



$I(t) = I_0 exp(-t/\tau) + I_1$

τ ~ 0.95 ± 0.04 s

τ ~ 1.03 ± 0.09 s