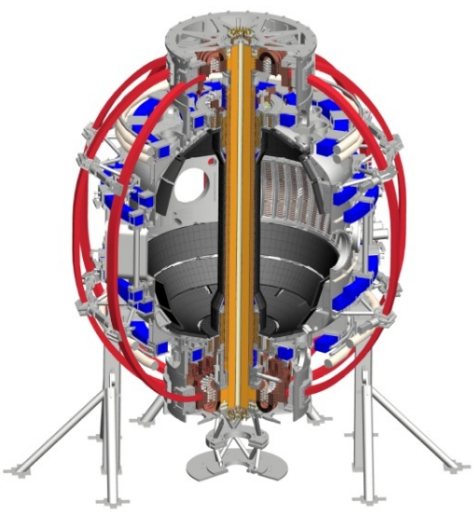
NSTX-U Research Goals and Plans for Materials and Plasma Facing Components

Coll of Wm & Mary
Columbia U
CompX
General Atomics
FIU
INL
Johns Hopkins U
LANL
LLNL
Lodestar
MIT
Lehigh U
Nova Photonics
Old Dominion
ORNL
PPPL
Princeton U
Purdue U
SNL
Think Tank, Inc.
UC Davis
UC Irvine
UCLA
UCSD
U Colorado
U Illinois
U Maryland
U Rochester
U Tennessee
U Tulsa
U Washington
U Wisconsin
X Science LLC

R. Kaita, A. M. Capece, M. A. Jaworski, B. E. Koel, J. P. Roszell, C. H. Skinner, D. P. Stotler and the NSTX-U Team

55th Annual Meeting of the American Physical Society Division of Plasma Physics
Denver, Colorado
November 11 - 15, 2013



Culham Sci Ctr
York U
Chubu U
Fukui U
Hiroshima U
Hyogo U
Kyoto U
Kyushu U
Kyushu Tokai U
NIFS
Niigata U
U Tokyo
JAEA
Inst for Nucl Res, Kiev
Ioffe Inst
TRINITI
Chonbuk Natl U
NFRI
KAIST
POSTECH
Seoul Natl U
ASIPP
CIEMAT
FOM Inst DIFFER
ENEA, Frascati
CEA, Cadarache
IPP, Jülich
IPP, Garching
ASCR, Czech Rep

Abstract

A major need for NSTX-U is plasma facing components (PFCs) that can survive heat and particle fluxes that result from increasing the maximum heating power to 19.2 MW, which leads to one of highest divertor PFC power densities in the world. This is expressible as the ratio of heating power to major radius of about 21 MW/m, which NSTX-U PFCs are expected to withstand for five to eight seconds. From the perspective of materials and PFCs, this challenge is being addressed through research in three major areas. 1) Understanding why lithium is effective for PFC conditioning, and determining its suitability for long-pulse discharges. Surface analytic techniques are thus being applied to study the complexes that are formed when lithium is deposited on various substrates. 2) Investigating erosion and re-deposition of PFCs, including research on lithium-conditioned materials in linear plasma devices that simulate particle fluxes to tokamak walls. 3) Developing techniques for mitigating plasma-surface responsible for reducing wall lifetimes, such as continuous vapor shielding. Present plans are to change NSTX-U PFCs gradually from low-Z carbon to high-Z metallic PFCs. Liquid metals may provide the only long-term PFC solution, and a program to develop flowing lithium PFCs has been initiated.

Work supported by DOE Contract No. DE-AC02-09CH11466

High-level goals for NSTX-U 5 year plan

1. Demonstrate 100% non-inductive sustainment at performance that extrapolates to ≥ $1 MW/m^2$ neutron wall loading in FNSF

2. Access reduced ν^* and high-β combined with ability to vary q and rotation to dramatically extend ST physics understanding

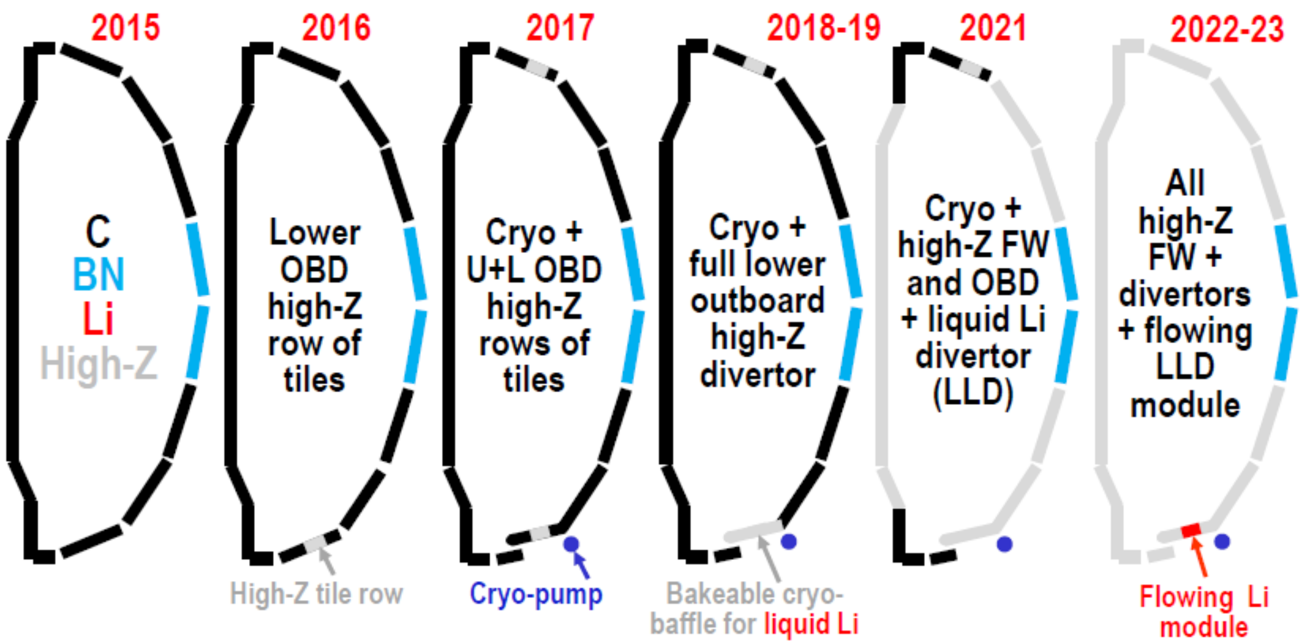
3. Develop and understand non-inductive start-up and ramp-up (overdrive) to project to ST-FNSF with small/no solenoid

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 solutions for next-steps

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 examine role of PFCs (including liquids) on integrated scenarios with good core, pedestal, divertor
- NSTX-U has two emphases for addressing power exhaust and PMI issues for next step devices
  - Magnetic topology, radiative divertor
  - **Self-healing/replenishable materials (e.g. liquids)**
- Significant uncertainties in both solid- and liquid-PFCs motivates parallel research



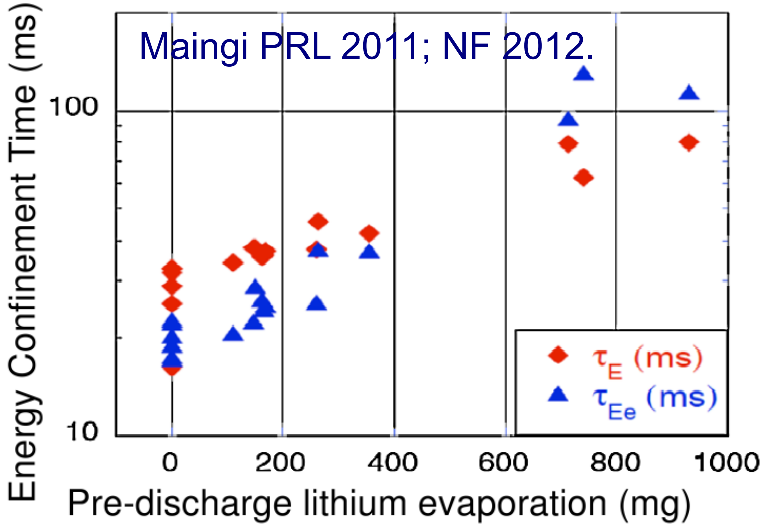
M&P research will develop understanding of material migration and heat-flux handling of high-Z and liquid Li PFCs

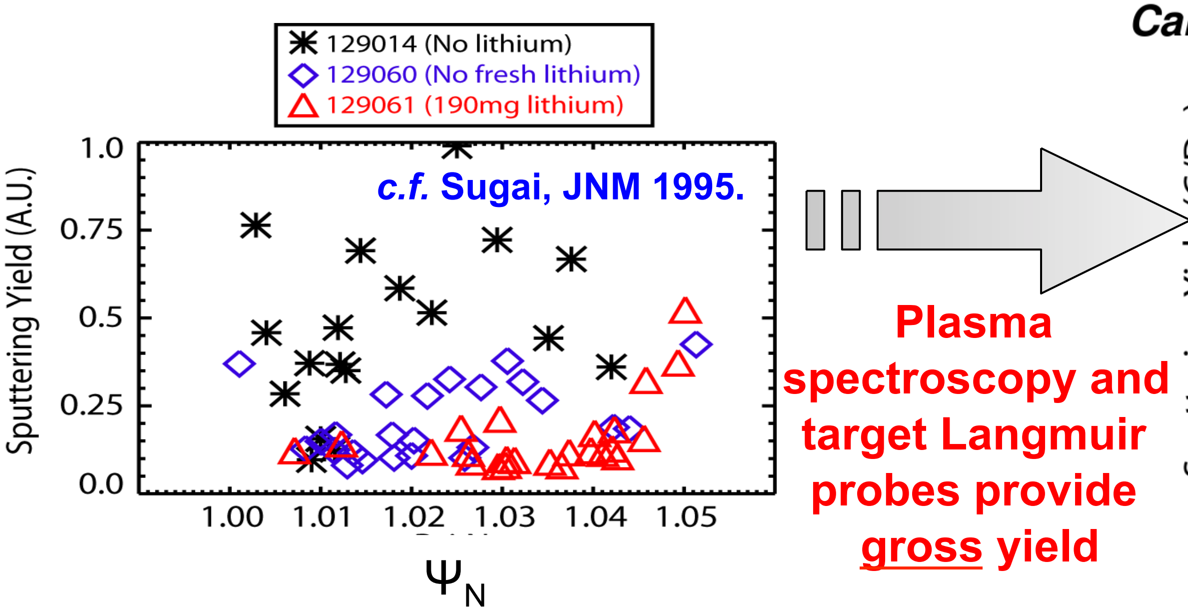
- MP-1: Understand lithium surface-science for long-pulse PFCs
  - Assess impact of more complete Li coverage
  - Use the new Material Analysis and Particle Probe (MAPP) and laboratory studies to link tokamak performance to PFC surface composition
- MP-2: Unravel the physics of tokamak-induced material migration and evolution
  - Confirm erosion scalings and evaluate extrapolations
  - Determine migration patterns to optimize technical solution
- MP-3: 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 with downward facing evaporators

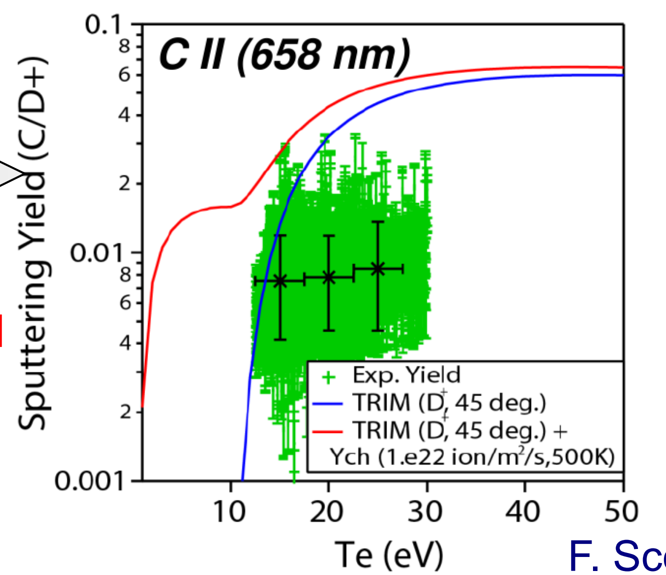
- Carbon influx in divertor reduced after application of lithium conditioning





Plasma spectroscopy and target Langmuir probes provide gross yield

Carbon sputtering yield with lithium

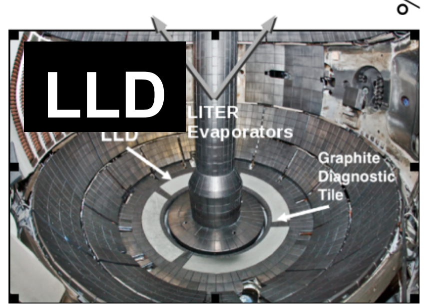


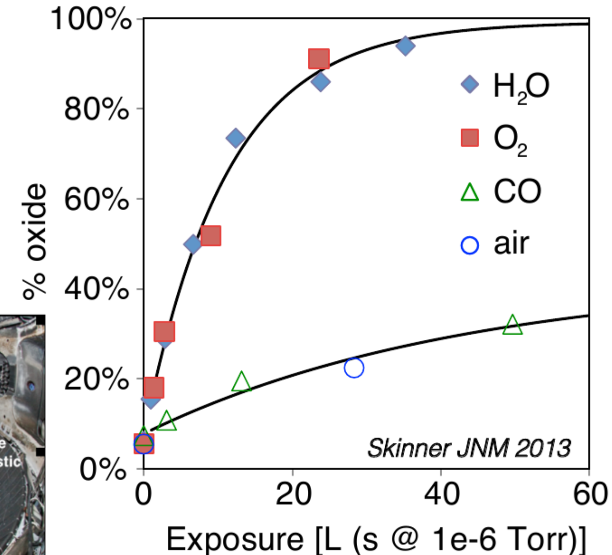
F. Scotti

Oxygen recently identified as important to lithium chemistry and sputtering

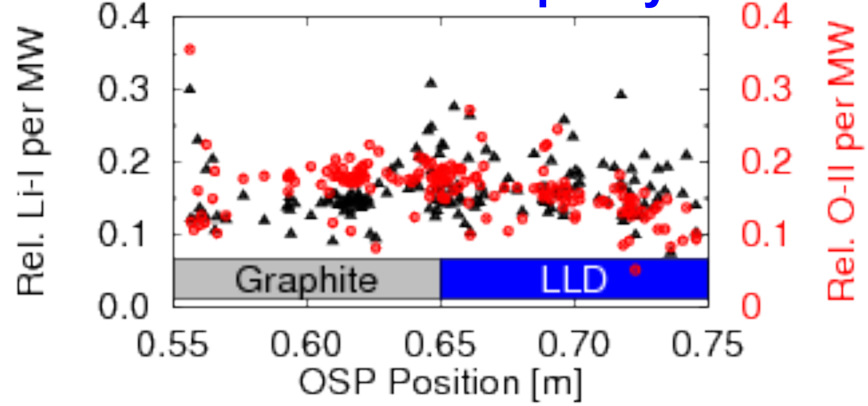
- Oxygen uptake by lithium films quantified in laboratory experiments
  - Oxide layer formation in ~200s in NSTX (~600s inter-shot time)
  - Consistent with Liquid Lithium Divertor (LLD) results showing little change in impurity emission
- Influence of oxygen contaminants being investigated in laboratory
  - 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)
- Rapid impurity accumulation motivates flowing systems

Oxygen uptake by Li coating on Mo





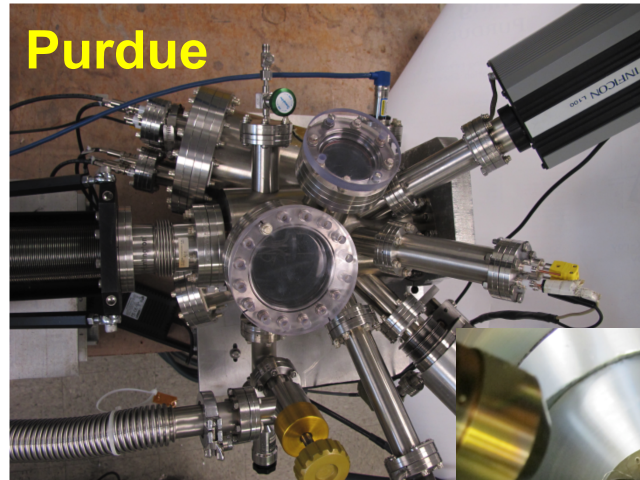
NSTX whole-divertor impurity emission



Jaworski, IAEA 2012

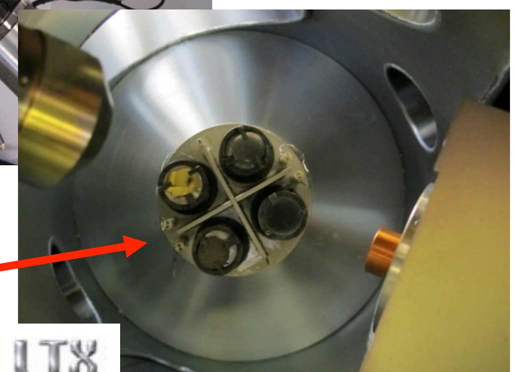
MAPP-U will be a key diagnostic for bridging the gap between discharge performance and lab-based surface science

- **M**aterial **A**nalysis and **P**article **P**robe-**U**pgrade will determine material composition and surface chemistry inside tokamak
  - Exploit MAPP-U capabilities to link with surface science labs at PPPL, Purdue, U. Illinois
  - Identify role of contaminants in Li PMI
  - Initial results obtained on LTX this year
- Optimize areal coverage of wall conditioning techniques
  - Diffusive evaporations and upward-facing evaporators
  - Examine energy confinement, impurity production, particle control...

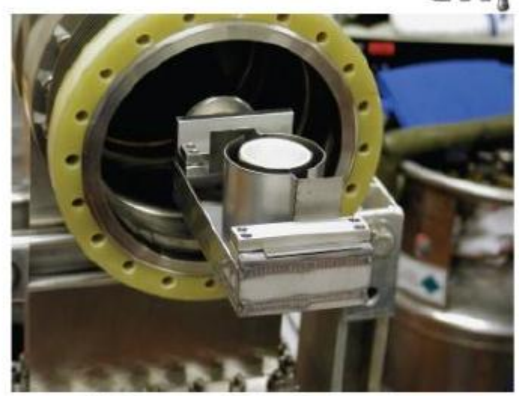


MAPP capabilities
TDS
XPS
LEISS
DRS

Up to 4 samples exposed



LTX

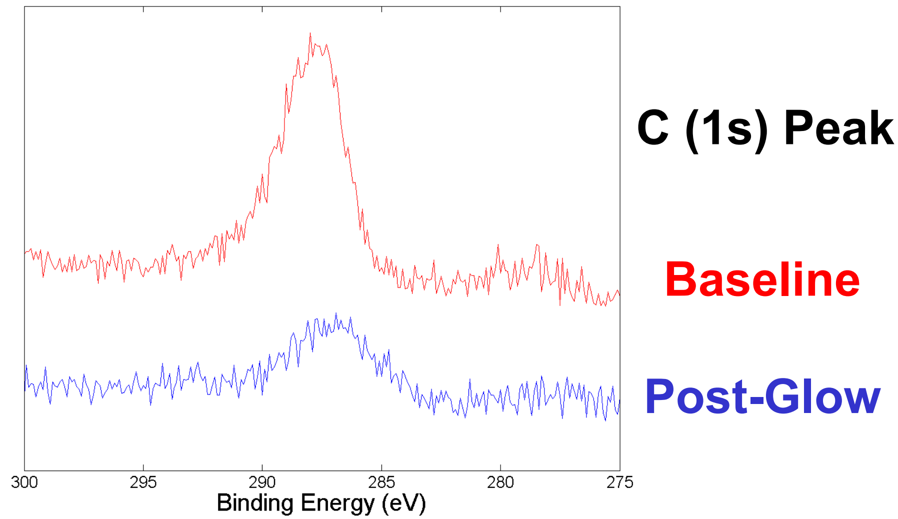


Y_2O_3 crucible, Ta heater
➤Tested to 700 °C

Upward evaporator under development for NSTX-U

Variations in surface composition observed with MAPP-U on LTX

- X-ray photoelectron spectroscopy used for *in vacuo* surface composition measurements of samples inserted into LTX



- Atomic concentrations for MAPP-U samples shown to depend on changes in surface conditions

	Li (at. %)	C (at. %)	O (at. %)
Baseline	0 ± 0	86 ± 1	14% ± 1
Post-Li Evaporation	24 ± 9	62 ± 8	14 ± 1
Post-Plasma Exposure	37 ± 5	47 ± 1	16 ± 1

F. Bedoya, BP8.00055 and M. Lucia, TP8.00031

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

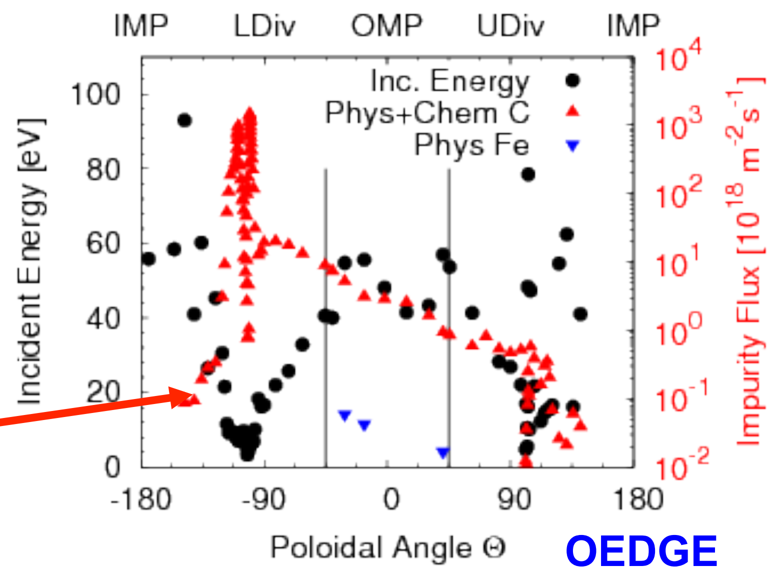
- FY14 – Surface science laboratory and LTX experiments
  - Utilization of MAPP to examine high-Z substrates in LTX
  - Measurements of deuterium retention in lithium on high-Z substrates in laboratory experiments (PU collaboration)
- FY15 – Comparison of boronization with more complete PFC coverage 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

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

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

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

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

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

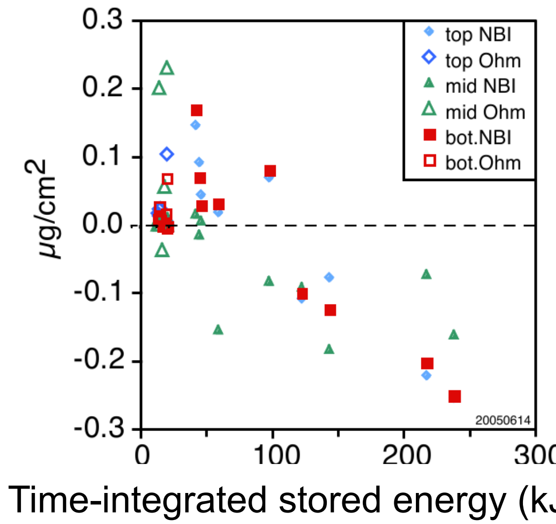
- MP-1: Understand lithium surface-science for long-pulse PFCs
  - Assess impact of more complete Li coverage
  - Use the new Material Analysis and Particle Probe (MAPP) and laboratory studies to link tokamak performance to PFC surface composition
- MP-2: Unravel the physics of tokamak-induced material migration and evolution
  - Confirm erosion scalings and evaluate extrapolations
  - Determine migration patterns to optimize technical solution
- MP-3: 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

Complementary erosion diagnostics will enable identification of erosion/redeposition patterns

- Simple scaling estimates indicate factor of 10 increase in wall erosion in NSTX-U
- 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 used in high-heat flux regions
  - Upgraded MAPP with QCM will measure mass and composition simultaneously
  - **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
  - **Gross erosion** via plasma spectroscopy

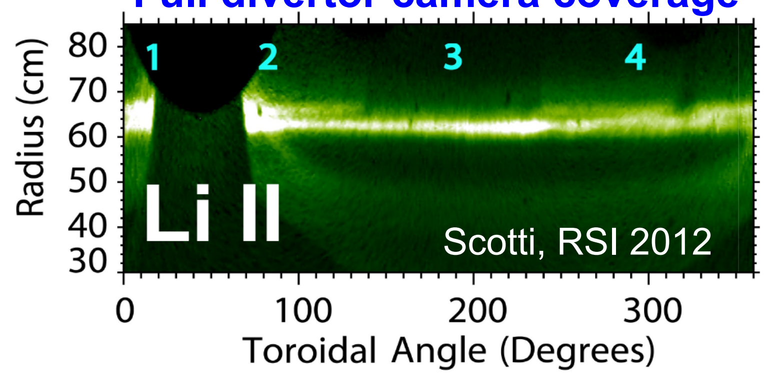
$$\Gamma^{Gross}_{sputt.} \approx Y_{sputt,cx} \frac{f_{cx} P_{heat}/E_{cx}}{S_{plasma}}$$

Mass-loss measured on QCMs



Skinner, JNM 2007

Full divertor camera coverage

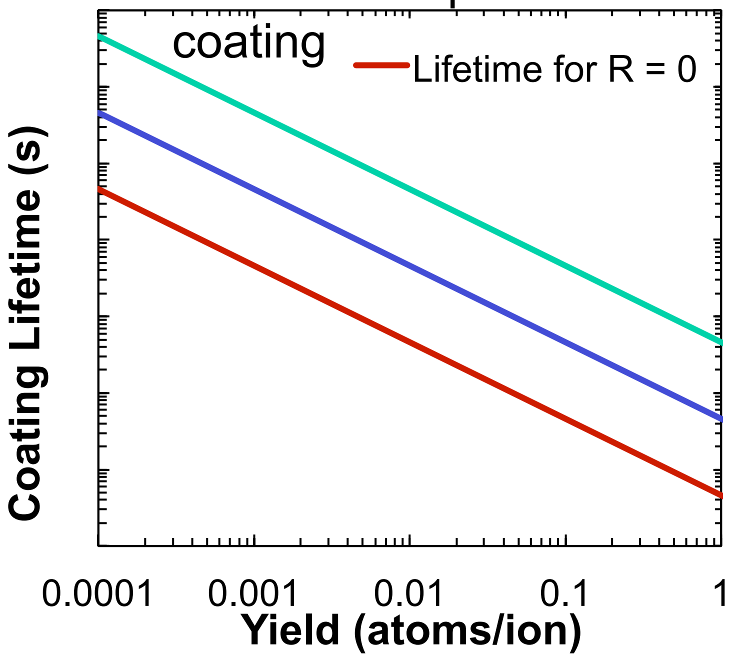


J. Nichols, NP8.00008

Erosion and redeposition for lithium-coated TZM molybdenum samples studied on Magnum-PSI linear plasma device

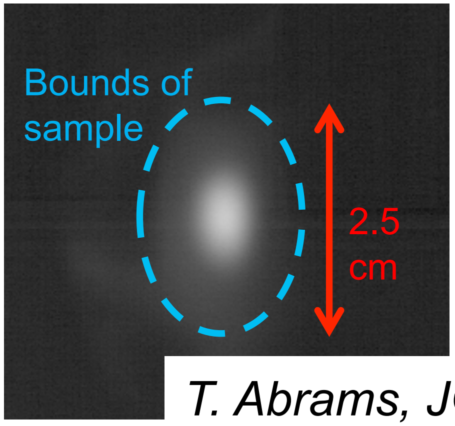
Lithium lifetime τ determined by:

- Areal density ρ_{Li}
- Yield $Y_{Li} = \Gamma_{Li,out} / \Gamma_{D+,in}$
- Ion flux Γ_{D+}
- Re-deposition fraction R_{li}



Magnum-PSI plasma parameters:

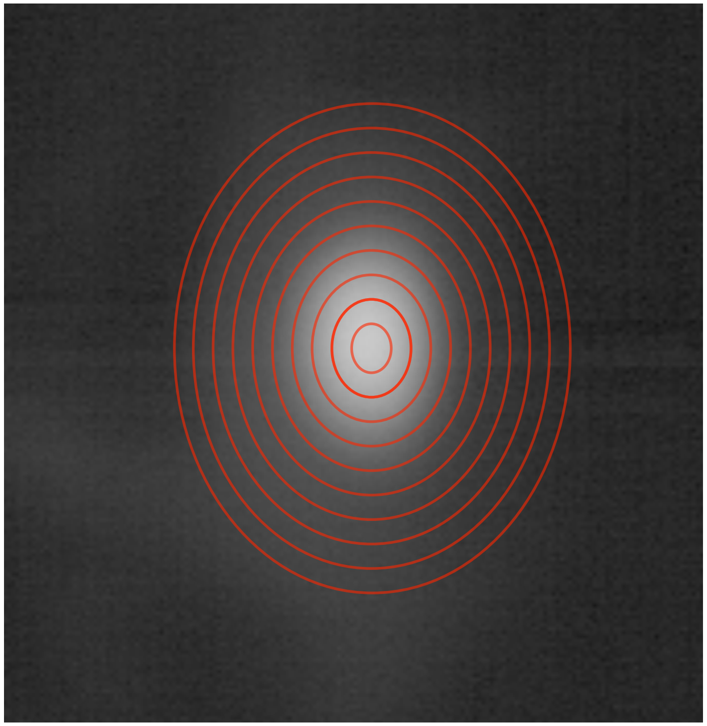
- $\Gamma_{D+} \lesssim 10^{24}\ m^{-2}s^{-1}$, $T_e \lesssim 3$ eV, $n_e \lesssim 8*10^{20}\ m^{-3}$
- 7 s pulses, B = 0.25 T at target
- Normal incidence: no magnetic pre-sheath
- Evaporative Li coatings applied in-vacuum



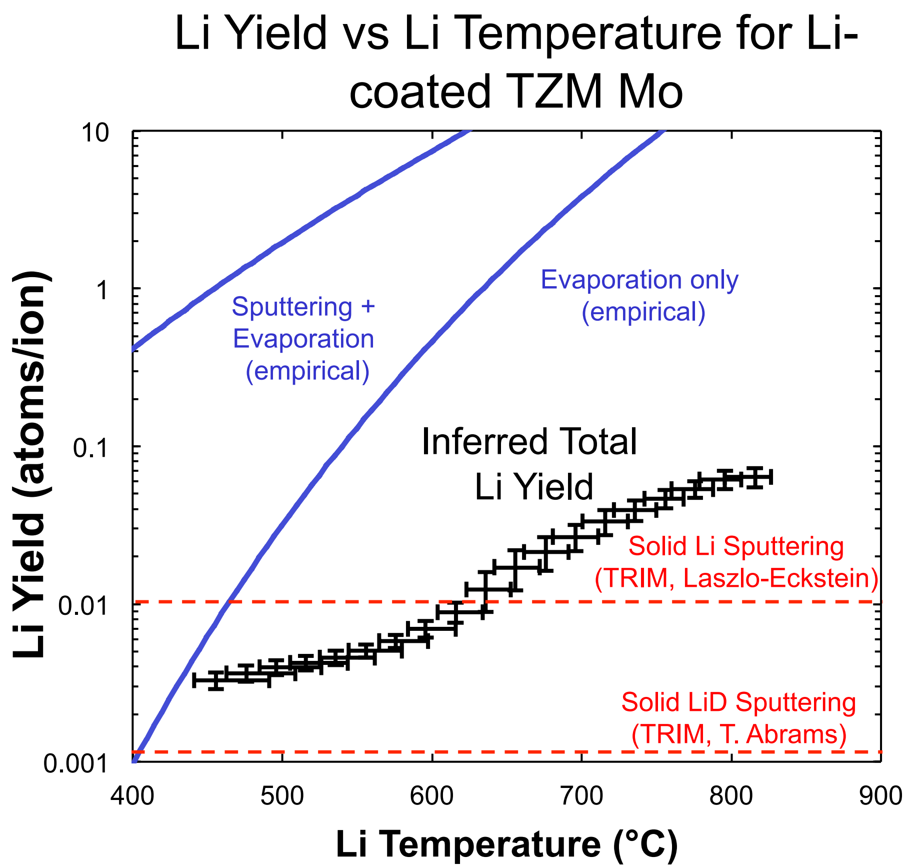
Example Fast Camera Image Li-I emission

T. Abrams, JO4.00014

Inferred Li yields in Magnum-PSI are much lower than predictions from empirical modeling



Axially average Li-I emission



- Determine Li yields from Li-I emission measurements

- Suggests existence of possible Li + (D/Mo) interactions that suppress erosion

Thrust MP-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

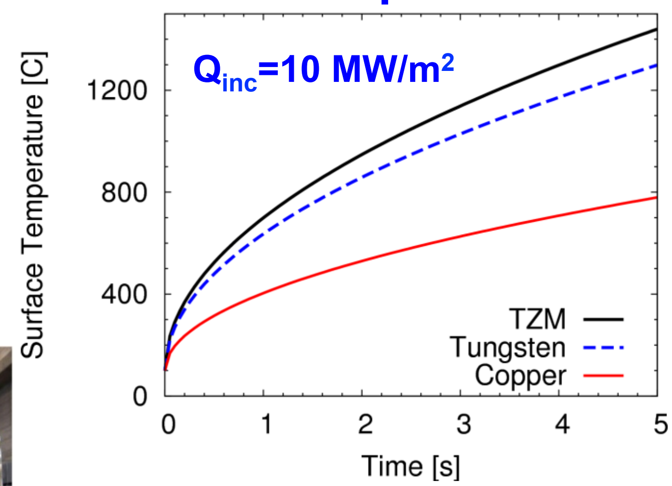
M&P research will develop understanding of material migration and heat-flux handling of high-Z and liquid Li PFCs

- MP-1: 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
- MP-2: Unravel the physics of tokamak-induced material migration and evolution
  - Confirm erosion scalings and evaluate extrapolations
  - Determine migration patterns to optimize technical solution
- MP-3: 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

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

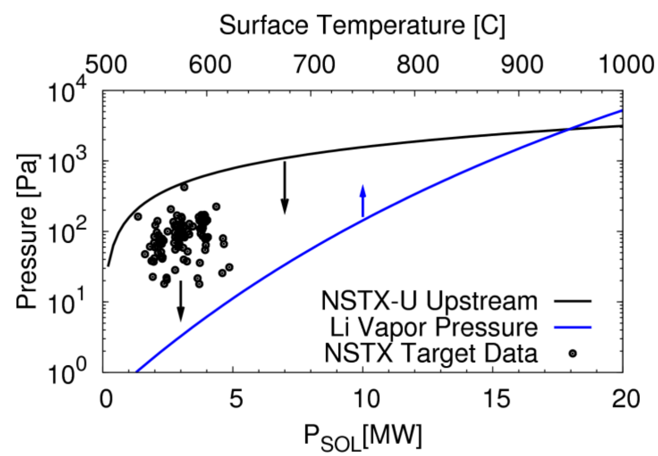
- Lithium vapor cloud can potentially provide effective power and pressure loss
  - Non-coronal Li radiation
  - Li vapor pressure vs. plasma pressure
- Capillary-Porous System targets have dissipated large incident heat fluxes - tested to 25MW/m^2 limited by Li inventory (Evtikhin JNM 2002)
- **What is $T_{max,surf}$ for a lithium PFC?**
- 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
- Preliminary experiments already performed at Magnum-PSI

Front-face Temperature Rise



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

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



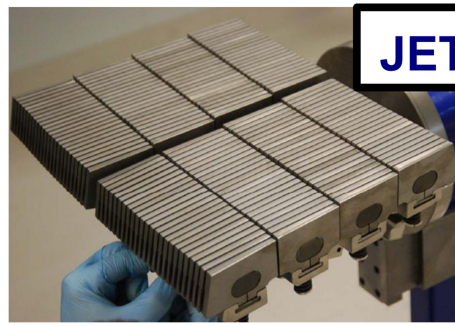
M. Jaworski, NP8.00006

Thrust MP-3 will establish the existence of vapor-shielded regime and assess compatibility with integrated scenarios

- 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

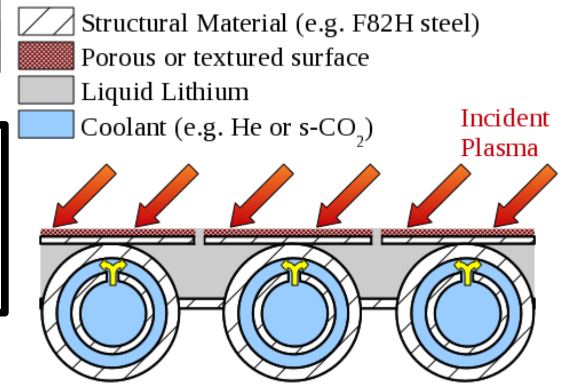
Parallel plasma-facing component research and development to support high-Z tile upgrade and vapor-shielding studies

- High-Z PFC assessment
  - Lamellae demonstrated technique (e.g. C-MOD and JET-ILW) to reduce stress
  - Both W and Mo are 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
- Long-term NSTX-U goal to implement LM divertor target

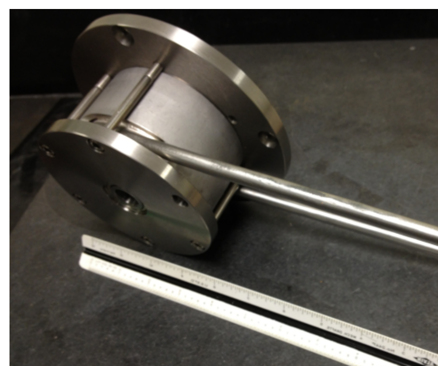


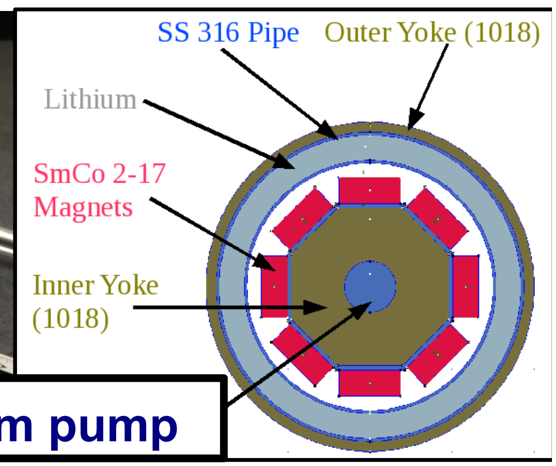
JET-ILW Divertor Cassette

Ph. Mertens, 13th PFMC, 2011



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





PPPL Liquid lithium pump

J. Schwartz, NP8.000036

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