NSTX-U Supported by U.S. DEPARTMENT OF ENERGY Office of Science

Overview of innovative PMI research on NSTX-U and related PMI facilities at PPPL

Masayuki Ono

NSTX-U Project Director

In collaboration with the NSTX-U Team

Joint Conference of OS 2012 & PMIF 2012
Tsukuba, Japan
August 27 - 31, 2012

Columbia U
CompX
General Atomics
FIU
INL
Johns Hopkins U
LANL
LLNL
Lodestar
MIT
Nova Photonics
New York U
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 Washington
U Wisconsin

Culham Sci Ctr
U St. Andrews
York U
Chubu U
Fukui U
Hiroshima U
Hyogo U
Kyoto U
Kyushu U
Kyushu Tokai U
NIFS
Niigata U
U Tokyo
JAEA
Hebrew U
Ioffe Inst
RRC Kurchatov Inst
TRINITI
NFRI
KAIST
POSTECH
Seoul National U
ASIPP
ENEA, Frascati
CEA, Cadarache
IPP, Jülich
IPP, Garching
ASCR, Czech Rep

Acknowledgements

M.A. Jaworski[1], R. Kaita[1], C. H. Skinner[1], J. Menard[1], M. Podesta[1], F. Scotti[1], J.P. Allain[2], C.N. Taylor[2], T.K. Gray[3], R. Maingi[3], A. McLean[4], V. Soukhanovskii[4], and the NSTX Research Team

[1] *Princeton Plasma Physics Laboratory, PO Box 451, Princeton, NJ 08543, USA.*

[2] *Purdue University, West Lafayette, IN 47907, USA.*

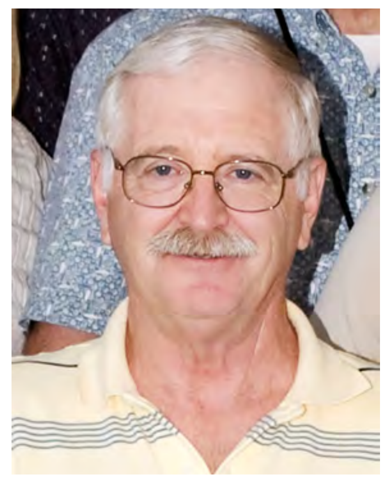
[3] *Oak Ridge National Laboratory, PO Box 2008, Oak Ridge, TN 37831, USA.*

[4] *Lawrence Livermore National Laboratory, Livermore, CA 94551, USA.*

Special thanks are due to!

Michael Bell

Henry Kugel



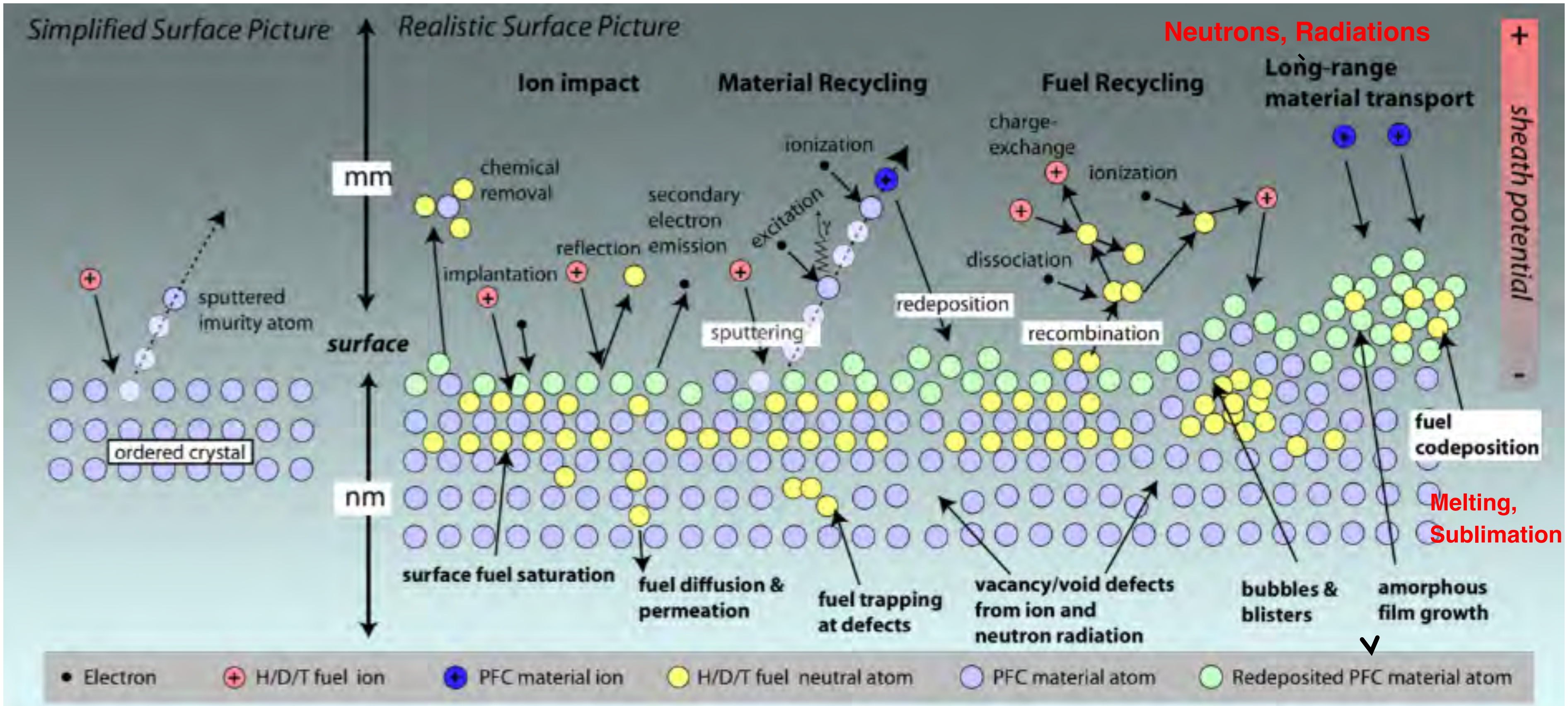
Dennis Mansfield

Talk Outline

- **Motivation of Divertor PMI Research**
- **NSTX-U PMI Mission**
- NSTX-U PMI Experimental Facility
- NSTX PMI Experimental Results and Plans: Snow flakes and Liquid Lithium Divertor
- Associated PMI Facilities at PPPL
- Summary

"Realistic" picture of first wall reveals complicated and dynamic system

that include "nanometer to micrometer sized particles, negative ions, molecules and radicals



From D. Whyte, APS Sherwood Meeting of Fusion Theory, Atlanta, April 2012

Peak heat flux on the diverter plate for 1 GW-electric tokamak power plant can be ~ 60 MW /m^2 or ~ 10 x higher than the present tungsten based design limit.

Divertor heat flux issue must be resolved

Before we can design next-step fusion facilities

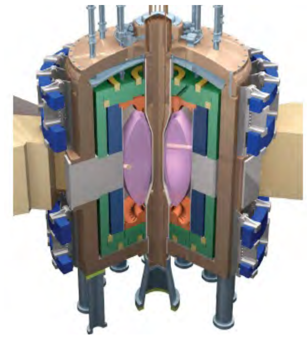
Major research emphasis is shifting toward PMI issues including divertor hear flux issue

Solutions are being sought in all fronts!

- Improved solid material to better survive heat and neutron flux – e.g., tungsten-based alloys?
- Divertor configuration changes to reduce heat flux – e.g., snow-flakes, super-x
- Liquid metal divertor? - e.g., radiative liquid lithium divertor

NSTX-U Mission Elements

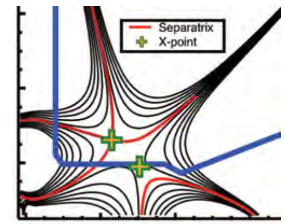
- Advance ST as candidate for Fusion Nuclear Science Facility (FNSF)



ST-FNSF

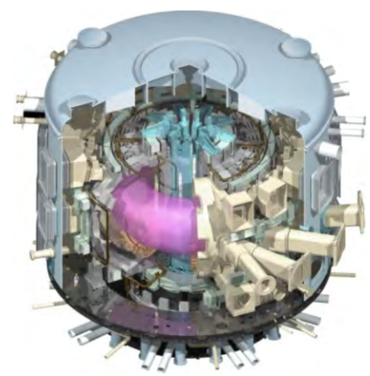
- Develop solutions for plasma-material interface

Lithium



"Snowflake"

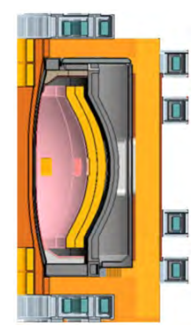
- Advance toroidal confinement physics for ITER and beyond



ITER

- Develop ST as fusion energy system

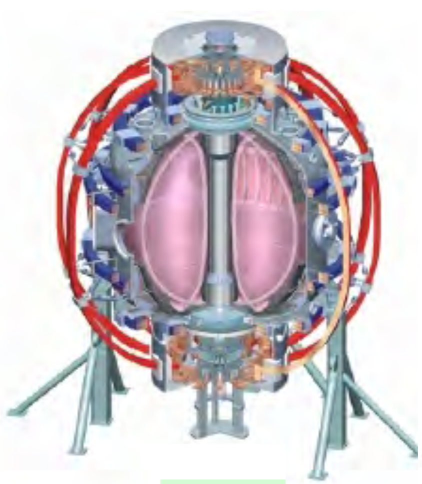
ST Pilot Plant

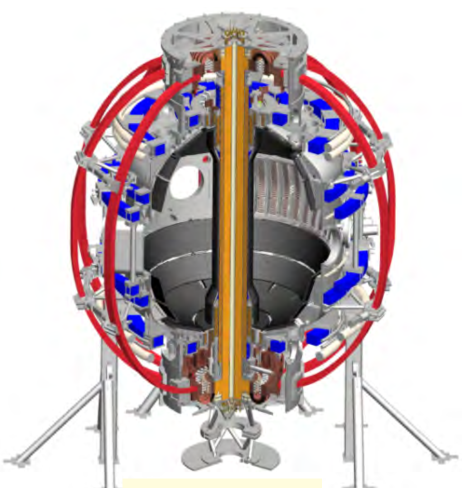


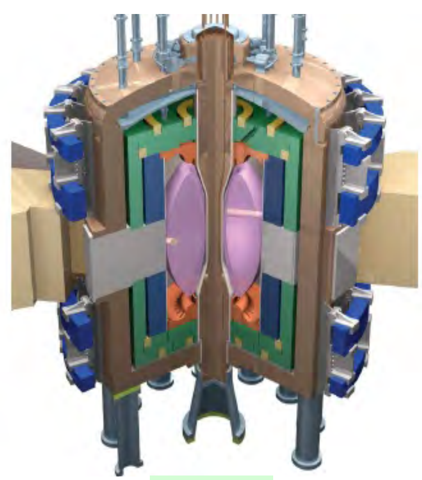
NSTX Upgrade aiming to bridge the device and performance gaps toward FNSF

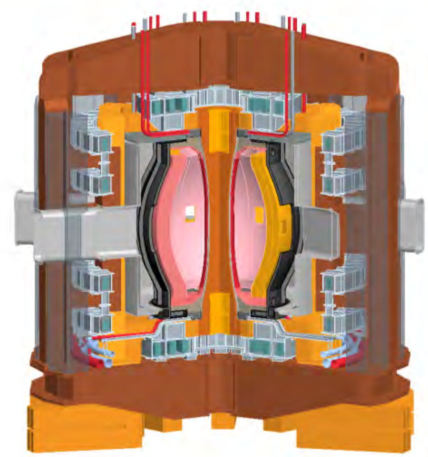
	NSTX	NSTX-U	Fusion Nuclear Science Facility	ST Pilot Plant
Major Radius R_0 [m]	0.86	0.94	1.3	2.2
Aspect Ratio = R_0 / a	≥ 1.3	≥ 1.5	≥ 1.6	≥ 1.7
Plasma Current [MA]	1	2	4 → 10	10 → 20
Toroidal Field [T]	0.5	1	2-3	2-3
P/R, P/S [MW/m,m^2]	10, 0.2*	20, 0.4*	30 → 60, 0.6 → 1.2	40 → 100, 0.3 → 1
Div. heat flux [MW/m^2]	10	40?	50?	60?

** Includes 4MW of high-harmonic fast-wave (HHFW) heating power*


NSTX


NSTX-U


FNSF


ST Pilot Plant

J. Menard NF 2010

Talk Outline

- Motivation of Divertor PMI Research
- NSTX-U PMI Mission
- **NSTX-U PMI Experimental Facility**
- NSTX PMI Experimental Results and Plans: Snow flakes and Liquid Lithium Divertor
- Associated PMI Facilities at PPPL
- Summary

NSTX-U is a 2 MA-class ST facility

NSTX Upgrade Project is aiming for operation in 2014

2nd NBI to be located here

Neutral Beam #1 operating since Sept 2000

NSTX Device operating since February 1999

Facility Capabilities

Major Radius 0.90 m

Minor Radius 0.60 m

Elongation 1.8 - 3.0

Triangularity 0.2 - 0.8

Plasma Current
2 MA

Toroidal Field
1 T

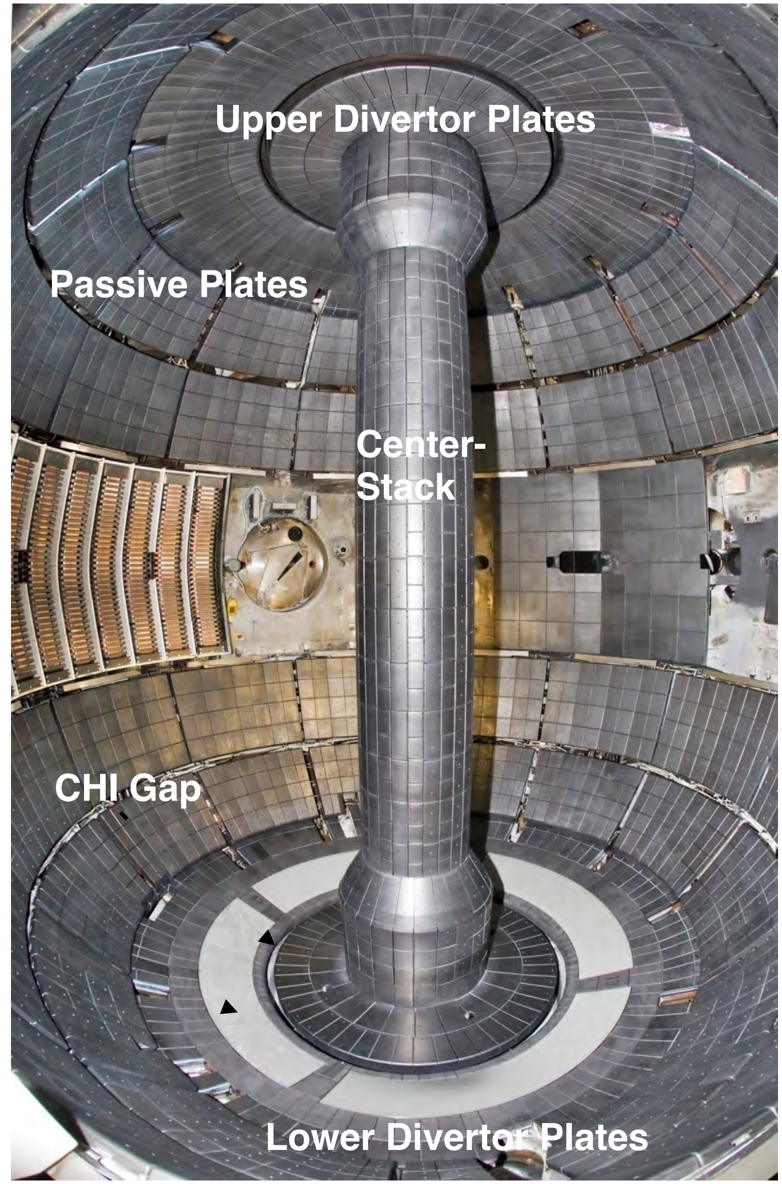
Heating and CD
14 MW NBI (2 sec)
10 MWNBI (5 sec)
6 MW HHFW (5 sec)
0.4 MA CHI

Pulse Length
~ 5 sec at 1 T

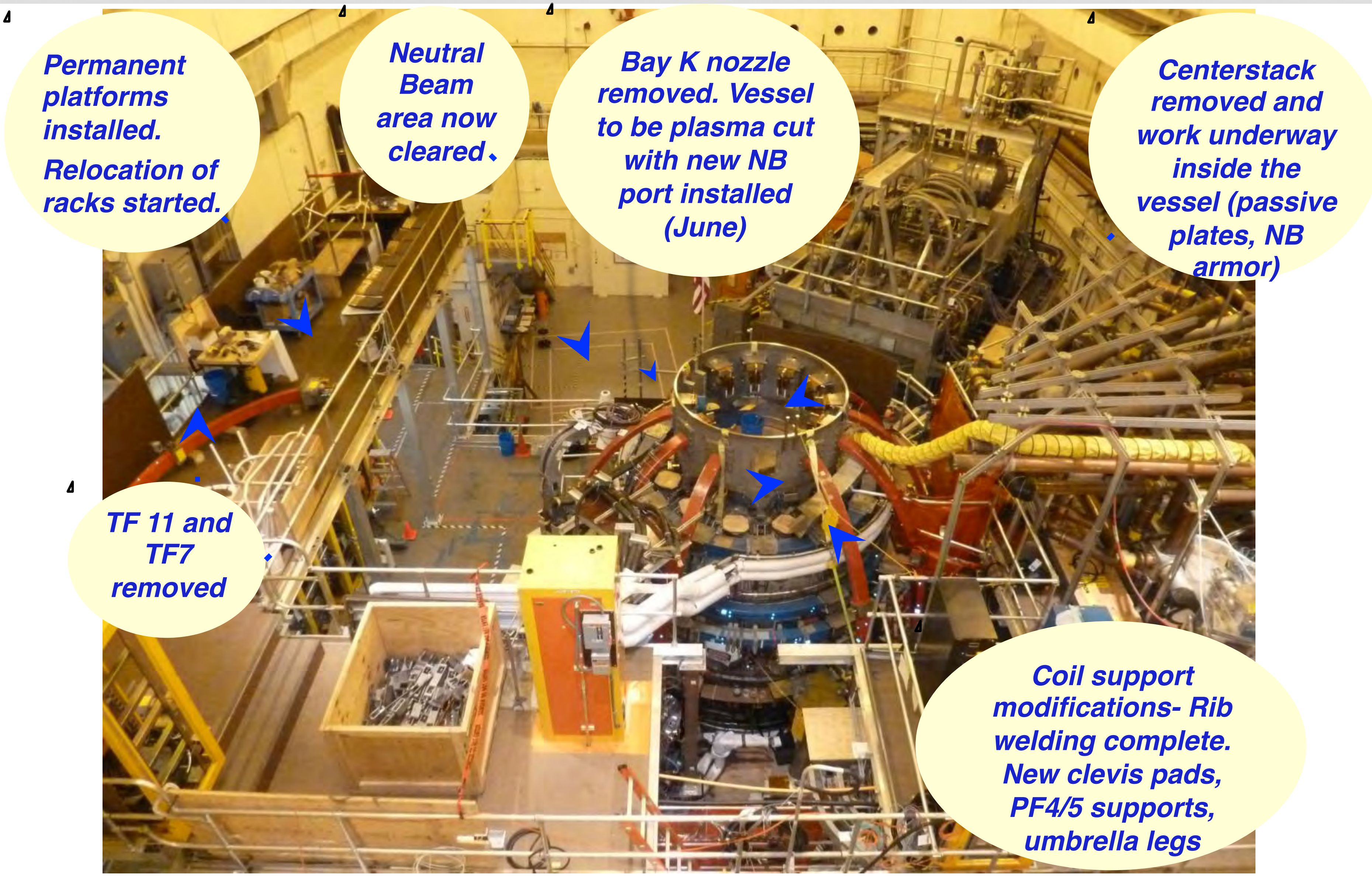
NSTX Device Cross-Section and VV Internal Components
Mainly graphite tiles but plans to transition into metal PFCs

- Tall and open vacuum vessel ~ 3.5 m
- Elect. Insulated Center Stack for Coaxial Helicity Iinjection (CHI) Start-up
- 350°C Tile Bakeout

- ATJ graphite tiles were utilized for much of PFC surfaces:
  - Molybdenum mesh (Liquid Lithium Divertor, LLD) `
  - Possibility of independently heating LLD segments up to 300 ºC
- Lithium coatings are routinely evaporated on the PFCs



Much work has been performed since the shutdown began in Sept 2011 working toward 2014 first plasma



Half of NSTX-U Diagnostics Are PMI Related

Half of NSTX-U Diagnostics Are Collaboration Led

MHD/Magnetics/Reconstruction
- Magnetics for equilibrium reconstruction
- Halo current detectors
- High-n and high-frequency Mirnov arrays
- Locked-mode detectors
- RWM sensors (n = 1, 2, and 3)

Profile Diagnostics
- MPTS (42 ch, 60 Hz)
- T-CHERS: $T_i(R)$, $V_\phi(r)$, $n_C(R)$, $n_{Li}(R)$, (51 ch)
- P-CHERS: $V_\theta(r)$ (71 ch)
- MSE-CIF (15 ch)
- MSE-LIF (10 ch in FY 11, up to 24 ch in FY 12)
- FIReTIP interferometer
- Midplane tangential bolometer array (16 ch)

Turbulence/Modes Diagnostics
- Tangential microwave high-k scattering
- Beam Emission Spectroscopy (24 ch)
- Microwave reflectometers
- Ultra-soft x-ray arrays – multi-color
- Fast X-ray tangential camera (500kHz)

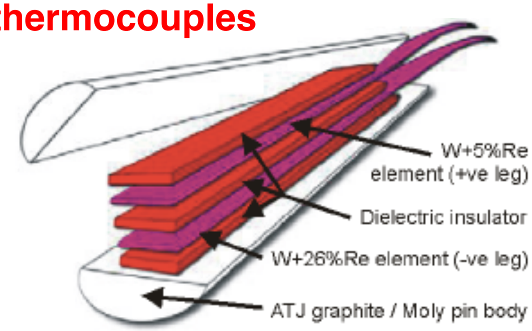
Energetic Particle Diagnostics
- Neutral particle analyzer
- Solid-State neutral particle analyzer
- Fast lost-ion probe (energy/pitch angle resolving)
- Neutron measurements
- Fast Ion D_α profile measurement (perp + tang)

Edge Divertor Physics
- Gas-puff Imaging (500kHz)
- Fixed Langmuir probes
- High density Langmuir probe array
- Edge Rotation Diagnostics (T_i, V_ϕ, V_{pol})
- 1-D CCD H_α cameras (divertor, midplane)
- 2-D divertor fast visible camera
- Divertor bolometer (20ch)
- IR cameras (30Hz) (3)
- Fast IR camera (two color)
- Tile temperature thermocouple array
- Divertor fast eroding thermocouple
- Dust detector
- Edge Deposition Monitors
- Scrape-off layer reflectometer
- Edge neutral pressure gauges
- Material Analysis and Particle Probe
- Divertor Imaging Spectrometer
- Lyman Alpha (Ly_α) Diode Array

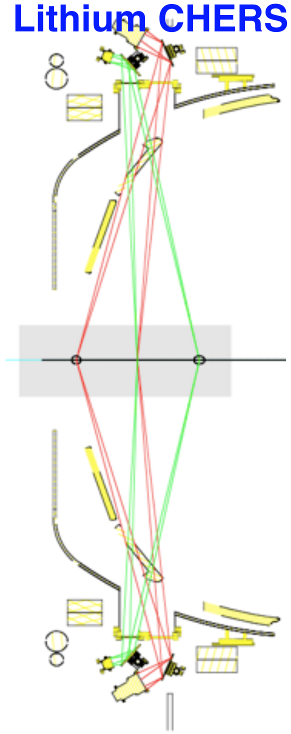
Plasma Monitoring
- Fast visible cameras
- Visible bremsstrahlung radiometer
- Visible and UV survey spectrometers
- VUV transmission grating spectrometer
- Visible filterscopes (hydrogen & impurity lines)
- Wall coupon analysis

Enhanced Capability for PMI Research
Multi-Institutional Contributions

Divertor fast eroding thermocouples

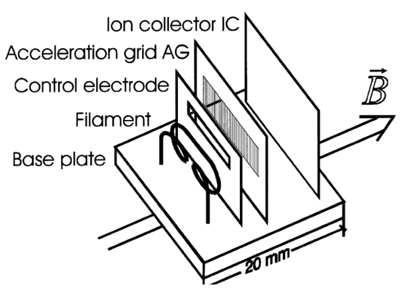


Lithium CHERS



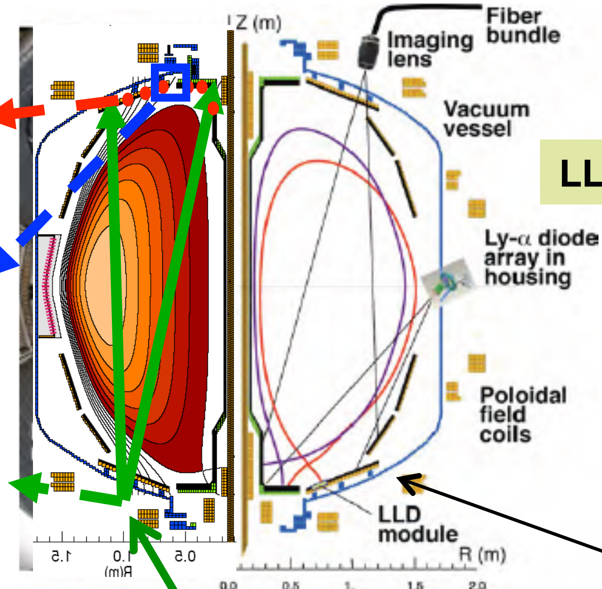
ORNL

Divertor fast pressure gauges

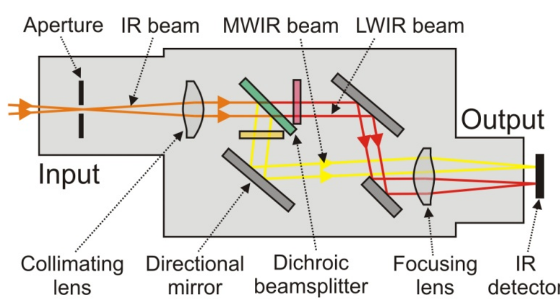


Divertor Imaging Spectrometer

LLNL

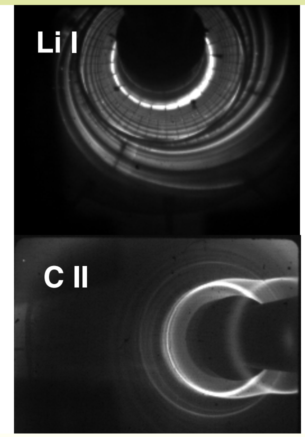


Dual-band fast IR Camera

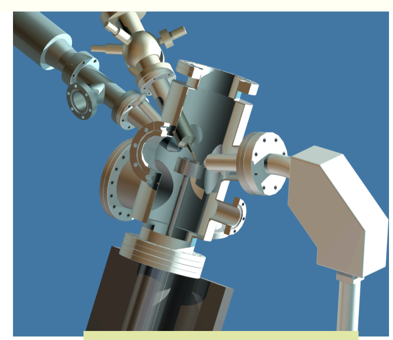


Two fast 2D visible and IR cameras with full divertor coverage

LLNL, ORNL, UT-K



MAPP probe for between-shots surface analysis

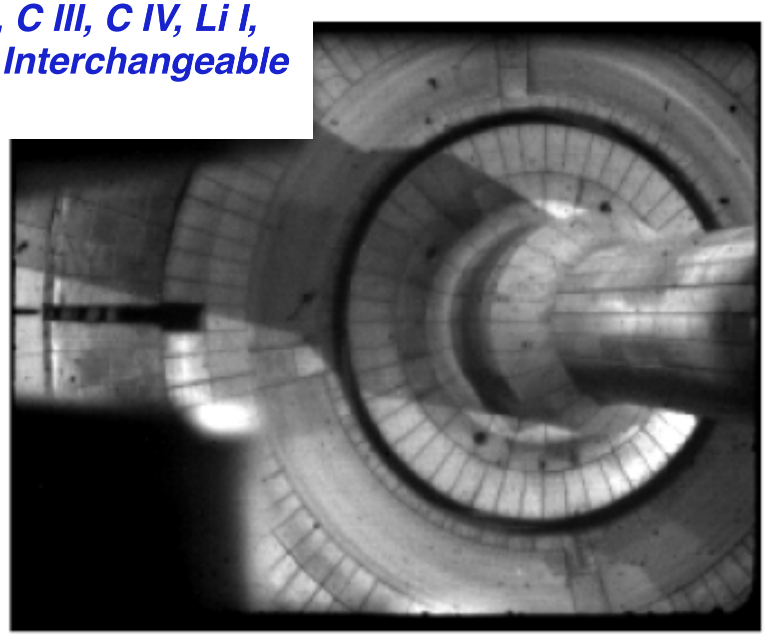


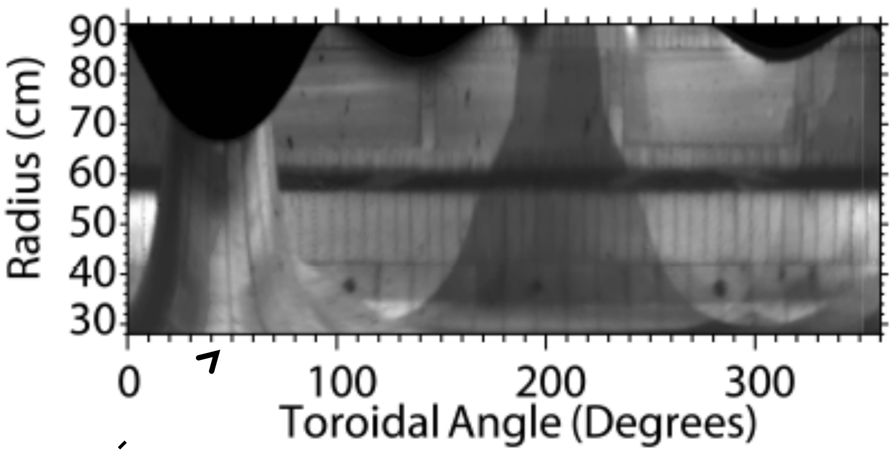
Purdue U.

Full Toroidal Imaging of Non-Axisymmetric PMI

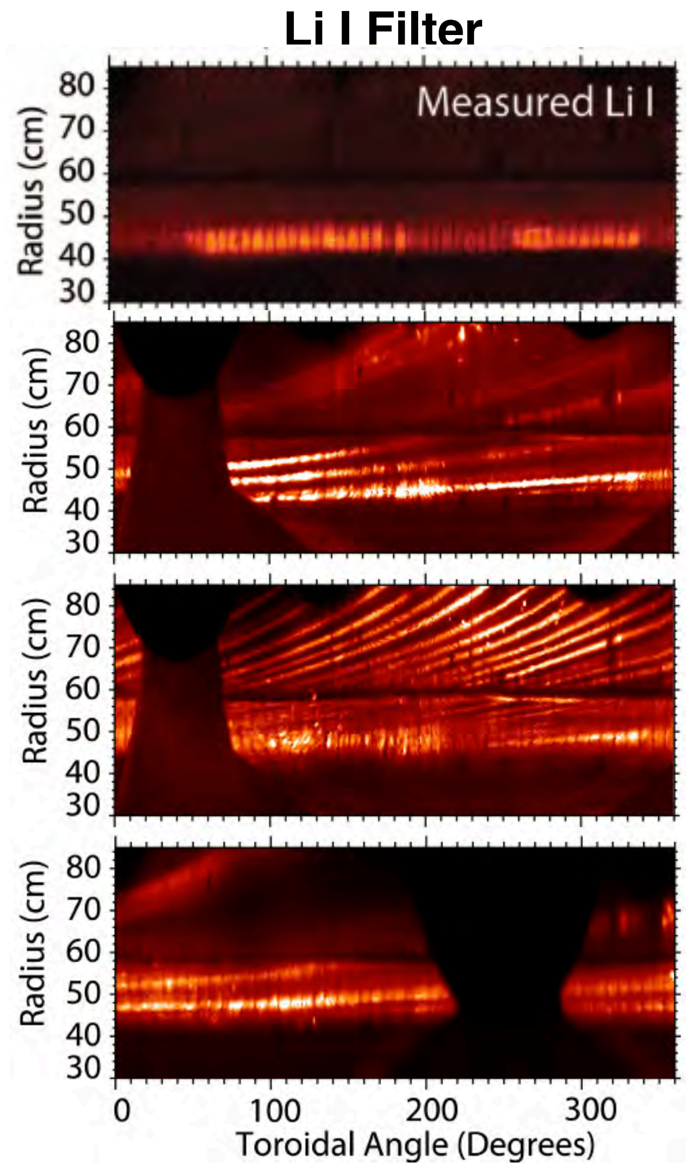
Enabled by a pair of 2-D fast cameras with a wide angle view

With C II, C III, C IV, Li I, Li II, D-α Interchangeable Filters





Poloar Remapping



Divertor outer strike point (OSP)

OSP with 3D fields

Type V ELM

RF-induced Divertor Hot Zone

F. Scotti, RSI2012

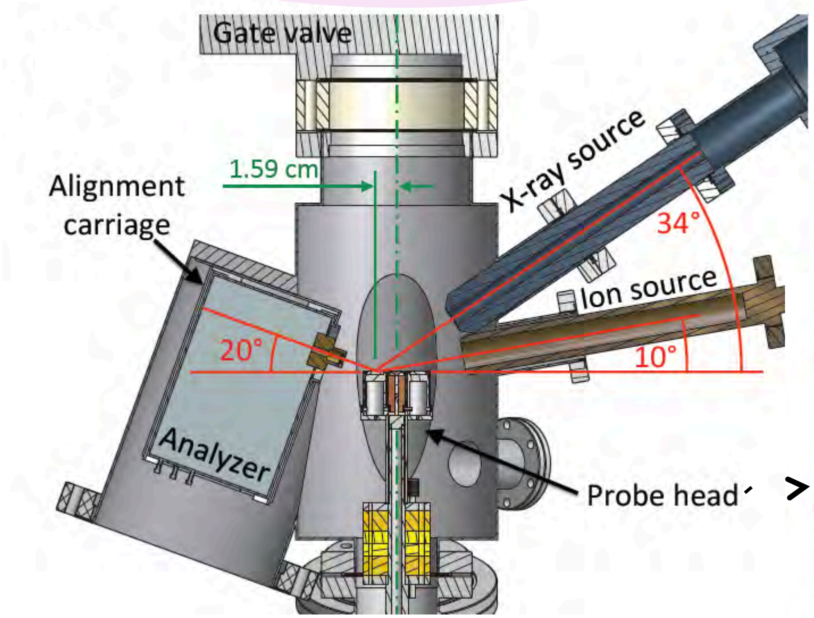
MAPP: Material Analysis Particle Probe

Correlate plasma performance to state of the plasma-facing surface

Design objectives:

– *In-vacuo* surface analysis of materials exposed to plasma discharge
– Provide immediate, shot-to-shot analysis
– Operate within 12 min minimum between-shot time window

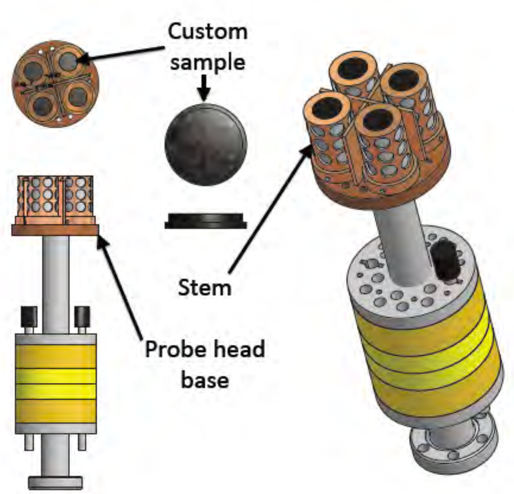
NSTX-U Plasma



C.N. Taylor, RSI2012

Capabilities:

– X-ray photoelectron spectroscopy (XPS)
– Thermal desorption spectroscopy (TDS)
– Ion scattering spectroscopy (ISS)
– Direct recoil spectroscopy (DRS)



Probe Head:

- Hold four samples
- Independent heating of each sample
  – Radiation shields
  – Perforated stems
- Geneva gear to position samples for analysis
- Quick release probe head

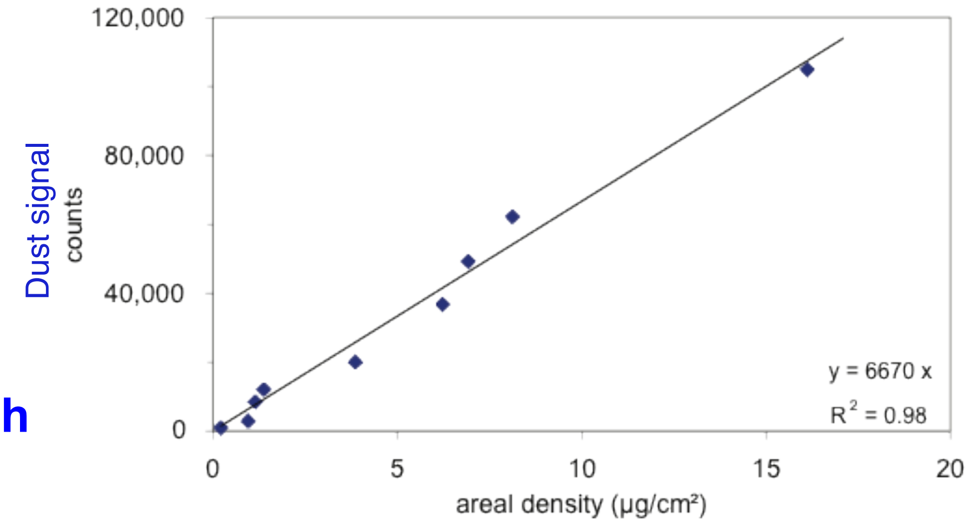
Electrostatic dust detection demonstrated on NSTX

Real-time dust measurement is necessary to safely manage dust in ITER

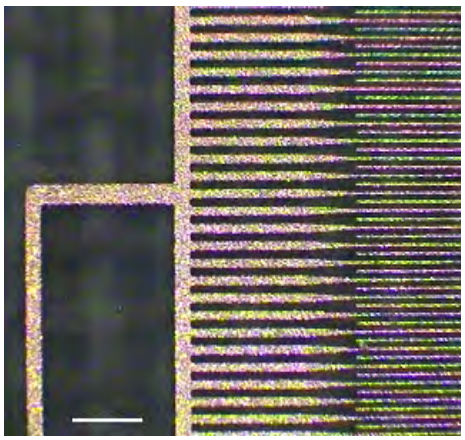
- **A novel electrostatic dust detector was developed at PPPL and demonstrated on NSTX.**
- **Detector is extremely sensitive:**

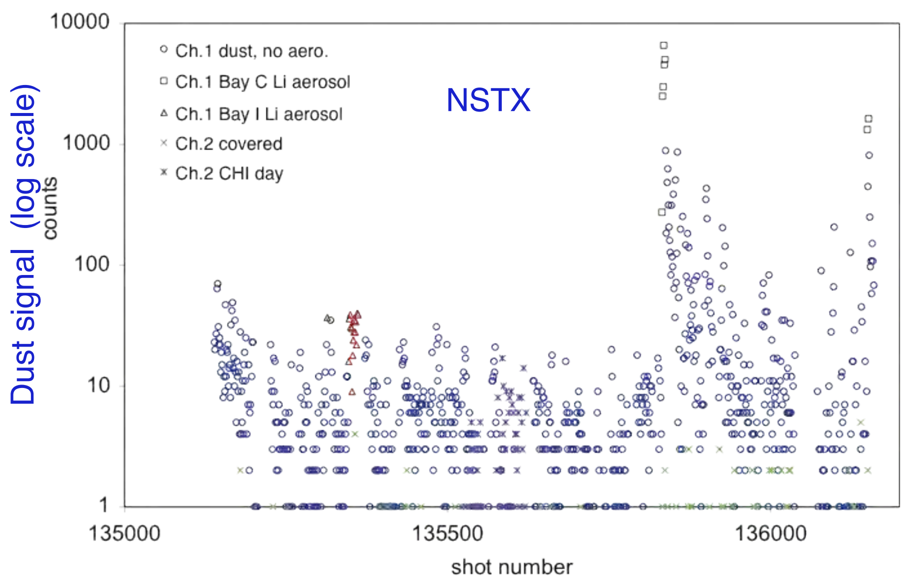
  0.15 ng/cm²/count

- **Dust production was correlated with plasma events.**



Detection grid with 25 μm spacing.





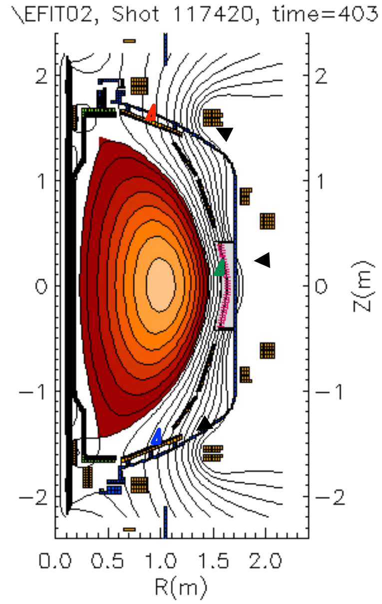
C. H. Skinner, RSI 2010

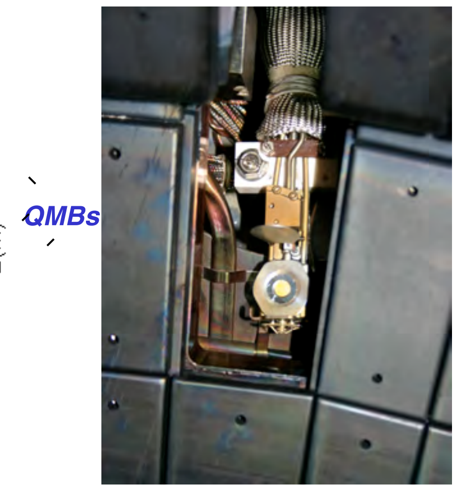
Li evaporation and deuterium dynamic retention monitored with four quartz microbalances

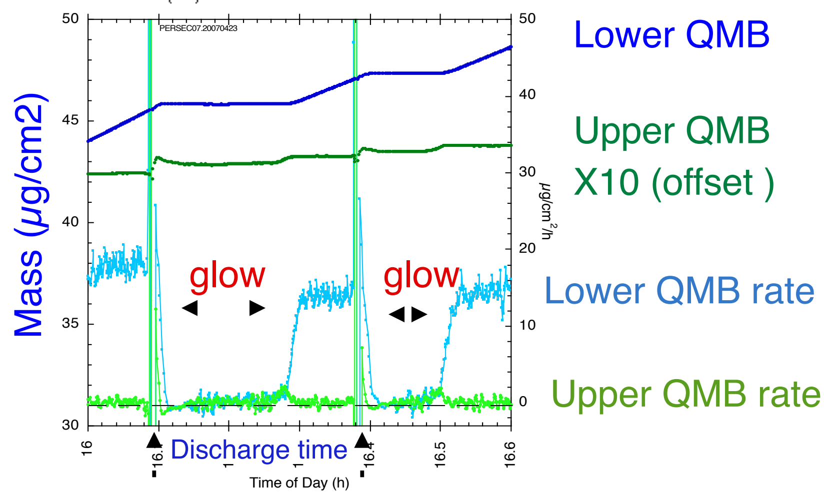
- **Four Quartz Microbalances (QMBs) measure dynamic retention and Li evaporation in NSTX.**

- **During helium glow discharge conditioning both neutral gas collisions and the ionization of lithium interrupt lithium deposition on the lower divertor.**

- **Location of deuterium dynamic retention depends on plasma shape.**





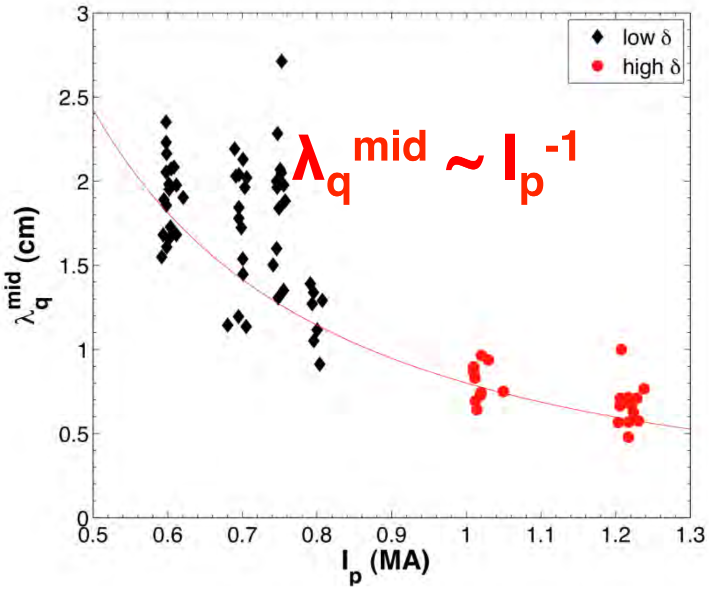


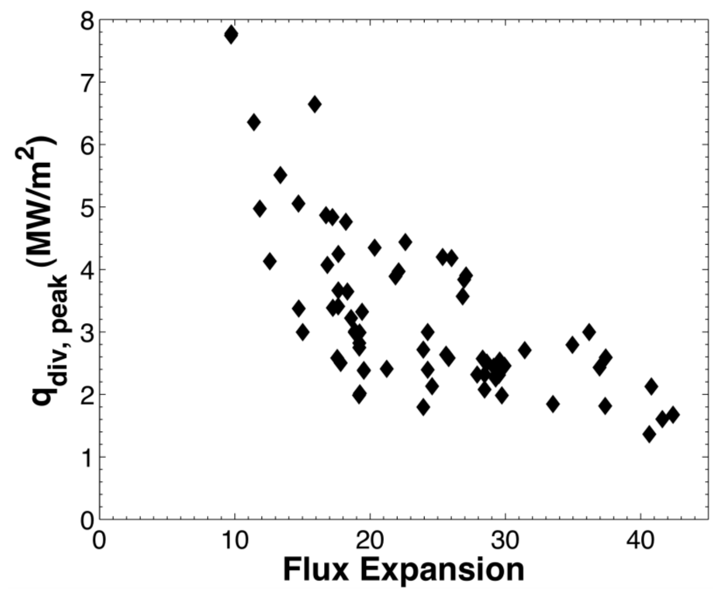
C. H. Skinner, JNM 2009

Talk Outline

- Motivation of Divertor PMI Research
- NSTX-U PMI Mission
- NSTX-U PMI Experimental Facility
- **NSTX PMI Experimental Results and Plans: Snow flakes and Liquid Lithium Divertor**
- Associated PMI Facilities at PPPL
- Summary

Comprehensive data obtained from NSTX for divertor heat-flux width scaling for projecting to ITER

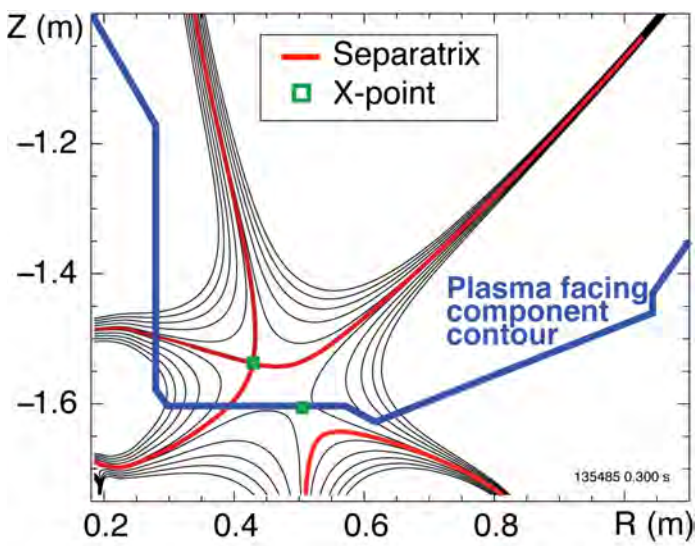


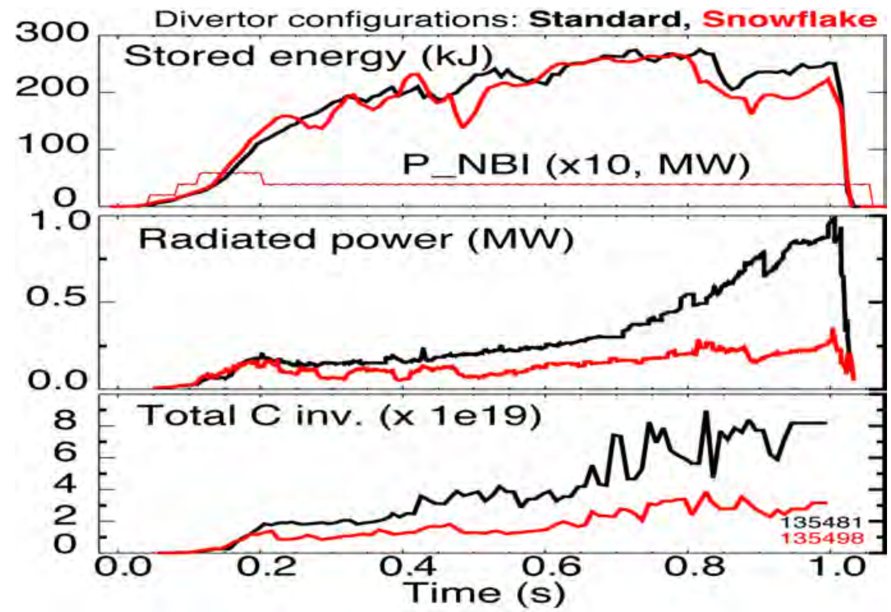


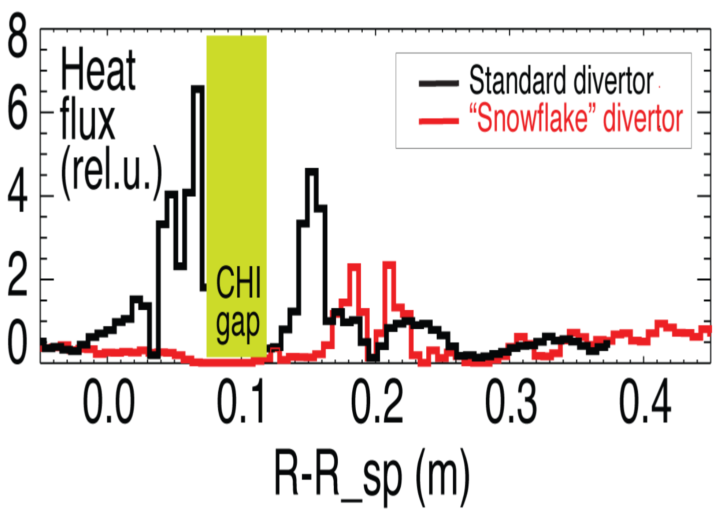
- **Divertor heat flux width, magnetically mapped to the midplane, shows a strong decrease as I_p is increased (suggests NSTX-U may have 40 MW/m² heat flux)**
  - **Research continuing to determine if adverse Ip scaling is offset by favorable size scaling to future devices.**
- **Divertor heat flux inversely proportional to flux expansion over a factor of five (motivates snow-flake divertor)**

T.K. Gray, JNM 2011

"Snowflake" Divertor Configuration resulted in significant divertor heat flux reduction and impurity screening





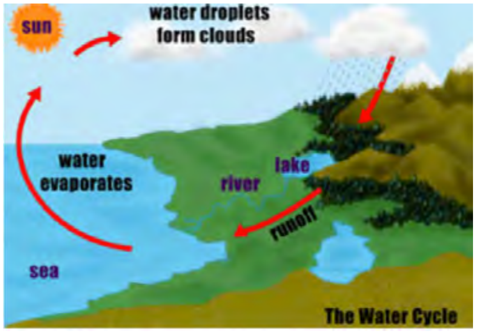


- **Higher flux expansion (increased div wetted area)**
- **Higher divertor volume (increased div. losses)**
- **Maintained stable "snowflake" configuration for 100-600 ms with three PF coils**
- **Maintained H-mode confinement with core carbon reduction by 50 %** **V. Soukhanovskii, NF 2009**

Liquid Lithium Pursued as Possible Divertor PFC Material
Handling heat flux and improve plasma performance!?

Liquid lithium is resilient against high heat flux!

- It can melt, vaporize, and ionize
- It can be collected, condensed
- It can be renewed and recycled



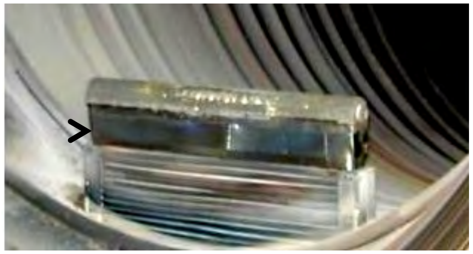
Liquid lithium could protect solid surface from high heat flux!

- Heat of melting, vaporization, ionization
- Radiation could provide high heat dissipation! Potentially very high in the divertor region due to low confinement.

T. D. Rognlien and M. E. Rensink, Physics of Plasmas 9, 2120 (2002).
S. V. Mirnov, et al., Plasma Phys. Control. Fusion, 48 821 (2006).

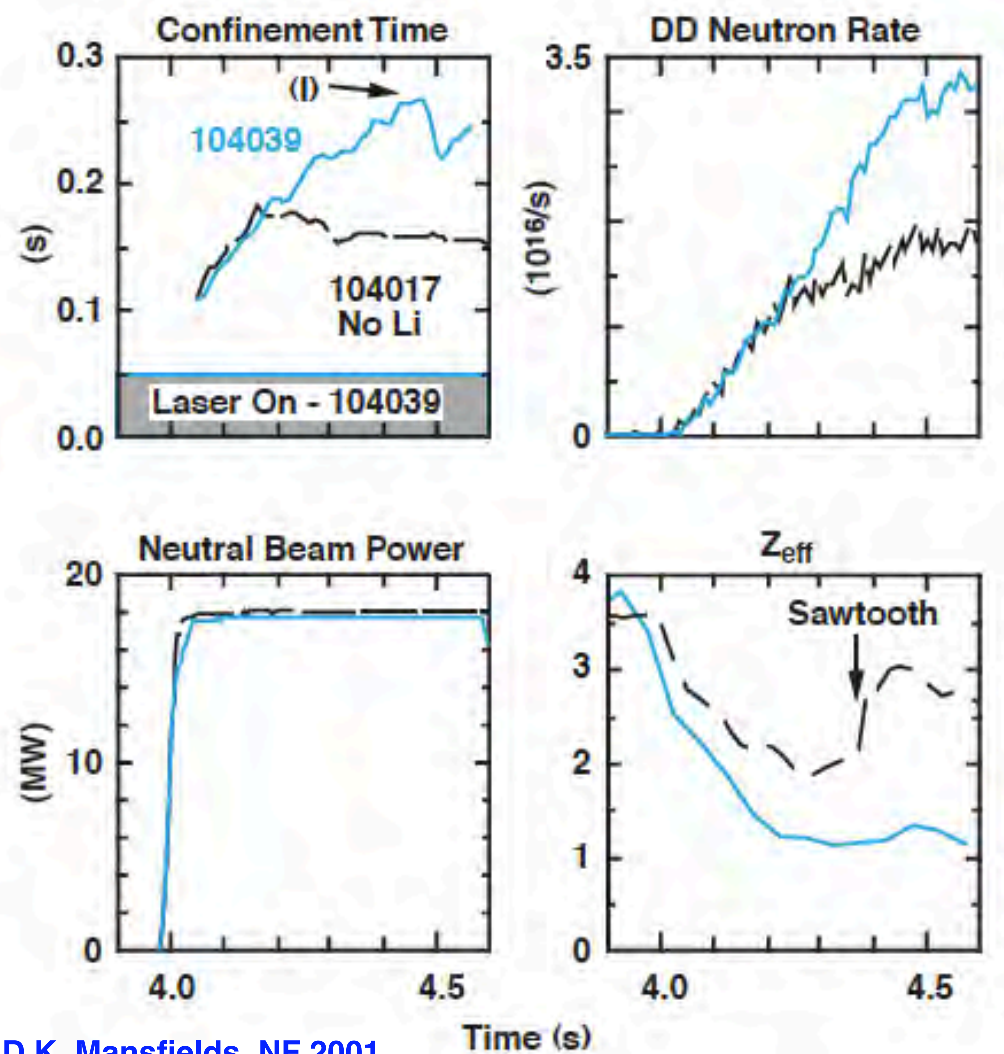
Capillary-Porous Systems (CPS) developed in Russia utilizes similar principle to oil lamp. Very high heat flux handling capability demonstrated!

N. V. Antonov,, et al., Journal of Nuclear Materials 241-243,1190 (1997).



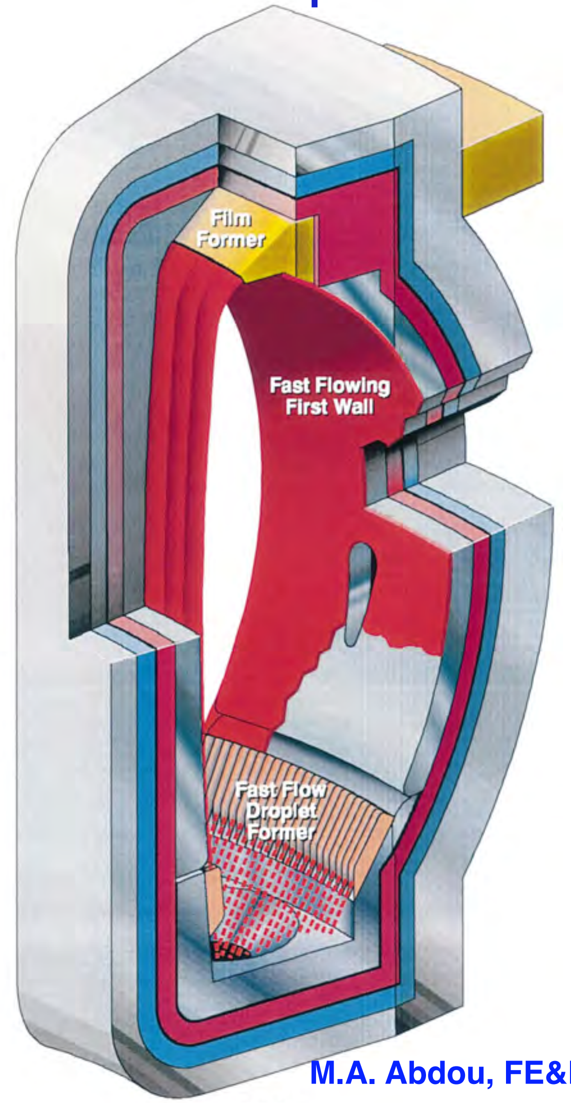
Lithium was a remarkable success on TFTR
APEX Studies has explored reactor applications

Lithium Coating Doubled TFTR Fusion Output



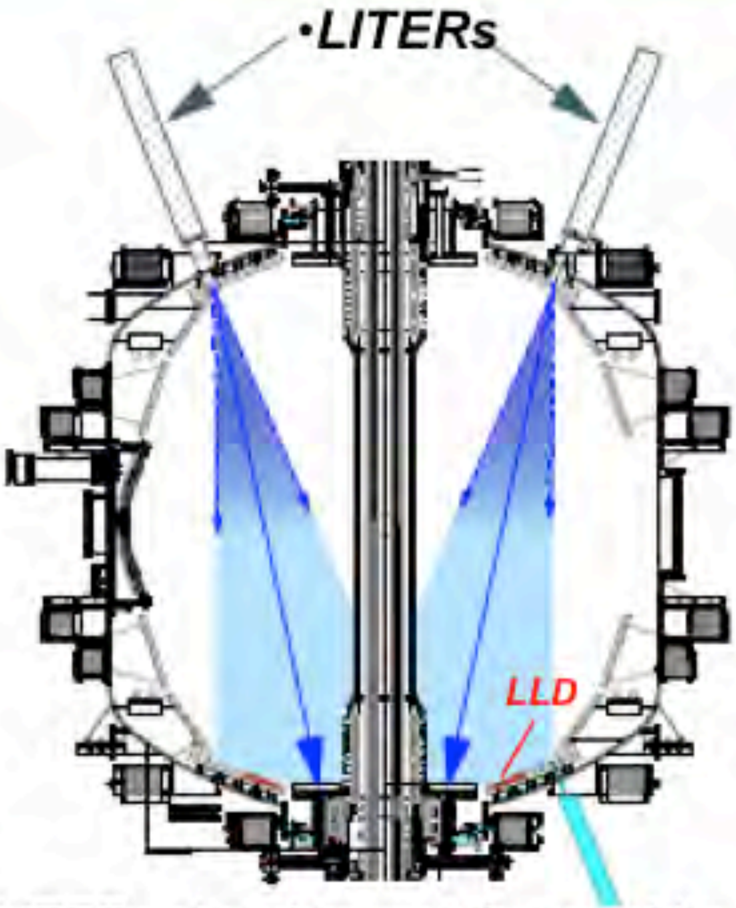
D.K. Mansfields, NF 2001

APEX CLiFF Concept in ARIRES-RS



M.A. Abdou, FE&D 2001

Since 2008, Dual Lithium Evaporators (LITERs) Are Used to Deposit Lithium Coatings on NSTX Lower Divertor



- LITERs aimed toward the graphite divertor. Shown are 1/e widths of the emitted gaussian-like distribution.

- Lithium transported over broad area by wings of LITER distribution and plasma migration.

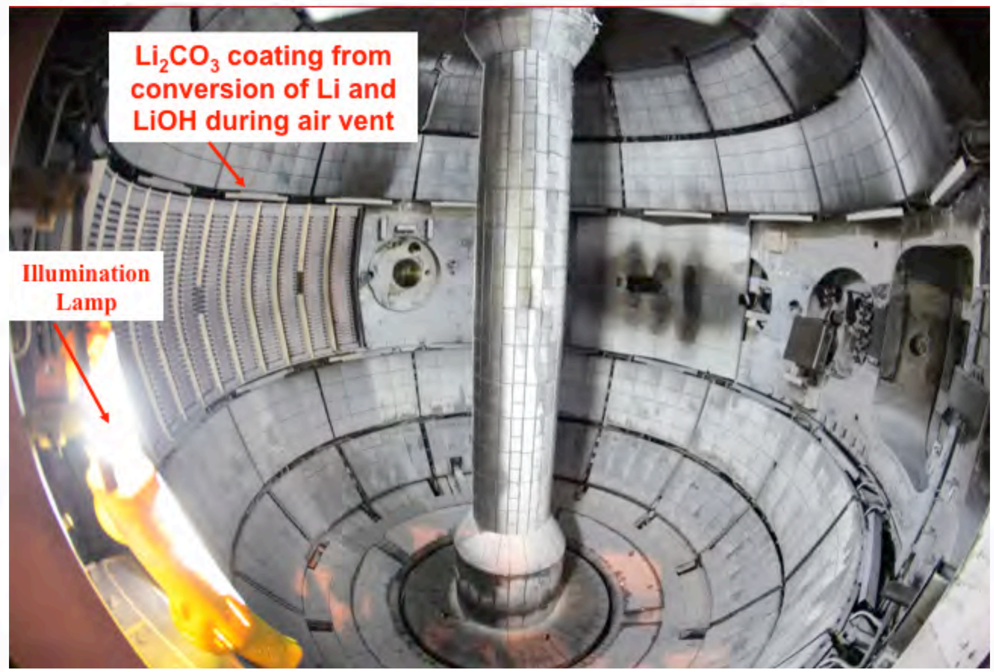


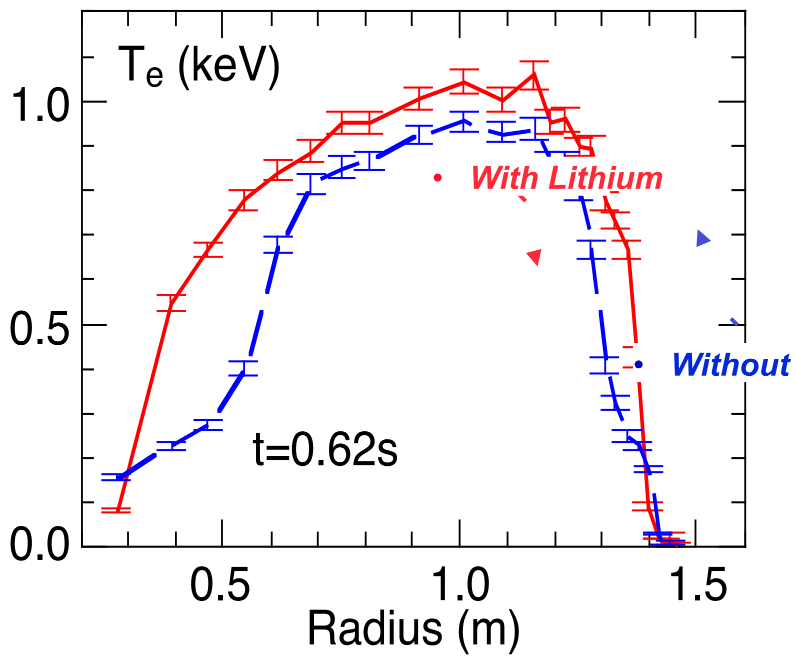
Photo of NSTX interior following 1.3 kg lithium deposition applied during 2010-2011 experimental campaigns indicating extensive lithium coverage due to direct evaporation and plasma transpot

H.W. Kugel, FE&D 2011

Lithium Improved H-mode Performance in NSTX

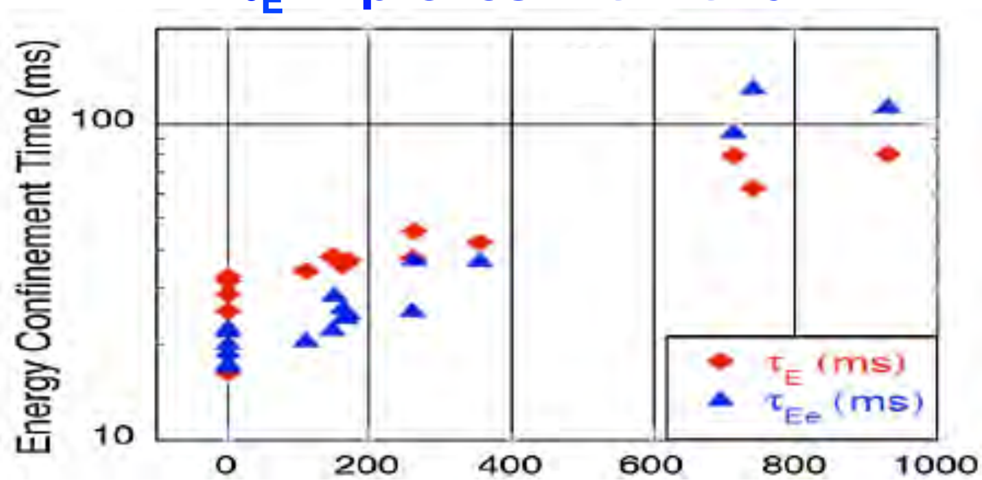
T_e Broadens, τ_E Increases, P_H Reduces, ELMs Stablize

T_e broadening with lithium



Radial profiles of electron temperature before (blue) and after 260 mg lithium deposition (red) in the NSTX H-mode discharges.

τ_E improves with lithium



Pre-discharge lithium evaporation (mg)

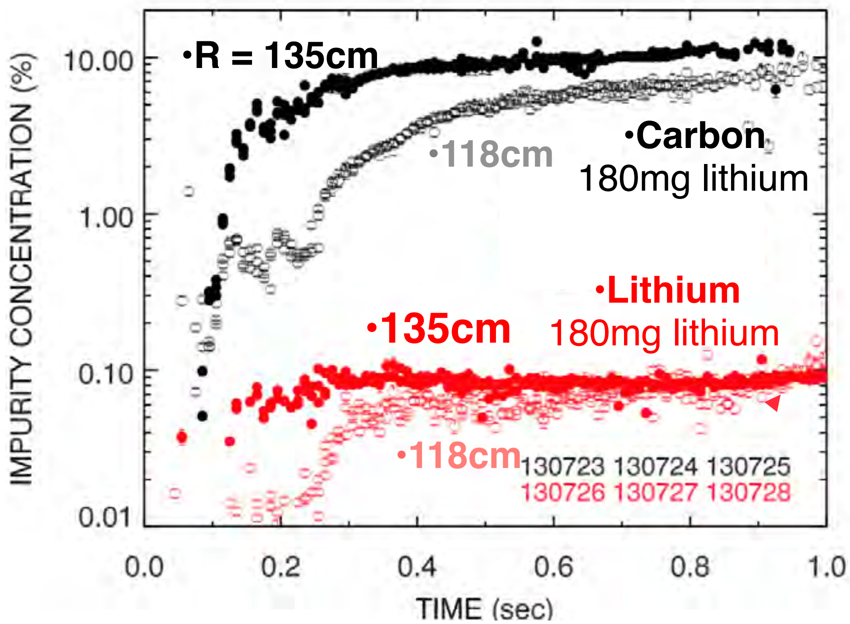
Total and electron energy confinement time continued to increase with pre-discharge lithium evaporation.

H. W. Kugel, PoP 2008

R. Maingi, PRL (2011)

Lithium Concentration in Plasma Core Remains Very Low Compared to Higher Z Carbon even for H-mode Plasmas

- Quantitative measurements of C^{6+}, Li^{3+} with charge-exchange recombination spectroscopy
- $n_C/n_{Li} \sim 100$
- Hollow profiles early for both C and Li fill in as time progresses



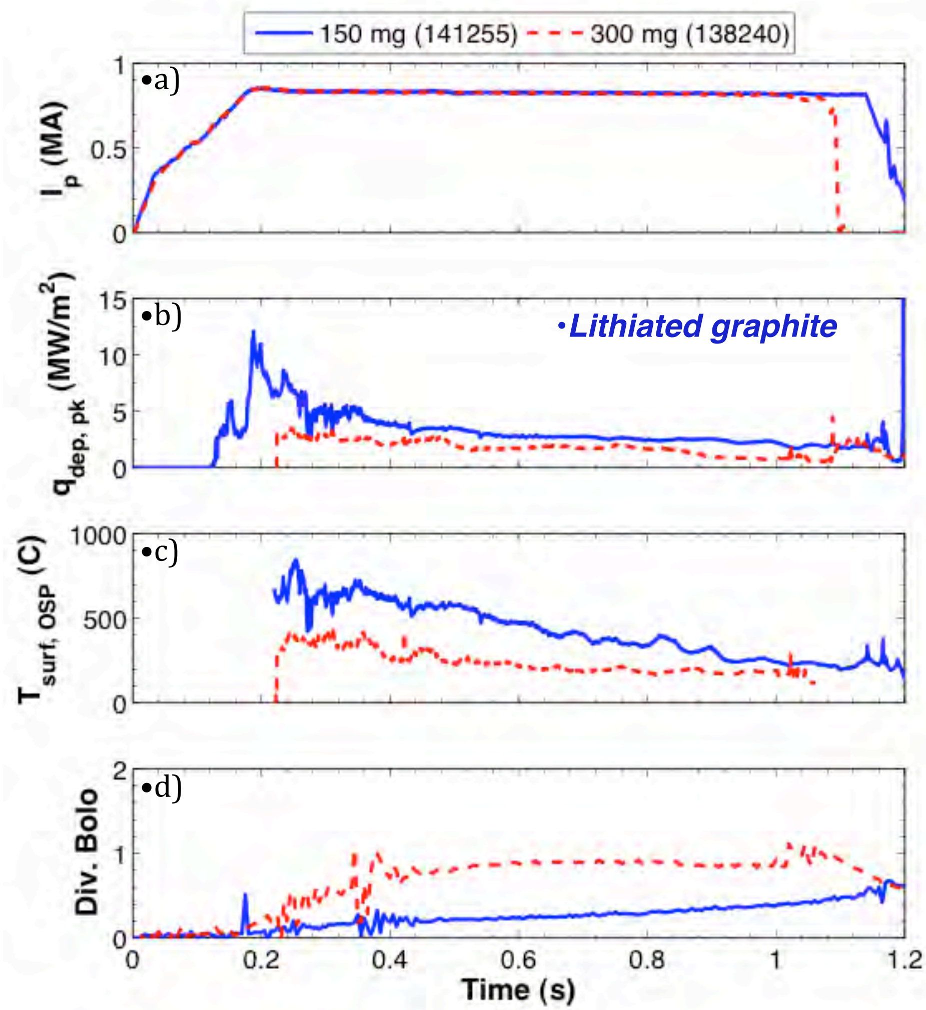
- No sign of Li accumulation in core

- Low lithium core contamination < 0.1% continues to hold true for LLD operation
- Very good news for lithium based divertor concepts
- Low level of lithium accumulation consistent with neo-classical theory (C.S. Chang *et al.*)

M. Podesta, NF 2012

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/m² with heavy lithium evaporation

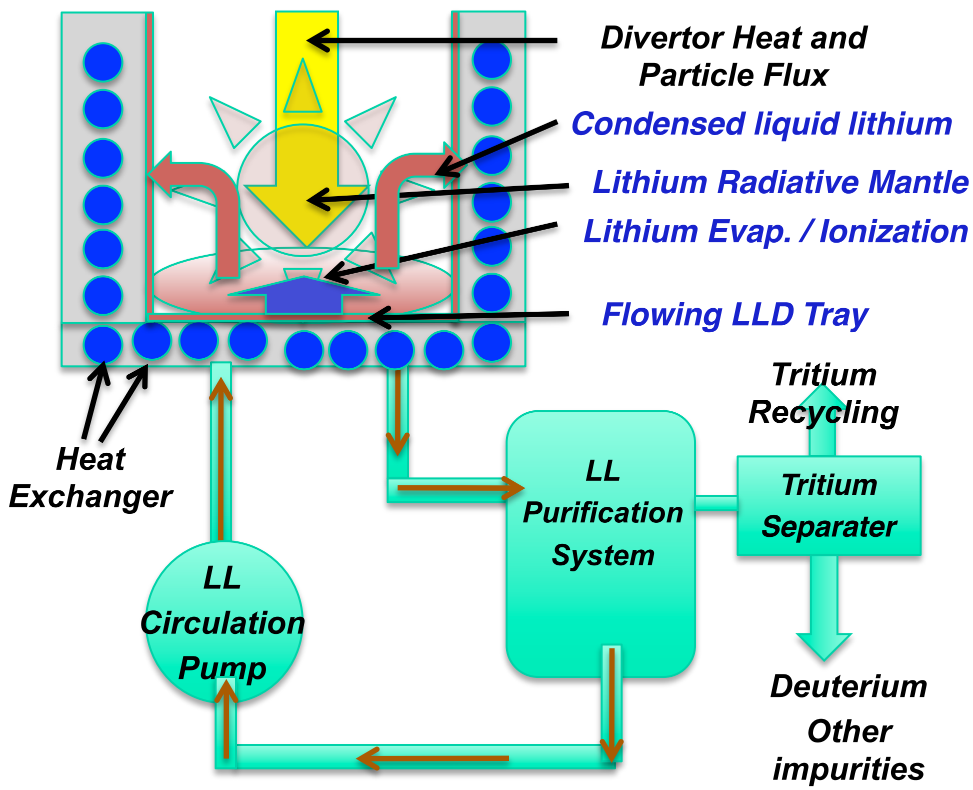


T. Gray. IAEA 2012

Radiative LL Closed Divertor Being Examined

LL to protect divertor surface, radiate away heat, and pump particles

- LL being provided to protect divertor strike point
- LL evaporates, ionizes, and radiates, spreading divertor heat to chamber wall
- Chamber wall cooled by a heat exchanger
- Lithium condenses on the colder chamber wall surfaces
- Colder temperature LL on chamber wall surface also acts as a strong particle pump for D, T, and impurities
- LL collected, purified and reapplied to divertor strike poin



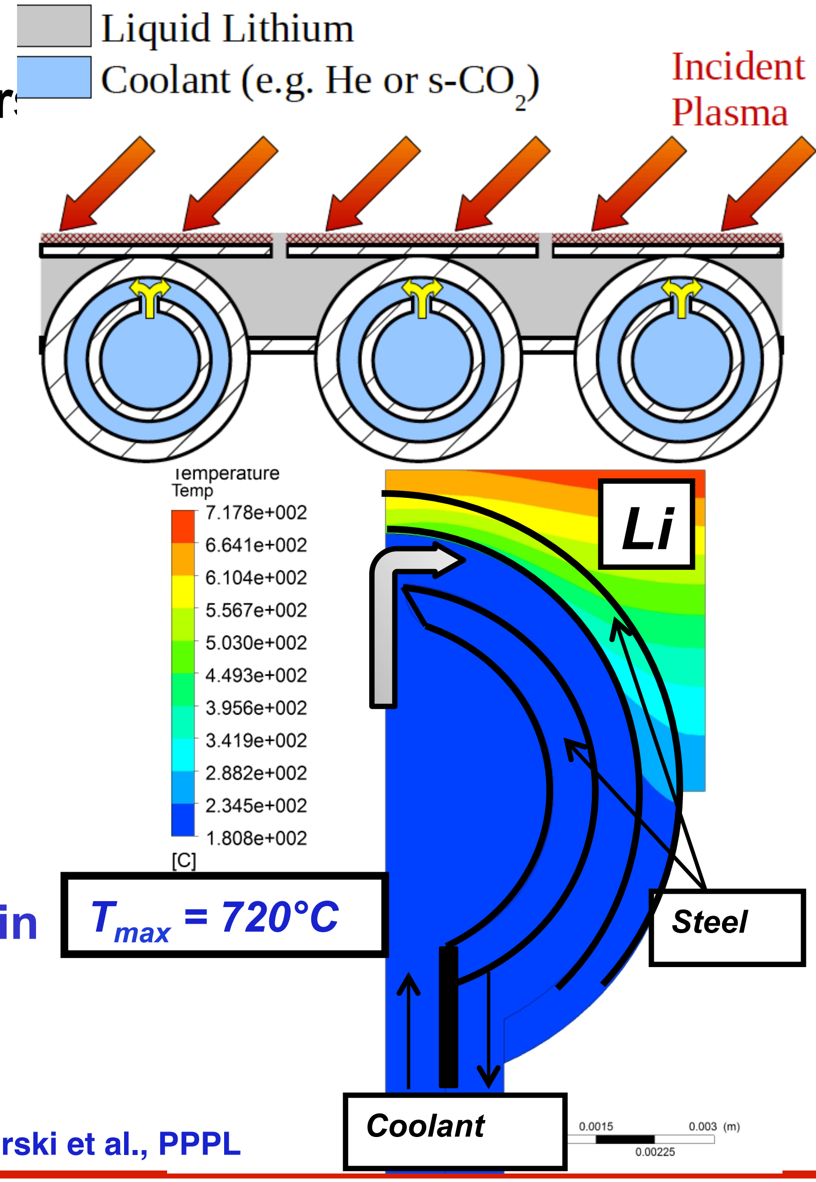
M. Ono et al., IAEA 2012

Talk Outline

- Motivation of Divertor PMI Research
- NSTX-U PMI Mission
- NSTX-U PMI Experimental Facility
- NSTX PMI Experimental Results and Plans: Snow flakes and Liquid Lithium Divertor
- **Associated PMI Facilities at PPPL**
- Summary

PPPL Liquid Metal R&D for Future PFCs

- Design studies focusing on thin, capillary-restrained liquid metal layers
  - Combined flow-reservoir system in "soaker hose" concept
  - Building from high-heat flux cooling schemes developed for solid PFCs
  - Optimizing for size and coolant type (Helium vs. supercritical-CO_2)
- Laboratory work establishing basic technical needs for PFC R&D
  - Construction ongoing of liquid lithium loop at PPPL with internal funding
  - Tests of lithium flow in PFC concepts in the next year
  - Coolant loop for integrated testing proposed



M. Jaworski et al., PPPL

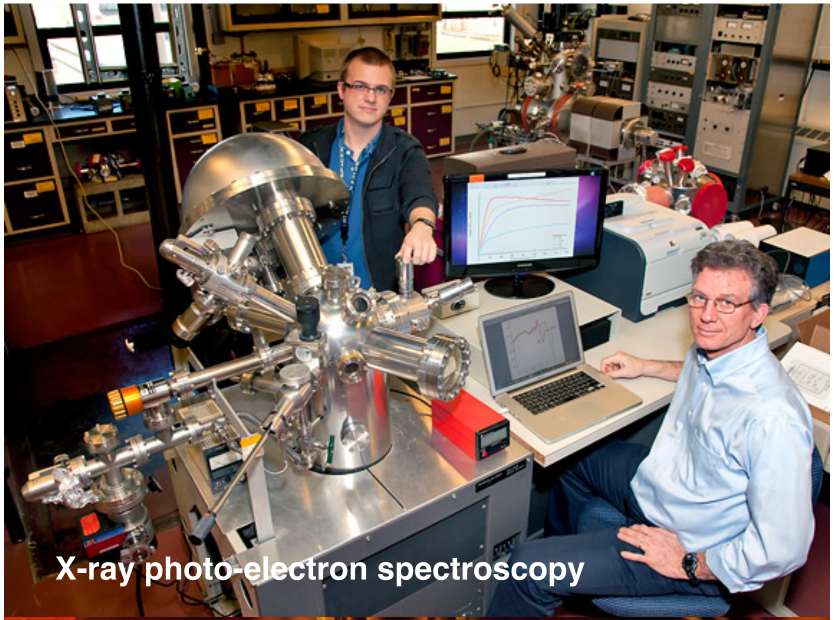
Surface Analysis Facilities to Elucidate Plasma-Surface Interactions

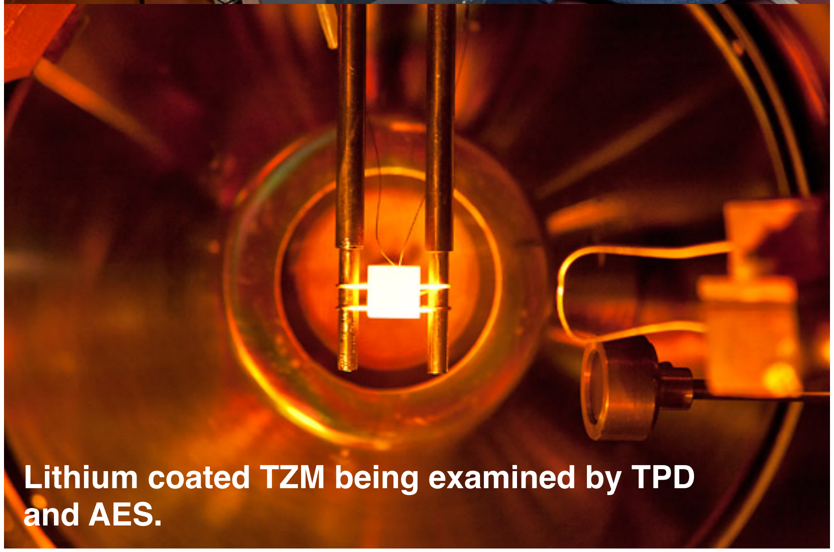
PPPL Collaboration with B. Koel et al., Princeton University

- The Surface Science and Technology Laboratory (SSTL) with three surface analysis systems and an ultrahigh vacuum deposition chamber.

- The Surface Imaging and Microanalysis Laboratory (SIML) with a Thermo VG Scientific Microlab 310-F High Performance Field Emission Auger and Multi-technique Surface Microanalysis Instrument.

- Recently solid lithium and Li coated TZM were examined using X-ray photoelectron spectroscopy (XPS), temperature programmed desorption (TPD), and Auger electron spectroscopy (AES) in ultrahigh vacuum conditions and after exposure to trace gases.
  - Determined that lithiated PFC surfaces in tokamaks will be oxidized in about 100 s depending on the tokamak vacuum conditions. (C. H. Skinner et al., PSI_20 submitted to J. Nucl. Mater.)


X-ray photo-electron spectroscopy


Lithium coated TZM being examined by TPD and AES.

LTX research focuses on the technology of lithium plasma facing components and their effects on plasma performance

Lithium Tokamak Experiment (LTX) to investigate:

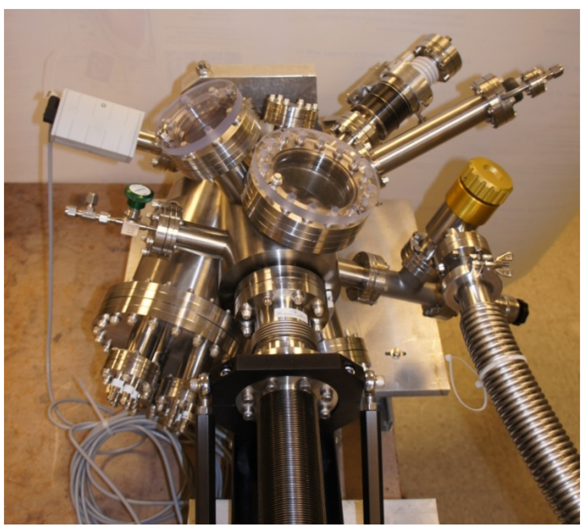
- Plasma interactions with lithium surfaces and temperature dependence of lithium influx
- Effect of lithium walls on confinement and electron temperature profiles
- Liquid metal flows in B fields up to 0.3T

LTX lithium plasma-facing components include:

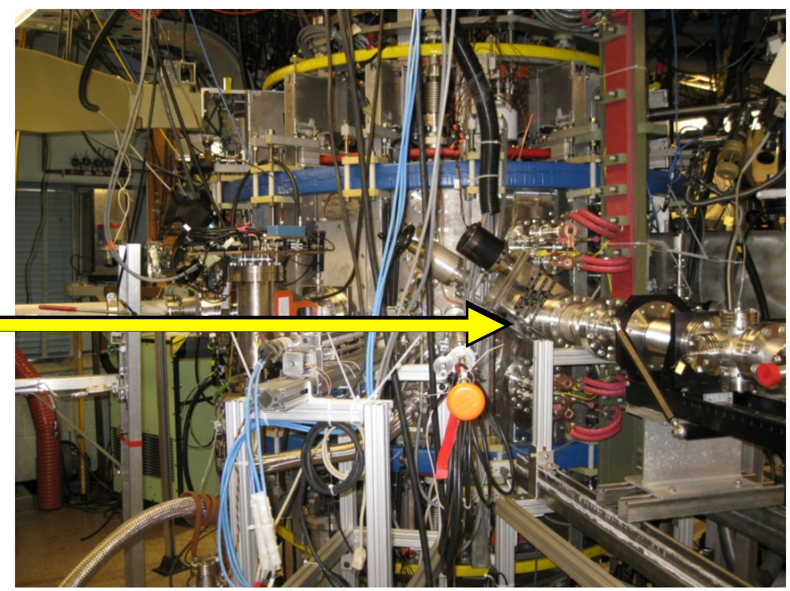
- Lithium-filled movable limiter - 120 cm^2 dendritic W heated to temperatures up to 500 C
- Lithium surfaces - 100 micron films on upper shell & liquid lithium "pool" in lower shell

Specialized Materials Analysis and Particle Probe (MAPP) allows samples to be exposed to plasmas and withdrawn between shots for X-ray and ion scattering measurements

MAPP



MAPP will be installed on midplane LTX port



R. Kaita FE&D 2010

Summary

- **PMI is a high priority research area for the magnetic fusion research and for NSTX-U / PPPL.**
- **Divertor heat flux solution needs x 10 improvements for practical steady-state magnetic fusion reactors.**
- **Progress is being made in a variety of PMI fronts.**
- **An integrated PMI experimental research is being implemented at high priority on NSTX-U.**
- **Snow-flake divertor concept and LL PMI are two promising innovative PMI research topics pursued on NSTX-U for a possible reactor divertor heat flux solution.**
- **Specialized science and PFC/LL test facilities at PPPL / PU will support advanced PFC/LL development.**