Plasma-Wall Boundary Control With Lithium Divertor and Associated Plasma Confinement Improvements in NSTX

Masayuki Ono

NSTX-U Project Director

PPPL, Princeton University

In collaboration with the NSTX-U Team

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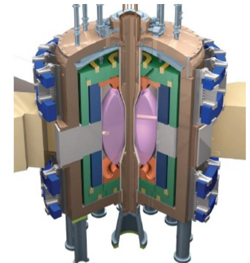
Talk Outline

- NSTX-U Mission and Motivation for Liquid Lithium PMI Research
- NSTX Lithium Experimental Results
- Closed Radiative Liquid Lithium Divertor (RLLD) Concept
- Summary

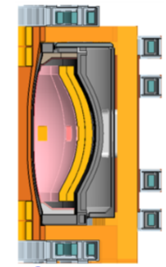
NSTX-U Aims to Develop Physics Understanding Needed for Designing Fusion Energy Development Facilities

- **Enable devices: ST-FNSF, ST-Pilot/ DEMO, ITER**
  - Leveraging unique ST plasmas provides new understanding for tokamaks, challenges theory

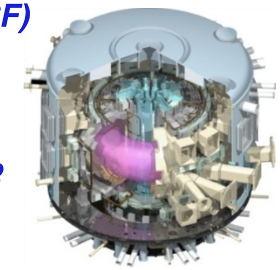
- **Develop key physics understanding to be tested in unexplored, hotter ST plasmas**
  - Study high beta plasma transport and stability at reduced collisionality, for extended pulse
  - Prototype methods to mitigate very high heat/particle flux
  - Move toward fully non-inductive operation



Fusion Nuclear Science Facility (FNSF)

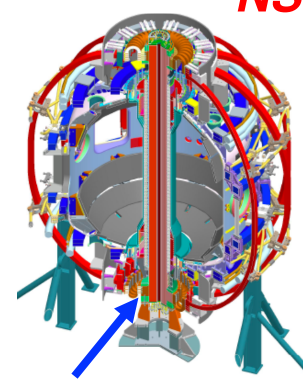


ST Pilot Plant

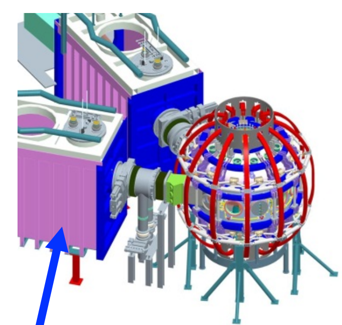


ITER

NSTX-U



New center-stack



2nd neutral beam

B_T	0.5 → 1 T	P_{NBI}	6 → 12 MW
I_p	1 → 2 MA	pulse	1 → 5 s

NSTX-U Bridges Physics Gaps Toward Designing 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
Peak Div. heat flux [MW/m^2]	**10**	**40 (5 sec)**	**50**	**60**

ITER ~ 10 **DEMO ~ 40 - 60**

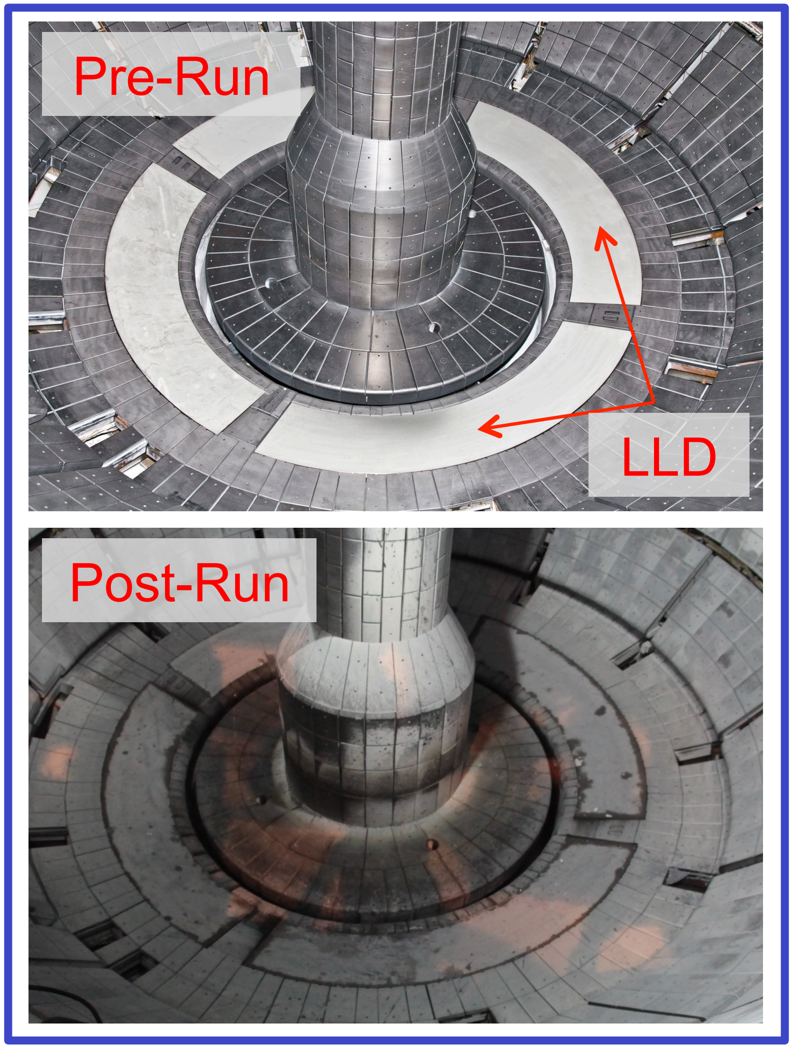
- **DEMO/FNSF projected to require X 10 the tungsten reactor divertor design limit**
- **FNSF / DEMO level divertor heat flux needs innovative solution**
- **NSTX-U aims to provide database to begin FNSF design in this decade including the diverter heat flux solution**

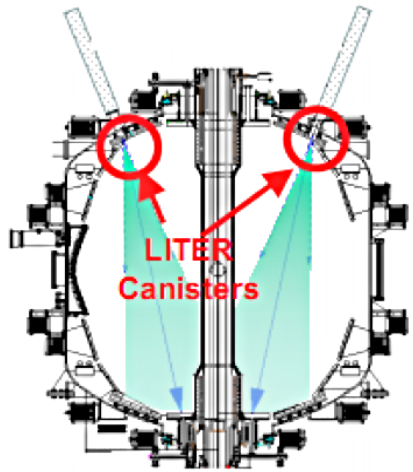
Talk Outline

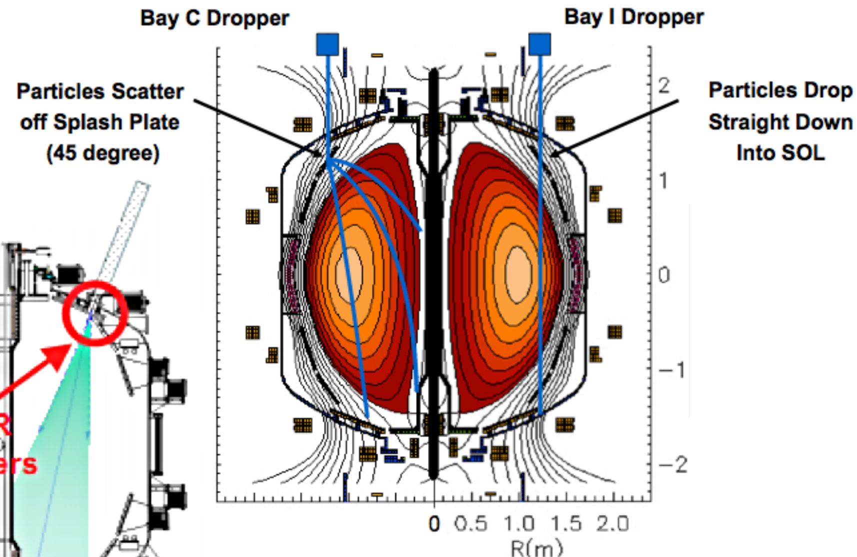
- NSTX-U Mission and Motivation for Liquid Lithium PMI Research
- **NSTX Lithium Experimental Overview**
- Closed Radiative Liquid Lithium Divertor (RLLD) Concept
- Summary

NSTX Tested Various Lithium Conditioning Systems

Effects of solid / liquid lithium surfaces investigated with LLD





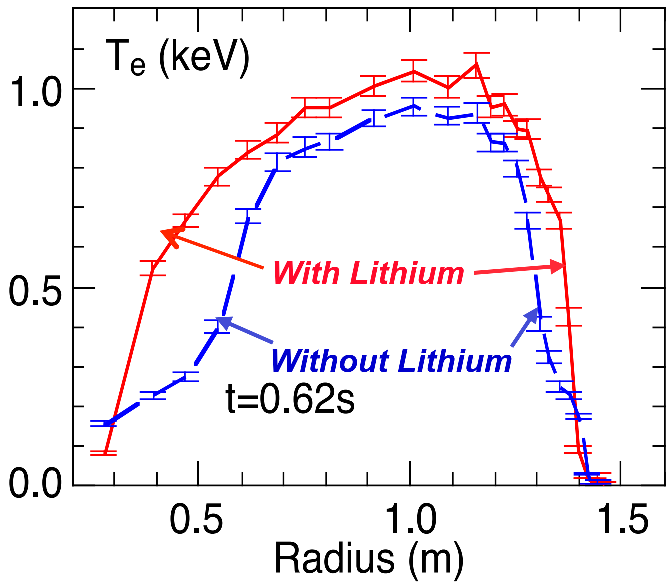


- **Lithium conditioning systems**
  - Li Evaporator (LITER) – 1.3 kg evaporated during last campaign
  - Liquid Lithium Divertor (LLD) – Moly surface with over 300 °C temperature
  - Li Dropper – Fast injection into plasma
  - Li Pellets – Used initially

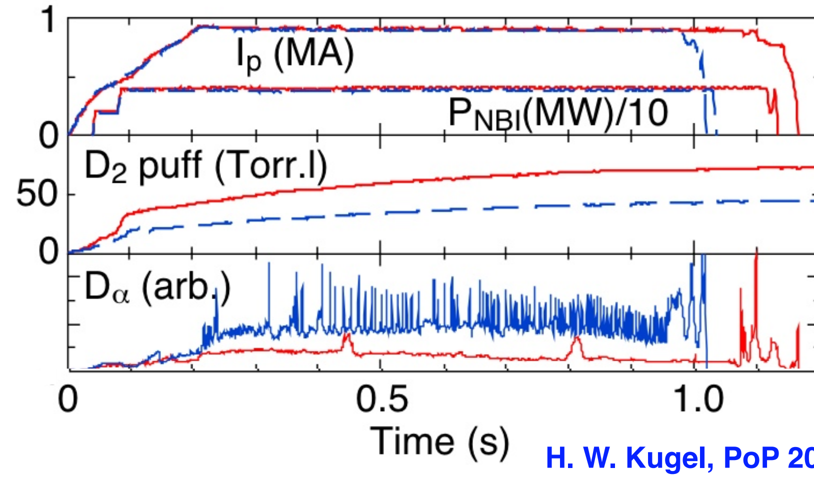
Lithium Improved H-mode Performance in NSTX

T_e Broadens, τ_E Increases, P_H Reduces, ELMs Stabilize

T_e broadening with lithium

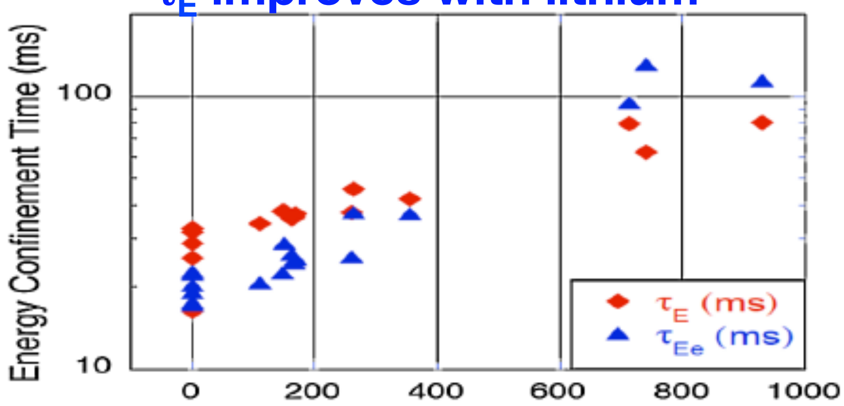


No lithium (129239); 260mg lithium (129245)



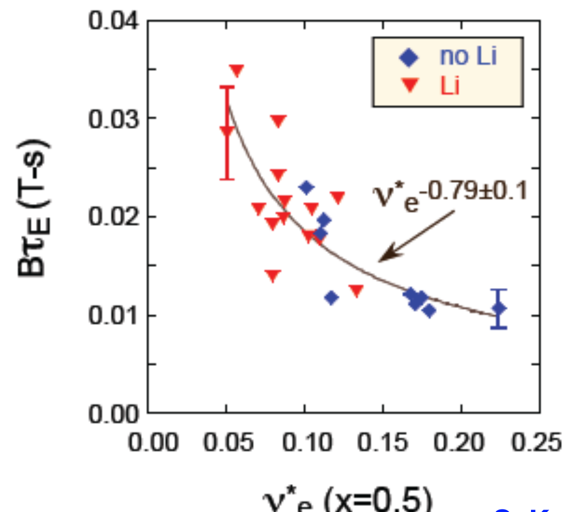
H. W. Kugel, PoP 2008

τ_E improves with lithium



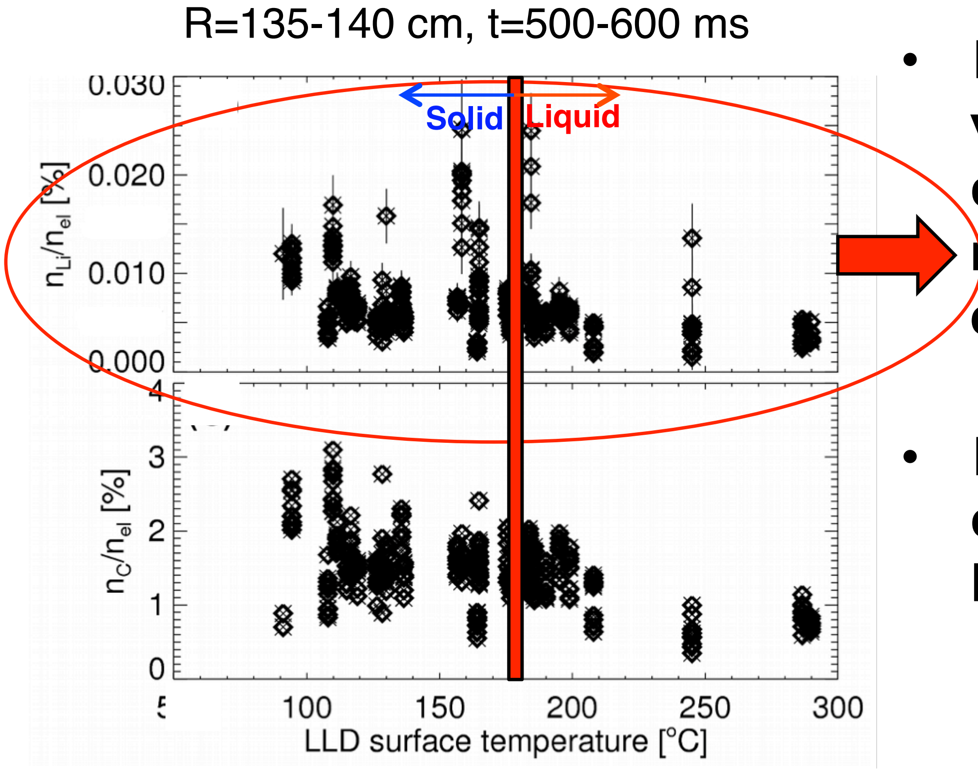
R. Maingi, PRL (2011)

τ_E improves with lower collisionality



S. Kaye, IAEA (2012)

Li core concentration stays well below 0.1% for LLD temperature range of 90°C to 290°C

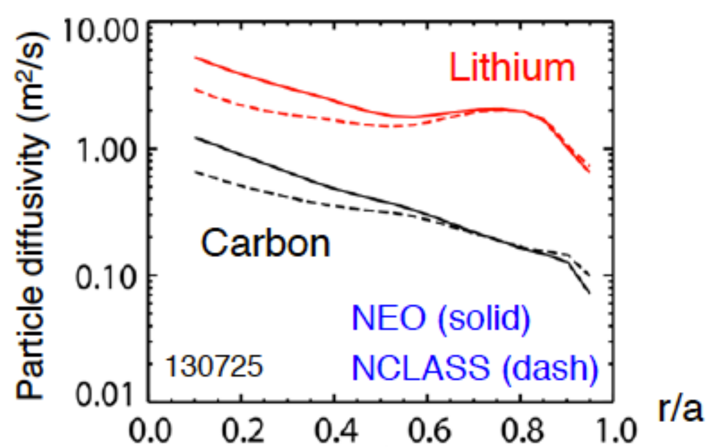


- **Li core concentration remained very low ≤ 0.05%. C remains dominant impurity even after massive (hundreds of milligrams) Li evaporation**
- **No apparent increase in Li nor C core concentration even at higher LLD surface temperature.**

M. Podesta, IAEA (2012)

Reason for low lithium core dilution?:

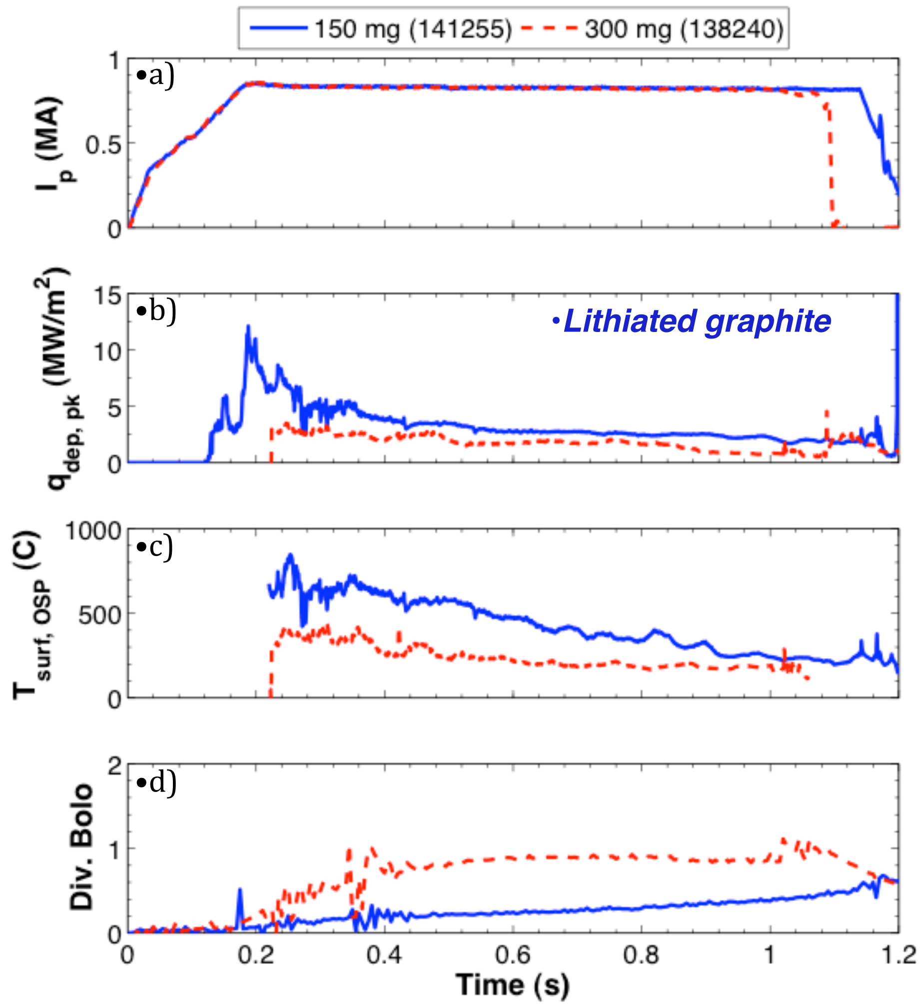
- **Li is readily ionized ~ 6 eV**
- **Li is low recycling – sticks to wall**
- **Li has high neoclassical diffusivity**



F. Scotti, APS (2012)

Clear reduction in NSTX 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



T. Gray. IAEA 2012

1-D Cylindrical RLLD Model
Two Point Model with Given Lithium Profile

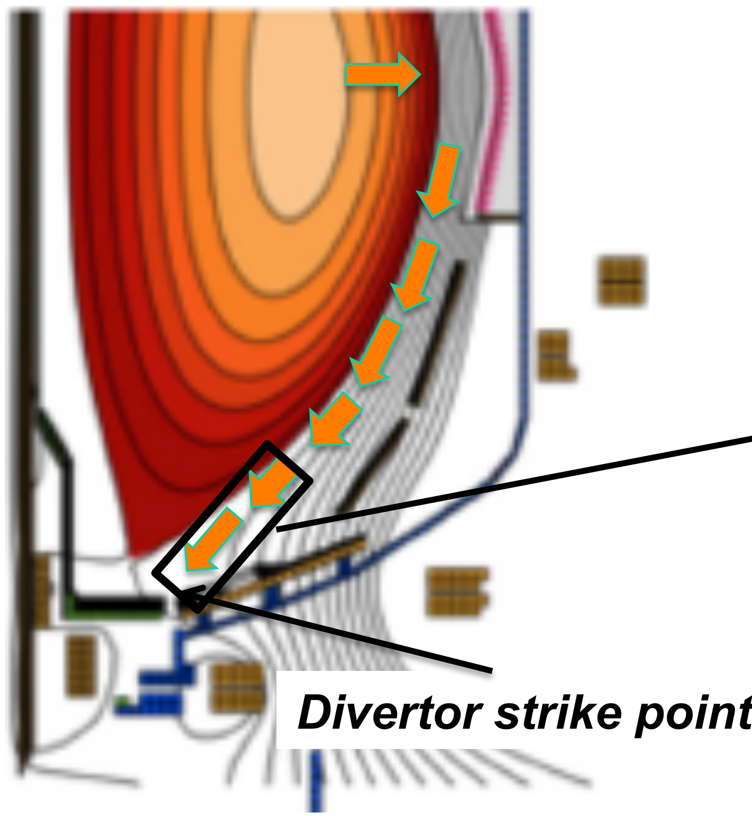
NSTX-like conditions

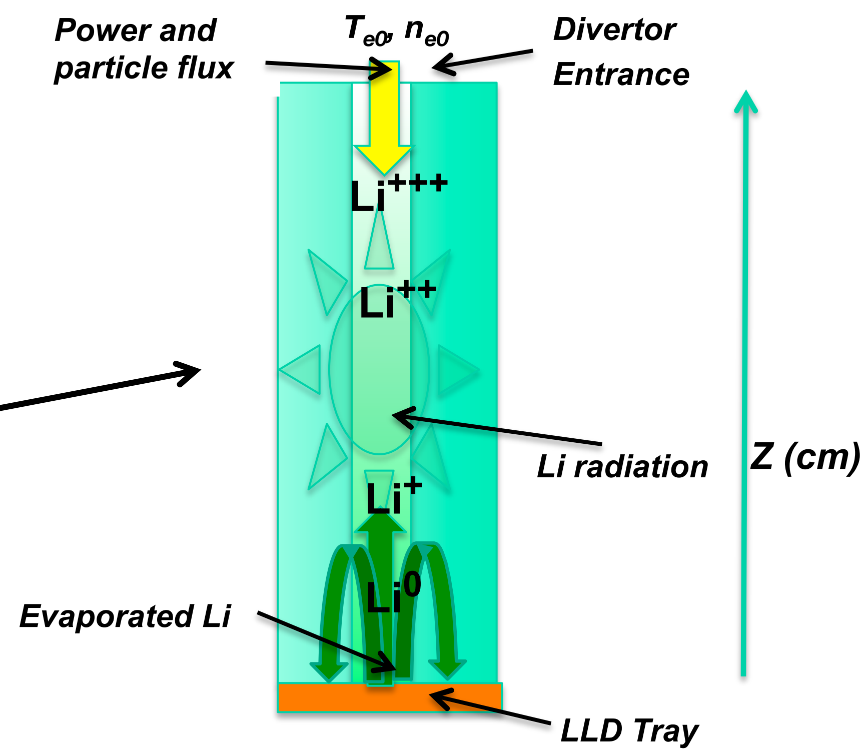
Assumptions: *R = 0.75 m, ΔR = 3 cm, cylinder, deuterium ions, Z = 23 cm,*

At the divertor entrance $T_{e0} = T_{i0} = 50$ eV,

$n_{e0} = 2 \times 10^{13} cm^{-3}$, Two-Point Model, Constant B_T

Given Li profile, Li radiation = 10^{-26} W/Li-electron

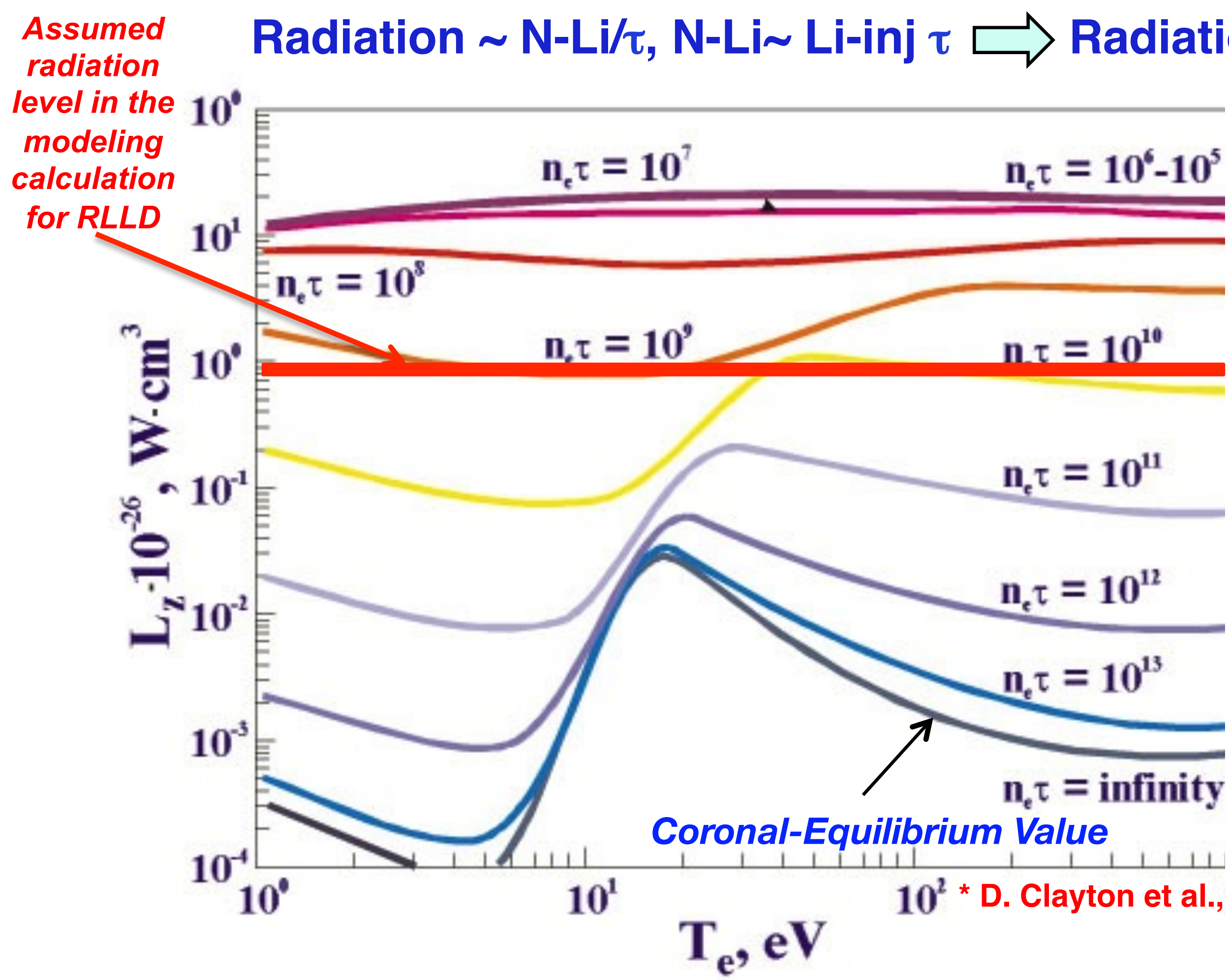




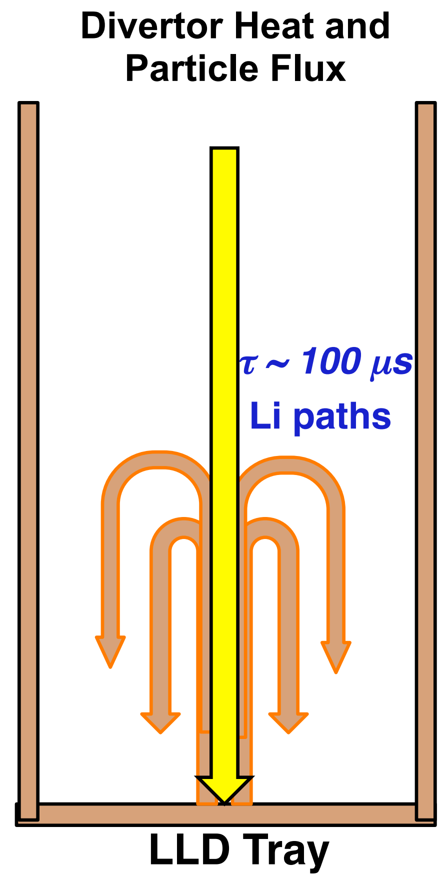
M. Ono. IAEA 2012

Strong (~x100) Li Radiation Level Over Coronal Eq. Expected in Divertor Due to Low Confinement

Radiation ~ N-Li/τ, N-Li~ Li-inj τ ⇨ Radiation ~ Li-inj



* D. Clayton et al., JHU

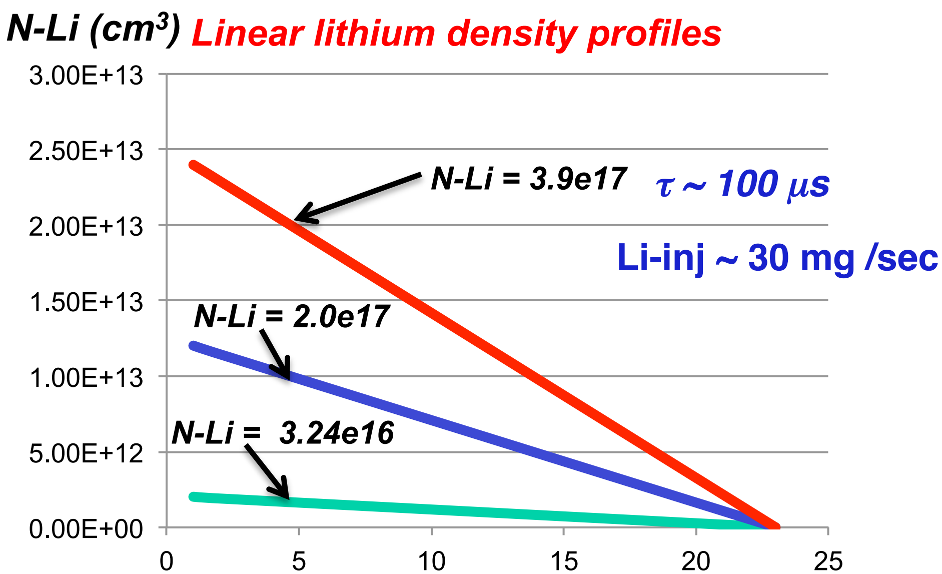


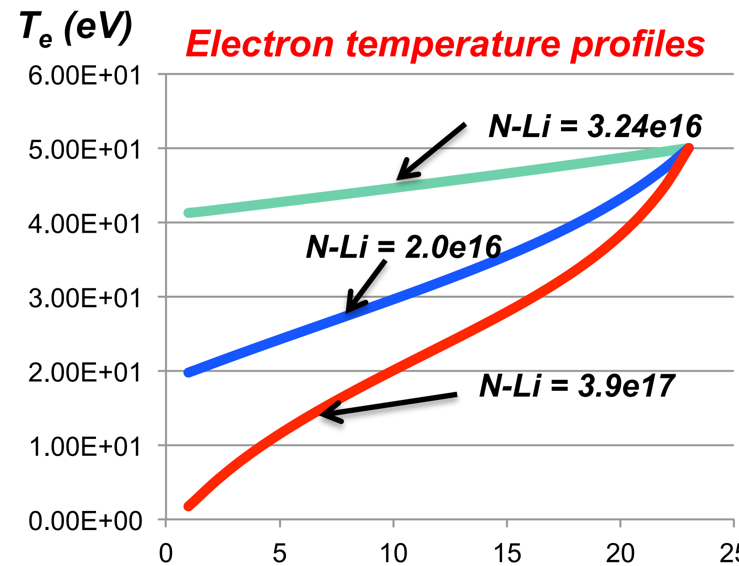
The Li radiation power per one atom and one electron in coronal-quilibrium ($n_e t$ = infinity) and non-equilibrium regimes.

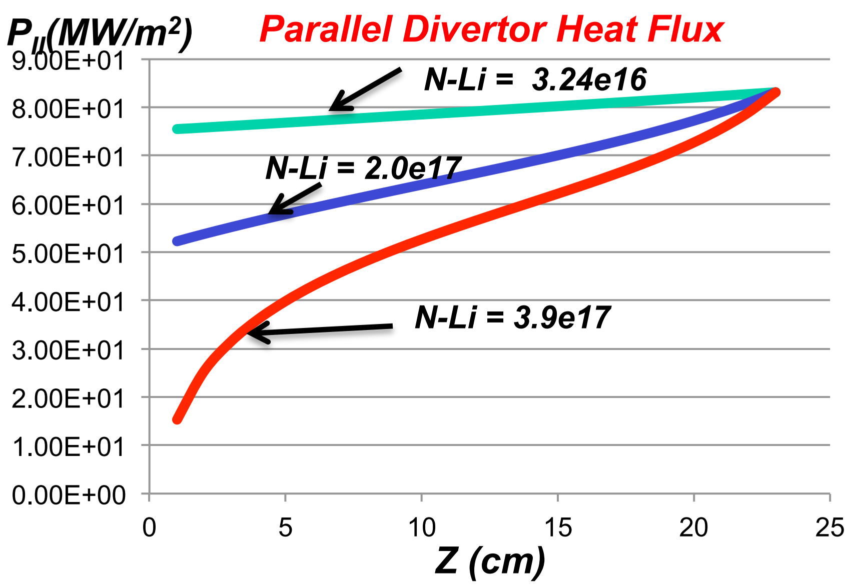
S. V. Mirnov, et al., Plasma Phys. Control. Fusion (2006)

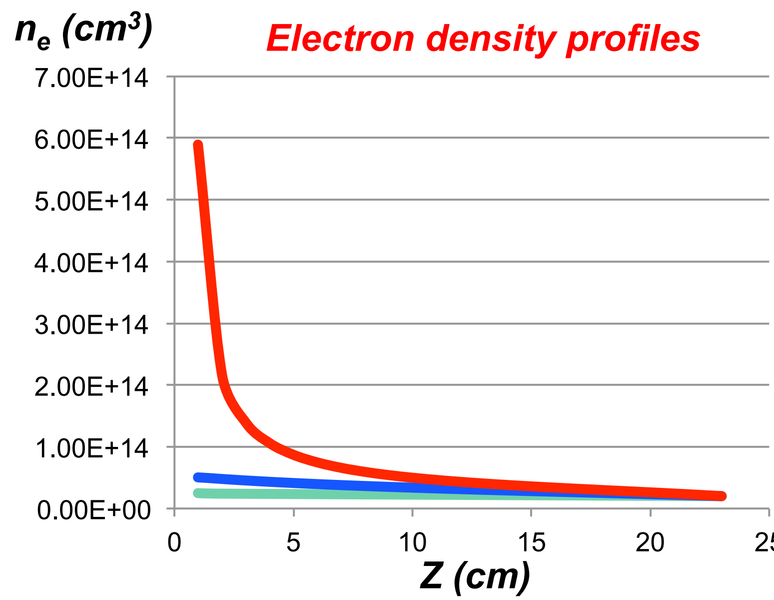
1-D Cylindrical RLLD Two Point Model

Explains NSTX LLD Observation with Modest Amount of Li



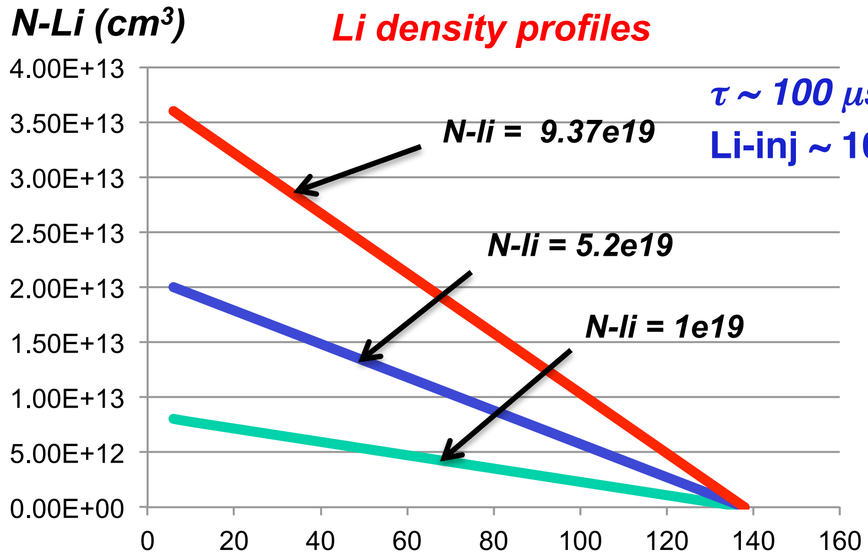


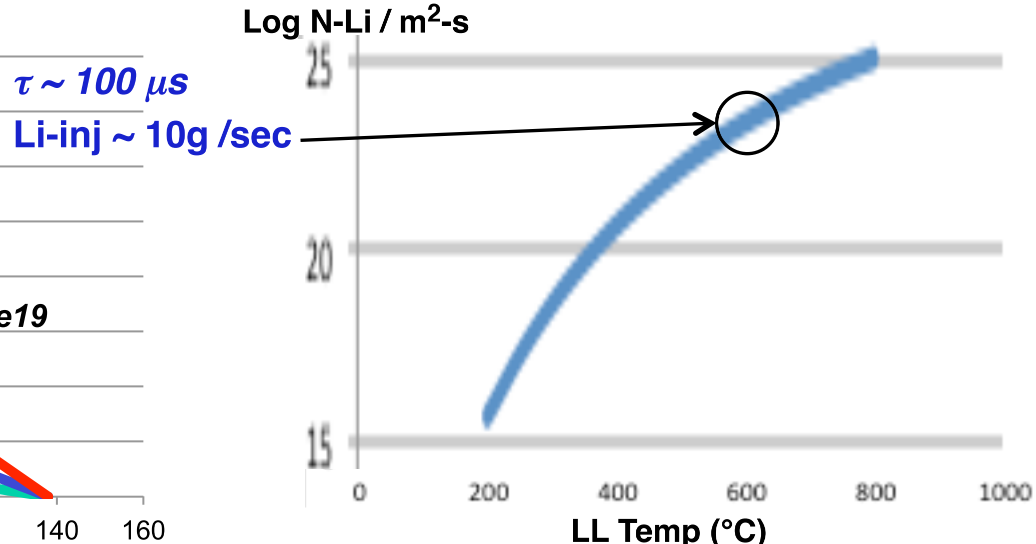


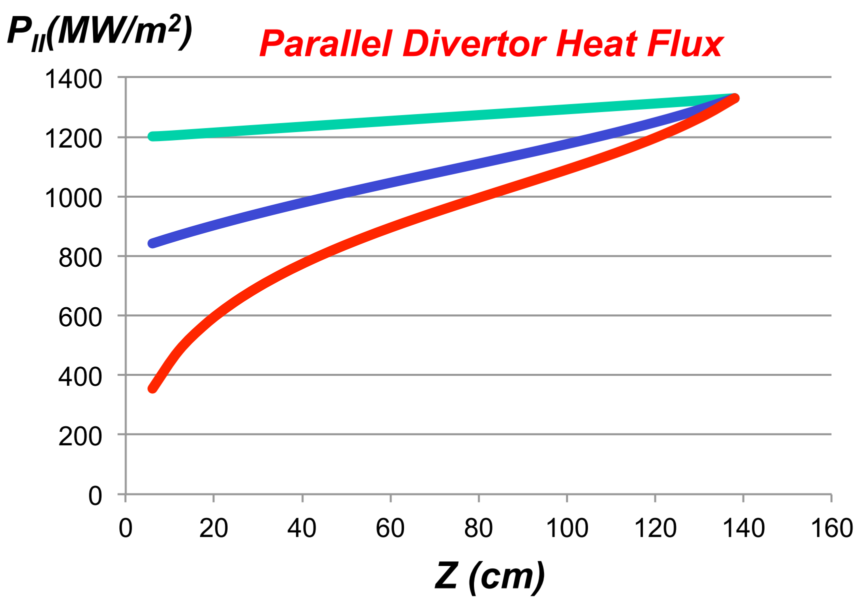


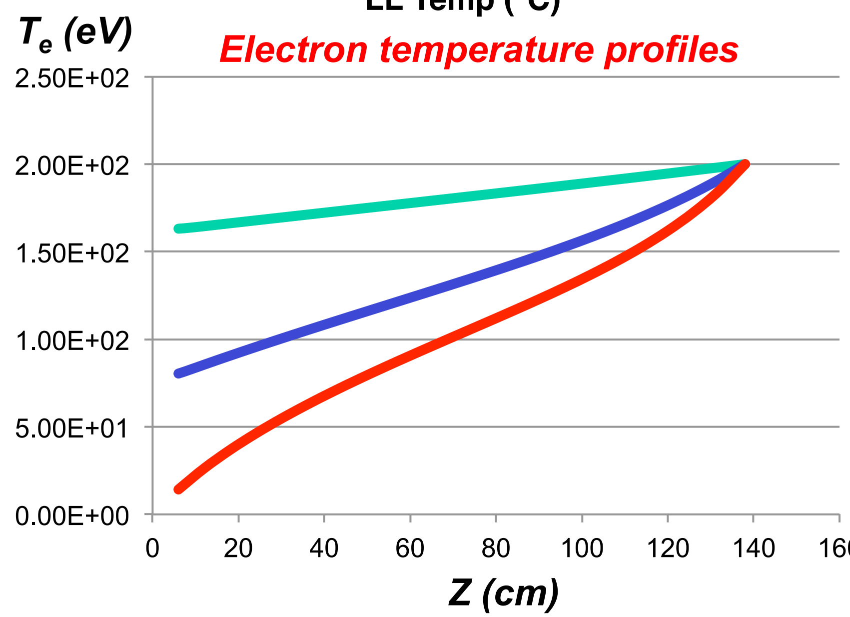
RLLD Works for Fusion Power Plant

R = 6 m, ΔR = 10 cm, Z = 138 cm with modest amount of Li









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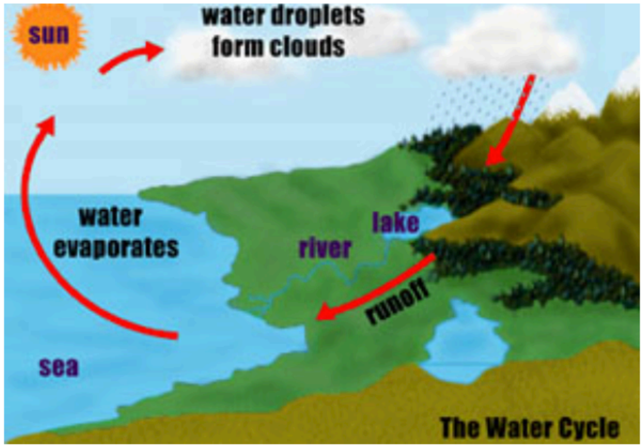
Liquid Lithium (LL) as Divertor PFC Material

Handling heat & particle flux while improving plasma performance!

- **Low melting temperature (180°C) makes LL in natural state in reactor environment**

- **LL is resilient against high heat flux**
  - **It can vaporize, ionize but it can be collected, renewed and recycled**

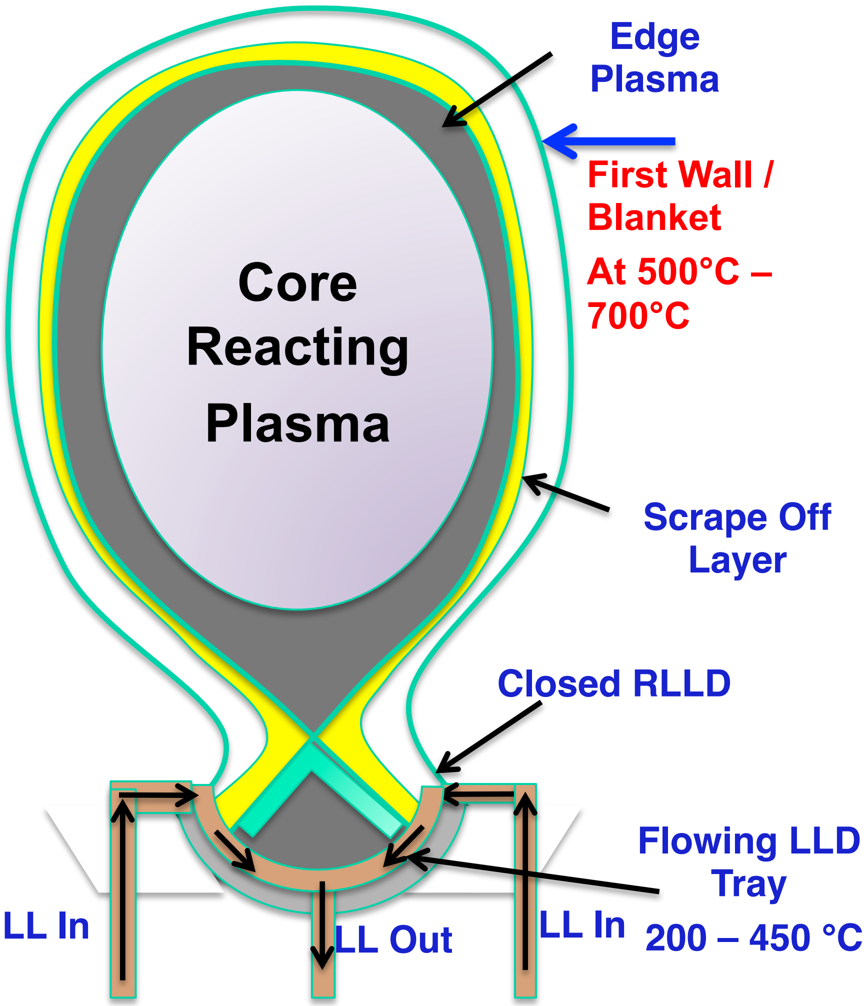


- **LL could protect solid surface from high heat flux!**
  - **Cooling due to vaporization and ionization**
  - **Lithium plasma radiation could provide potentially very efficient cooling in the divertor region where lithium particle confinement is low.**

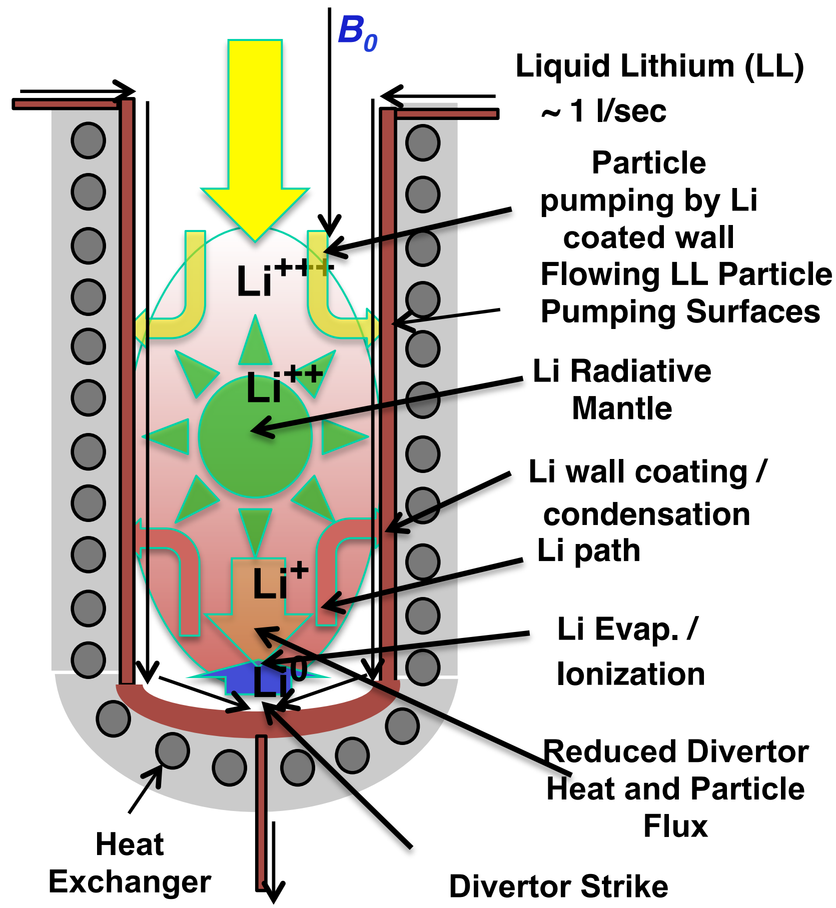
T. D. Rognlien and M. E. Rensink, Physics of Plasmas 9, 2120 (2002).

Radiative Liquid Lithium Divertor Proposed

Based largely on the NSTX Liquid Lithium Divertor Research



M. Ono. IAEA 2012



LL Purification System to remove tritium, impurities, and dust

Is lithium PFC viable in magnetic fusion reactors such as ITER?

First Lithium Symposium in 2010: Y. Hirooka. et al., Nucl. Fusion (2010)
Second Lithium Symposium in 2011 : M. Ono, et al., Nucl. Fusion (2012)

1. Handling high divertor heat flux,
2. Removal of deuterium, tritium, and impurities from liquid lithium,
3. Removal of high steady-state heat flux from divertor,
4. Flowing of liquid lithium in magnetic fields,
5. Longer term corrosion of internal components by liquid lithium,
6. Safety of flowing liquid lithium, and
7. Compatibility of liquid lithium with a hot reactor first wall.

Handling and Removal of High Divertor Heat Flux

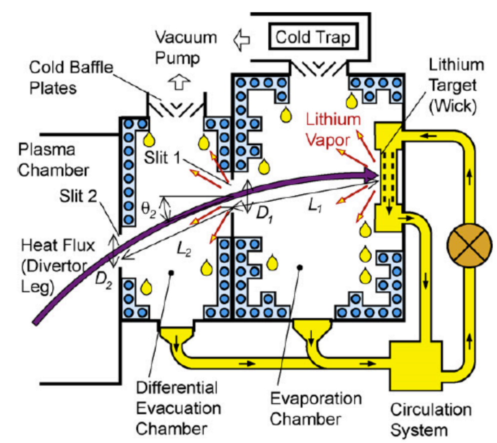
1. Handling high divertor heat flux?

✓ Radiative Liquid Lithium Divertor (RLLD)

3. Removal of high steady-state heat flux from divertor?

✓ RLLD

Acknowledgment: The present RLLD was stimulated by LL Evaporative Cooling Divertor by Y. Nagayama, Fusion Eng. & Design (2009)



Impurity and Dust Removal by LL Circulating Loop

Low melting point of Li (180°C) makes such a loop practical in reactor

For 1 GW-Electric Power Plant:

- LL loop removes tritium ~ 0.5 g / sec and recycle for plasma fueling.
- Modest LL flow of ~ 1 l/sec should be sufficient to transport impurities out of the system with LL impurity level ~ 1 %.
- Tritium (T) level ~ 0.5 g / l before filtering or 1000 l RLLD system contains ~ 500 g of tritium or ~ one day of T burn.

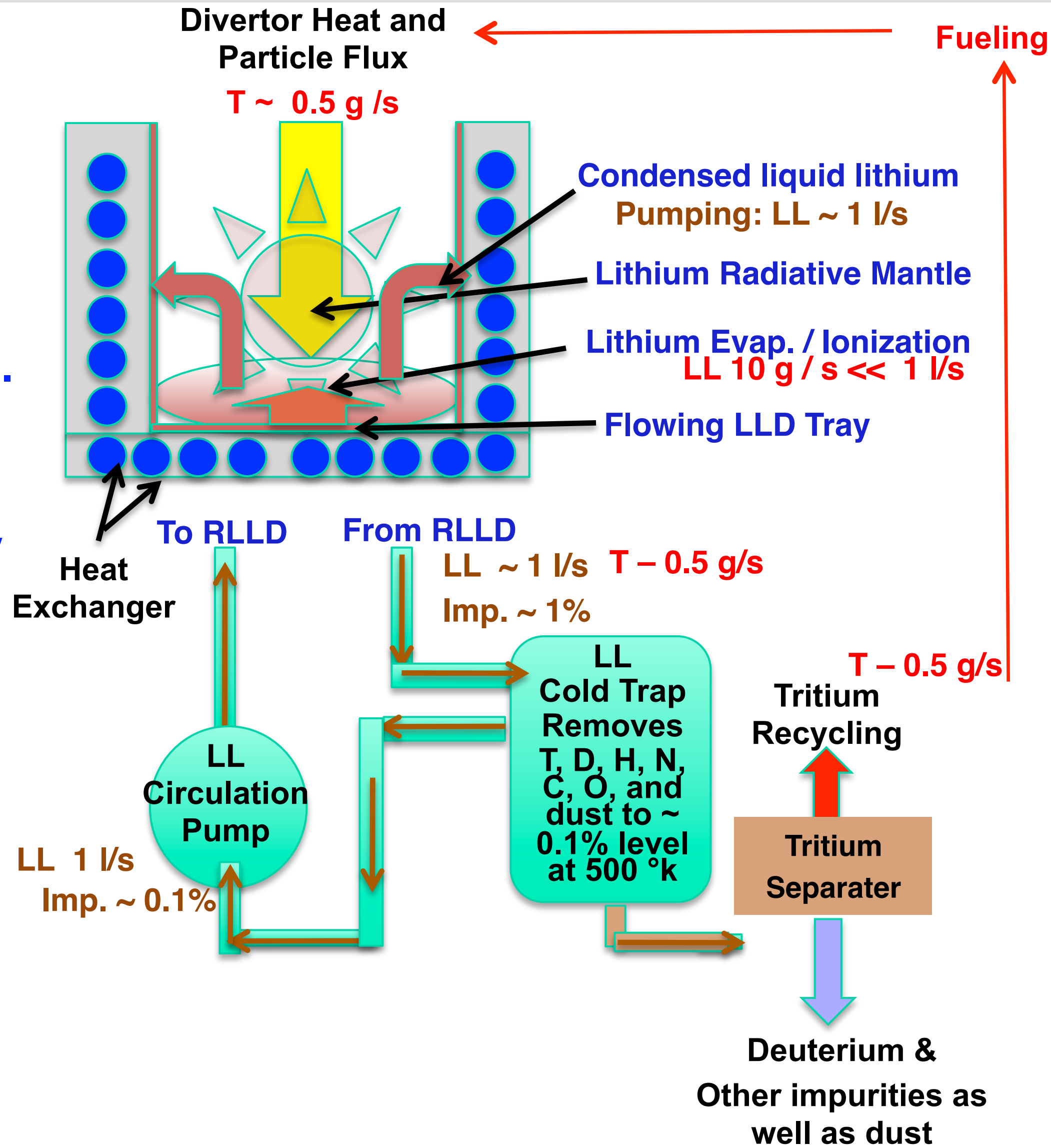
  M. Nishikawa, Fusion Sci. & Tech. (2011)

- Purification systems developed by IFMIF could provide particle removal and keep LL relatively clean ≤ 0.1 %.

  H. Kondo, Fusion Eng. & Design (2011)

  K. Katekari, J. Energy and Power Eng. (2012)

- A simple filter can remove the dust generated within reactor chamber ~ 0.1 - 10 μ D.



Is lithium PFC viable in magnetic fusion reactors? Flowing LL purification loop for issues 2, 4, 5, & 6

The # 2,4, 5, & 6 are mostly technology issues:

2. Removal of deuterium, tritium, and impurities from liquid lithium?

✓ Lithium purification loop with cold trap - small LL volume – high T concentration, taking advantage of the IFMIF and TBM R&D

4. Flowing of liquid lithium in magnetic fields?

✓ Minimize flowing LL volume for purification ~ 1 l/sec for 1 GW-electric power plant

5. Longer term corrosion of internal components by liquid lithium?

✓ Operate RLLD at lower temperature < 450 °C, purify LL free of oxygen and nitrogen, taking advantage of the IFMIF and TBM R&Ds

6. Safety of flowing liquid lithium?

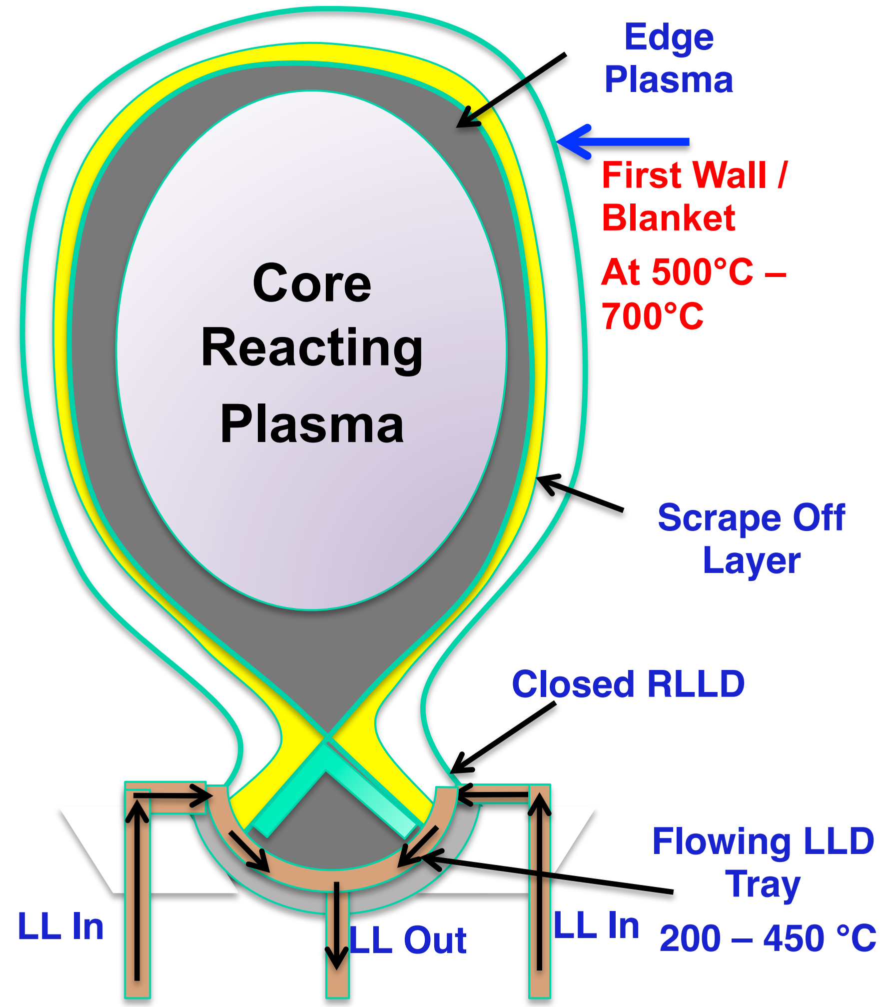
✓ Operate at lower temperature, minimize LL volume, use of He as coolant, taking advantage of the IFMIF and TBM R&Ds

7. *Compatibility with liquid lithium with a hot reactor first wall?*

✓ ***Closed RLLD configuration permits operation at lower T < 450 °C.***

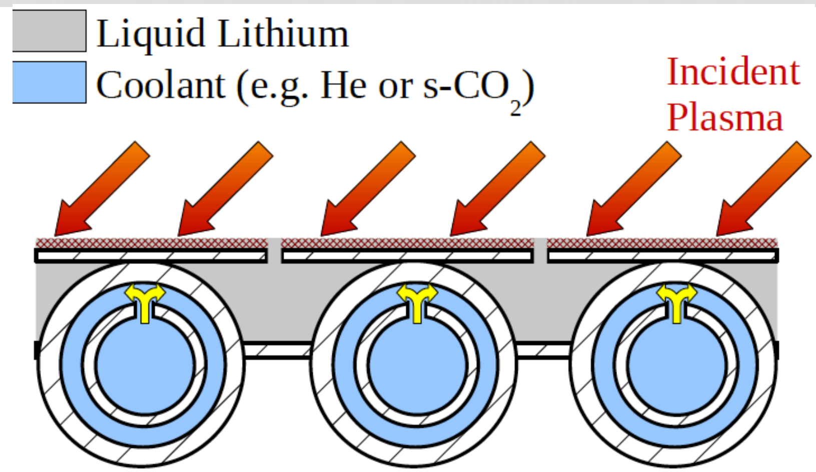
Lower RLLD Operating Temperature:

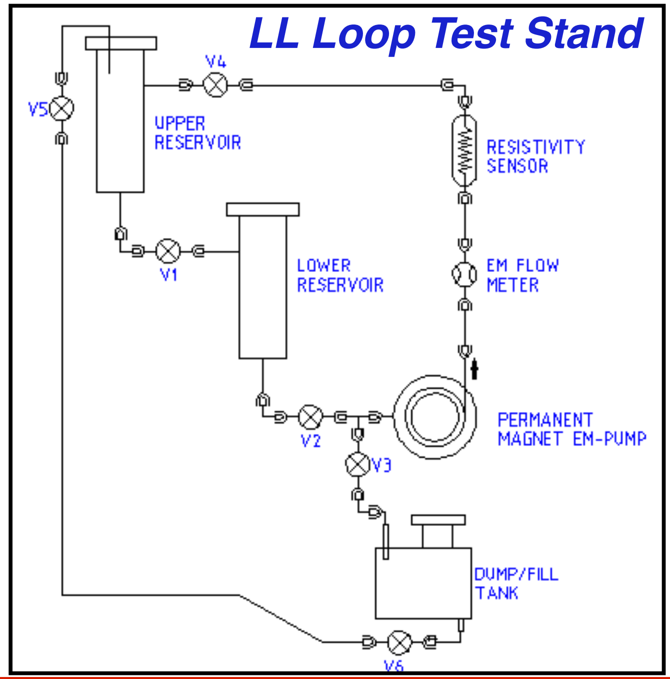
- **Prevents excessive Li vaporization pressure.**
- **Provides natural collection (pumping) surfaces for entire reactor chamber.**
- **Permits use of iron based material for substrates and structural material.**
- **Reduces Li corrosive issues.**
- **Provides safer LL utilization.**



PPPL Liquid Metal R&D for Future PFCs
For NSTX-U and Future Fusion Facilities

- **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 LL loop at PPPL**
  - **Tests of LI flow in PFC concepts in the next year**
  - **Coolant loop for integrated testing proposed**



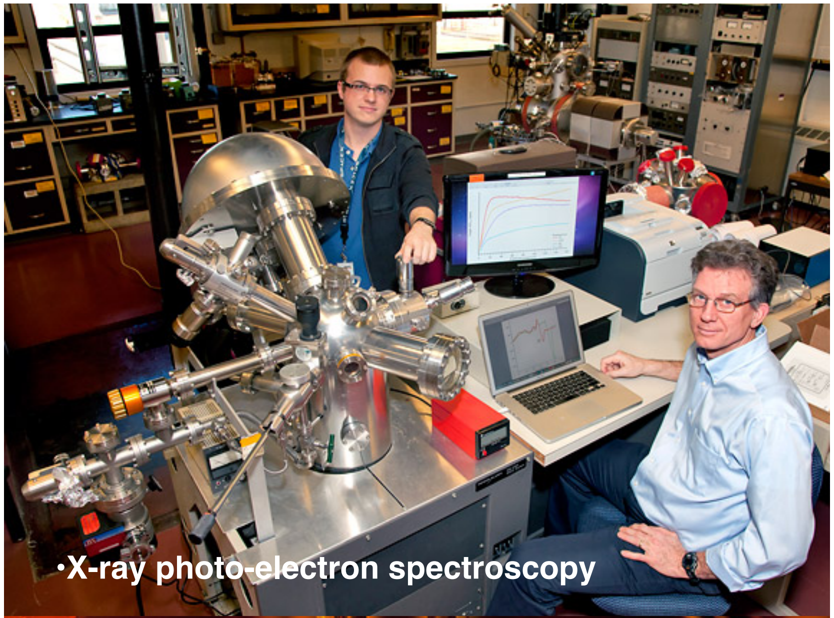


M. Jaworski et al., PPPL

Surface Analysis Facilities to Elucidate Plasma-Surface Interactions

In 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.)

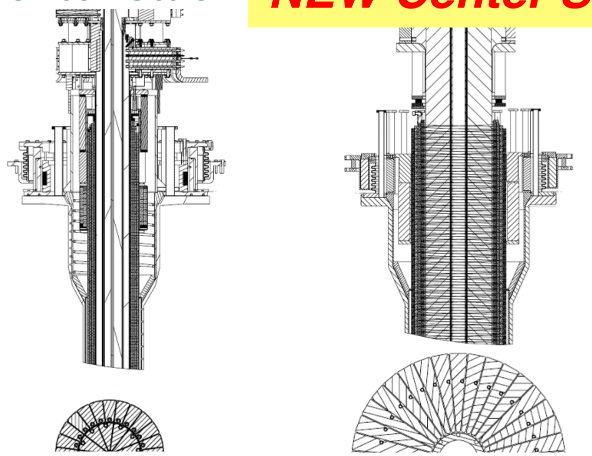


•X-ray photo-electron spectroscopy

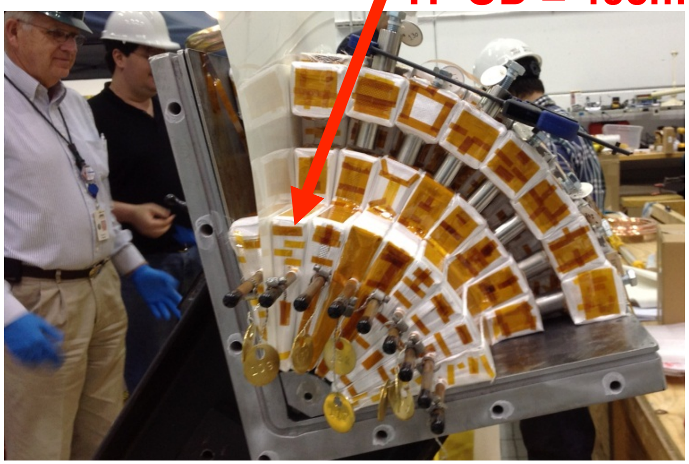
•Lithium coated TZM being examined by TPD and AES.

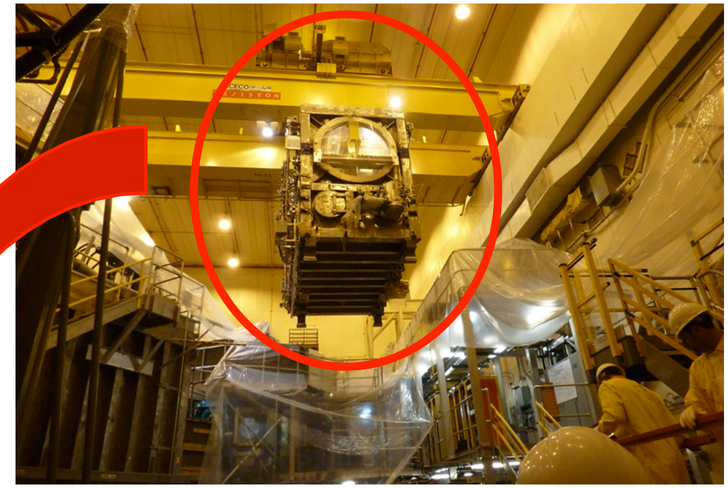
Rapid Progress is Being Made on NSTX Upgrade
First Plasma Anticipated in Summer 2014

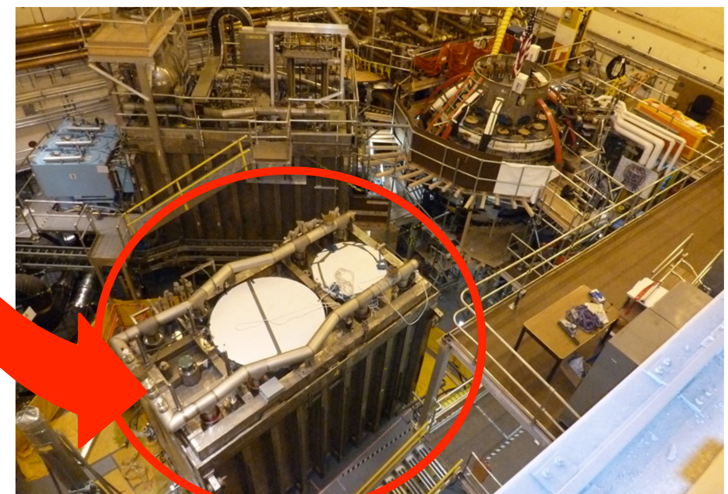
Old center stack *NEW Center Stack*



TF OD = 20cm TF OD = 40cm







- ***TF quadrant assembled***
- **2nd neutral beam moved into place**

Summary of NSTX-U / RLLD

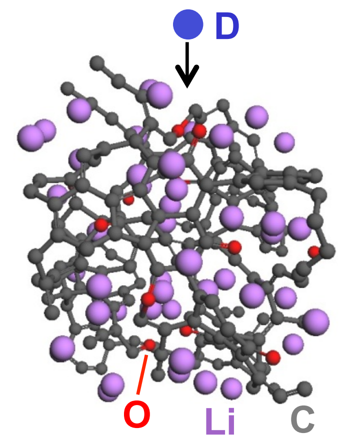
- Divertor PMI and liquid lithium is a high priority research for NSTX-U.
- For next-step devices FNSF and DEMO, an acceptable divertor heat flux solution is needed; x 10 higher heat flux than the tungster-based divertor PFC design limit.
- Lithium coating has shown to significantly improve H-mode performance and divertor heat flux in NSTX.
- Radiative LL Divertor (RLLD) is proposed to solve the reactor divertor heat flux issue.
- A preliminary assessment indicates a good compatibility of RLLD for fusion reactor divertor application.
- NSTX upgrade is progressing well and it aims to develop Demo-FNSF relevant divertor solutions

Backup Slides

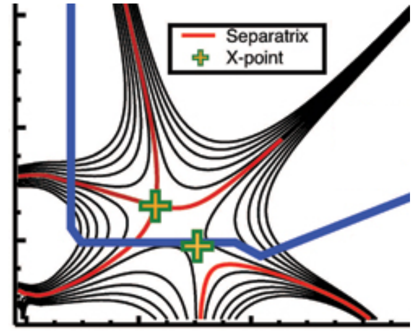
Innovative Divertor Solution Needed

Expected Divertor Heat Flux ~ 10 x Tungsten Design Limit

- Improved solid material to better survive heat and neutron flux – e.g. Develop fundamental understanding at microscopic level - Solid material research is needed to optimize fusion reactor PFCs and blanket issue



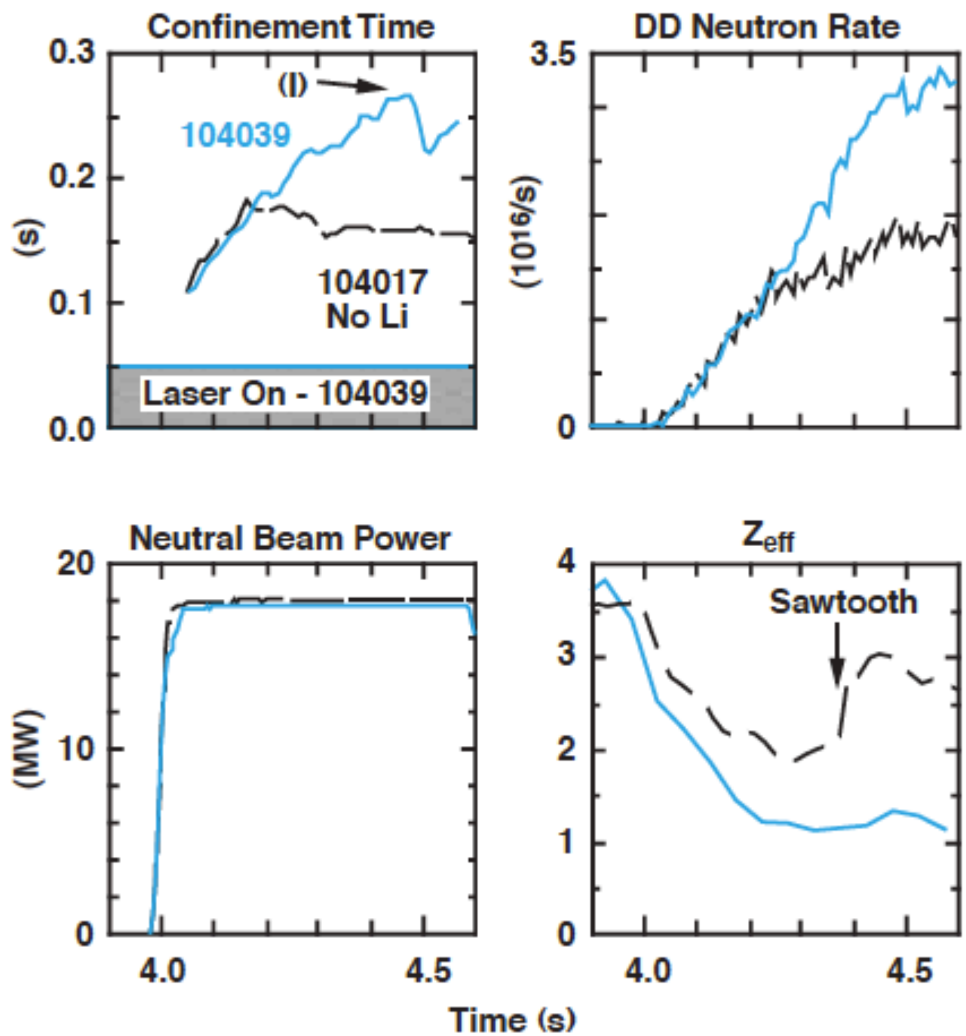
- Innovative divertor configuration to reduce divertor heat flux – e.g., snow-flakes, super-x - Snow flake was shown to reduce divertor heat flux by x 3 in NSTX



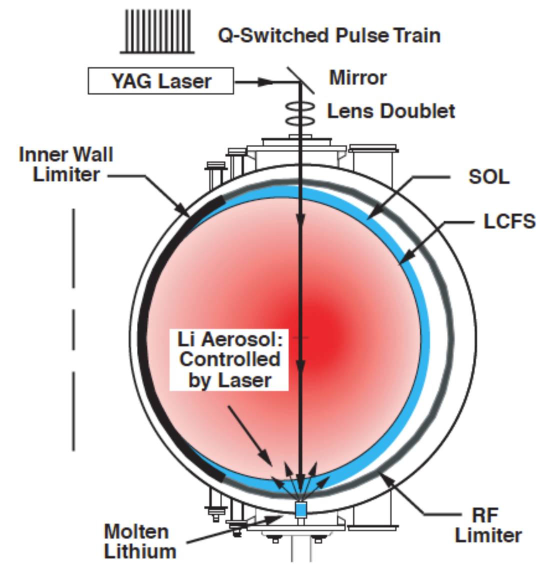
- Liquid metal divertor? - e.g., radiative liquid lithium divertor

TFTR Demonstrated Small Amount of Li ~ 20 mg/sec can Greatly Enhance Plasma Confinement and Fusion Reaction

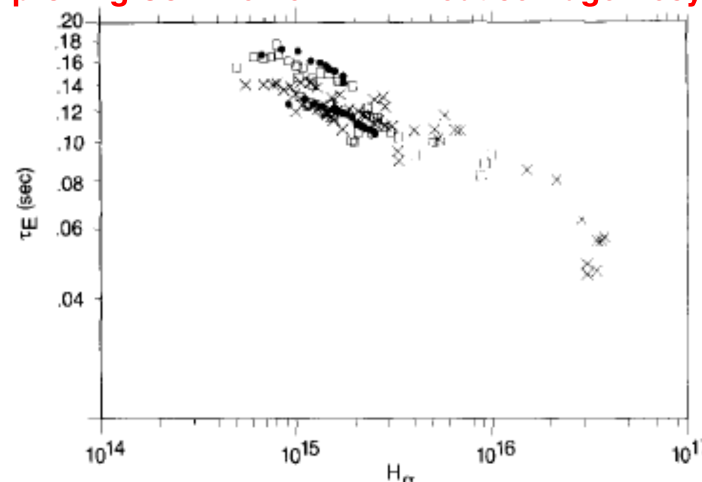
Effects of Li coating with DOLLOP on TFTR



D. K. Mansfield, NF 2001



Improving Confinement with Reduce Edge Recycling



J.D. Strachan, JNM 1992

Simple 2-D Diffusion Model of Li Transport

Li diffuses radially then axially back to divertor wall