# Lithium Research - Progress and Plans

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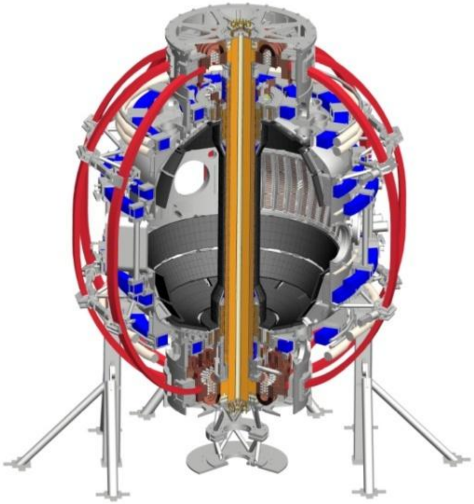
*and the NSTX Research Team*

**NSTX PAC-31**
**PPPL B318**
**April 17-19, 2012**





# Outline

Outline of talk:

1. Motivation for lithium.
2. Research approach, FY2011-12 highlights.
3. Near term Li R&D through year 2 of NSTX-U ops.
4. Goals for years 3-5 of NSTX-U ops.
5. Summary.

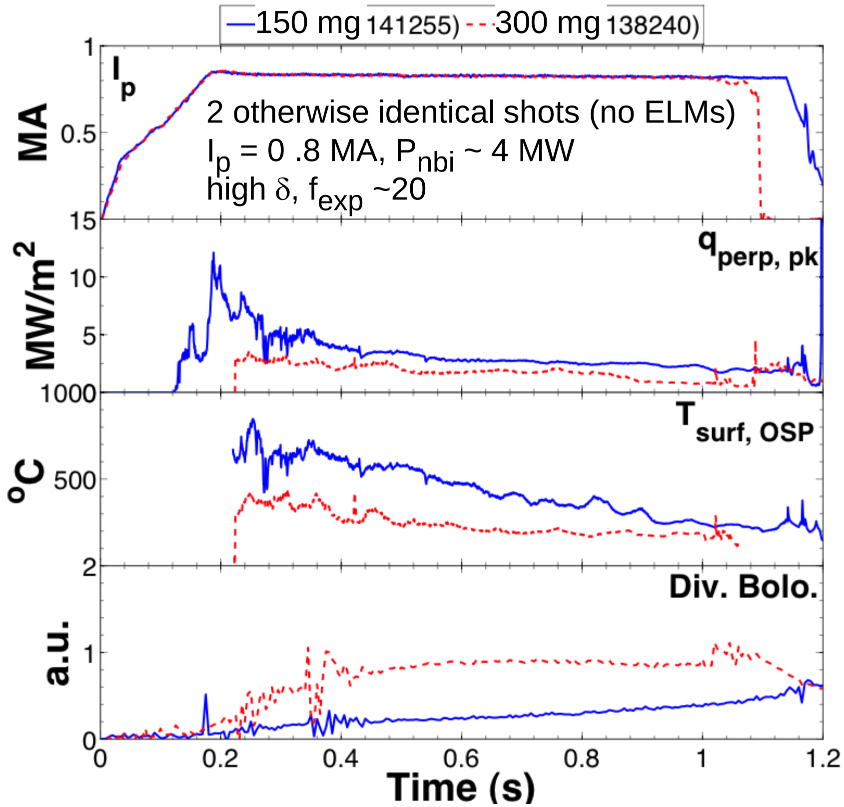
# Liquid metal PFCs should be pursued to mitigate risk of tungsten not extrapolating to fusion reactor.

- Recent FESAC report: "The uncertainty in establishing PFC solutions is high, as the environment is severe and the requirements for long lifetime are challenging."
  - Tungsten is leading candidate but has issues with neutron damage, erosion, melting, brittleness, thermal fatigue.
- ReNeW highlighted that DEMO PFCs are much more challenging than ITER's.
  - advocated substantial program to assess new ideas, incl. liquid metals (Li, Sn, Ga).
  - No neutron damage, erosion, thermal fatigue in liquids – but technical base less mature.
- Importantly, liquid flow over tungsten substrate may be unique way to eliminate net erosion and flaking to help make tungsten work
- **Liquid PFCs have potential to relieve over-constrained problem: they do not need to *simultaneously* satisfy plasma and nuclear loading constraints.**
- Significant uncertainties in both approaches suggest both W and liquids should be investigated
- ReNeW recommended: "*Liquid surface PFC operation in a tokamak environment…*"

# Liquid metals have the potential to mitigate steady-state and transient heat-loads, and protect underlying PFCs

FTU capillary porous system (CPS)

- CPS in T-11 handles > $10 MW/m^2$
  - Self-shielding radiative layers observed
- CPS e-beam tested to:
  - $25 MW/m^2$ for 5 - 10 minutes
  - $50 MW/m^2$ for 15s
- Plasma focus tested to 60 $MJ/m^2$ off-normal load




NSTX: Increased Li evaporation correlated with lower $q_{pk}$

- $T_{surf}$ at OSP = 800˚C → 400˚C with heavy Li
- $q_{pk}$ stays < 3 $MW/m^2$ with heavy Li, divertor $P_{rad}$ increases
- This occurs despite narrowing of heat-flux width at divertor
- **Much more work to be done to understand roles of C, Li radiation, detachment physics, etc.**

# Pursuing multidisciplinary approach to developing liquid metal PFCs for NSTX-U, FNSF and beyond

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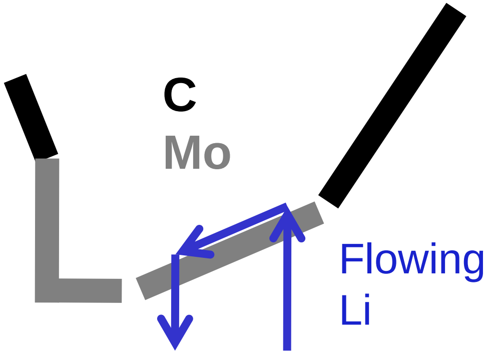
Issues: Li surface reactivity, saturation & diffusion of D in Li, impurity segregation, wetting, replenishment of Li, graphite/Mo PFC substrates, heat flux limits with passive/active cooling, recovery after vents, reliability…

Multi-scale R&D approach from atoms to PFCs,

1. Understand impact of lithium on core and edge transport and stability.
2. Assess D pumping vs. surface conditions:
   - Atomistic MD modeling (ORNL)
   - Lab expt. on ideal systems e.g. single xtal Mo + monolayer Li + $D^0$, $D^+$ beam. detailed surface analysis via XPS, AES, TPD, SAM… (Purdue / PPPL Labs)

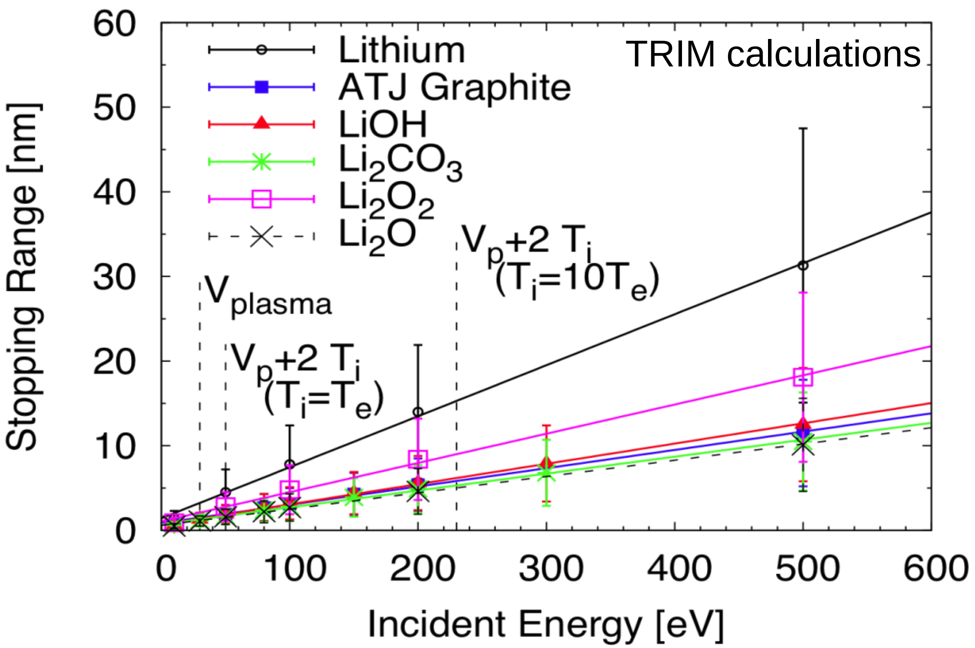
2. Assess Heat Flux handling in linear plasma facility:
   - PFC prototype tests with high power plasmas in Magnum PSI

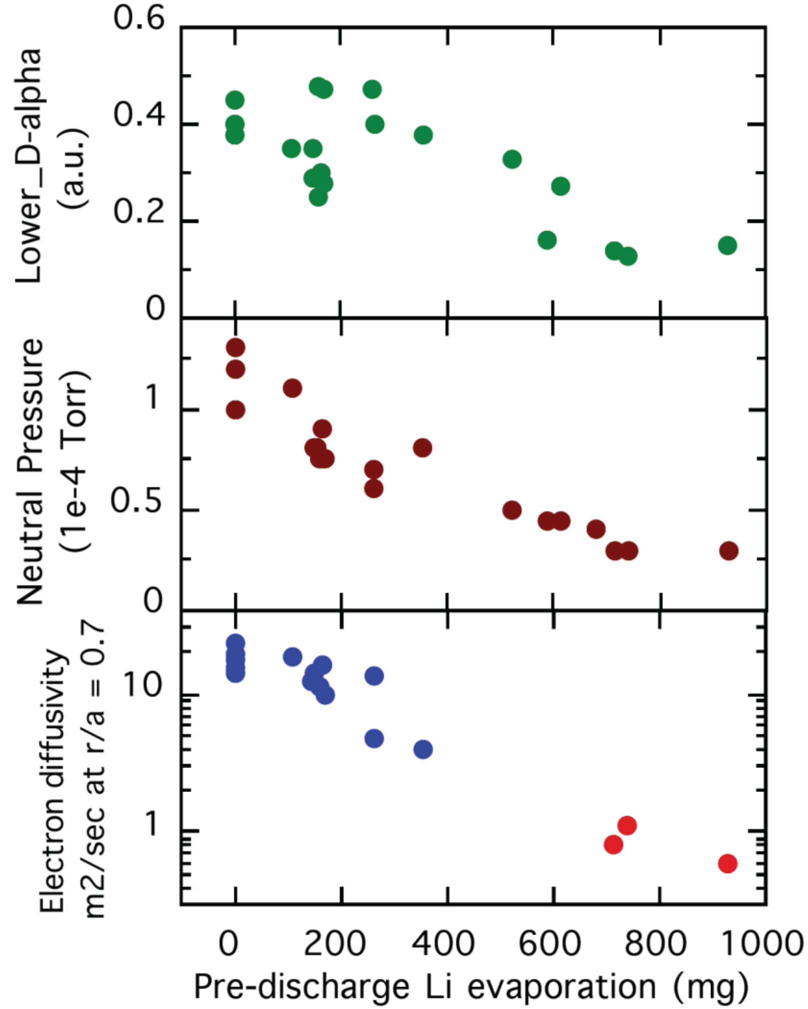
3. Tokamak integration:
   - XGC Kinetic modeling, non-equilibrium Li radiation
   - LTX liquid Li studies, MAPP -> LTX then NSTX-U
   - Li granule injector tests on EAST, then NSTX-U
   - Divertor Li-PFC design, then testing in NSTX-U.



# Divertor recycling, edge neutral density and electron transport all decrease monotonically with progressively increasing lithium dose

This continuous improvement is surprising, since even the smallest Li dose (110 mg) has a 30 – 125 nm nominal thickness in the divertor that exceeds the ~10 nm D implantation range.
*(Maingi PRL, DPP highlighted press release)*



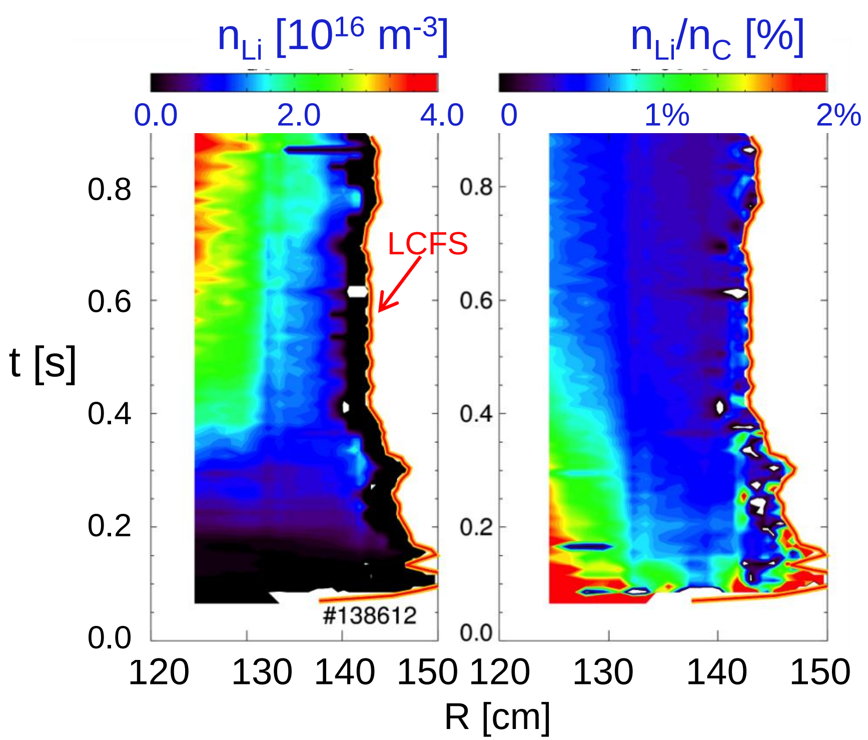




Impact of Li on ELM stability- see backup #22

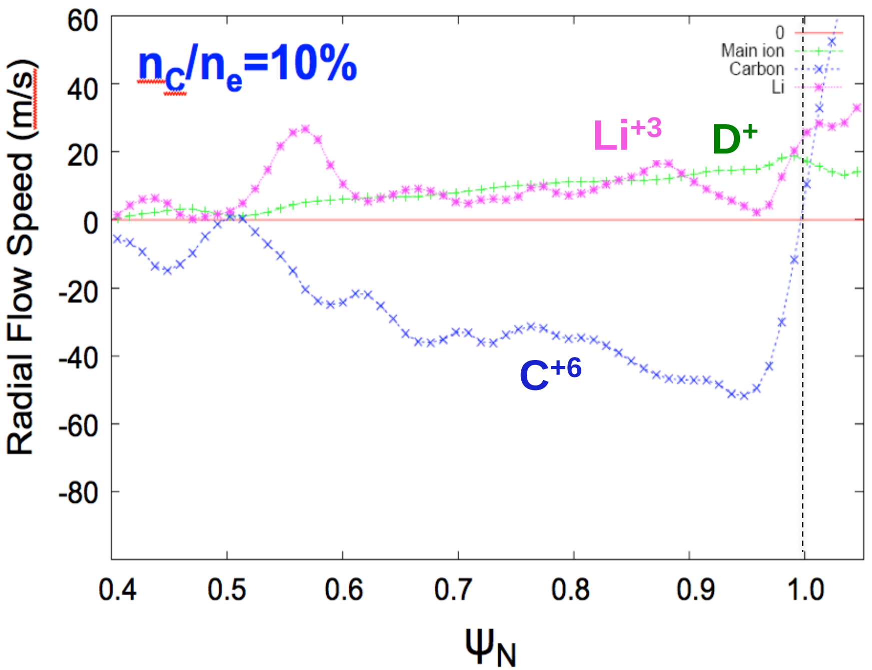
Core transport TRANSP analysis of cross-field electron diffusivity at r/a=0.7. Points > 650mg had reduced NBI.

# Low Li concentration in core is consistent with collisional neoclassical transport with carbon

Core lithium and carbon density from CHERS




Kinetic neoclassical transport of multi-species diverted plasma simulated by XGC0




- Many of the Li and C behaviors in NSTX can be related to neoclassical physics
  - Enhanced flux of ionized C into core
  - Inhibition of Li influx by collisions with C
    - Similar effect seen from core-only simulation in NCLASS/MIST
  - Reduction of C and Li ion density in pedestal from screening of influxes from scrape-off layer
    - They can come in across the separatrix in the form of neutrals

NYU-PPPL

# Simulations + lab results show importance of O in Li PMI

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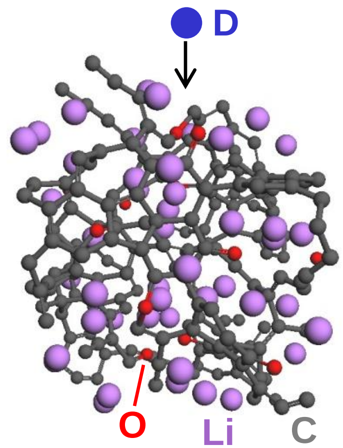
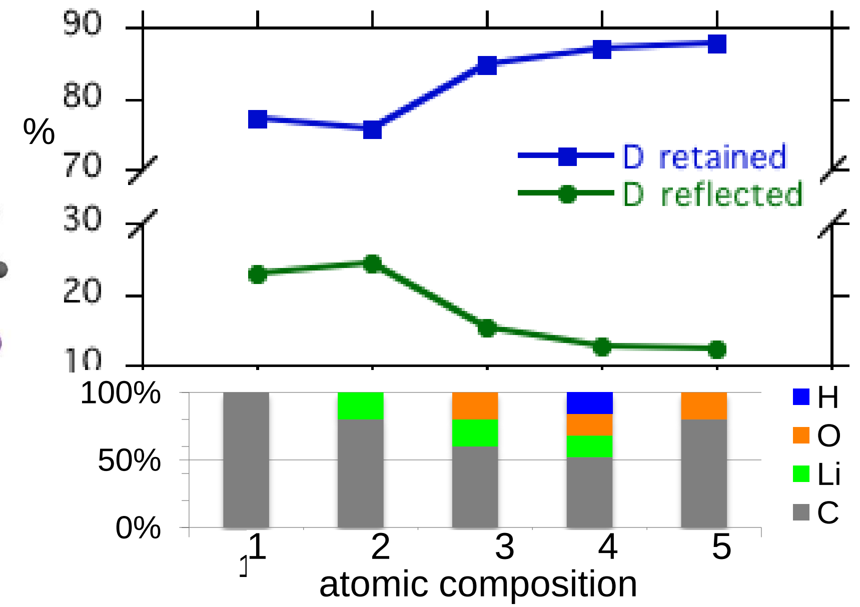
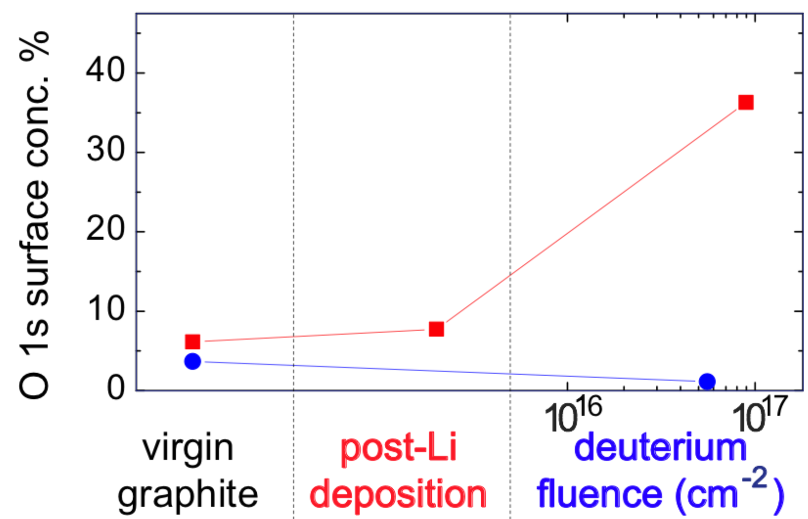
Quantum-classical atomistic simulations show that surface oxygen plays a key role in the deuterium retention in graphite.
[ORNL, submitted to Nature Comm.]




- XPS measurements *(Purdue)* show that 2 µm lithium increases the surface oxygen content of lithiated graphite to about 10%.
- Deuterium ion irradiation of lithiated graphite greatly enhances the oxygen content to 20% - 40%.
- In stark contrast, D irradiation of a graphite sample without lithium actually *decreases* the amount of O on the surface.

- Result explains why Li on C pumps D so effectively



# PPPL/PU collaboration shows lithium reacts quickly with residual gases

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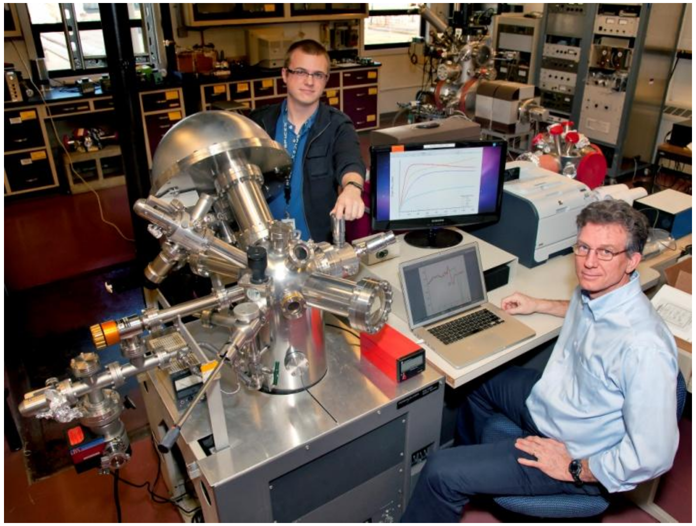
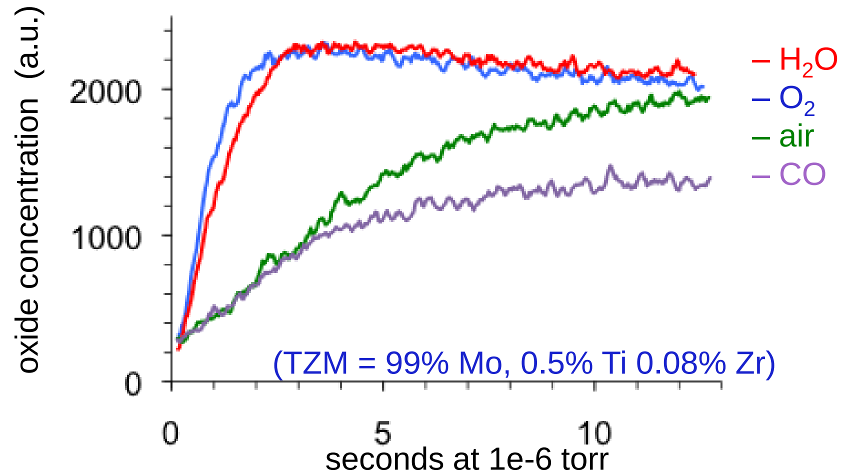
New Surface Analysis Labs at PPPL



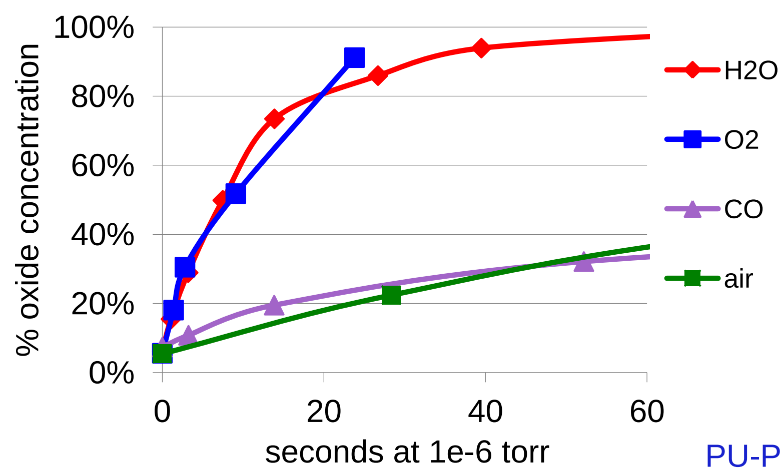
- Surface analysis experiments show PFC oxide coverage is expected in 10s of seconds from residual $H_2O$ at typical NSTX intershot pressures ~1e-7 torr.
- Plasma facing surface after Li evaporation is a mixed material rather than 'lithium coating'.
- **Short reaction times motivate flowing Li PFCs**

Li surface oxidation time

1 monolayer of lithium on TZM Mo (AES O 1s)




Solid lithium (XPS Li 1s))




PU-PPPL

# LLD with optimized pore size and layer thickness can provide stable lithium surface

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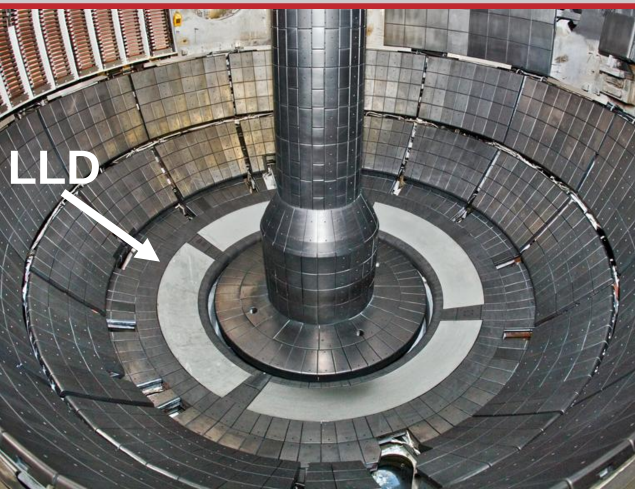
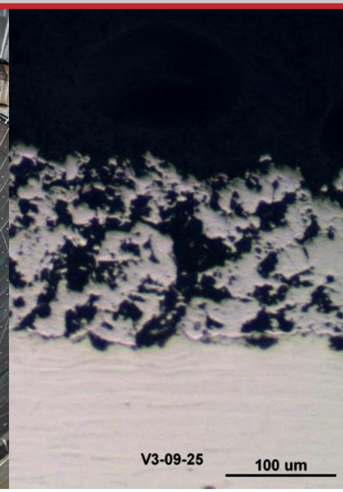
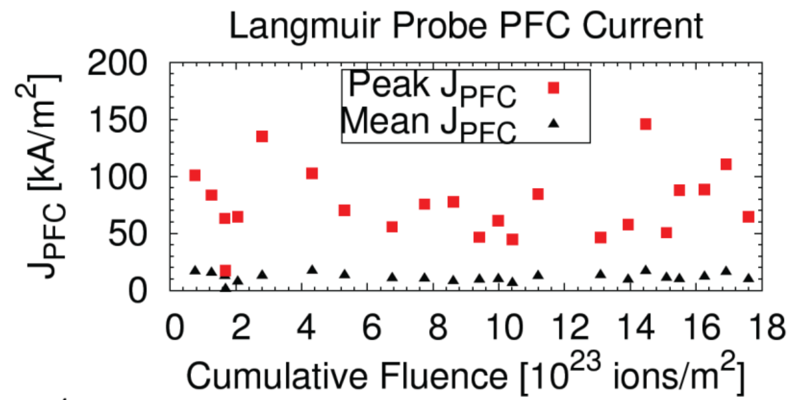
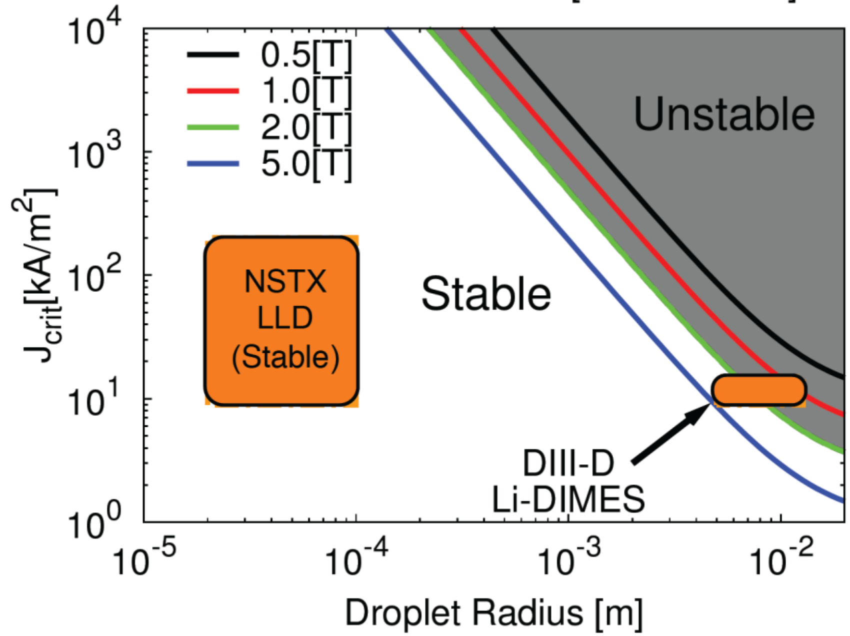



LLD surface cross section: plasma sprayed porous Mo

- LLD filled with 67 g-Li by evaporation, (twice that needed to fill the porosity).
- No major Mo or macroscopic Li influx observed even with strike point on LLD.
- No lithium ejection events from LLD observed during NSTX transients > 100 kA/m$^2$
  - Thin layers and small pore diameters increase critical current ($J_{crit}$) for ejection.
  - Modelling consistent with DIII-D Li-DIMES ejection at 10kA/m$^2$ and NSTX experience.




M.A. Jaworski, et al., J. Nucl. Mater. 415 (2011) S985.
D. Whyte, et al., Fusion Eng. Des. 72 (2004) 133.

# Prototype Li-PFC materials testing at Magnum-PSI

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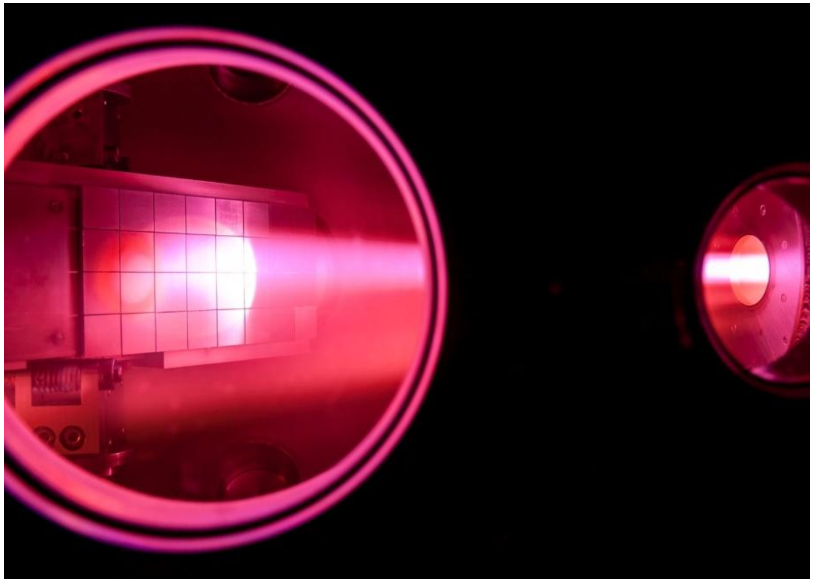
NSTX-U PFCs (ATJ, TZM (Mo), W) will be tested with and without Li coatings at NSTX-U pulse lengths and power levels with extensive diagnostics

Planned investigations:

– Li coating lifetime

– Hydrogenic recycling/retention as a function of exposure time & temperature.

– Erosion, migration, impurity production with and without lithium.



Magnum-PSI parameters relevant to NSTX-U

- 1.4 T for 12 s
- 10 $MW/m^2$
- $N_e \sim 1.2 x 10^{20} m^{-3}$
- $T_e \sim 3$ eV
- Bias ≤ 100 V
- Extensive diagnostics

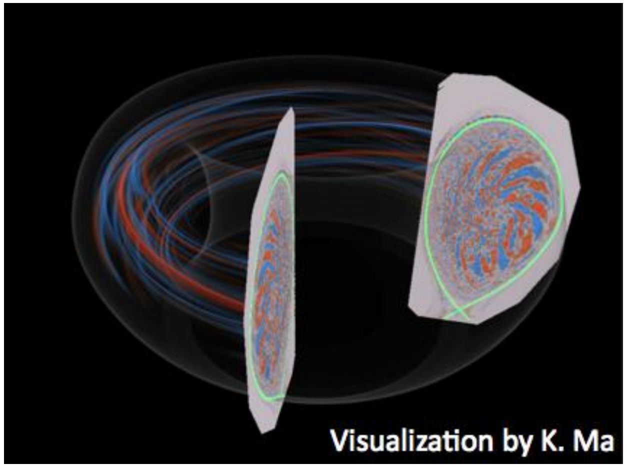
# Modeling support: Li physics simulation plan using XGC

Short term plan (2012-2014)

- Neoclassical Li-physics simulation with XGC0 + DEGAS2
  - Self-consistent "kinetic" plasma modeling capability
    - successor to fluid plasma codes B2-EIRENE, UEDGE-DEGAS2 et al.,
  - Non-equilibrium Li radiation, non-Maxwellian electrons (see backup #23).
  - Includes effect of Mo impurities, compared to C
  - Effect of Li influx on pedestal and plasma behavior

Long term plan (2015-2018)

- Neoclassical-turbulence Li simulation in XGC1 + DEGAS2
  - Add self-consistent turbulence to the above
  - Adapt the code geometry to Magnum-PSI for Li radiation simulation validation
  - Study Li issues under 3D RMPs

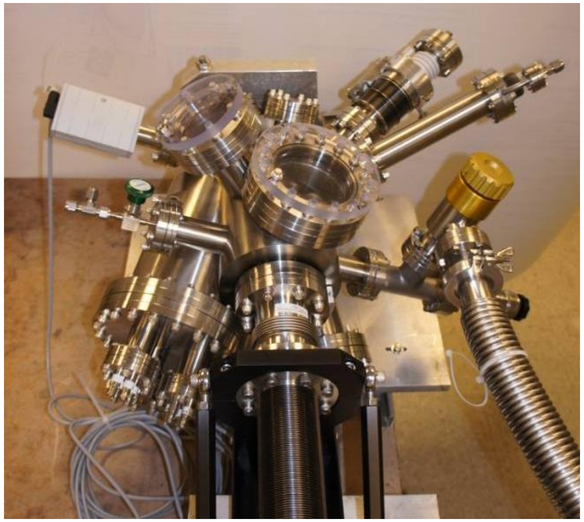



XGC1 simulation of ITG turbulence in separatrix geometry

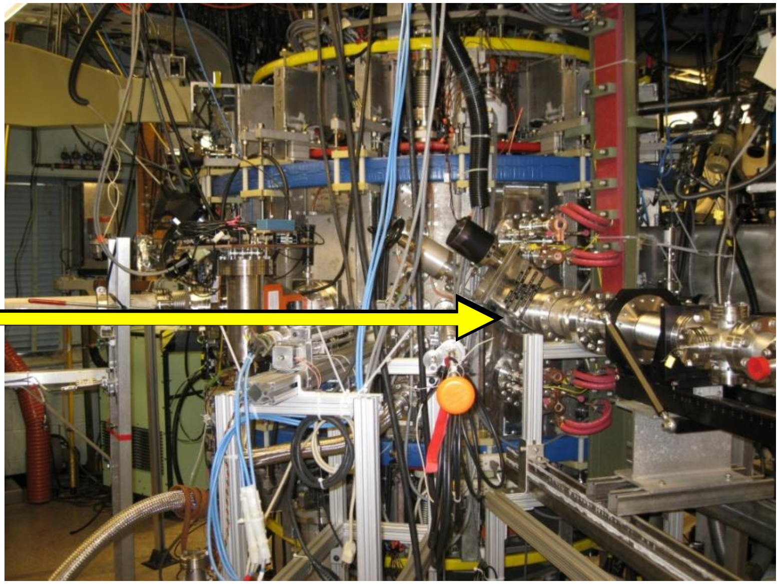
# LTX is providing all-metal-wall tokamak investigating Li chemistry, temperature, thickness…

- Lithium Tokamak Experiment has: 1. 120 $cm^2$ Li-filled dendritic W limiter heatable ≤ 500 C
  2. Thick (>100 micron) evaporated Li films on 3,000 – 5,000 $cm^2$ upper heated liner
  3. Few hundred $cm^3$ pool of liquid Li in the lower shells (total ≤ 85% of plasma surface)
- Will investigate plasma-surface interactions, Li influx vs. temp., confinement, Te profile, liquid metal flows in B fields up to 0.3T
- Materials Analysis and Particle Probe (MAPP) will be used first on LTX in support of NSTX milestone R(13-2): "*Investigate relationship between lithium-conditioned surface composition and plasma behavior*" and transferred to NSTX-U later.
- MAPP's innovative design enables sample exposure to plasma and inter-shot surface analysis.

MAPP



MAPP will be installed on midplane LTX port



# NSTX/EAST lithium collaborations

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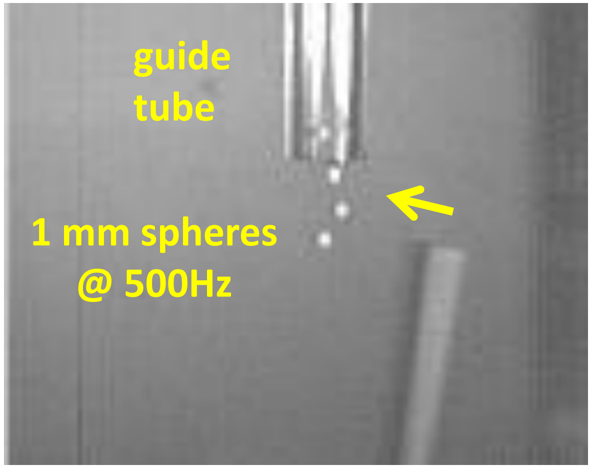
EAST is only other divertor H-mode facility using Li

- NSTX Li powder dropper achieved 1st H mode on EAST and drastically reduced MHD (in backup).
- 2nd dropper being built by ASIPP.
- Li granule injector to be installed on EAST midplane - will be used to trigger ELMs and control MHD

Plans:

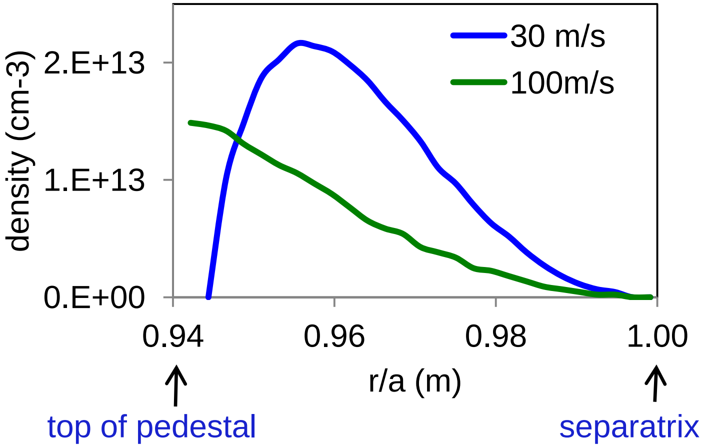
- Assess interplay between cryo-pumping and lithiumization, and high- Z PFC interactions/synergies with lithium
- Study effects of Li on thermal and particle transport, further develop sustained/long-pulse lithium delivery systems (Li injector, dropper)

Continuous Li delivery may be essential for long pulses.




Lithium granules injected using 95 m/s “impeller”

Li deposited between pedestal and separatrix



# Lab-based R&D on liquid metal technology will inform long term PFC decisions:

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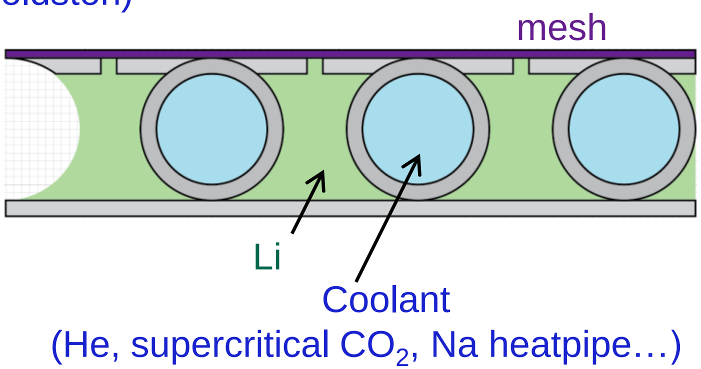
Pre-NSTX-U restart R&D initiated by PPPL:

1. Laboratory studies of D uptake as a function of Li dose, C/Mo substrate, surface oxidation, wetting…
2. Tests of prototype of scalable flowing liquid lithium system (FliLi) at PPPL and on HT7
3. Basic liquid lithium flow loop on textured surfaces
4. Analysis and design of actively-cooled PFCs with Li flows due to capillary action and thermoelectric MHD
5. Magnum-PSI tests begin June 2012

Thin flowing Li film in FLiLi (Zakharov)

- Four proposals on Li-PFCs submitted to OFES Materials Solicitation to extend above work.
- Preparing for upcoming international collaboration solicitation, which will include possible tests of Li PFCs on HT-7 and EAST

Soaker hose capillary porous system concept (Goldston)



# Lithium capabilities planned for NSTX-U operation

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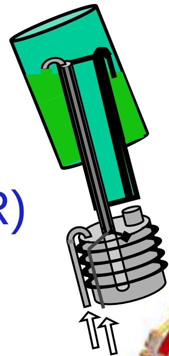
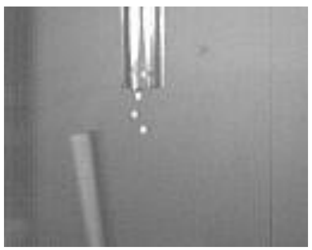
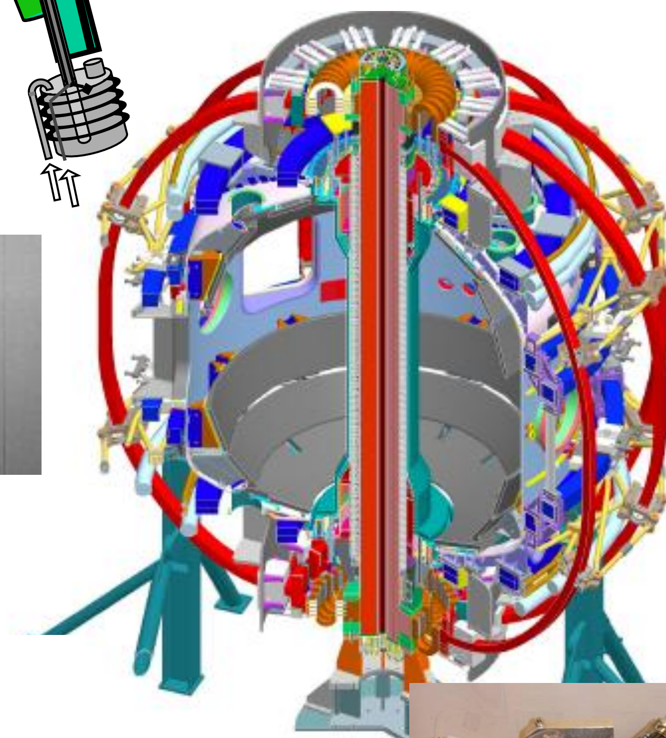
NSTX-U Baseline:

Existing Lithium evaporator (LiTER)

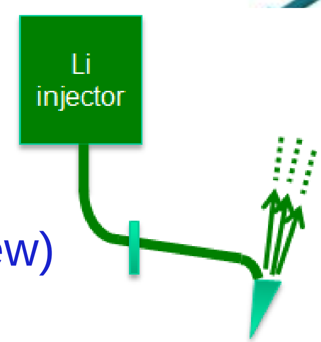


midplane Li granule injector for ELM control






Upward Li evaporator (new)




Yttrium crucible 700°C

MAPP probe

# NSTX-U Plan for Years 1-5 of operation:

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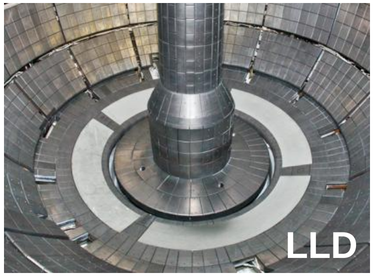
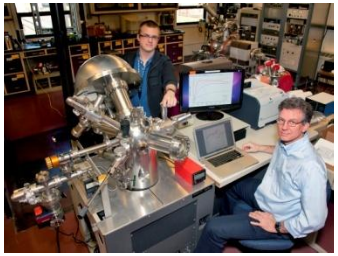
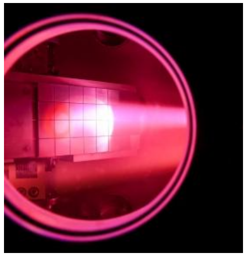
- Year 1-2:
  - Test Li evaporation for pumping longer pulse duration NSTX-U plasmas.
  - Test Li evaporation to upper vessel by evaporator/injector, He diffusion, electrostatic sprayer.
  - Assess impact of full wall Li coverage on pumping, confinement
  - Test ELM control by midplane Li granule injector
  - Test Li-PFC prototypes on Magnum PSI and possibly LTX or EAST
- Year 2:
  - Down select to best flowing Li-PFC concepts
  - Test on Magnum PSI and LTX or EAST
- Year 3-5:
  - Test flowing Li-PFC on at least one toroidal sector of NSTX-U, possibly full toroidal coverage system, pending lab-based tests and modelling

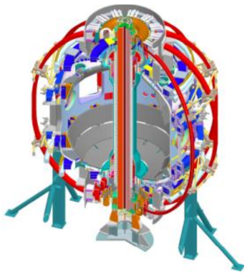
# Summary:

- Li PFCs have demonstrated promise for
  - Superior plasma performance
  - High heat flux handling
  - May solve PFC neutron damage and erosion issues in FNSF and demo.
- High confidence implementation requires R&D on:
  - Surface chemistry
  - Off-line heat flux tests of PFC prototypes
  - Tokamak integration
- Staged approach in place from atomistic simulations & lab experiments to test stands, LTX, EAST collaborations, leading to Li-PFC implementation in NSTX-U







# Backup:

# Metered Li evaporator for NSTX-U upper vessel Li coverage

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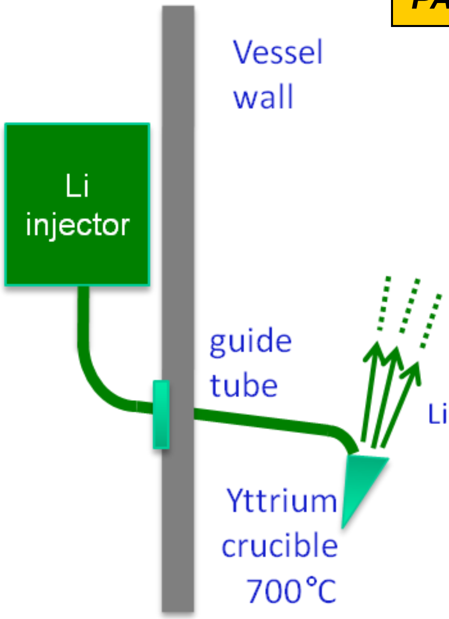
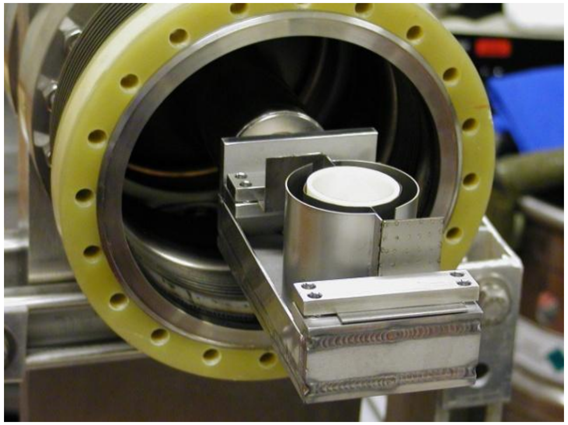
Concept combines Dropper and Li crucible technology

- drop ~ 200 mg of Li granules into yttria crucible at 700°C seconds before discharge.
- all Li promptly evaporated to upper vessel.

Advantages:

- no shutters
- minimal reactions with residual gases
- controllable Li dose
- small source collimation - avoid RF antenna
- combines mature technologies
- Testing, installation details in progress.



$Y_2O_3$ crucible, Ta heater tested to 700 °C on LTX

# Preliminary erosion modeling of Mo tiles shows low sputtering and plasma contamination

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- WBC modeling of SOLPS background plasma
- Debye (normal sheath) model near self-sputtering limit, grazing sheath model acceptable

| Parameter | Reference sheath model (Debye-only) | Alternative sheath model (Magnetic+Debye) |
|---|---|---|
| Mean free path[a], mm | 0.24 | 0.58 |
| Charge state[c] | 3.1 | 1.8 |
| Energy[c], eV (standard deviation. eV) | 491 (303) | 213 (212) |
| $D^+$ sputtering fraction | 0.47 | 0.77 |
| Self-sputtering fraction | 0.53 | 0.23 |
| Sputtered Mo current/incident $D^+$ current | $9.6x10^{-4}$ | $3.6x10^{-4}$ |
| Sputtered Mo to core plasma | -0- | -0- |
| Peak gross erosion rate, nm/s | 5.2 | 2.8 |
| Peak net erosion rate, nm/s | 0.46 | 0.23 |

*J. Brooks (Purdue)*

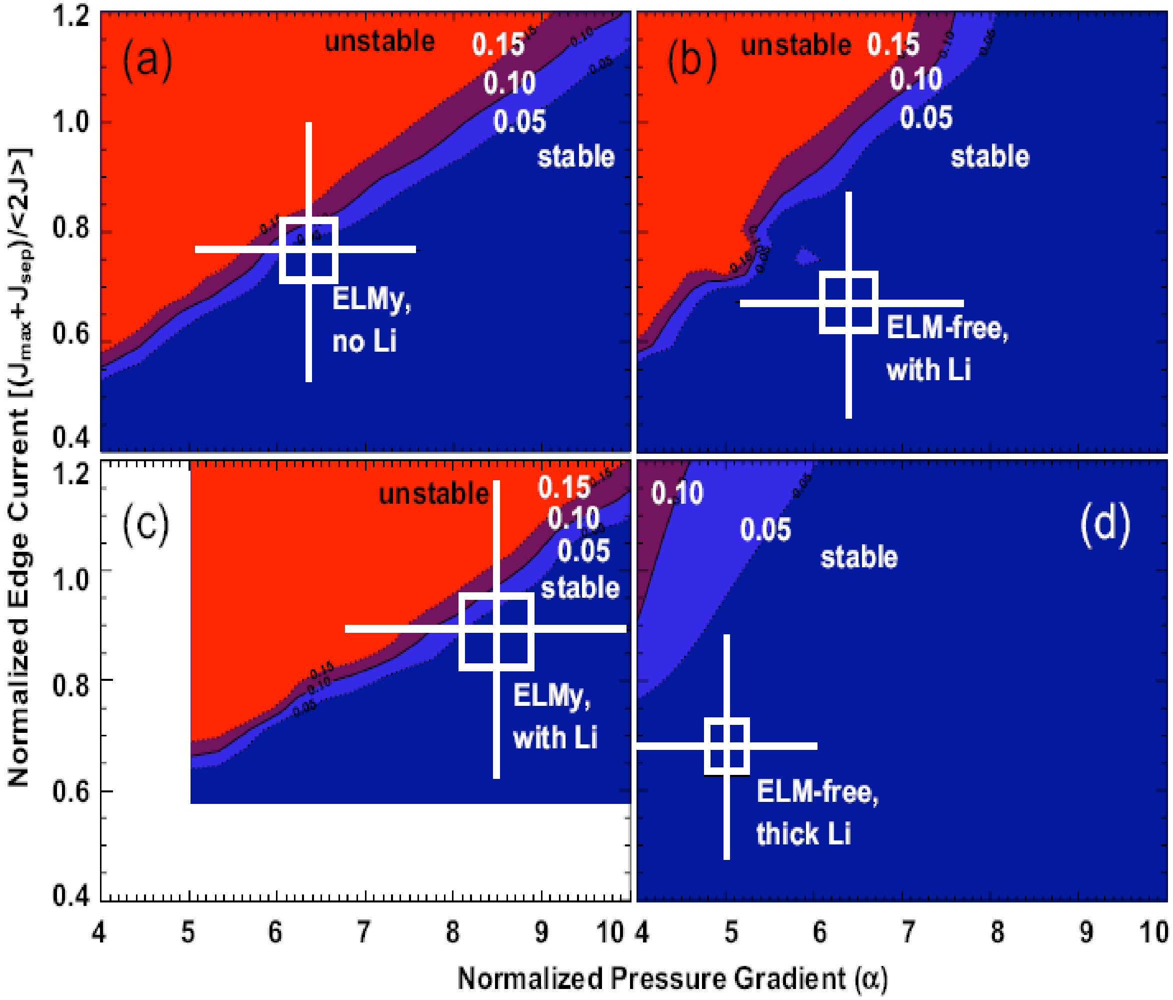
# ELM stability improves as a result of density profile modification due to lithium application

Density and ∇p alteration

- Recycling reduced by lithium evaporation
- Density profile altered, $\nabla T_e$ clamped: results in ∇p moving away from separatrix

Kink/peeling stability improves

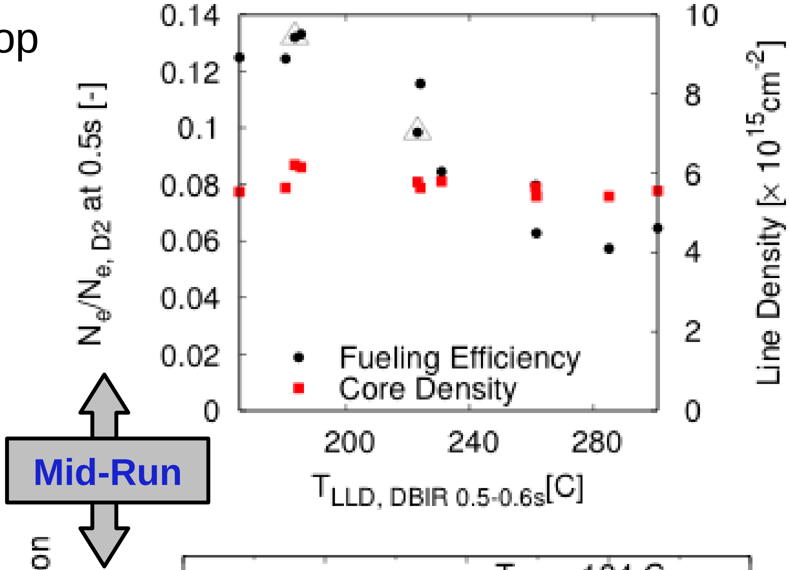
- Analysis indicates mode is current driven
  - Not near ballooning boundary
- The change in ∇p modifies edge bootstrap current, which modifies kink/peeling boundary.

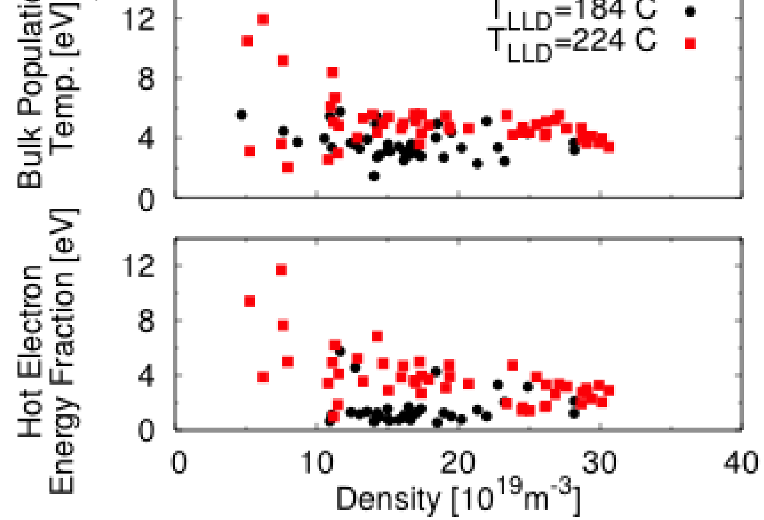


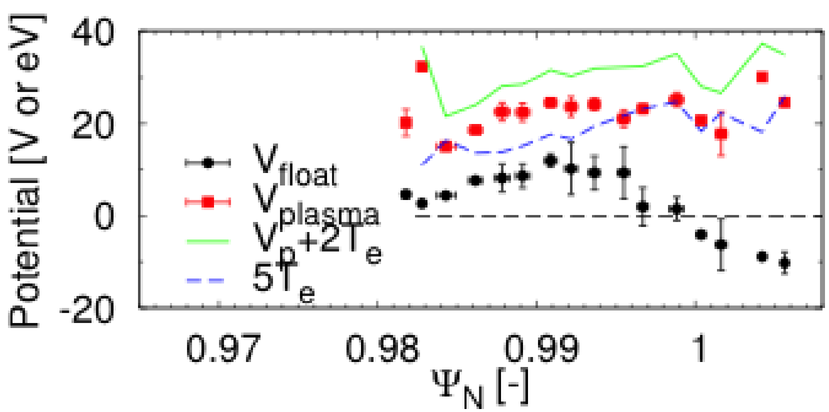

Boyle, et al., PPCF 53, 105011 (2011)

# Molten lithium by plasma bombardment coincided with reduced fueling efficiency and higher target $T_e$

- Mid-run experiments indicated fueling efficiency drop when $T_{LLD} > T_{Li,melt}$
- Increases in both bulk $T_e$ as well as tail fraction consistent w/ absorbing surface
- Fueling efficiency decreased about 50%, but multi-variable experiment (increased gas with increased surface temperature)
- Impact energies lower than earlier estimates
- TRIM runs indicate little penetration
- Motivates flowing system to mitigate continual gettering during vacuum exposure




H.W. Kugel, et al., Fusion Eng. Des. 2011 in press.
M.A. Jaworski, et al., Fusion Eng. Des. 2012, in press.

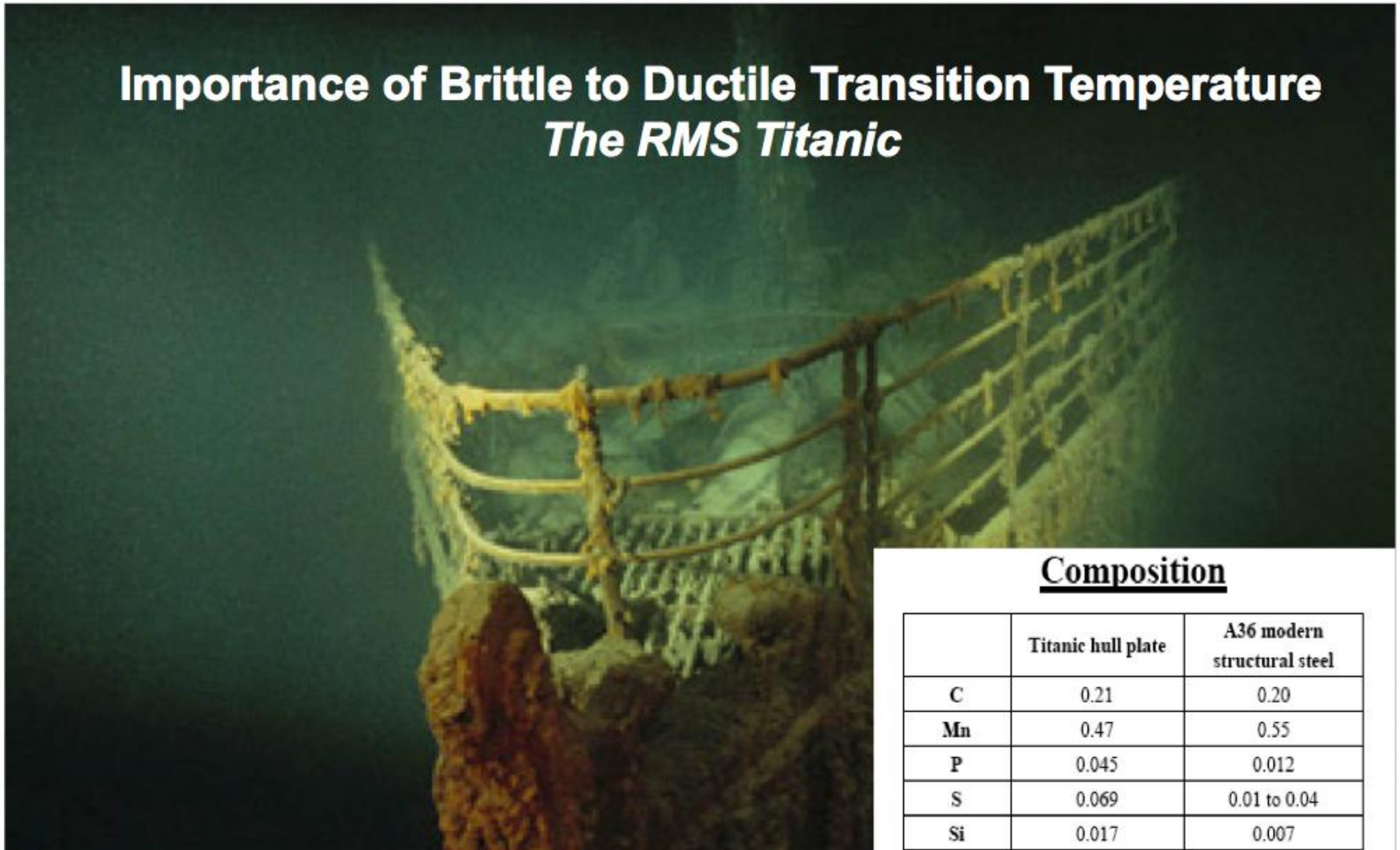
# Main Research Needs for Implementing Liquid Metal Plasma Facing Components

PAC29-5c

PAC29-18

- **Need 1:** Demonstrate stability of the liquid metal (LM) surface √ (LLD)
  - Design against ejection events and substrate exposure.
  - **Near-term strategy: Emphasize capillary-restrained schemes**
- **Need 2:** Establish control over the in-vessel inventory of liquid metal
  - Control evaporation and condensing surface locations and material collection
  - **Near-term strategy: Leverage existing active cooling technologies for thermal control while developing next-step schemes**
- **Need 3:** Develop adequate means of maintaining the liquid metal
  - Perform efficient purification and establish robust operation and maintenance
  - **Near-term strategy: Learn from IFMIF EVEDA and develop robust, maintainable systems from day 1**
- **Need 4:** Understand plasma response and physics of LM-PFC (13-2 Milestone)
  - Develop descriptive and prescriptive models for the SOL/PMI of LM-PFCs
  - **Near-term strategy: Validate fluid and kinetic codes and databases against available linear-machine data as well as tokamak database**
- **Develop engineered, LM-PFC modules to a significant technological maturity for implementation in NSTX-U or other devices**

# The Effect of Neutron Irradiation on PFC's at DEMO-Relevant Conditions
## Lance L Snead Oak Ridge National Laboratory
## Presented at the 19th PSI Conference



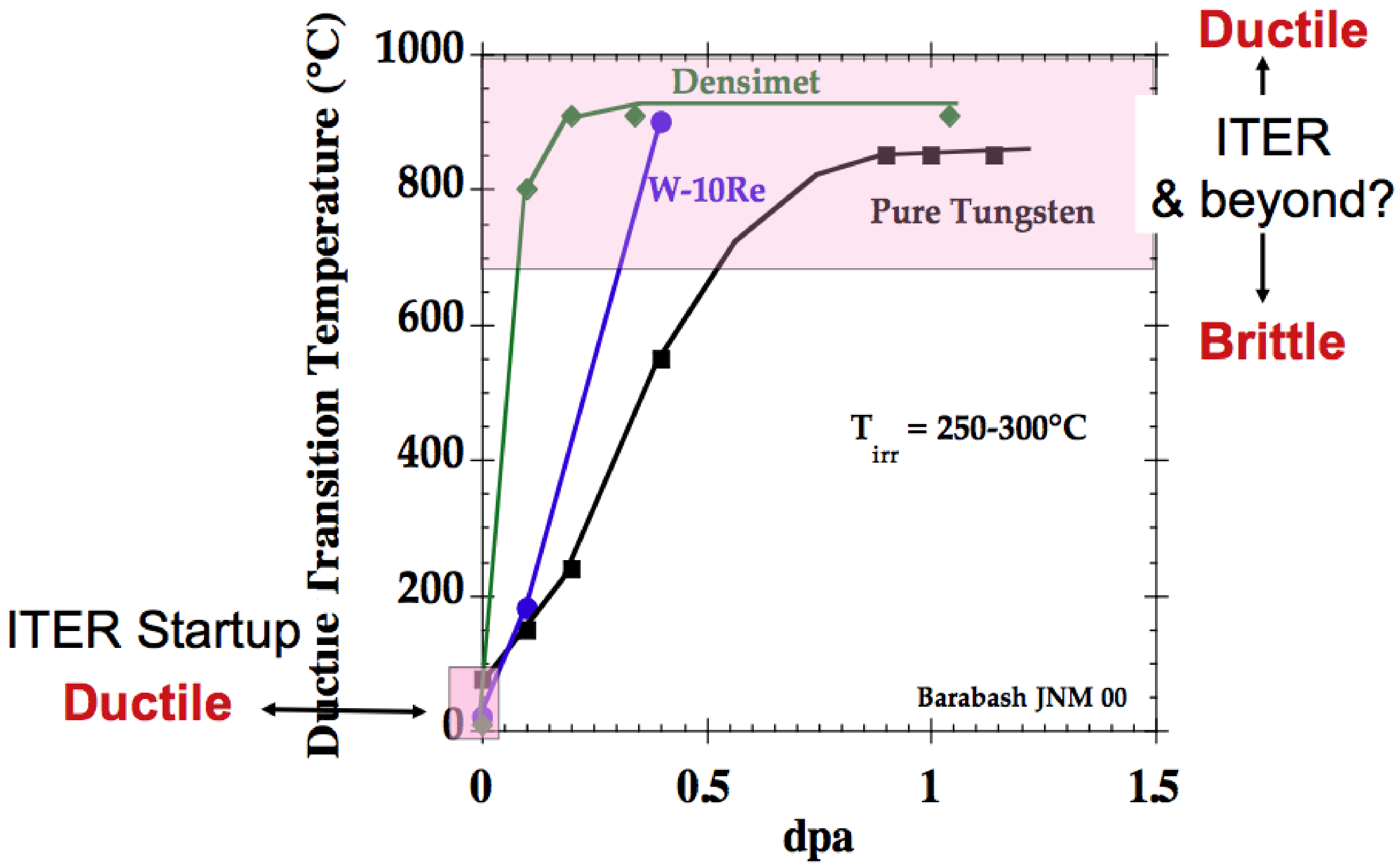

| | Titanic hull plate | A36 modern structural steel |
|---|---|---|
| Mn:S Ratio | 7:1 | 15:1 (typical) |

**Composition**

| | Titanic hull plate | A36 modern structural steel |
|---|---|---|
| C | 0.21 | 0.20 |
| Mn | 0.47 | 0.55 |
| P | 0.045 | 0.012 |
| S | 0.069 | 0.01 to 0.04 |
| Si | 0.017 | 0.007 |
| Cu | 0.024 | 0.01 |
| O | 0.013 | - |
| N | 0.0035 | 0.0032 |
| Mn:S Ratio | 7:1 | 15:1 (typical) |

K. Felkins, H. P. Leighly, and A. Jankovic. JOM, 50(1), 1998, 12-18

# Tungsten Under Irradiation




- **Present forms of tungsten undergo significant embrittlement following low dose irradiation. It currently appears that for end of life ITER and higher dose fusion reactors, tungsten alloys will be fully brittle.**

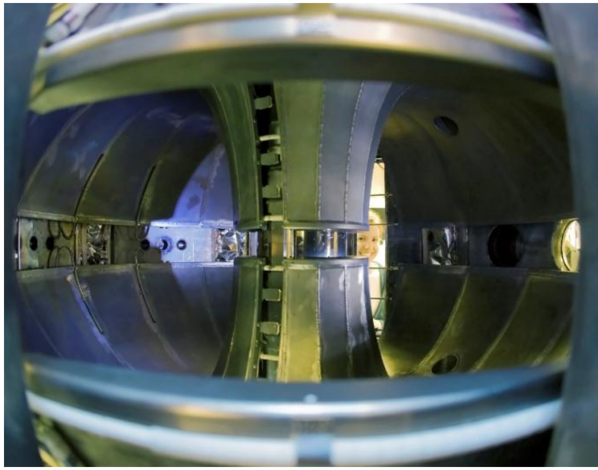
# NSTX divertor conditions in 2010 vs. Magnum-PSI

| Parameter | Magnum design | Pilot achieved | Pulsed CA source design | NSTX discharges with heavy lithium (Liquid Lithium Divertor) |
|---|---|---|---|---|
| Power [kW] | 270 | 100 | 3500 | 4 MW NBI |
| Pressure source [Pa] | $10^4$ | $10^4$ | | |
| Pressure target [Pa] | <3 | 1-10 | | ~0.1-1 |
| Ti target [eV] | 0.1-10 | 0.1-5 | | 1-50? |
| Te target [eV] | 0.1-10 | 0.1-5 | ~10 | 1-15 (non-Maxwellian) |
| Ni target [$m^{-3}$] | $10^{20}$-$10^{21}$ | $10^{21}$ | ~$2x10^{22}$ | $5x10^{20}$ at SP |
| Ion flux target [$m^{-2}s^{-1}$] | $10^{24}$-$10^{25}$ | $2x10^{25}$ | | $2x10^{23}$ at SP |
| Power flux target [MW $m^{-2}$] | 10 | 30 | 2000 | 2-5 at ~5 deg. incl. |
| B [T] | 1.4 (3) | 1.6 | 1.6 | 0.6 |
| Beam diameter [cm] | 10-1.5 | 1.5 | 2.0 | ~4cm FWHM |
| Pulse length [s] | 12 (ss) | 4 | 0.0005 | 1s |
| Extra heating [kW] | 50 | 0 | 0 | NA |
| Target size [cm] | 60x12 | 2.5 | 2.5 | Order~10cm |
| Bias [V] | $-100 < V_{target} < 0$ | | | $-20 < V_{floating} < 20$ |

M. Jaworski

# LTX is complementary all-metal tokamak; investigations of Li chemistry, temperature, thickness…

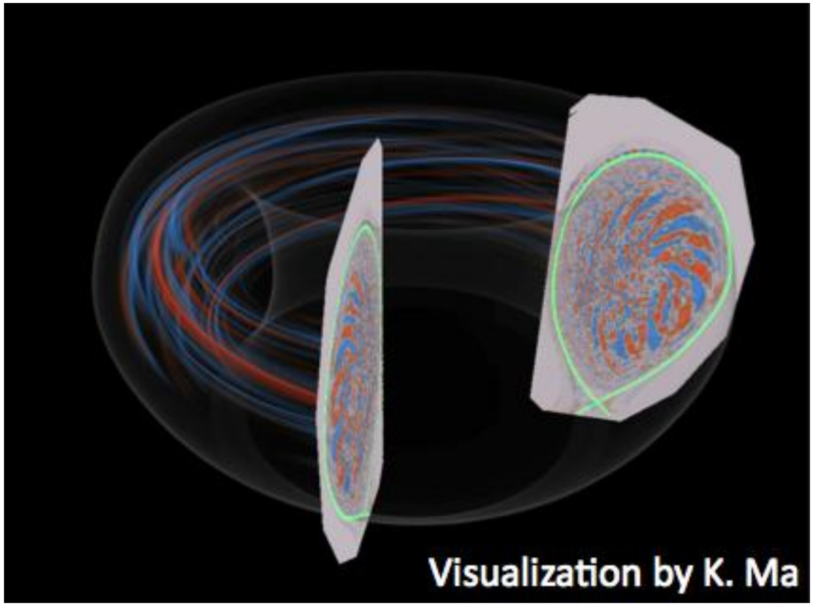
LTX



- Now: Liquid lithium limiter experiments
  - Insertable lithium-filled dendritic tungsten limiter
  - 120 $cm^2$ area, can be heated to 500 C
  - Monitored with fast framing camera, spectroscopy
  - Investigate plasma-surface interactions, Li influx vs. temperature, confinement effects
- Soon (few weeks):
  - Thick (>100 micron) evaporated films on upper heated liner
  - Liquid area 3,000 – 5,000 $cm^2$
  - Investigate confinement, electron temperature profile modifications
- ~ May:
  - Few hundred $cm^3$ pool of liquid lithium in the lower shells
  - Electron-beam stirred (Marangoni, TEMHD effects)
  - Investigate liquid metal flows in magnetic fields up to 0.3T (late FY12)
  - Investigate confinement with 5 $m^2$ liquid lithium boundary (85% of plasma surface)
  - Electron temperature profile modifications, lithium influx with full liquid metal boundary

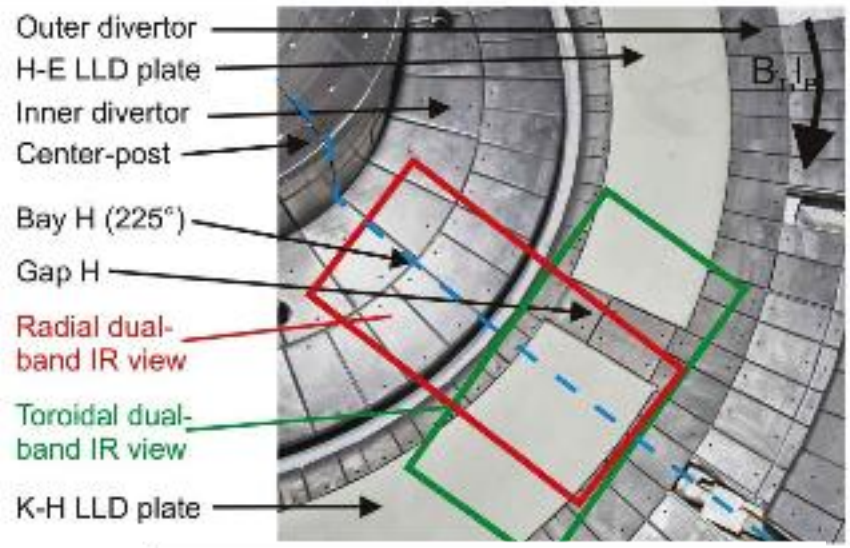
# SciDAC-3 Project "Partnership for Edge Physics Simulation" (EPSI) Will Provide Simulation Capabilities Vital to NSTX-U

- Multi-institution collaborative project proposed 10/2011 (C.S. Chang, PI),
  - Would run through ~2017 if funded.
  - Building on capabilities from SciDAC-2 Center for Edge Plasma Simulation (2005-2011).
  - Will allow necessary upgrade of XGC1, concurrently with extreme scale computing development using ASCR collaboration
- Main objectives are to study: edge turbulence, L-H transition, pedestal structure, RMP suppression of ELMs, edge and wall effect on core, heat & particle loads to wall, etc
- Use first principles, kinetic codes to study multi-scale & multi-physics self-organization
  - Plasma turbulence, transport & RMP: XGC
  - Neutrals, wall and atomic physics: DEGAS2 (built into XGC)
  - ELMs: M3D, M3D-C1, BOUT++ (coupled simulation with XGC)

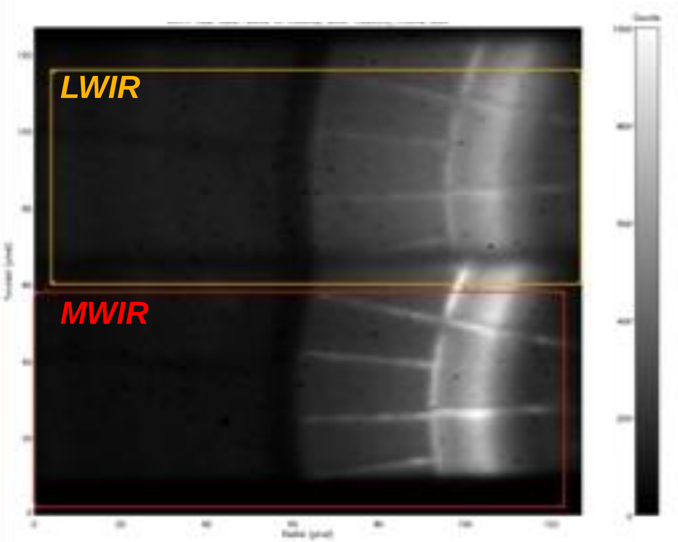


# The Dual-Band IR Camera Allows Measurement of Divertor Surface Temperature with Variable Surface Emissivity

- The addition of lithium complicates the measurement of divertor surface temperature, $T_{surf}$
  - Lithium and Carbon are eroded and redeposited constantly through out the discharge
  - Surface emissivity is unknown
- 2 different IR wavelength bands are imaged simultaneously
  - Santa Barbra Focal Plane ImagIR camera
    - 1.6 – 6.3 kHz, 1.5 – 11 µm, 128x128 pixels
  - MWIR: 7 – 10 µm
  - LWIR: 10 – 13 µm
- The ratio of the 2 bands yields $T_{surf}$
- Once $T_{surf}$ is known, heat flux is calculated using a 2D finite difference heat conduction code (THEODOR)

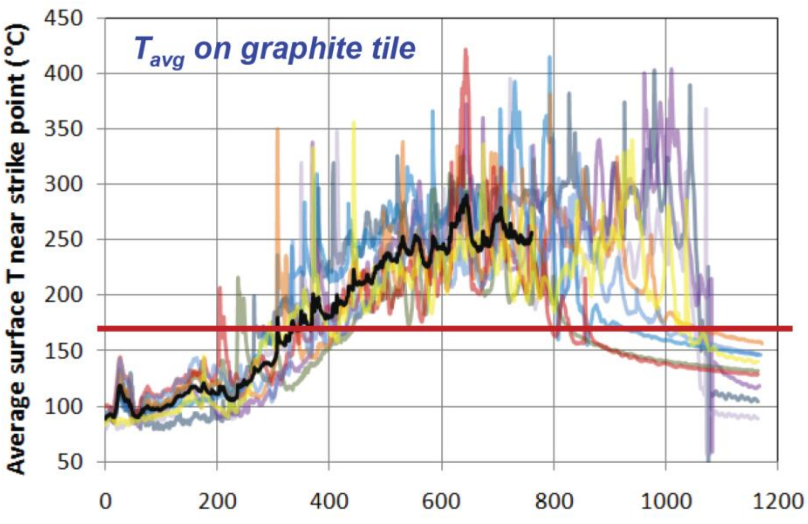


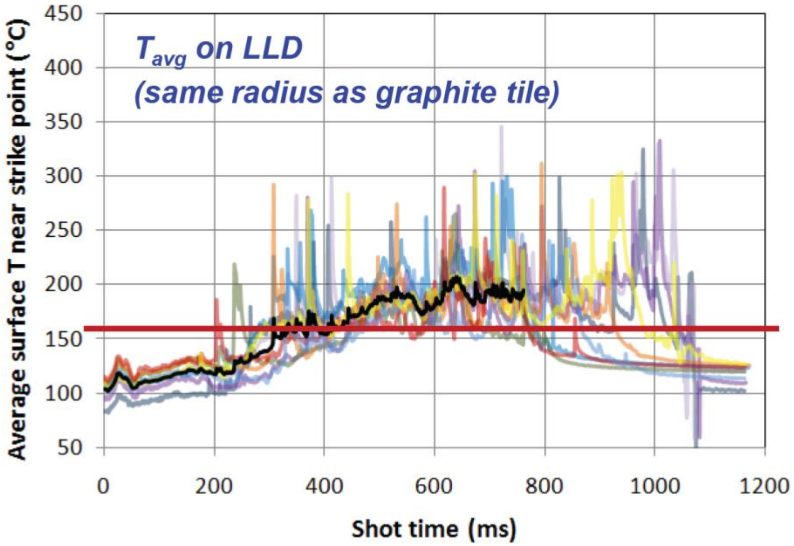

**_Raw Dual Band IR Image_**



# Average $T_{surf}$ on LLD and graphite tile at equal radii suggests that $T_{surf}$ is reduced due to improved heat removal through the LLD Cu

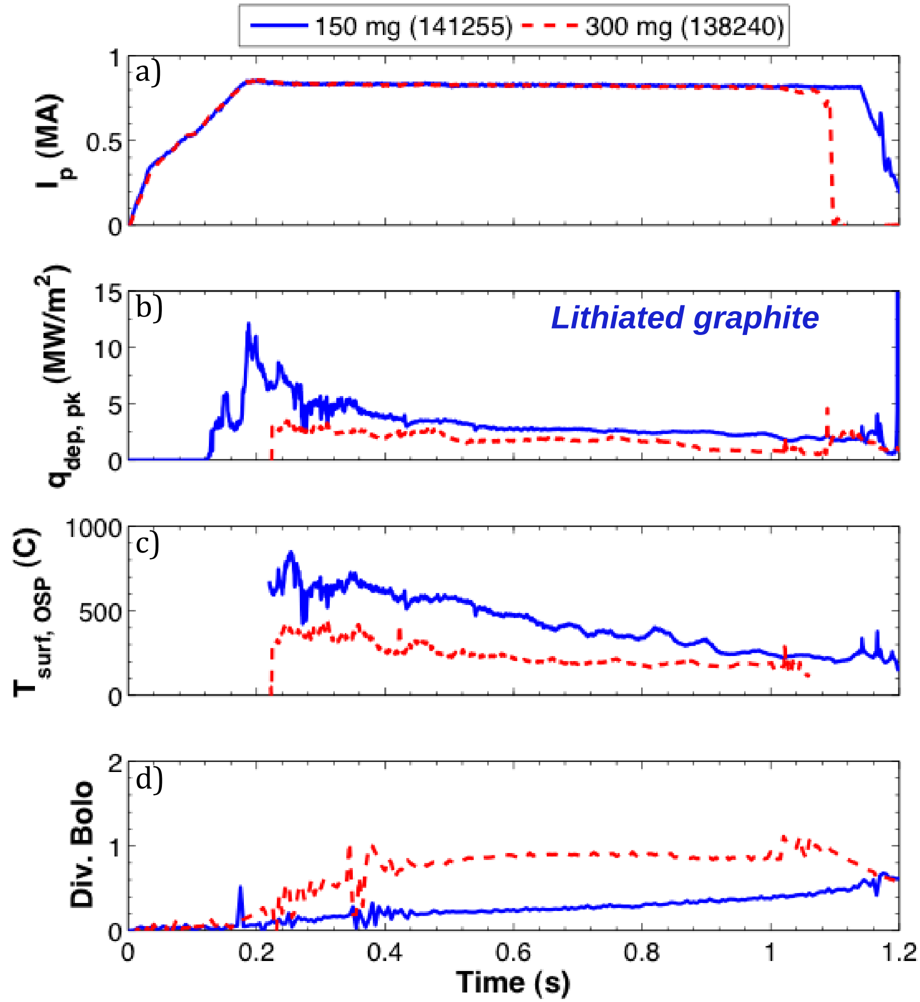
- Series of 10 repeat discharges with outer strike point on the LLD
  - Graphite and LLD in this case begin with $T_{surf}$~70°C
- $T_{avg}$ on graphite gap tile increases through all shots in √t fashion
  - Average $T_{surf}$ of ~250°C
- $T_{avg}$ plotted at same radius, but on LLD
  - $T_{surf}$ increases more slowly
  - Efficient heat removal through LLD depth/Cu
- However during transients such as ELMs, $T_{LLD} > T_{ATJ}$ during the transient
  - Measured $T_{surf}$ response is dominated by thin film on the upper surface during transients [K Gan, APS 2011]



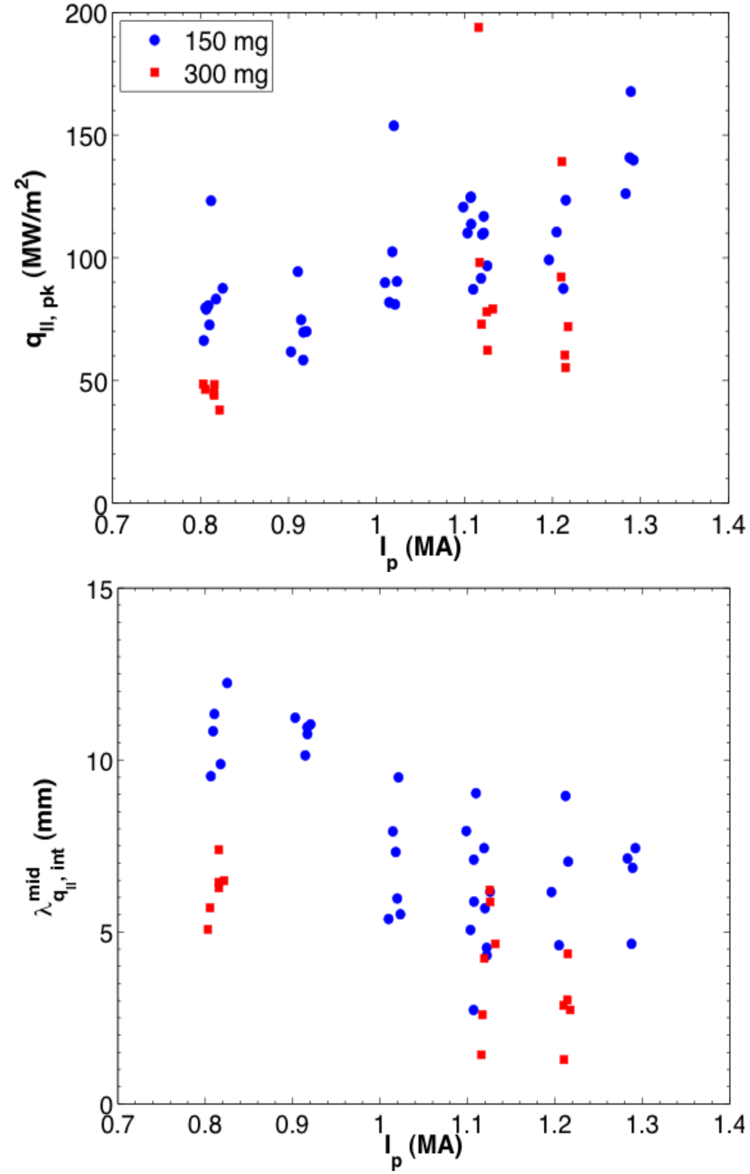
# Clear reduction in divertor surface temperature and heat flux with increased lithium evaporation

- 2 identical shots (No ELMs)
  - $I_p$ = 0.8 MA, $P_{nbi}$ ~ 4 MW
  - high δ, $f_{exp}$ ~ 20
- 2, pre-discharge lithium depositions
  - 150 mg: 141255
  - 300 mg: 138240
- $T_{surf}$ at the outer strike point stays below 400 C for 300 mg of Li
  - Peaks around 800 C for 150 mg
- Results in a heat flux that never peaks above 3 $MW/m^2$ with heavy lithium evaporation



# Peak Divertor Heat Flux and inter-ELM $\lambda_q$ are reduced when 300 mg of Li Evaporation is Used

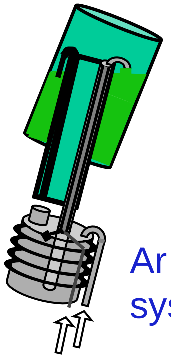
- Both deposited and parallel divertor heat flux is reduced when 300 mg of Li is evaporated
- $\lambda_{q,\ int}$ contracts with increased Li deposition
  - Trend is not predicted by current SOL width models
  - Suggests the importance of including divertor recycling in estimations of $\lambda_q$
- SOLPS modeling is in progress to better understand divertor physics

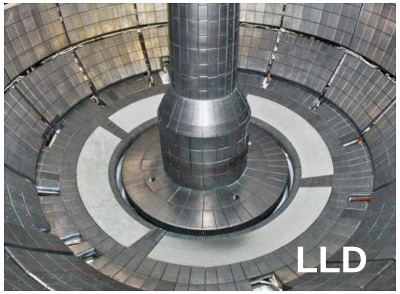


# PPPL is increasingly active in exploring lithium and liquid metals as a possible divertor solution for FNSF/Demo.

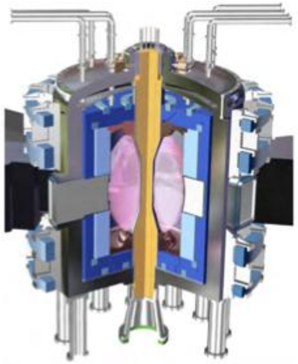
**PAC29-5c**

- Lithium evaporated onto NSTX PFCs achieved:
  - Reduced D-recycling,
  - Lower H-mode power threshold,
  - Broader electron temperature profiles, decreased electron thermal diffusivity and improved confinement
  - ELM suppression
  - (also positive results from LTX, FTU, T11, TFTR…)
- Short-pulse power handling with divertor strike point on lithium-filled surface successfully demonstrated by LLD.
  - Thermal response dominated by thermal mass of Cu substrate
  - No introduction of Mo or iron into plasma



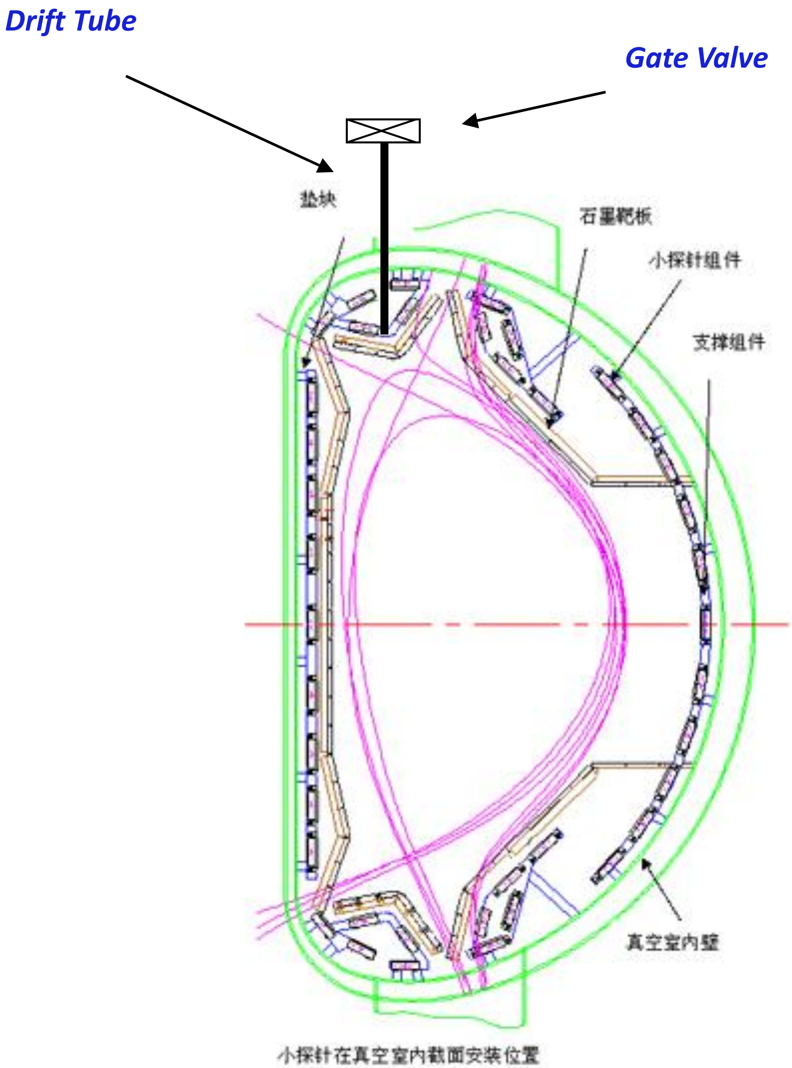

- Long term potential benefits of Li for fusion include:
  - Wide area high heat flux removal through Li radiation and evaporation
  - Divertor pumping over large surface area
  - No neutron damage and erosion lifetime issues in future fusion reactors.

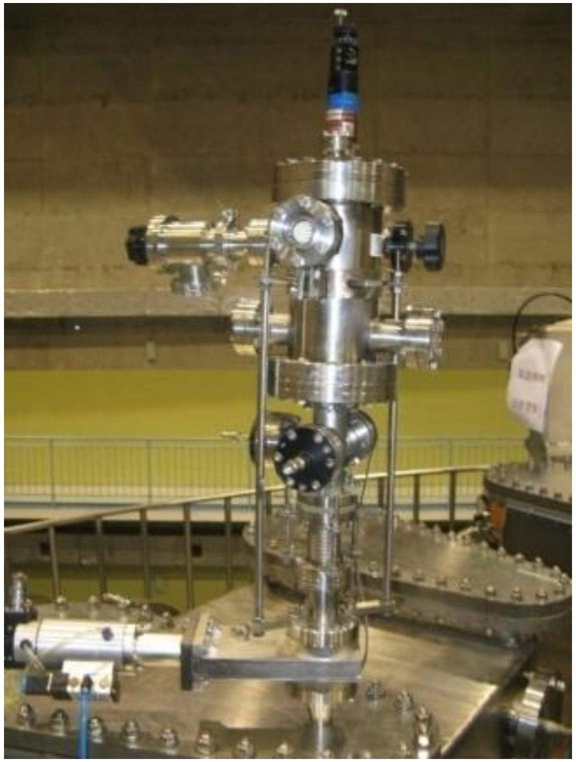


FNSF-ST (ORNL)

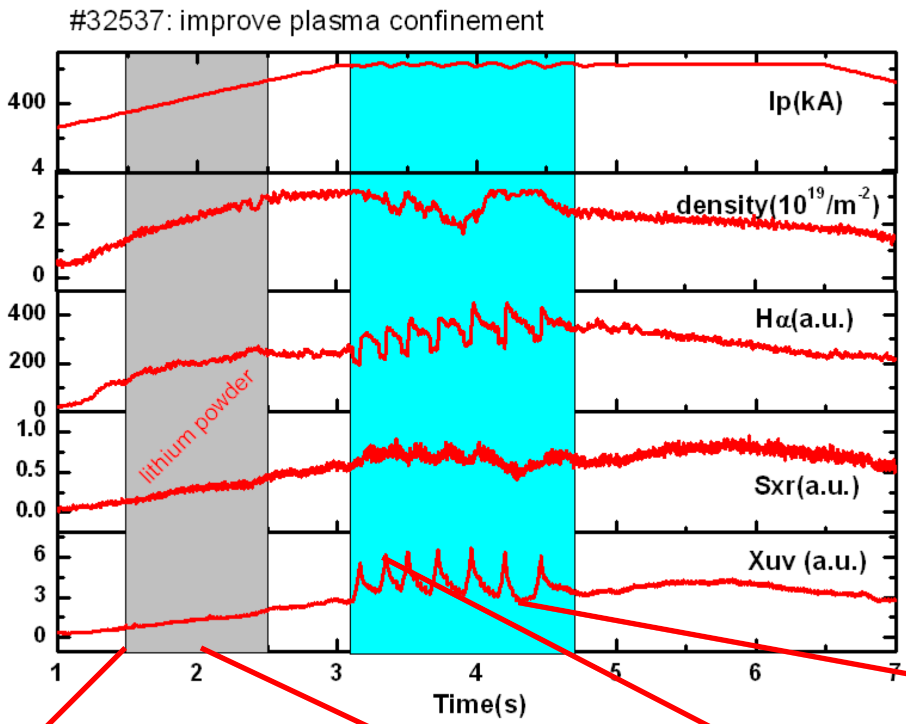
# The EAST Lithium Aerosol Dropper / Injector

PAC29-5c



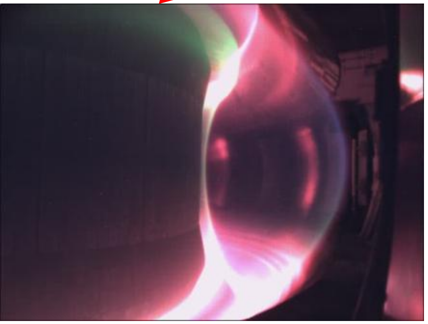
# Improve plasma performance using lithium powder injection-H mode

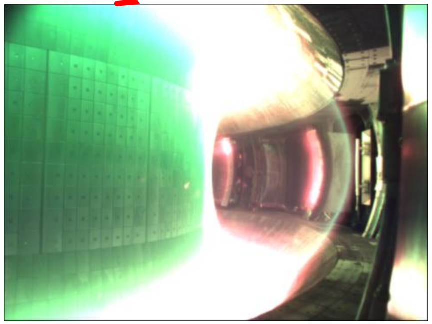


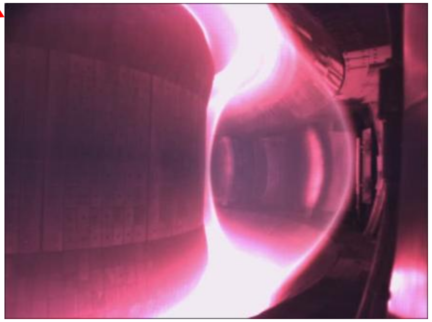

***#32525** :Before the shot , ~100g lithium coated by oven, powder injection from 1.9s to 2.9s, the confinement improves from about 4.8s;*

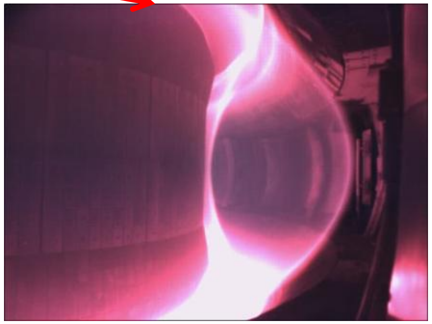
***#32537:** IT～6000A, IP～600kA， ne～ $2.1*10^{19}/m^2$， PLHCD~1MW, LSN from 3s; before the shots, about 30 shots lithium powder injection*

***Initial phase statistics about H mode:No.32525-33590:***
***Total H-mode plasma: 141 shots (37.5 %) ;***
***In H-mode plasmas, lithium powder injection:61 shots, 43.3 %.***

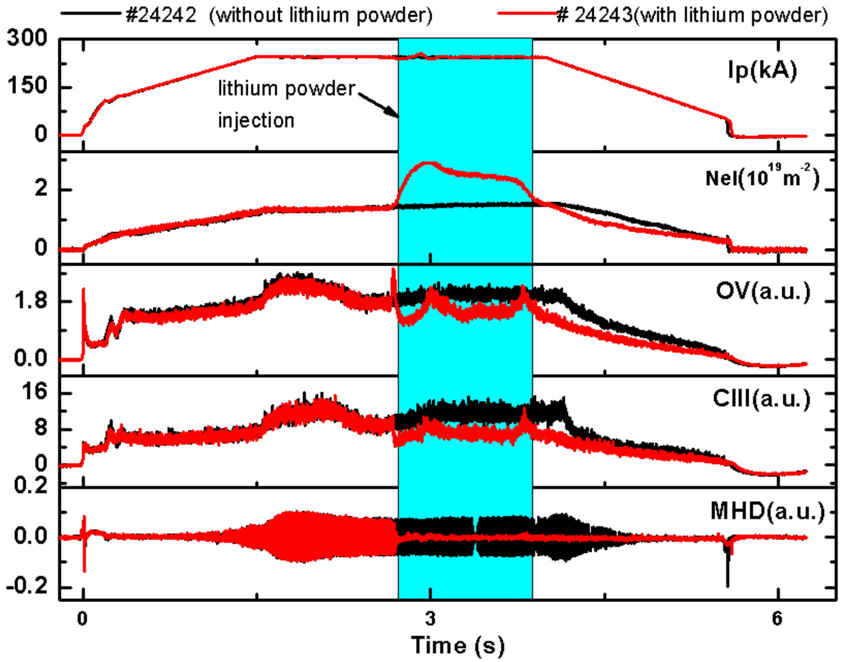


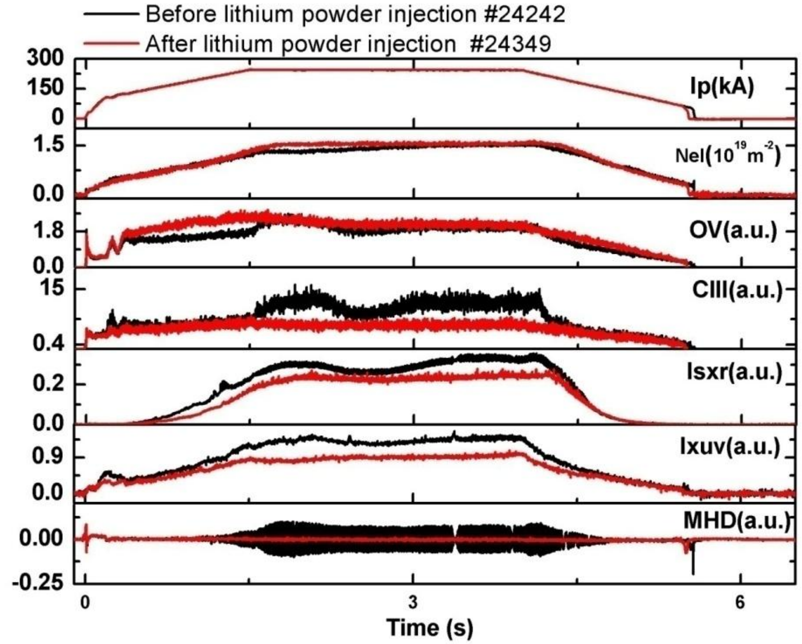






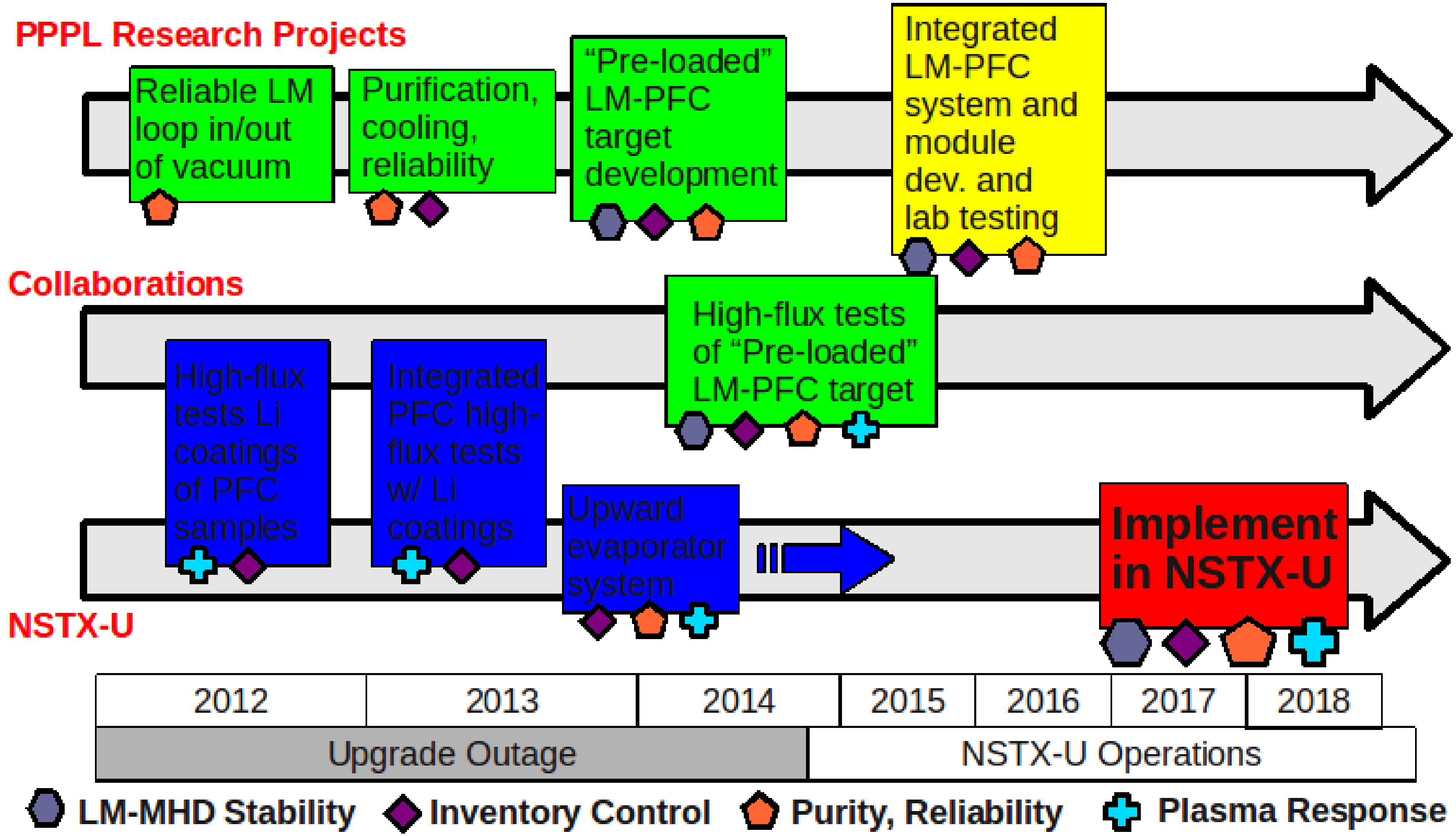
# Results of Lithium Powder Injection on EAST




➢ ***Lithium powder injection is very effective in suppressing MHD (spring campaign in 2010 on EAST ).***

# Near-Term Development Path to Address Research Needs and Implement in NSTX-U




*NSTX-U will be positioned to test LM-PFCs to determine if this approach provides a viable alternative to solid PFCs*

# Liquid metals provide possible solution for "first wall" problem in fusion reactors

- Liquid metals can simultaneously provide:
  - Elimination of erosion concerns
    - Wall is continuously renewed
  - Absence of neutron damage
  - Substantial reduction in activated waste
  - Compatibility with high heat loads
    - Potential for handling power densities > 25 $MW/m^2$

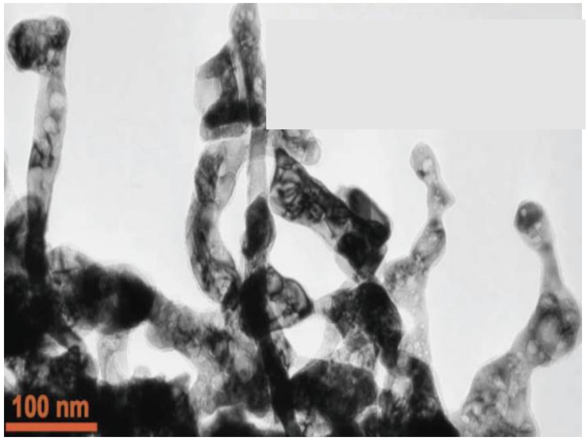
- Offers solution to near-term problems with solids:
  - Liquid lithium shown to protect substrates for capillary-porous systems and plasma-sprayed Liquid Lithium Divertor
    - No high-Z impurities when limiter and divertor surfaces placed in contact with plasma

# Need to mitigate damage to tungsten resulting from long-term exposure to plasma

Example: NAGDIS-II: pure He plasma

N. Ohno et al., in IAEA-TM, Vienna, 2006

• Bombardment with $3.5x10^{27}$ $He^{+}/m^{2}$ at $E_{ion}$ = 11 eV for t = 36,000 s




***<u>100 nm</u>*** ***(VPS W on C) (TEM)***

• Structures appear on scale of tens of nm and reflect swelling due to "nanobubbles"