The Present Status and Future Perspective of the Application of Liquid Metals as Plasma-Facing Materials in Magnetic Fusion Devices

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It has widely been recognized in the magnetic fusion research community that plasma-wall boundary control plays an important role in determining core plasma confinement [1, 2]. For the boundary control in fusion experiments, a variety of wall conditioning techniques have been developed to improve plasma confinement.

Among all these techniques, lithium coating on plasma-facing components has been found to be most effective in improving plasma cleanliness as well as energy confinement. Unfortunately, it is also true that, as plasma operation proceeds, solid lithium coatings become saturated with implanted hydrogen isotopes, forming lithium hydride, which then requires plasma shutdown for wall re-conditioning.

To avoid surface saturation, several innovative concepts have been developed over the past decade. As such, the application of liquid metals as plasma-facing materials continues to expand and to improve via problem solving. This paper reviews some of the important findings in recent fusion and laboratory experiments, and provides a future perspective of the plasma-wall boundary control by innovative liquid metal application concepts.

REFERENCES

[1] Y. Hirooka et al. (Ed.); Proc. 1st ISLA, Fusion Eng. and Des. **85**(2010) issue 6.

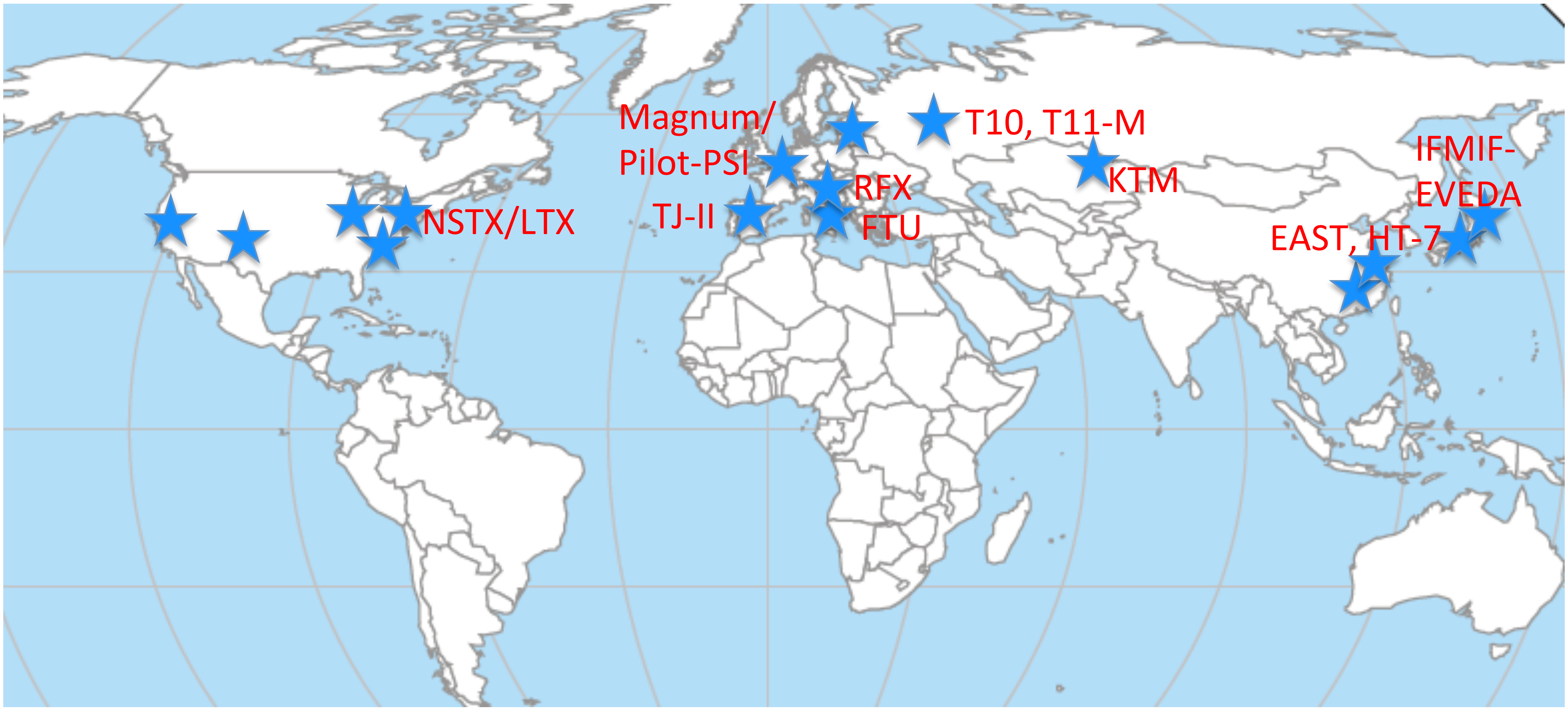
[2] M. Ono (Ed.); Proc. 2nd ISLA, Fusion Eng. and Des. **87**(2012) issue 10.

3rd International Symposium on Lithium Applications for Fusion Devices

ENEA, Frascati, October 9-11, 2013

ISLA-2013 - The largest and most important meeting dedicated to liquid metal application for the magnetic fusion research. Overall, 45 presentation plus 5 posters were given representing 28 institutions from 11 countries. Sessions were devoted to Lithium (Li) in magnetic confinement experiments, liquid lithium (LL) technology, Li laboratory test stands, Li theory / modeling / comments, Innovative Li applications, and Li-safety and Li handling.

Worldwide Participation on Liquid Lithium/Metal Research Presented at ISLA 2013, Frascati, Italy



PPPL, USA	U. Illionis, USA	ENEA-CNR, Italy	Red Star, RF	Funan U. China
LLNL, USA	CIEMAT, Spain	U. Latvia, Latvia	StP-SPU, RF	NIFS, Japan
SNL, USA	FOM-DIFFER, NL	Kurchatov, RF	AEI, Kazakhstan	JAEA, Japan
ORNL, USA	ENEA, Frascati, Italy	Trinity, RF	ASIPP, China	

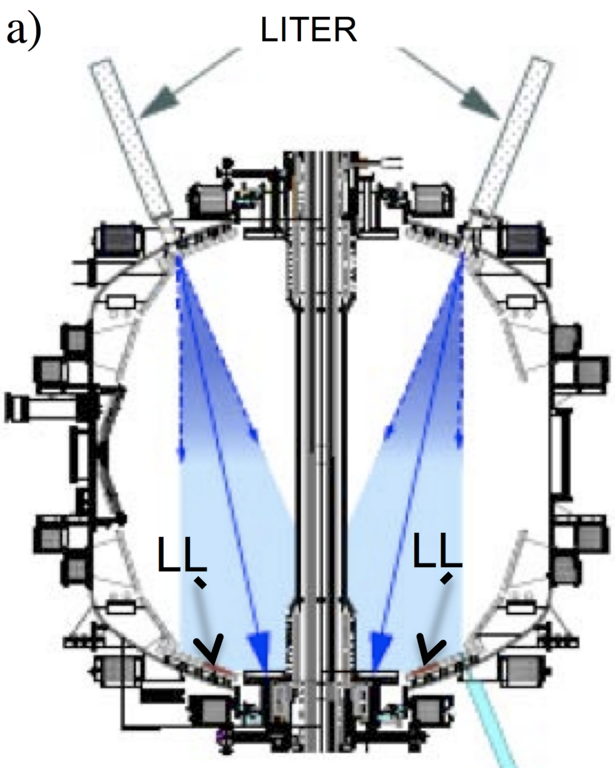
Why Liquid Lithium for fusion reactor?

- Lithium (Li) is highly reactive and Li pumps hydrogenic species and impurities such as oxgen.
- Li with 181° melting point can naturally stay liquid in reactor environment.
- Li coating of PFCs improves plasma performance – low recycling and collisionality (observed in nearly all the confinement systems using lithium)
- Li coating reduces divertor heat flux (NSTX LLD) and protects PFC substrates (in nearly all LL systems)
- Liquid Li (LL) collects / pumps particles/tritium/impurities and dust
- A modest lithium loop can bring collected particles and dust to outside of reactor chamber for removal (essential for steady-state reactor operation.)

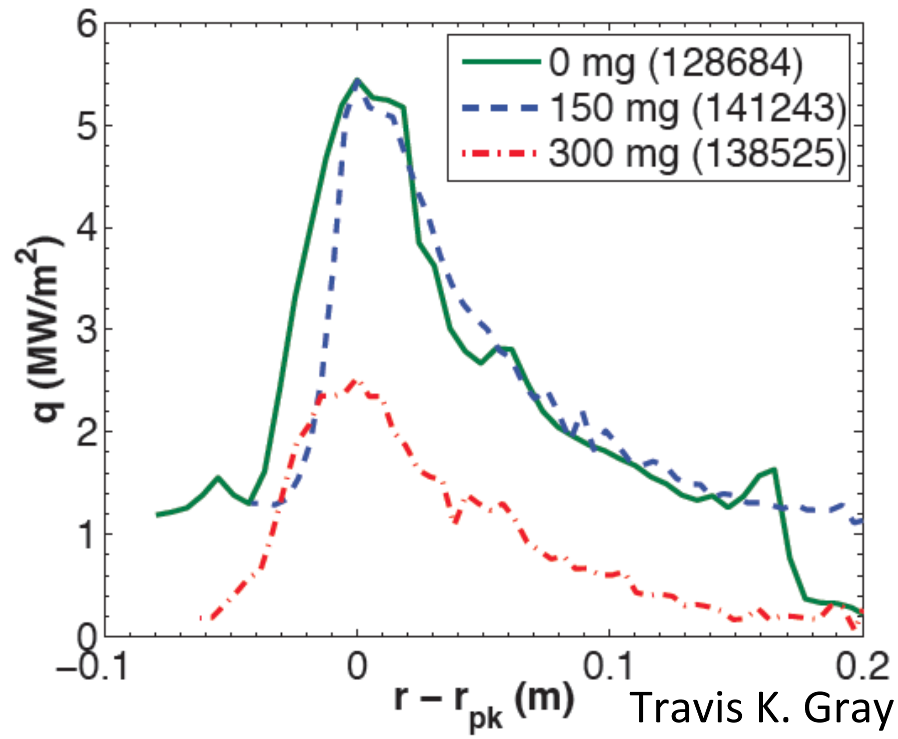
NSTX LLD Produced Many Beneficial Effects

Lithium Improves H-mode Performance via Strong Pumping

Yet, lithium does not contaminate the plasma core



Lithium Evaporation is shown to Reduce λq and Peak Divertor Heat Flux



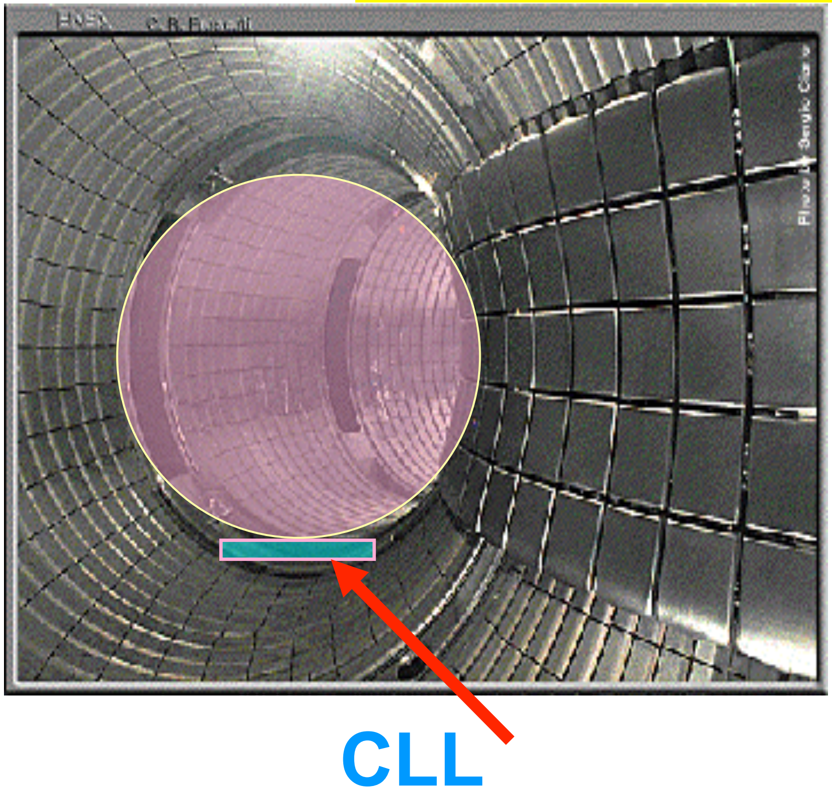
Travis K. Gray et al.,

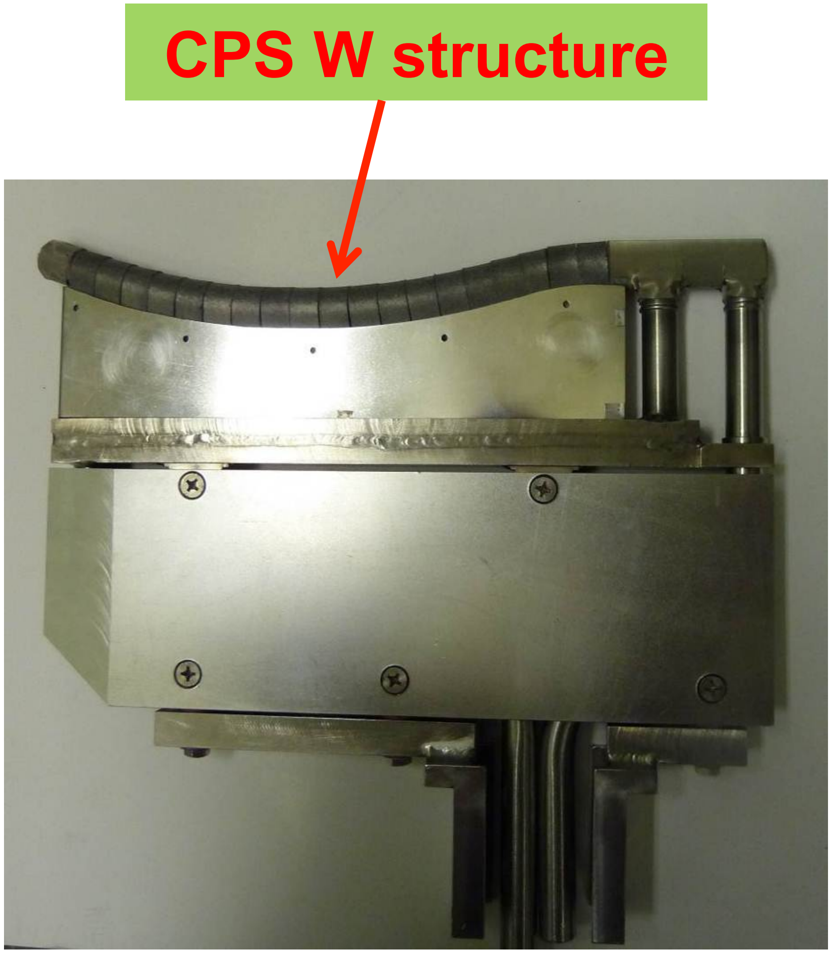
Lithium could provide strong divertor radiation, reducing heat flux and protect divertor PFCs. M. Ono, NF 2013

Liquid Lithium Experiments on FTU

G.Mazzitelli

Cooled Lithium Limiter (CLL)

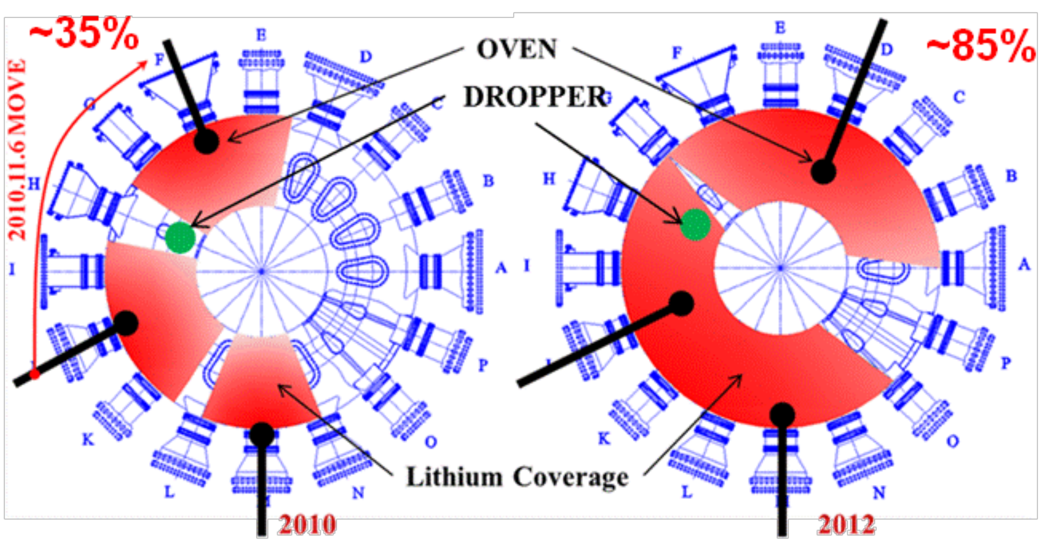




Melting point 180.6 °C
Boiling point 1342 °C

New Results: increase coverage and coat on Mo

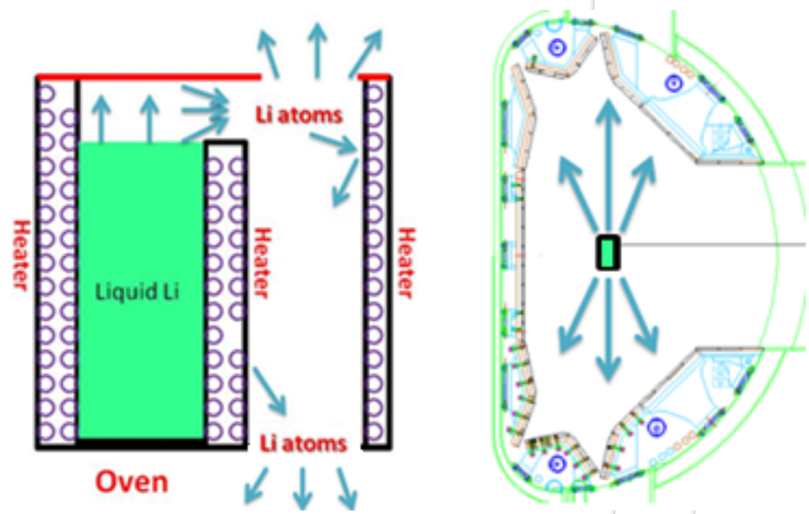
- Increasing Li Coverage (85% in 2012 vs 30% in 2010)
- Lithium coating are more uniform than in 2010
- Li well coated on C divertor.
- Li well coated on Mo first walls
- Need one more oven for full surface coating.



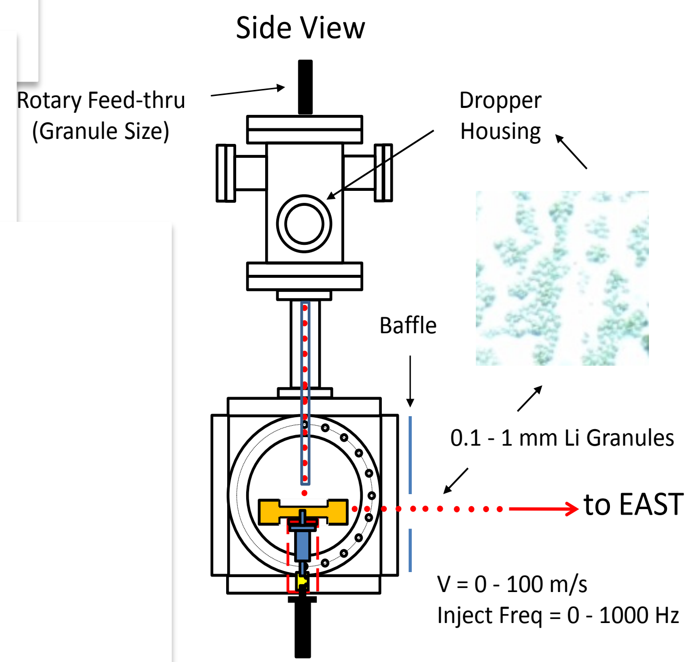
J.S. Hu et al.,

Lithium delivery systems in EAST and HT-7

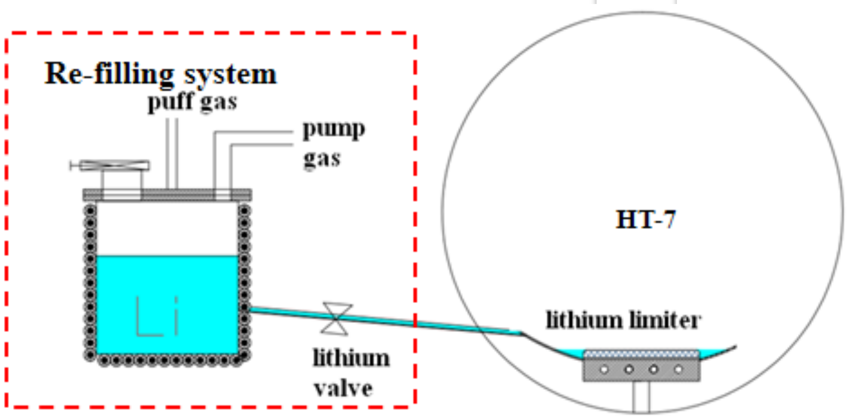
Upgraded Li coating system in 2012



Li granules injection on EAST

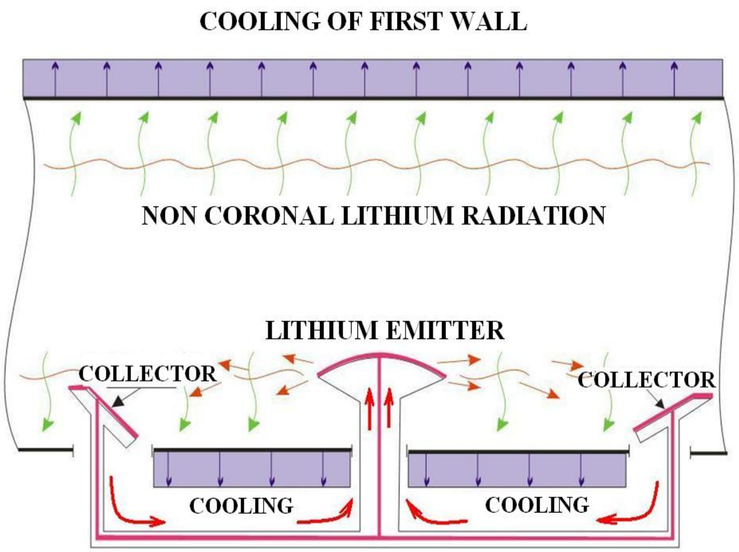


Liquid Li Limiters experiments on HT-7

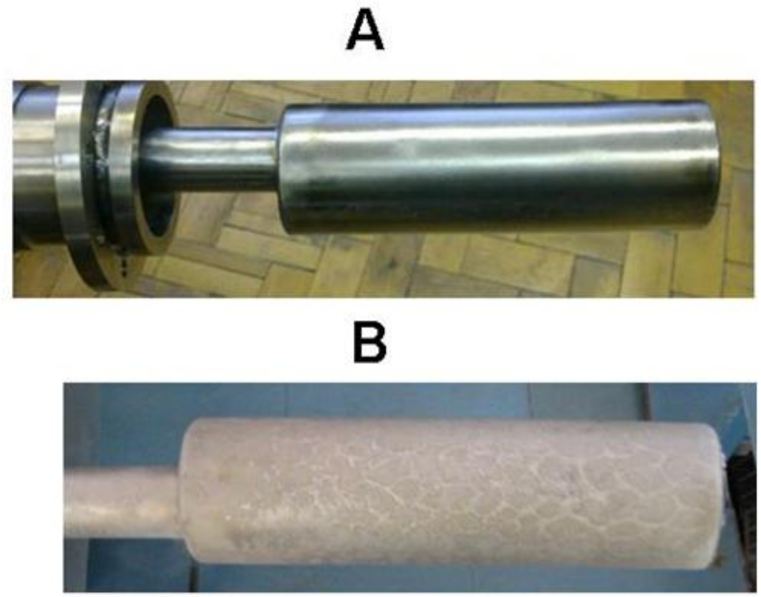


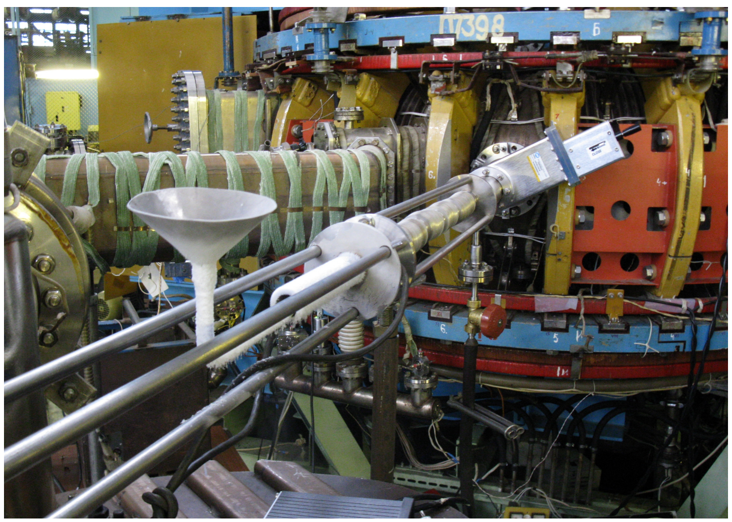
First observations of ELM triggering by injected lithium granules in EAST, by D.K. Mansfield, et al.,

Cryogenic target in T-11M chamber for lithium recovery

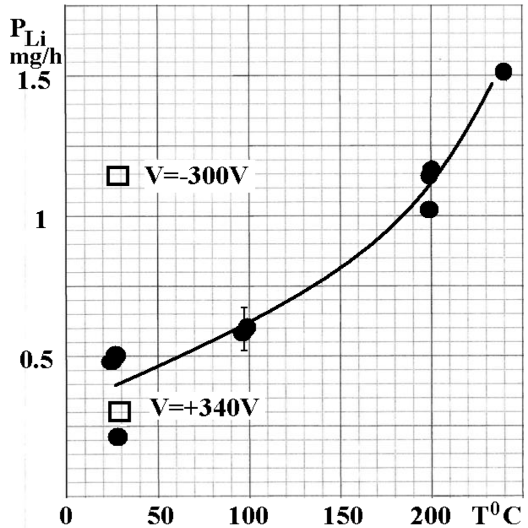


The view A of target is before installation, the view B is after exposure





Mirnov S.V. and V.B. Lazarev, et al.,

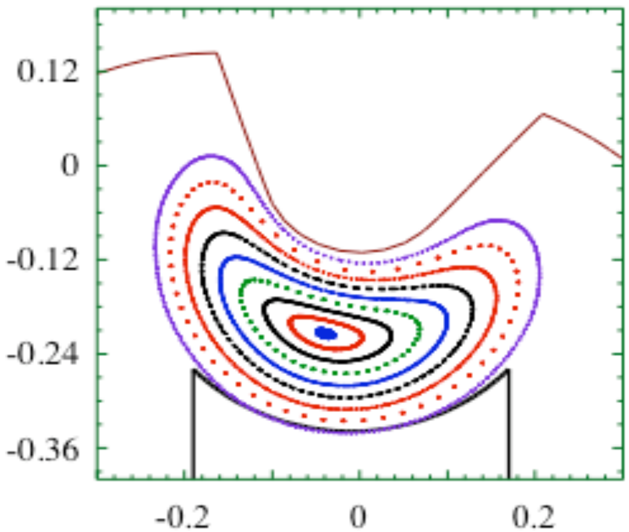


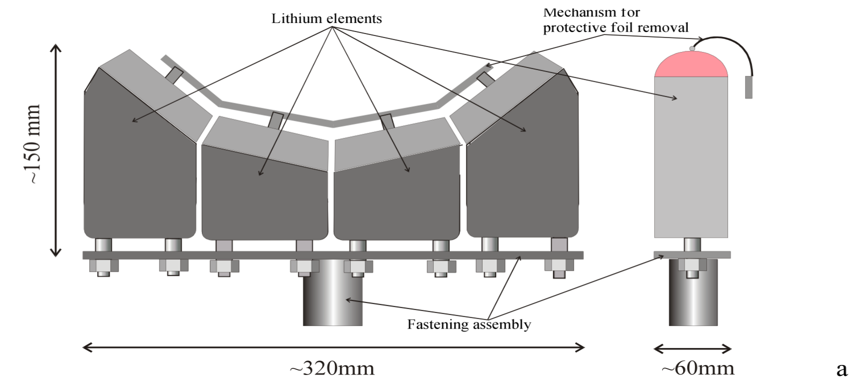
An evolution of the lithium collection rate with increasing of the wall heating (black rings, target connected electrically with the wall), two rectangular are cases with two different electric potentials of target relative to the wall

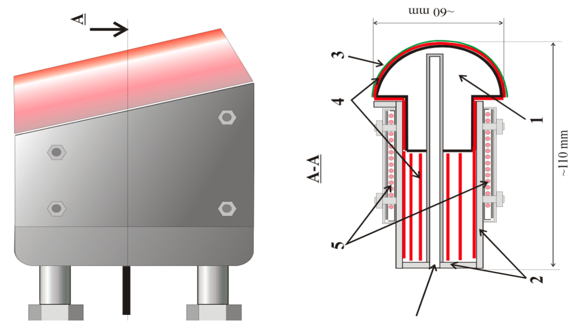
TJ-II experiments for testing lithium as a possible PFC for a Fusion Reactor

CPS-LLL in TJ-II: Description F. Tabarés et al.,

- LLL in TJ-II (Red Star) installation achieved in 2012





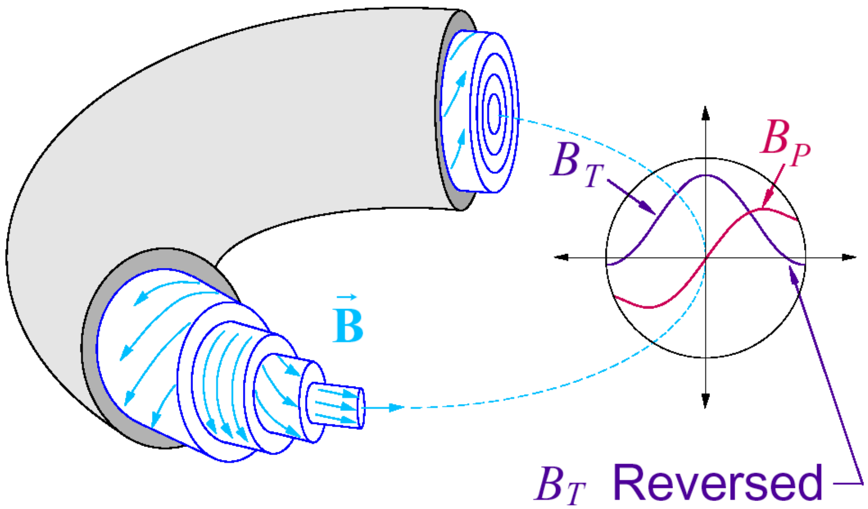


- *Two equivalent LLL installed in lower vertical ports of opposite sections of TJ-II.*
- *Special vacuum volume equipped with two vacuum gates, own pumping system, heater of the walls and mass-spectrometer provides:*
  - allows for TDS studies on hydrogen sorption – desorption study on liquid lithium at several T's
- *Electrically insulated from vacuum chamber, possibility for biasing*
- *LLL is provided with temperature control in the range of 20-550ºC.*

GOBIERNO DE ESPAÑA MINISTERIO DE ECONOMÍA Y COMPETITIVIDAD Ciemat Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas

Lithium wall conditioning experiments on RFX-mod reversed field pinch experiment by PP. Innocente et al.,

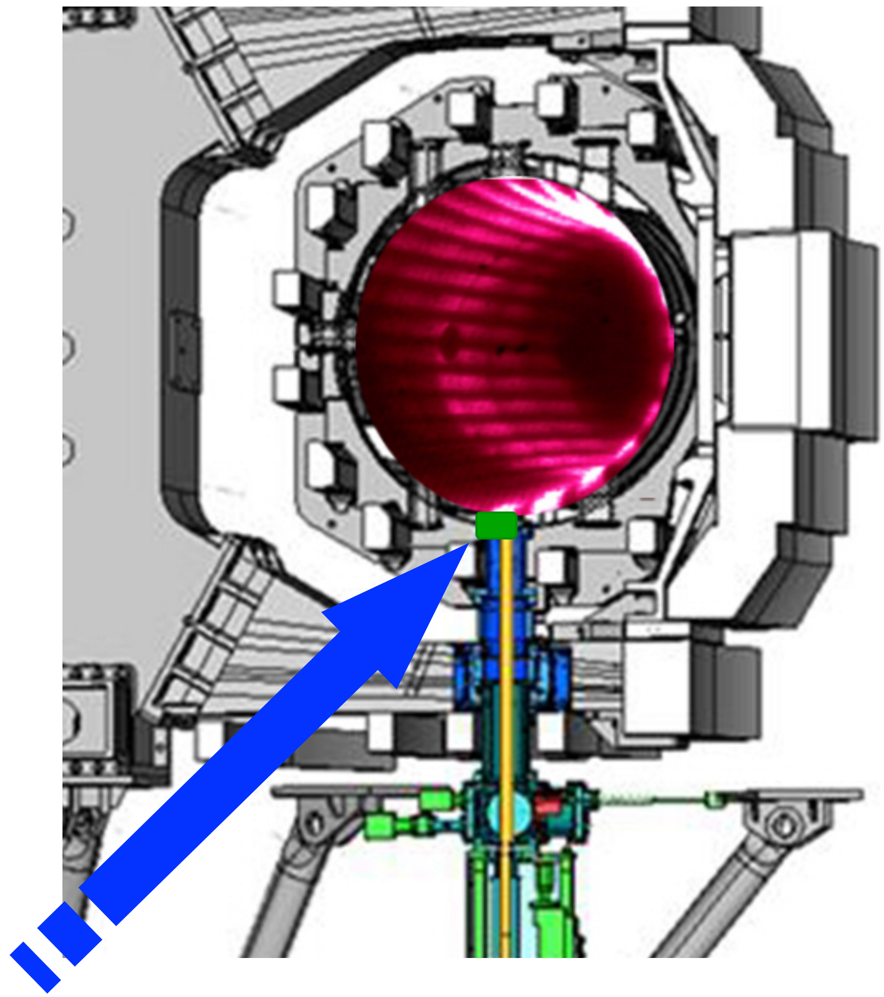
On RFP configuration edge field lines are nearly poloidal



➔ Poor toroidal distribution of ablated lithium

Partial solutions:

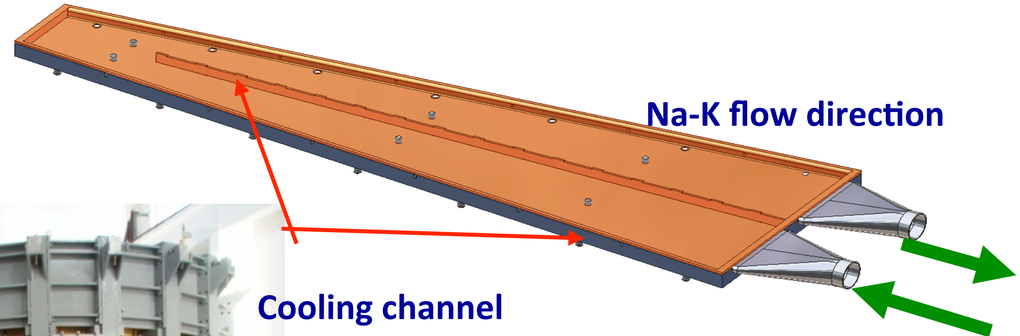
1) **High edge toroidal field**
2) **Externally induced stationary helical deformation intersecting LCPS (to move Li along the helical)**



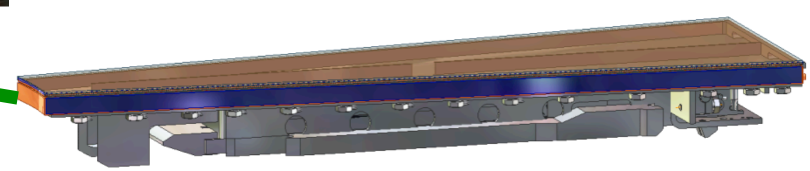
LCPS as Liquid Lithium Limiter (LLL)

TESTS OF MODULES OF LITHIUM DIVERTOR ON BASIS OF CAPILLARY-POROUS SYSTEM AT THE EXPERIMENTAL COMPLEX TOKAMAK KTM

The lithium divertor module design with the simple scheme of heat-transfer media (Na-K) circulation has been chosen



Module of lithium divertor will be placed on one of the ports of KTM

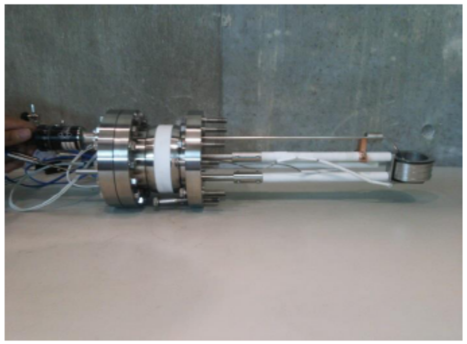


Tazhibayeva, I. Lyublinski, et al.

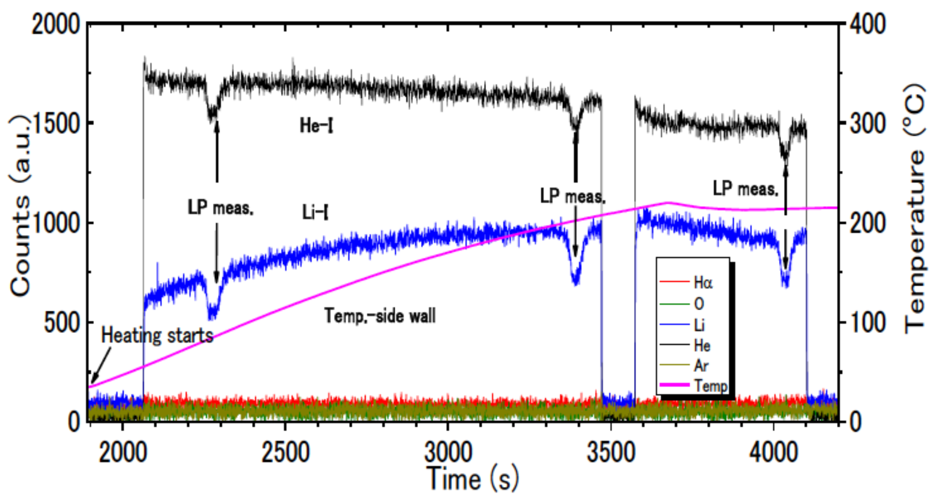
Liquid stirring effects on hydrogen and helium recycling from molten lithium under steady state plasma bombardment

by Y. Hirooka et al.,

Active liquid metal stirring setup

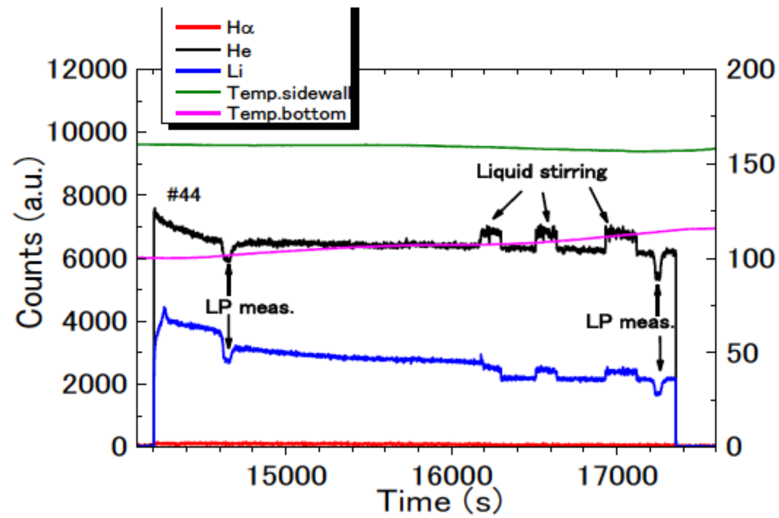


Liquid stirring effects on H-recycling



Liquid stirring can **de-saturate near-surface H** and **break solid impurity layers to restore H-absorptivity**.

Liquid stirring effects on He-recycling



Liquid stirring

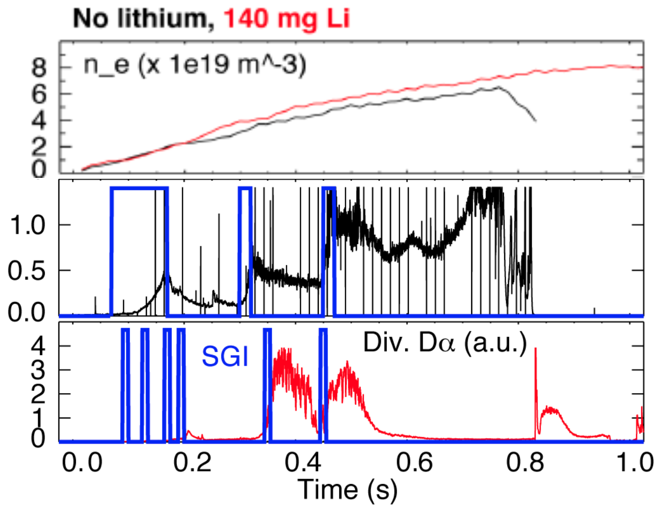
⇒decrease in surface temperature

⇒decrease in (He-solubility in Li + Li-vapor pressure)

⇒increase in He-I + decrease in Li-I

Li surface properties investigated

A supersonic gas jet was used to demonstrate strong divertor pumping by lithium coatings



V. A. Soukhanovskii et al.,

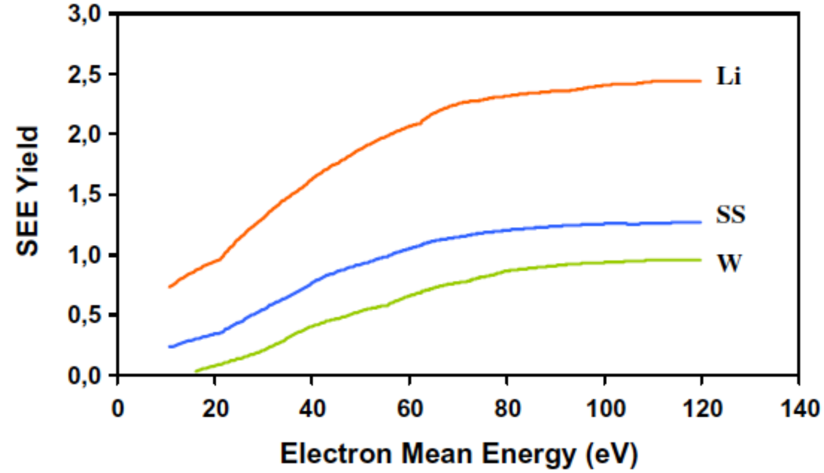
A new mechanism of deuterium retention by lithium coatings on graphite was proposed

Li-O-C-D chemistry

- D is bound by O and CO
- Carbon sputtering reduced
- Deuterium recycling reduced
- Lithium brings oxygen to surface

J. P. Allain and P. S. Krstic et. al,

Anomalous secondary electron emission (SEE) yields founds for Li coating



Results of the Li, SS and W SEE Yields vs. mean electron energy of the suprathermal electrons arriving to the targets at each bias.

Comparison between literature and experimental maximum SEE values for the studied targets.

Material	Maximum coefficient literature (experimental)	Incident energy at SEE maximum (eV)
Li	0.5 (2.44)	85
SS	1.3 (1.27)	400
W	1.35 (0.95)	650

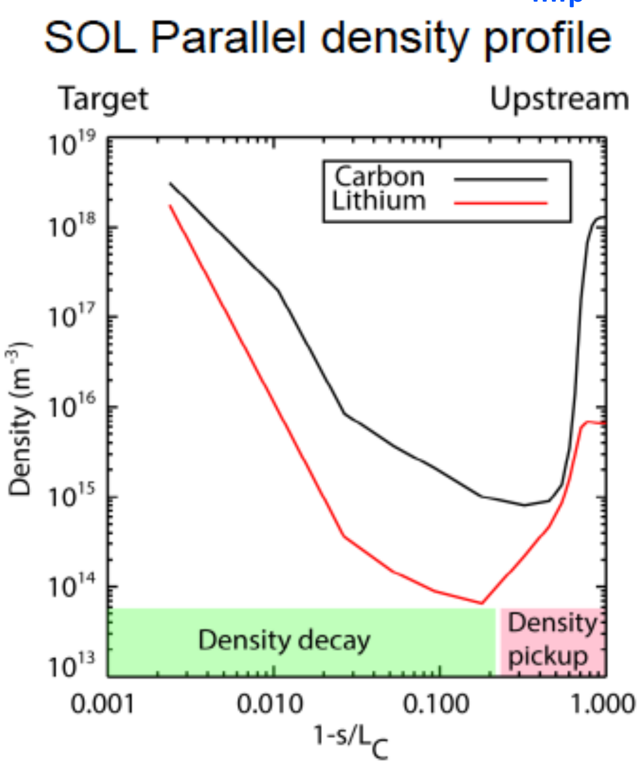
E. Oyarzabal, A.B. Martín-Rojo, et al.,

Li Transport Physics Investigated in NSTX

Showing strong lithium divertor retention and small penetration factors

Stronger divertor retention (n_{min}/n_{target}) for Li than carbon

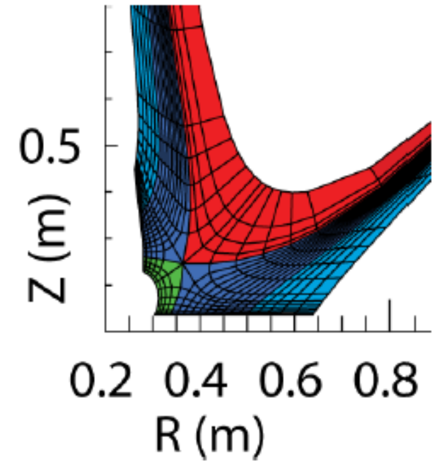
- controlled by difference in source profile
- due to short ionization λ_{mfp}



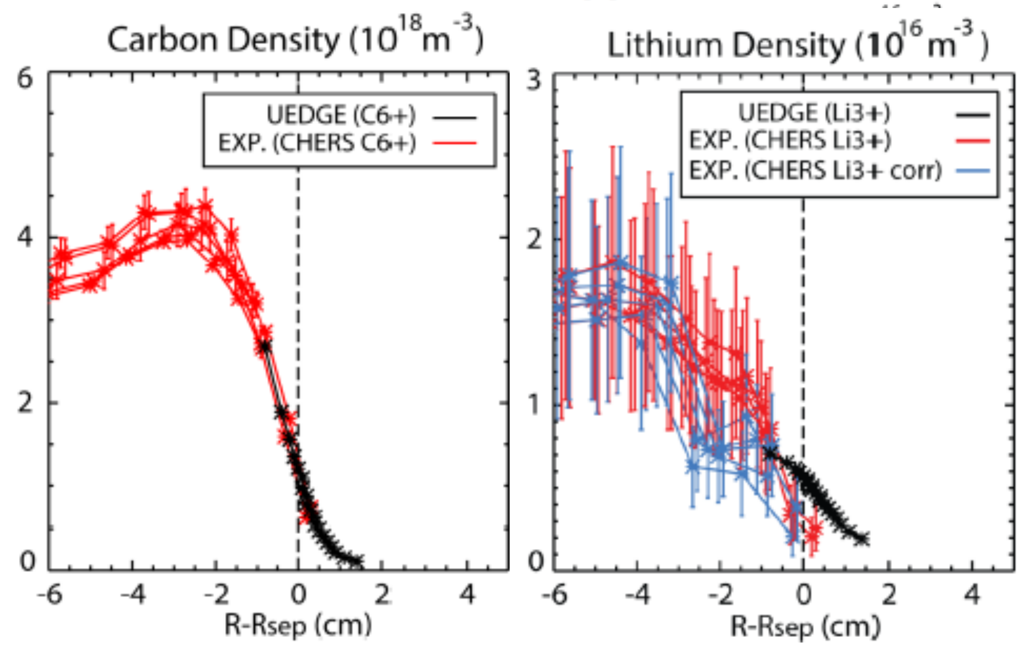
s distance from midplane

LC midplane-target connection length

2D multi-fluid UEDGE simulations performed to investigate reasons for small lithium penetration factors

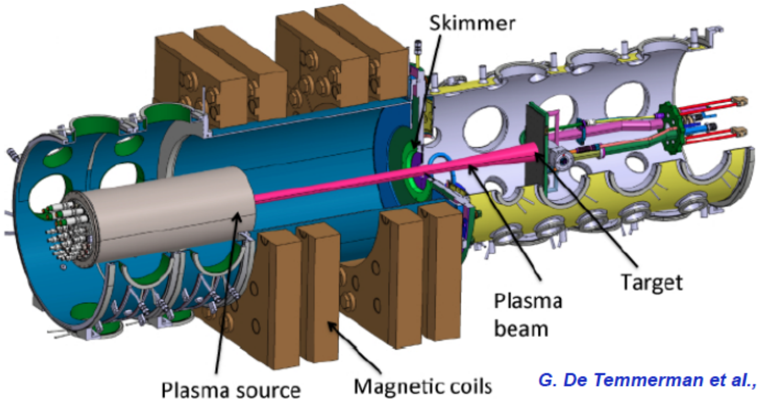


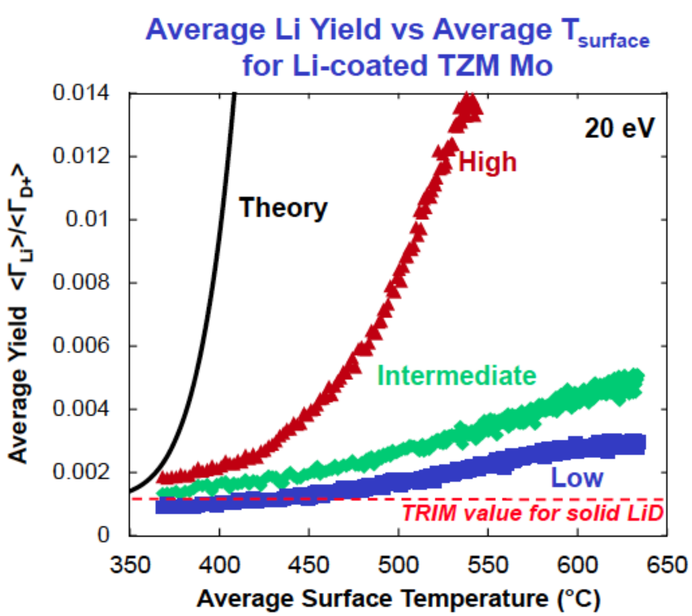
[1] S. Loch, ADNDT 2006.



F. Scotti, V. A. Soukhanovskii NF 2013

Magnum-PSI linear plasma device ideal for testing model

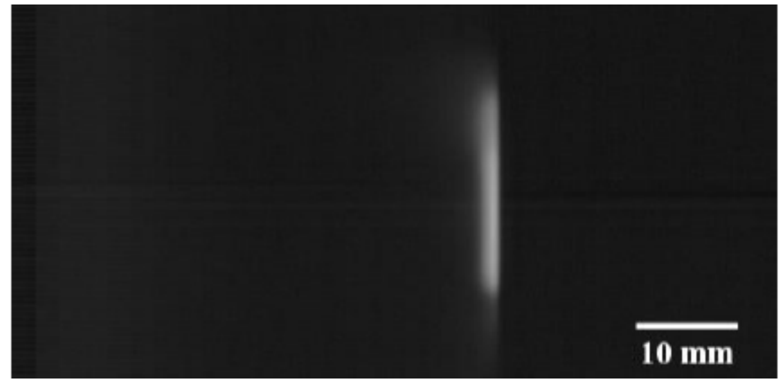




- Three different erosion "regimes" observed for Li-coated TZM Mo
- Even high-yield regime shows significantly less erosion than Langmuir lawevaporation + TRIM

Tyler Abrams et al.,

Picture of vapor-cloud PMI already showing rich physics



- Observation of reduced current to target consistent with
  - Increased effective ion mass due to large lithium fraction
  - Increased neutral particle bombardment
- Increased heating to the target consistent with
  - Increased plasma and neutral energy deposition due to replacement of high-Z target with low-Z lithium surface
  - Requires increased neutral particle flux due to decreased ion bombardment

Mike Jaworski et al.,

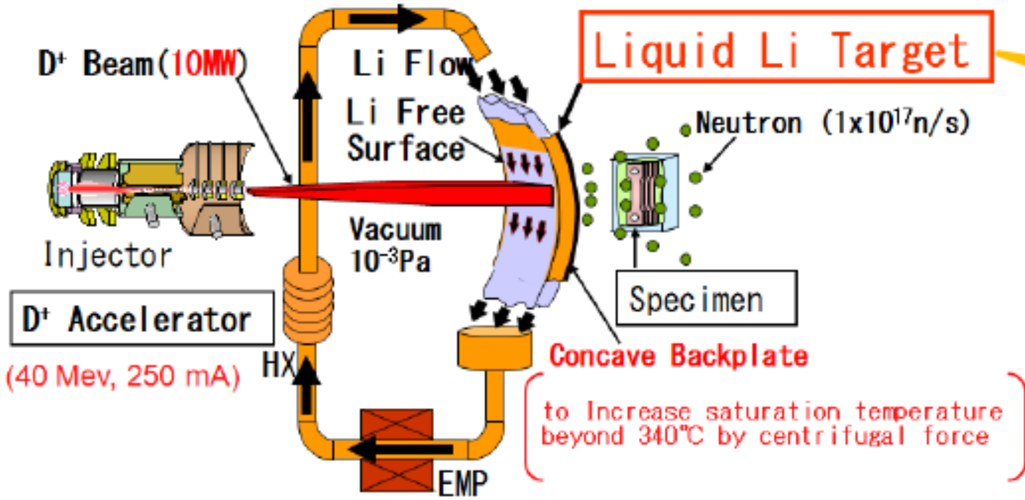
Development of Lithium Safety Handling Technology under IFMIF-EVEDA

Objective
To dedicate data needed for design relating safety and lithium treatment and impurity monitoring.

Research works

- **Experiments of Li chemical reaction**
- **Chemical analysis of impurity in Li**
- **Experiments of Li fire**

Lithium Safety Handling *was categorized as a sub-task in the task "PA LF5-JA Remote Handling" under the IFMIF-EVEDA.*



High-speed lithium flow along the concave back-plate is selected as the IFMIF target to handle the high heat loading (1GW/m^2) of 10MW D$^+$ beams.

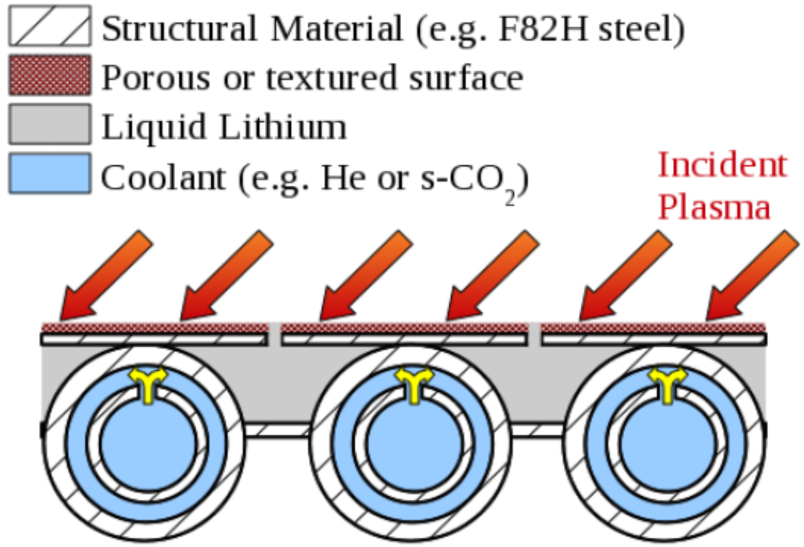
Conceptual Sketch of the IFMIF

T. Furukawa and E. Wakai et al.,

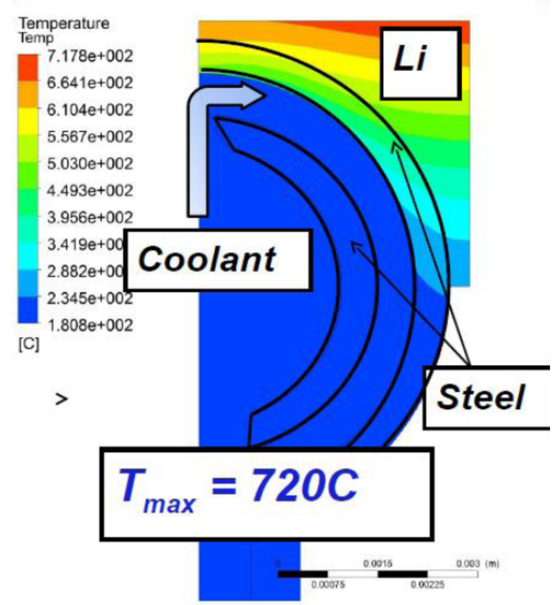
Actively-Supplied, Capillary-Restrained System

An Approach to a Liquid Metal PFC

- Closely connected primary coolant and liquid lithium reservoir/supply structure
- Continuous flow to the surface to flush gettered material and maintain wetted surfaces (substrate protection)
- Multiple coolant options exist (T-tube impinging jets shown as example)



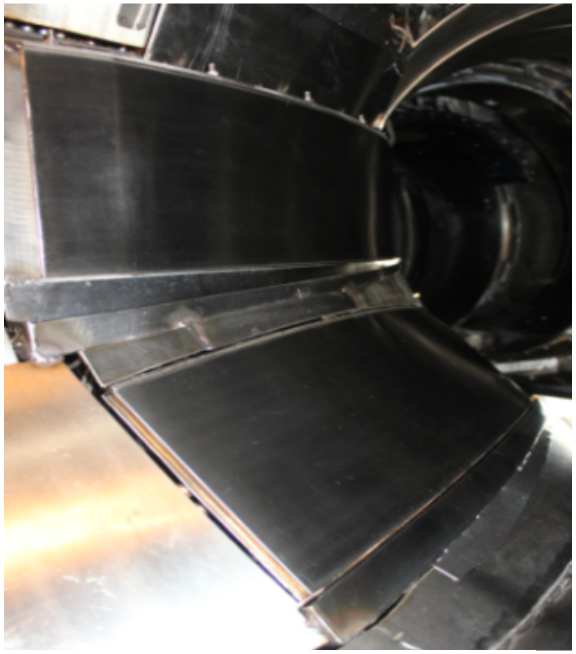
- T-tube1 uses impinging gas jets to increase local heat transfer coefficient
  - Altered T-tube for these simulations to have:
  - Smaller radius
  - Steel structure, s-CO2 coolant **(No tungsten)**
  - 10 MW/m2 incident
  - Consistent with strength limits of ODS-RAFM steel
- Previous studies considered <400C as limit for hydrogen retention

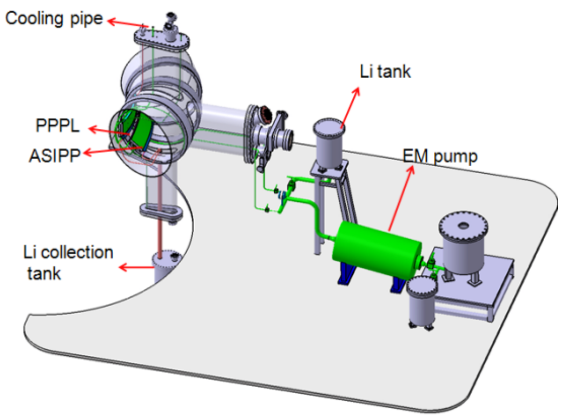


M. Jaworski et al.,

Innovative Liquid Lithium/Metal PFC Ideas

FLLL with slowly moved thin Li film on EAST

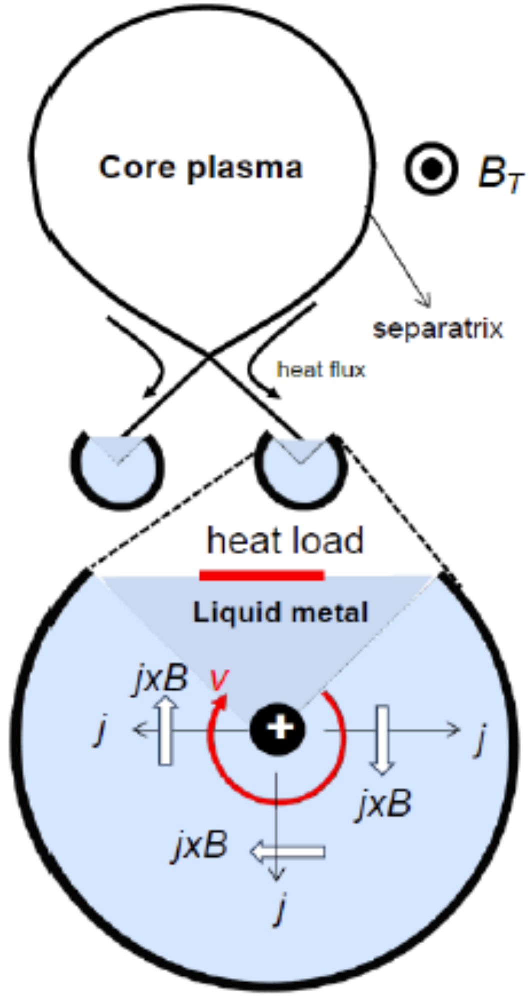




With L. Zakharov from PPPL

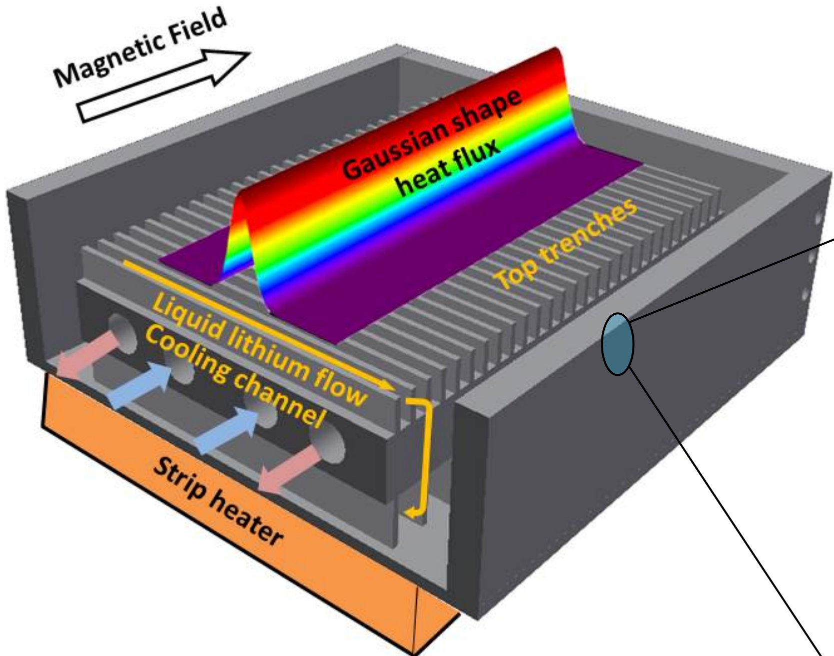
Actively circulated liquid metal divertor

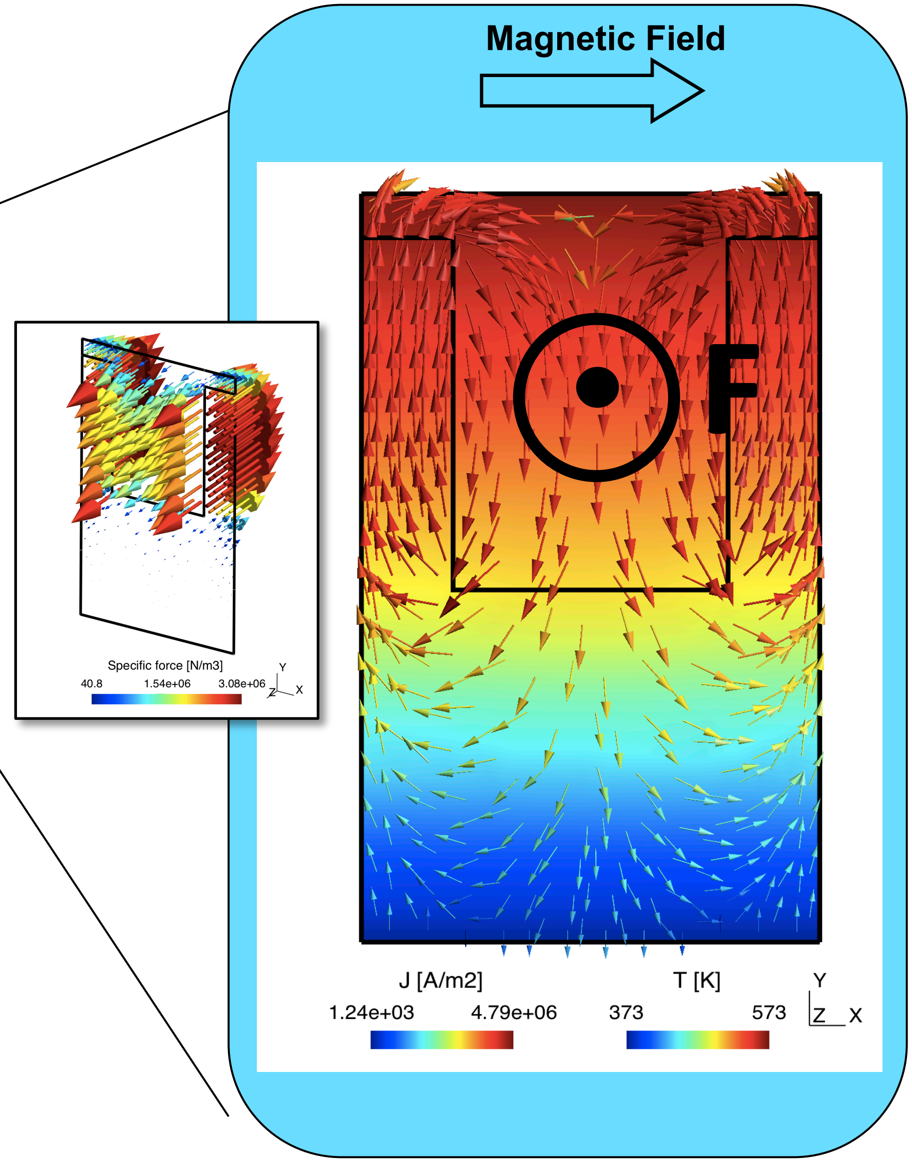
Michiya Shimada, Yoshi Hirooka

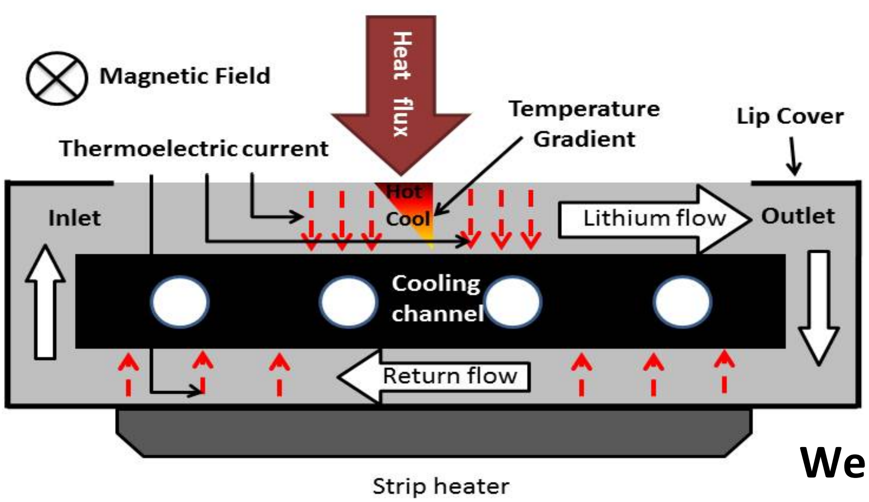


LiMIT: “Lithium/Metal Infused Trenches”

David N. Ruzic and the CPMI Fusion Group



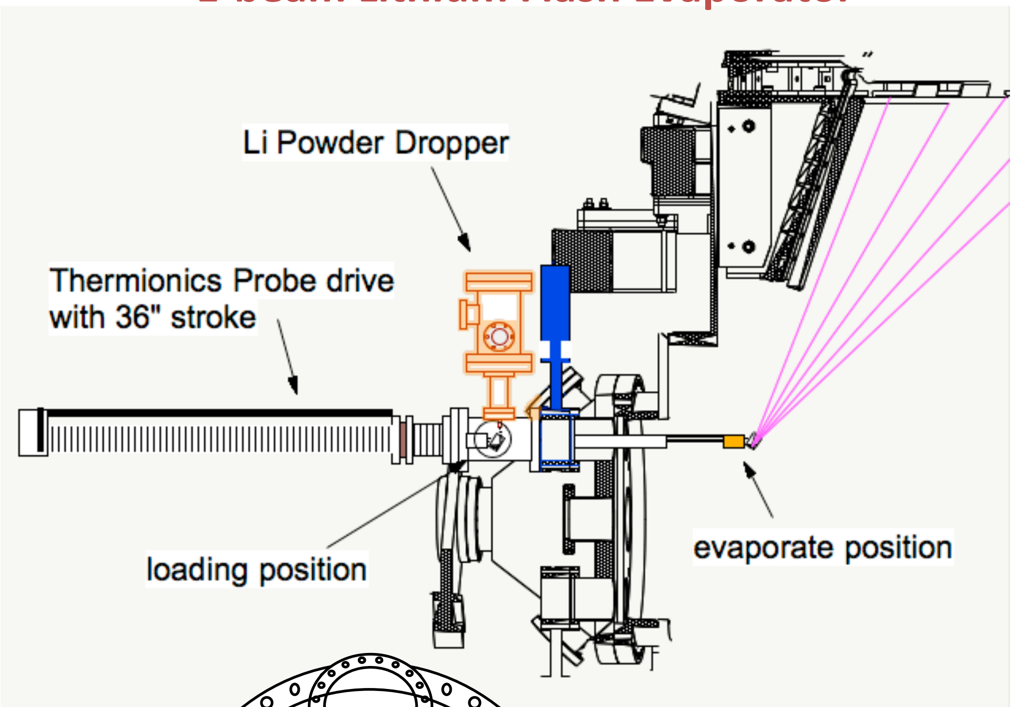


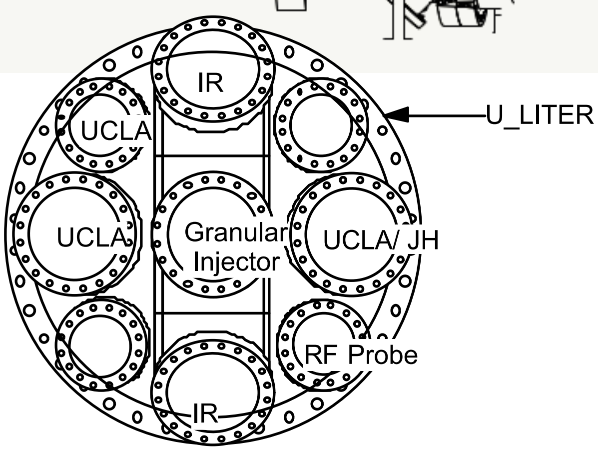


WenyuXu, Davide Curreli and David N. Ruzic

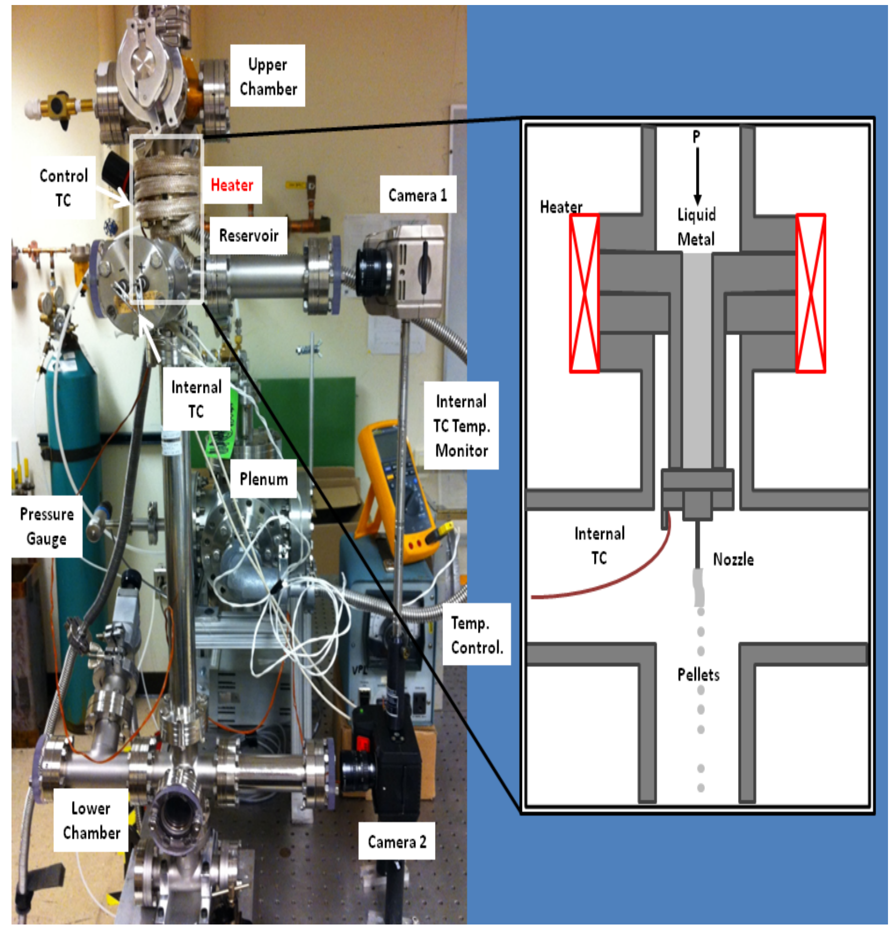
NSTX-U Liquid Lithium R&D

E-beam Lithium Flash Evaporator





Liquid Li Pellet Dripper



A. L. Roquemore, D. Andruczyk, et al.,

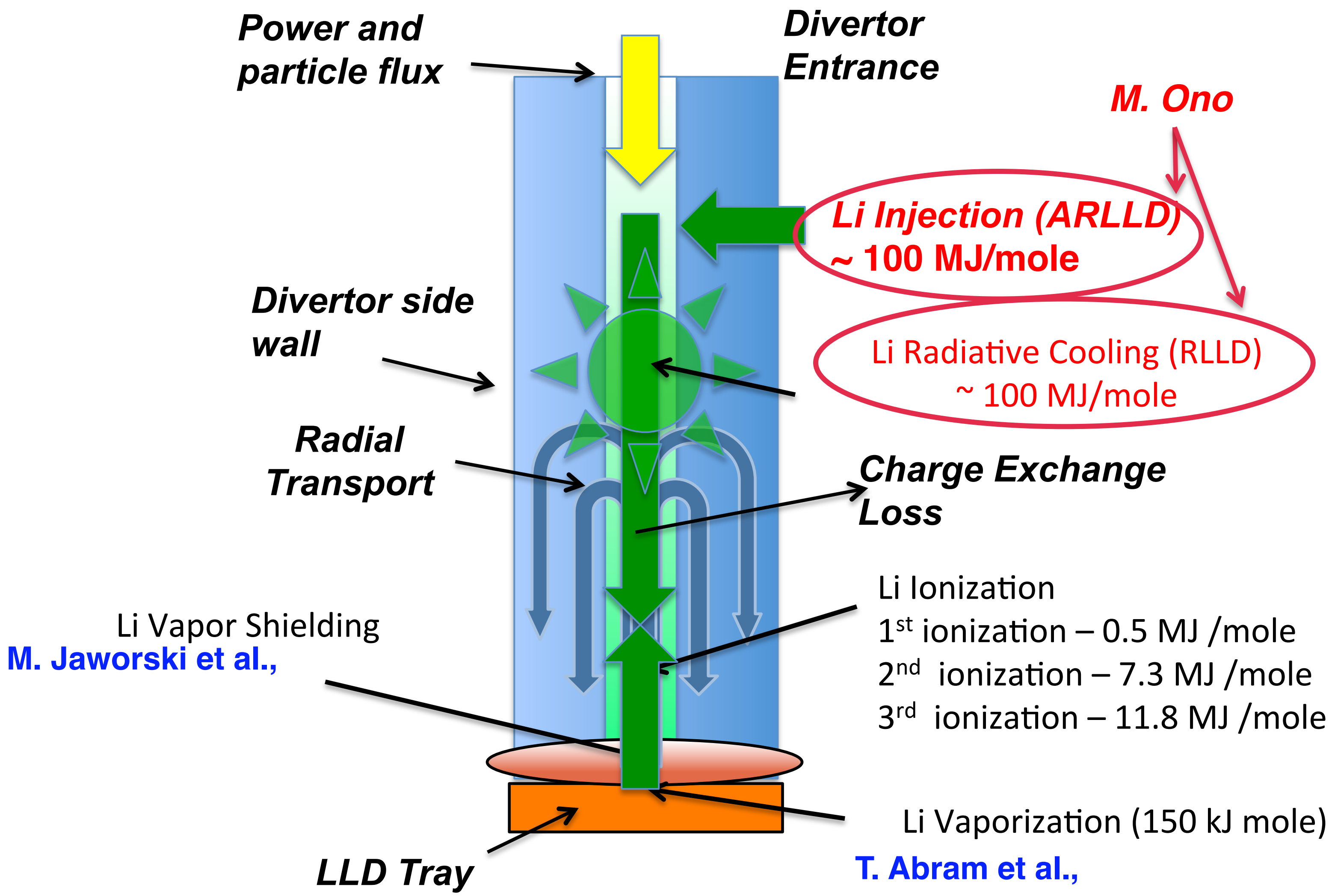
Is lithium PFC viable in magnetic fusion reactors?

(Questions from Dr. M. Shimada)

1. Handling high divertor heat flux – Vapor shielding and high Li radiation to reduce heat flux to acceptable level ~ 5 MW/m2
2. Removal of deuterium, tritium, and impurities from liquid lithium – External lithium loop
3. Removal of high steady-state heat flux from divertor – High Li radiation to spread heat flux over divertor chamber
4. Flowing of liquid lithium in magnetic fields – 1 l/s flow is modest
5. Longer term corrosion of internal components by liquid lithium – Engineering R&D required, IFMIF
6. Safety of flowing liquid lithium, - Leverage experience from IFMIF and
7. Compatibility of liquid lithium with a hot reactor first wall – Two T operation with Li divertor at lower T ≤ 450°C while the first wall in the main chamber at elevated T ≥ 600°C.

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

Li Provides Several Protective Layers
Vaporization, Ionization, Radiation

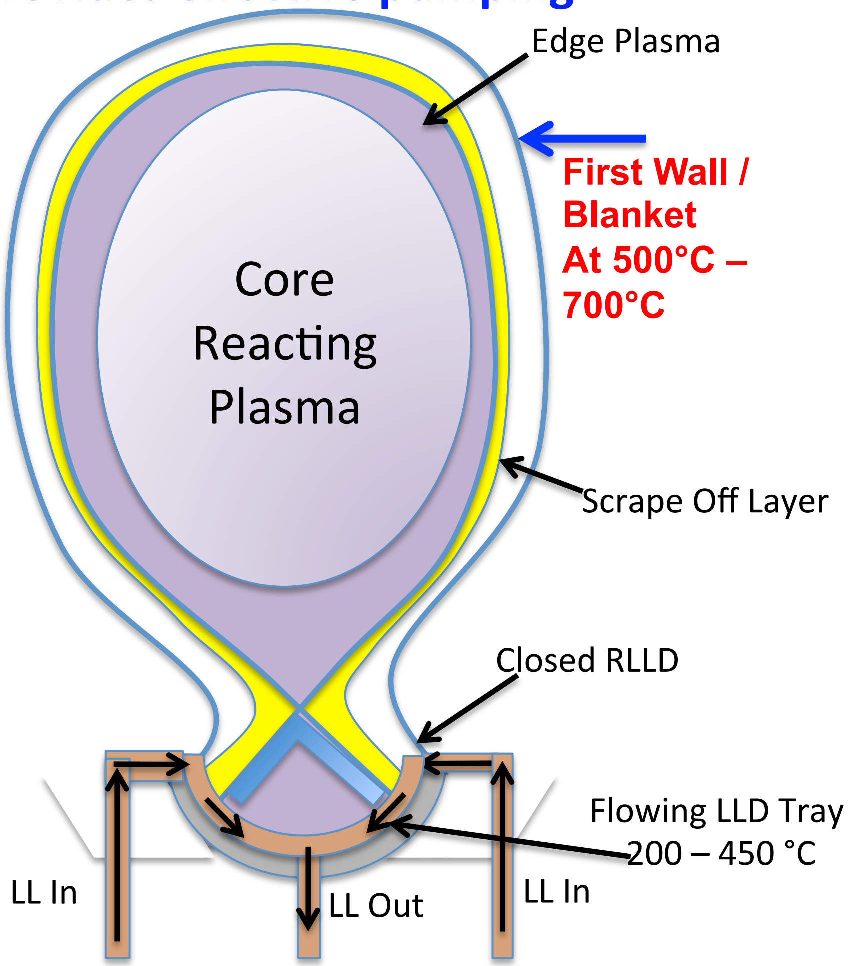


Radiative Liquid Lithium Divertor Concept

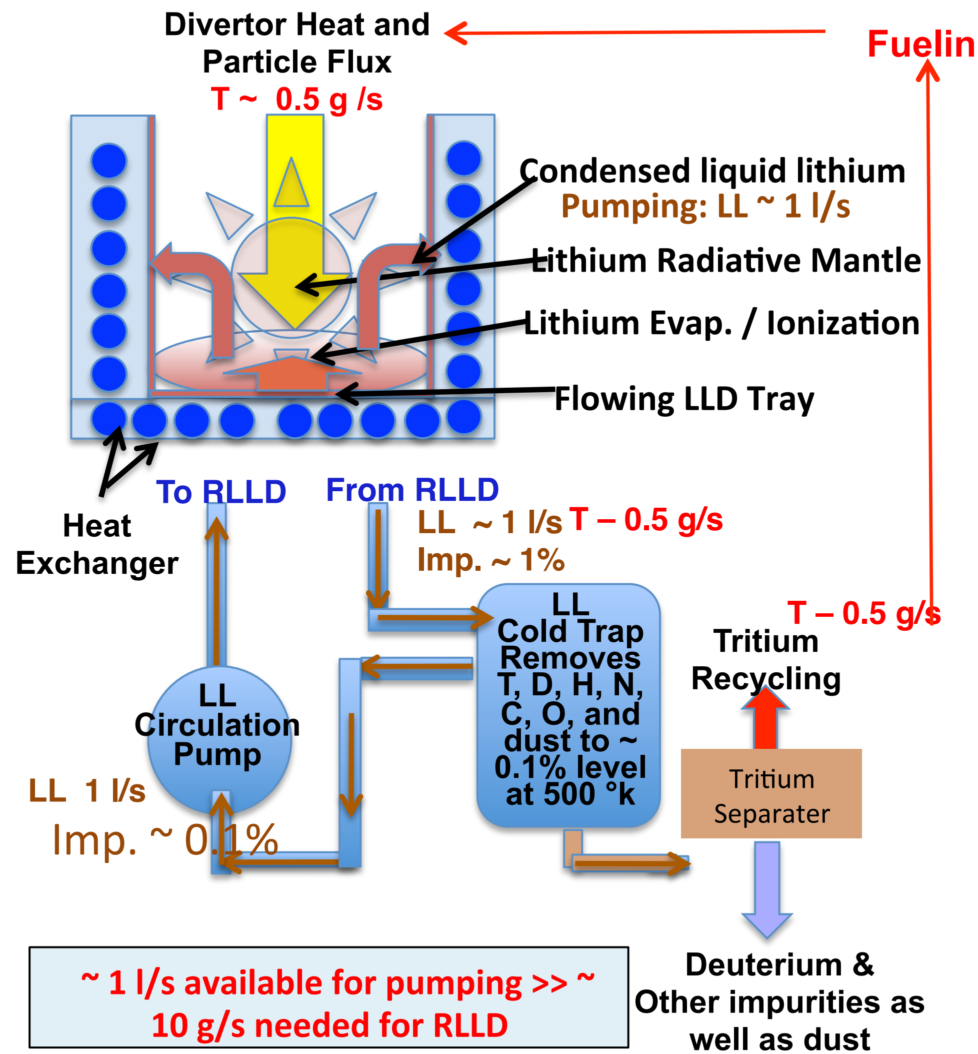
RLLD configuration permits operation at lower T < 450 °C

Lower RLLD Operating Temperature:

- Avoids excessive Li vaporization and provides effective pumping



Impurity and Dust Removal by LL Circulating Loop



M. Ono et al., NF 2013