Recent Progress in the NSTX/NSTX-U Lithium Program and Prospects for Reactor-Relevant Liquid-Lithium Based Divertor Development

M. Ono and NSTX-U Team

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Progress in NSTX-U Lithium Program And Prospects for Reactor-Relevant Radiative Liquid Lithium Divertor

Masayuki Ono and the NSTX-U Team

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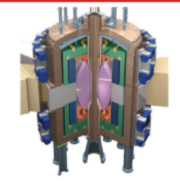
Columbia U, CompX, General Atomics, FIU, INL, Johns Hopkins U, LANL, LLNL, Lodestar, MIT, Nova Photonics, New York U, ORNL, PPPL, Princeton U, Purdue U, SNL, Think Tank, Inc., UC Davis, UC Irvine, UCLA, UCSD, U Colorado, U Illinois, U Maryland, U Rochester, U Tennessee, U Washington, U Wisconsin

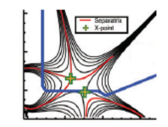
Culham Sci Ctr, U St. Andrews, York U, Chubu U, Fukui U, Hiroshima U, Hyogo U, Kyoto U, Kyushu U, Kyushu Tokai U, NIFS, Niigata U, U Tokyo, JAEA, Hebrew U, Ioffe Inst, RRC Kurchatov Inst, TRINITI, NFRI, KAIST, POSTECH, Seoul National U, ASIPP, ENEA, Frascati, CEA, Cadarache, IPP, Jülich, IPP, Garching,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

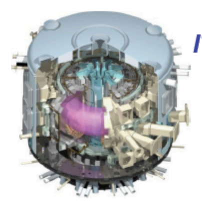

NSTX Mission Elements

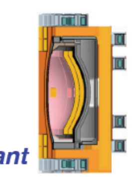
- Advance ST as candidate for Fusion Nuclear Science Facility (FNSF)
- Develop solutions for plasma-material interface
- Advance toroidal confinement physics for ITER and beyond
- Develop ST as fusion energy system


ST-FNSF


Lithium

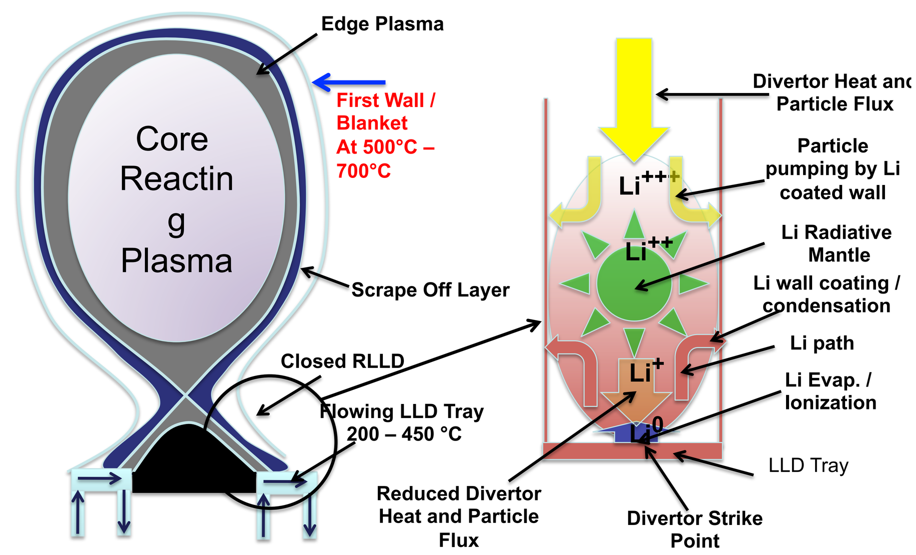

"Snowflake"


ITER


ST Pilot Plant

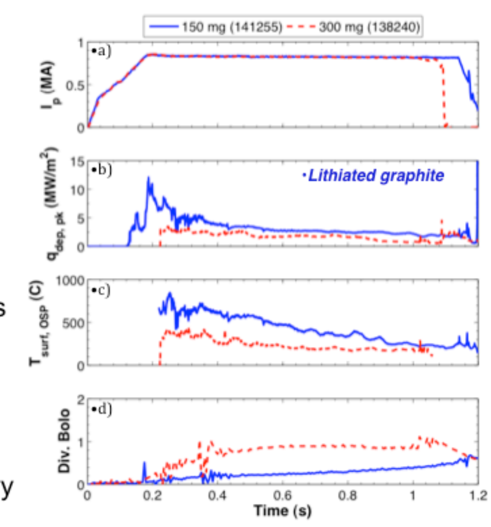
Closed Radiative Liquid Lithium Divertor (RLLD)

RLLD Operating at Lower T from Hot Reactor Fast Wall



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

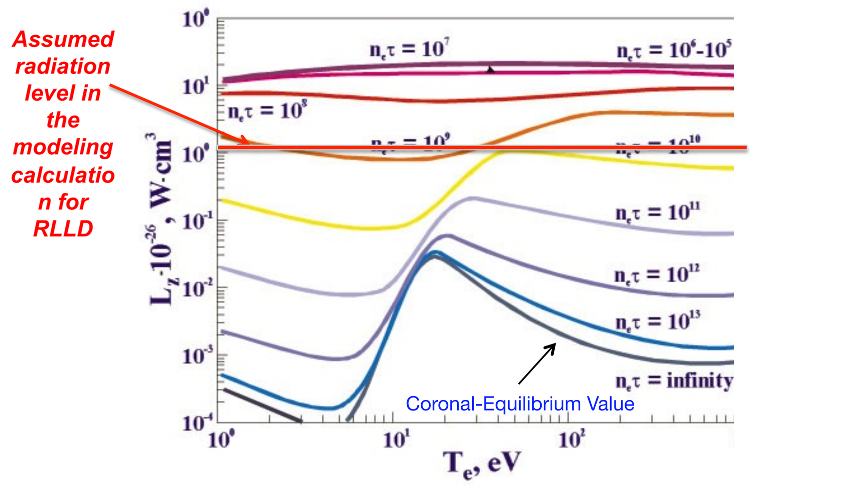
- 2 identical shots (No ELMs)
  - I_p = 0.8 MA, P_{nbi} = 4 MW
  - high δ, f_{exp} ~ 20
- 2, pre-discharge lithium depositions
  - 150 mg: 141255
  - 300 mg: 138240
- T_{surf} at the outer strike point stays below 400° C for 300 mg of Li
  - Peaks around 800° C for 150 mg
- Results in a heat flux that never peaks above 3 MW/m² with heavy lithium evaporation



T. Gray, IAEA 2012

Strong (~1000) lithium radiation Over Coronal Eq. Expected in Divertor Due to Low Confinement

Assumed radiation level in the modeling calculation for RLLD



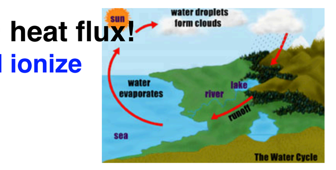
The Li radiation power per one atom and one electron in coronal-quilibrium ($n_e\tau$ = infinity) and non-equilibrium regimes.

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

Liquid Lithium as Divertor PFC Material

Handling heat flux and improve plasma performance

Liquid lithium is resilient against high heat flux!
- It can melt (at 180°C), vaporize, and ionize
- It can be collected, condensed
- It can be renewed and recycled

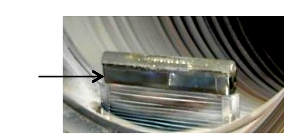


Liquid lithium could protect solid surface from high heat flux!
- Heat of melting, vaporization, ionization
- Radiation could provide high heat dissipation! Potentially very high in the divertor region due to low confinement.

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

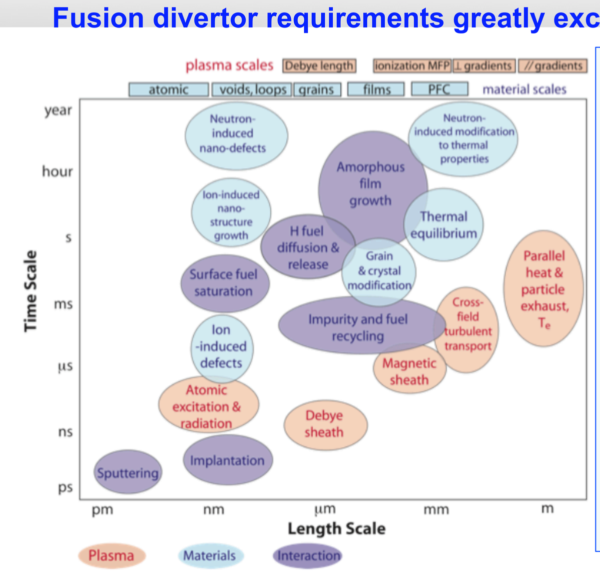
Capillary-Porous Systems (CPS) developed in Russia utilizes similar principle in oil lamp. Very high heat flux handling capability demonstrated!

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



Plasma-Material-Interaction: Highly Complex Issue

Fusion divertor requirements greatly exceed material limit!



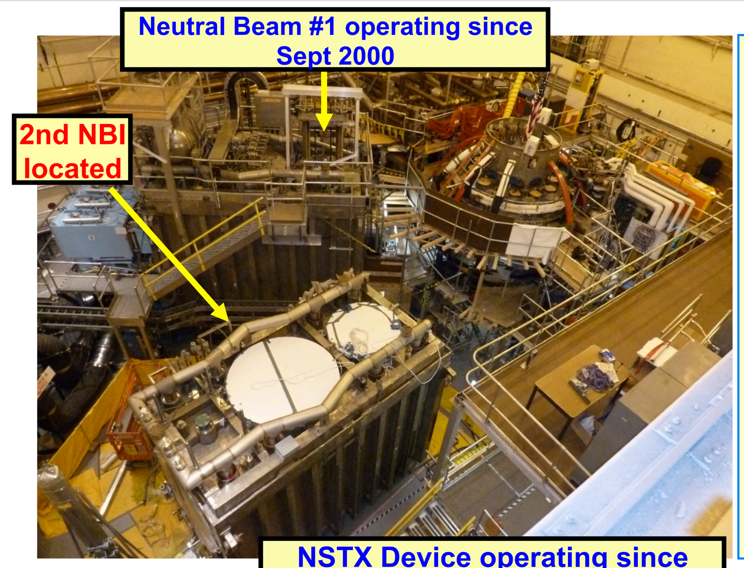
Peak divertor heat flux for a 1 GW-electric tokamak power plant can be ~ 60 MW /m²

or

~ 10 x the present tungsten based design limit!!!

NSTX-U is a 2 MA-class ST facility

NSTX Upgrade Project is aiming for operation in 2014



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

Closed RLLD Chamber:
- Provides Electro-magnetic shielding from fast disruptive events.
- Provides particle partition and physical separation of LL from the main plasma.
- Enables operating temperature differential from the main chamber.
- Facilitates Divertor Heat Removal
- With Li coating of the entire divertor chamber, provides strong particle pumping.

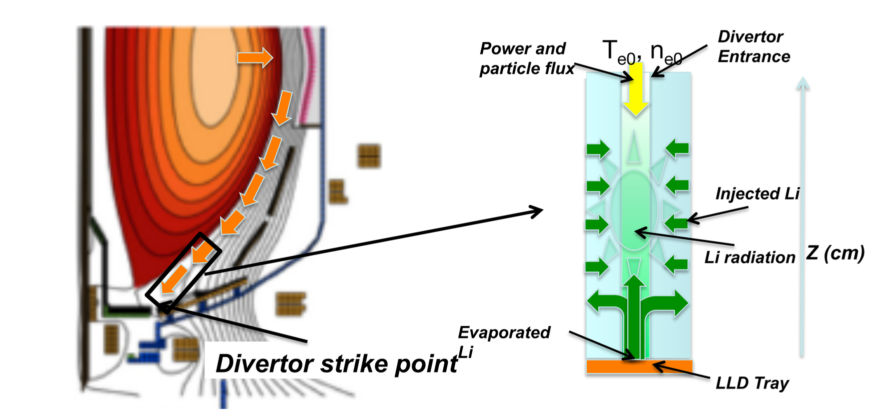
Lower RLLD Operating Temperature:
- Permit high efficiency power conversion with hot first wall.
- Prevent excessive Li vaporization pressure.
- Provides natural collection (pumping) surfaces for entire reactor chamber.
- Permits use of iron based material for substrates and structural material.
- Reduces Li corrosive issues.
- Provides safer for LL utilization.

1-D Cylindrical RLLD Model

Two Point Model with Given Lithium Profile

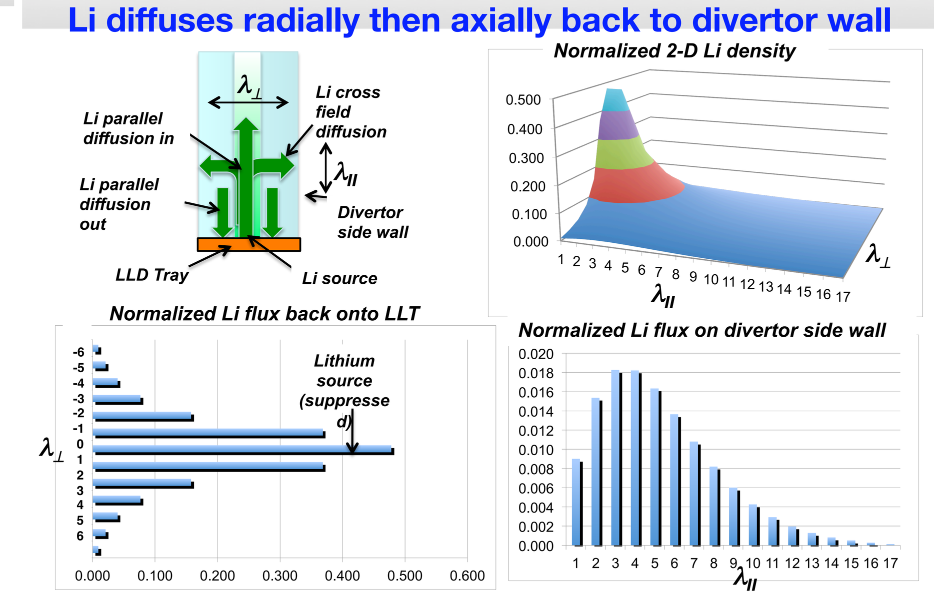
NSTX-like conditions

Assumptions: R = 0.75 m, ΔR = 1 cm, cylinder, deuterium ions, Z = 23 cm,
At the divertor entrance T_{e0} = T_{i0} = 50 eV,
n_{e0} = 2 x 10^{13}cm⁻³, Two-Point Model, Constant B_T
Given Li profile, Li radiation = 10^{-26} W/Li-electron



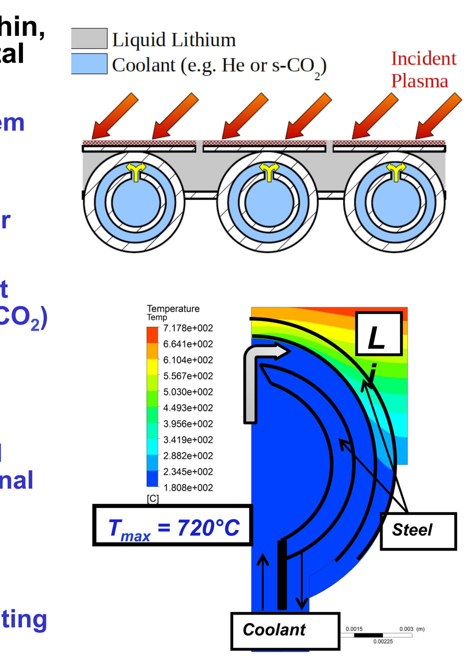
Simple 2-D Diffusion Model of Li Transport

Li diffuses radially then axially back to divertor wall



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

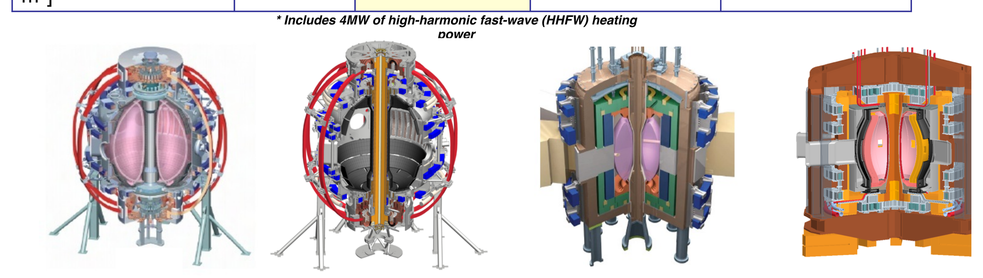


M. Jaworski et al., PPPL

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

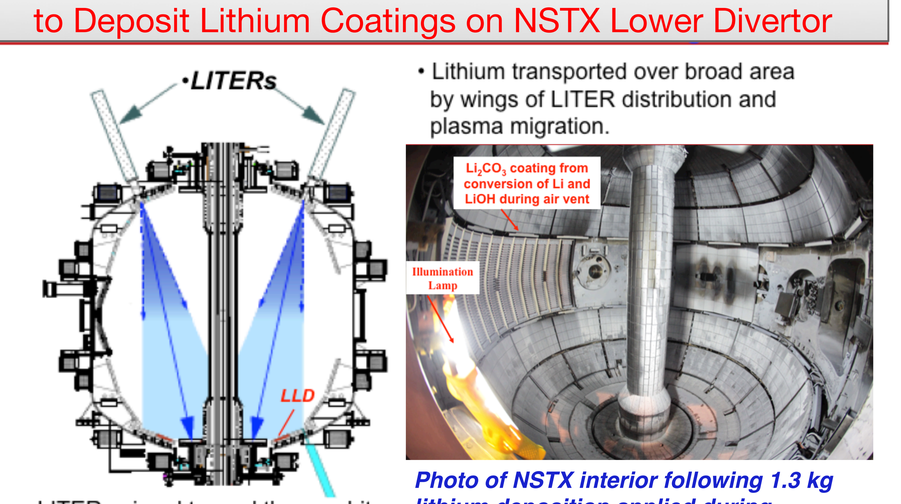
	NSTX	NSTX-U	Fusion Nuclear Science Facility	ST Pilot Plant
Major Radius R_0 [m]	0.86	0.94	1.3	2.2
Aspect Ratio = R_0 / a	≥ 1.3	≥ 1.5	≥ 1.6	≥ 1.7
Plasma Current [MA]	1	2	4 → 10	10 → 20
Toroidal Field [T]	0.5	1	2-3	2-3
P/R, P/S [MW/m,m²]	10, 0.2*	20, 0.4*	30 → 60, 0.6 → 1.2	40 → 100, 0.3 → 1
Div. heat flux [MW/m²]	10	40?	50?	60?

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



J. Menard NF 2010

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



- Lithium transported over broad area by wings of LITER distribution and plasma migration.
- LITERs aimed toward the graphite divertor. Shown are 1/e widths of the emitted gaussian-like distribution.

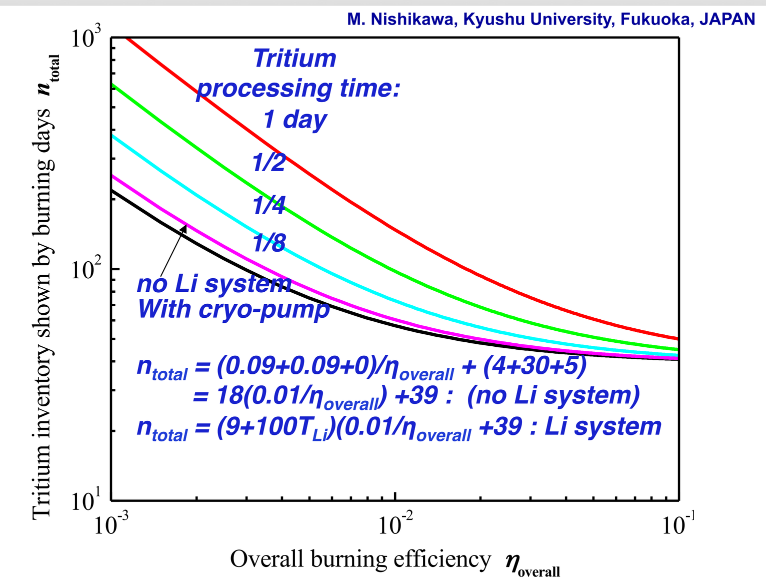
Photo of NSTX interior following 1.3 kg lithium deposition applied during 2010-2011 experimental campaigns indicating extensive lithium coverage due to direct evaporation and plasma transport

H. Kugel, FE&D 2011

Processing time for Tritium in Li divertor system T_{li}

Highly Critical Parameter for Determining Tritium Inventory

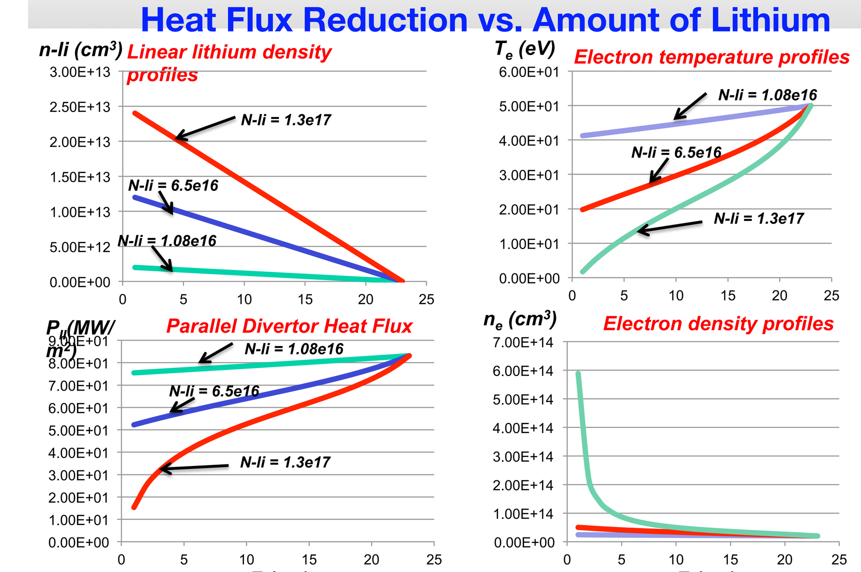
M. Nishikawa, Kyushu University, Fukuoka, JAPAN



n_{total} = (0.09+0.09+0)/$\eta_{overall}$ + (4+30+5)
= 18(0.01/$\eta_{overall}$) +39 : (no Li system)
n_{total} = (9+100T_{Li})(0.01/$\eta_{overall}$) +39 : Li system

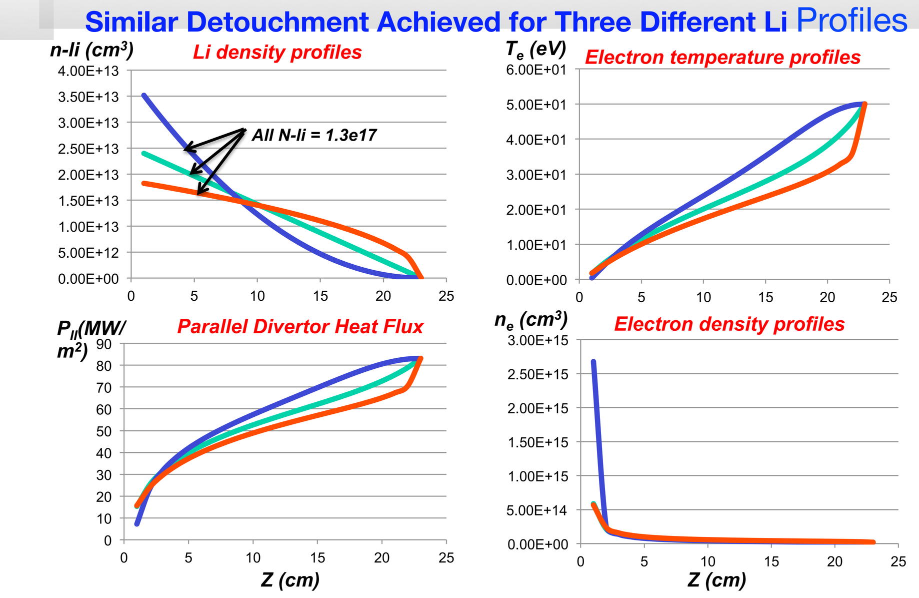
1-D Cylindrical RLLD Two Point Model

Heat Flux Reduction vs. Amount of Lithium



RLLD Relatively Insensitive to Li Profiles

Similar Detouchment Achieved for Three Different Li Profiles



Is lithium PFC viable in magnetic fusion reactors?

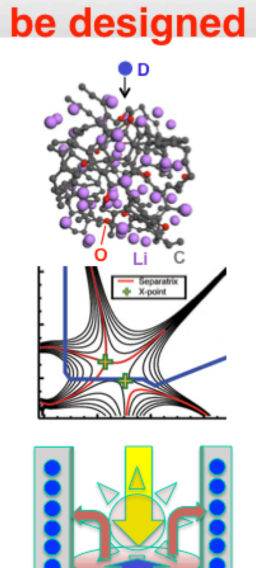
Closed RLLD System Could Provide a Solution!

1. Handling high divertor heat flux [Radiative Liquid Lithium Divertor (RLLD)]
2. Removal of deuterium, tritium, and impurities from liquid lithium (Lithium purification loop, IFMIF, tritium bleeding blanket)
3. Removal of high steady-state heat flux from divertor (RLLD)
4. Flowing of liquid lithium in magnetic fields (Minimize amount of flowing LL for purification)
5. Longer term corrosion of internal components by liquid lithium (Operate RLLD at lower temperature < 450 °C, IFMIF and tritium bleeding blanket),
6. Safety of flowing liquid lithium, (Minimize amount of LL, IFMIF, and tritium bleeding blanket) and
7. Compatibility with liquid lithium with a hot reactor first wall (Closed RLLD configuration permits operation at lower temperature< 450 °C).

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

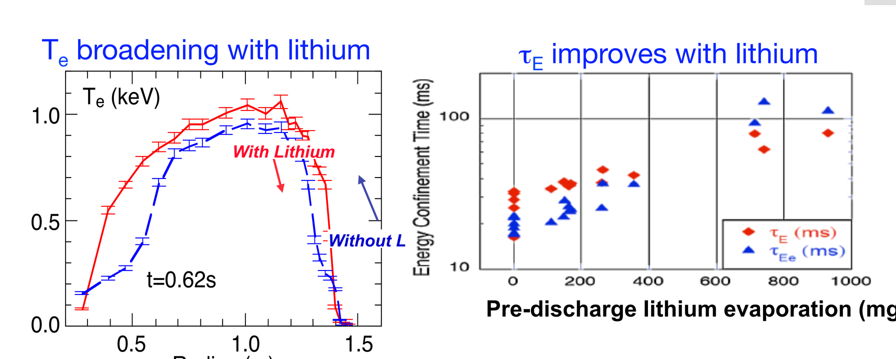
A realistic solution is needed before next-step fusion facilities can be designed

- Improved solid material to better survive heat and neutron flux – e.g. Develop fundamental understanding at microscopic level
- Divertor configuration changes to reduce heat flux – e.g., snow-flakes, super-x
- Liquid metal divertor? - e.g., radiative liquid lithium divertor



Lithium Improved H-mode Performance in NSTX

T_e Broadens, τ_E Increases, P_H Reduces, ELMs Stablize



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

H. W. Kugel, PoP 2008

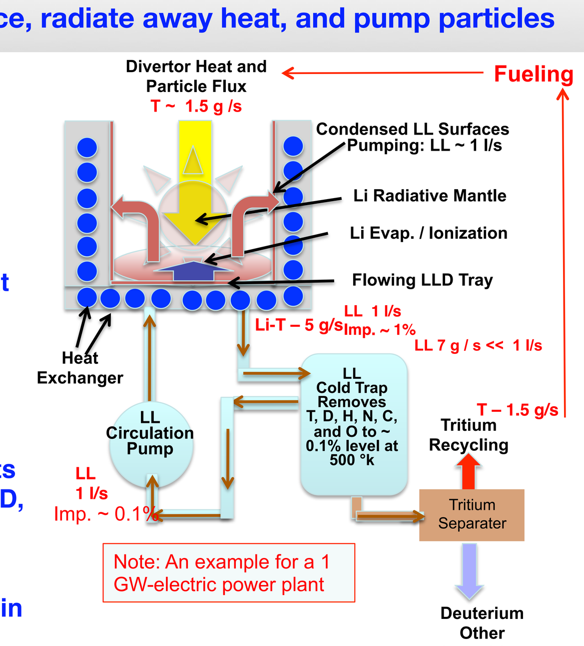
Total and electron energy confinement time continued to increase with pre-discharge lithium evaporation.

R. Maingi, PRL (2011)

Closed RLLD Circulating LL-Loop Concept

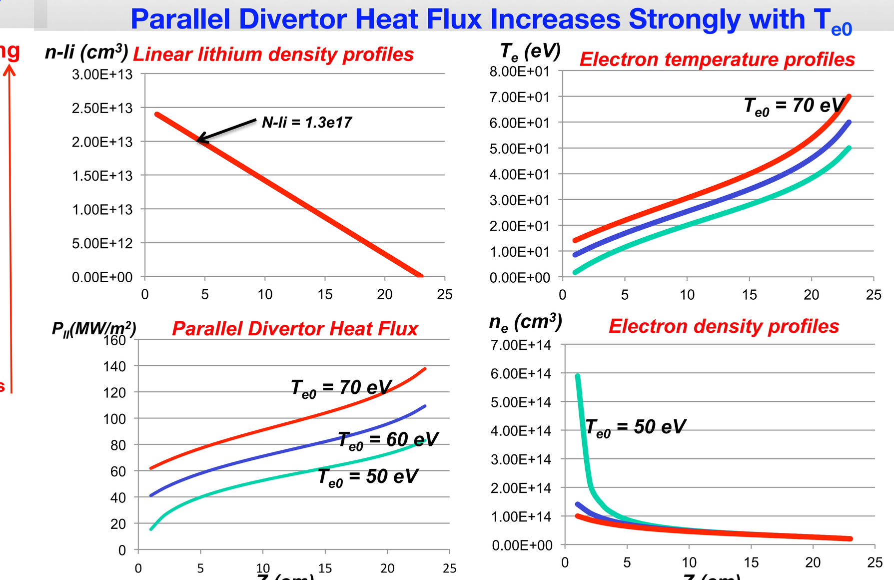
LL to protect divertor surface, radiate away heat, and pump particles

- 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



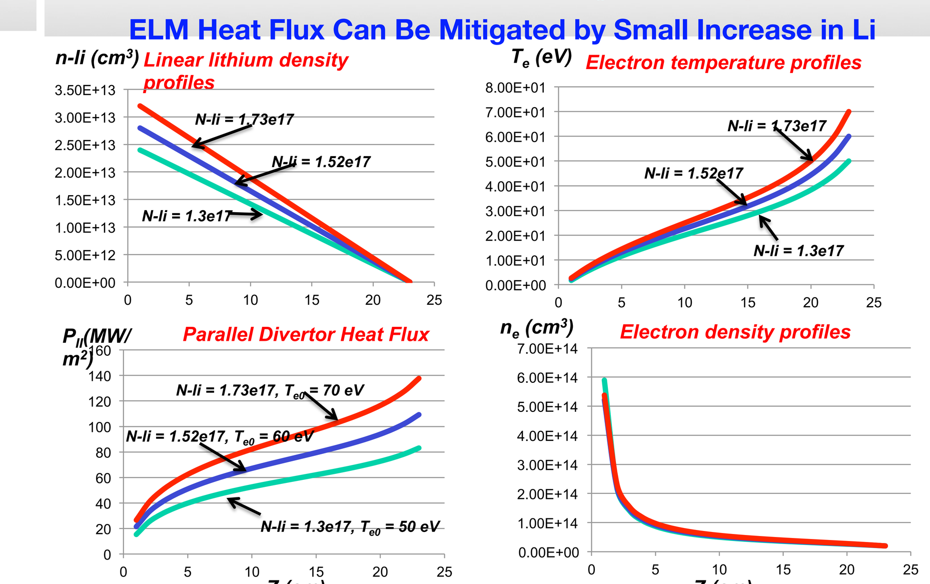
Transient Heat Flux Increase – e.g. ELMs

Parallel Divertor Heat Flux Increases Strongly with T_{e0}



"ELM" Heat Flux Mitigation by Li

ELM Heat Flux Can Be Mitigated by Small Increase in Li



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.