Lithium Technologies for Controlling the Plasma Wall Interaction

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

FTP/3-6Ra: NSTX Lithium Technologies and Their Impact on Boundary Control, Core Plasma Performance, and Operations

H. W. Kugel, D. Mansfield, R. Kaita, A.L.Roquemore, J. Timberlake (PPPL), R. E. Nygren (SNL) *and the NSTX Research Team*

and

КРАСНАЯ ЗВЕЗДА

State Atomic Energy Corporation "Rosatom"

Federal State Unitary Enterprise "Red Star"

РОСАТОМ

FTP/3-6Rb: Development and Experimental Study of Lithium Based Plasma Facing Elements for Fusion Reactor Application

I. Lyublinski, A. Vertkov, V. Evtikhin - *FSUE "Red Star", Moscow, Russia*

I. Tazhibayeva - *IAE NNC RK, Kurchatov, Kazakhstan*

S. Mirnov, V. Lazarev - *FSUE TRINITI, Troitsk, Moscow reg., Russia*

G. Mazzitelli, M.L. Apicela - *Euratom-ENEA RC Frascati, Italy*

F. Tabares, E. Ascasibar - *CIEMAT, Madrid, Spain*

23rd IAEA Fusion Energy Conference, Daejeon, Republic of Korea, 11-16 October, 2010

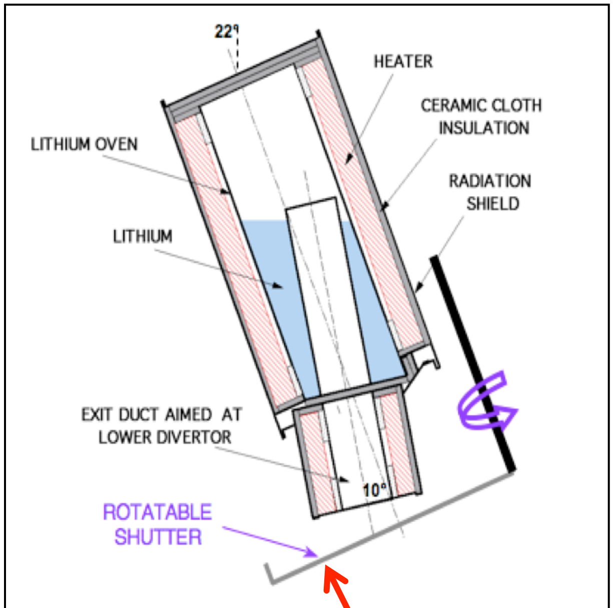
A Decade of International Research Indicates Liquid Lithium Shows Promise for Providing a Self-healing Plasma Facing Surface for DT Reactors

- **NSTX lithium program on *diverted H-modes* grew from experience in TFTR limiter plasmas. NSTX research with solid lithium is aimed initially towards using liquid lithium to control density, edge collisionality, impurity influxes, and eventually power handling.**
    - **Edge fueling is reduced as plasma D efflux incident on Li forms LiD**
        - ***Solid lithium provides short pulse capability but has limited LiD capacity***
        - ***Liquid lithium has much higher LiD capacity, and has potential for power handling and self healing***

- **Over the longer term, NSTX will investigate if liquid lithium can help integrate 4 important potential benefits for fusion**
    - **Divertor pumping over large surface area compatible with high flux expansion solutions for power exhaust and low collisionality**
    - **Improved confinement**
    - **ELM reduction and elimination**
    - **High-heat flux handling (e.g., via capillary-porous flow,…)**

Dual Lithium Evaporators (LITERs) Are Now Routinely Used To Deposit Lithium Coatings On NSTX Lower Divertor Between Discharges

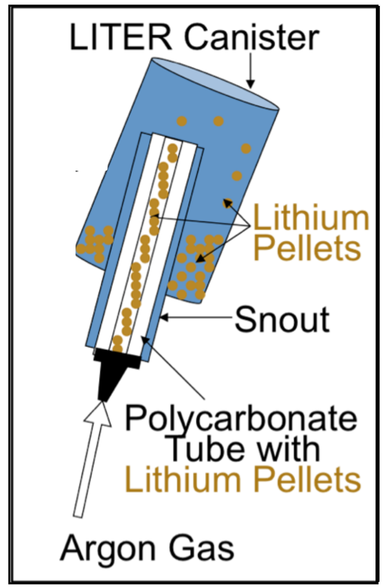
LITER Oven on 1.6 m Probe



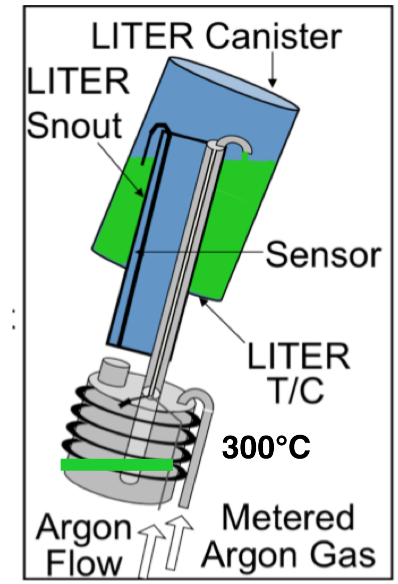
- **Rotatable shutter stops lithium when diagnostic window shutters open.**

- **Typ. Op. temp. 550-650°C.**

- **Initially, LITERs filled using solid Li pellets injected with argon (40 g max).**

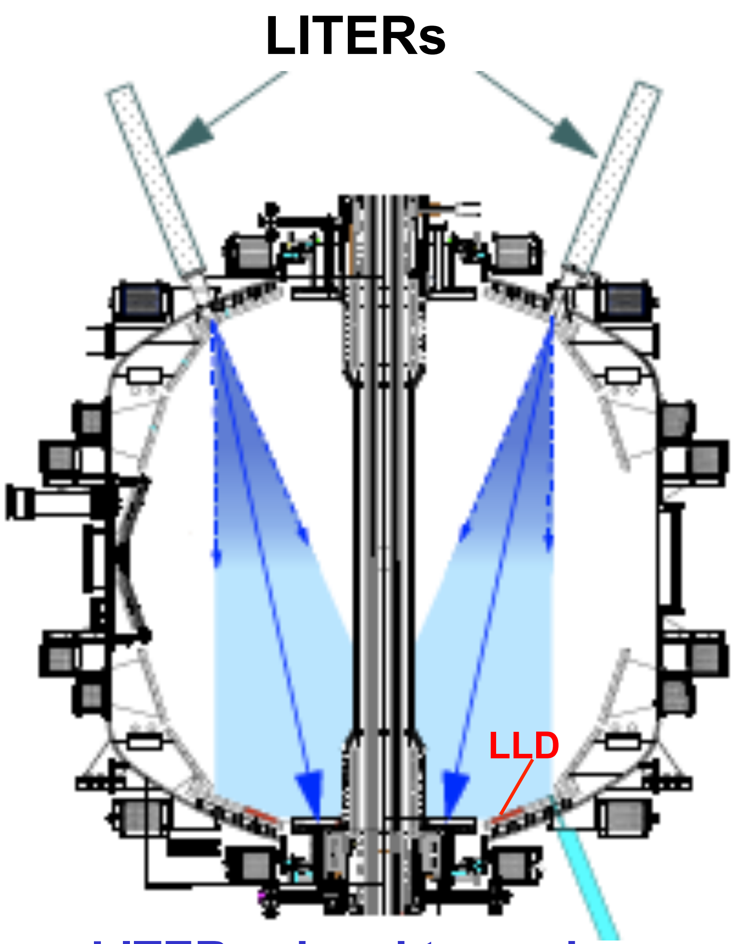


- **Recently, LITERs filled using liquid lithium injected with argon (80 g max, less impurities).**



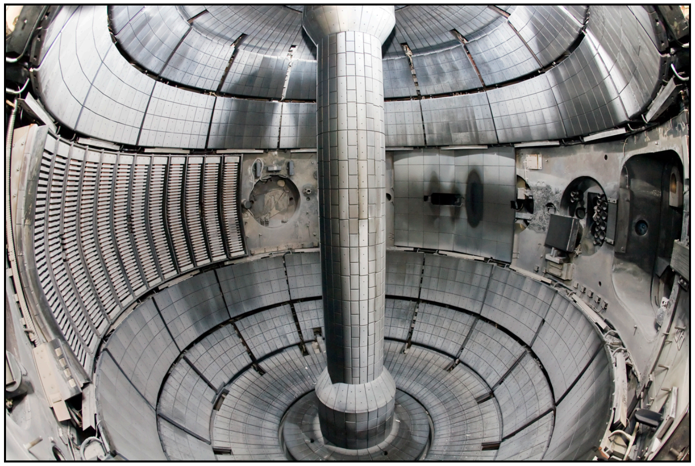
- **After Li filling, *prior to installation on NSTX*, LITERs are outgassed in vacuum to 600°C to remove any argon and dissolved gases.**

Dual LITERs Are Used Routinely To Deposit Lithium Coatings On NSTX Lower Divertor for 10 minutes Between About 80% of Discharges



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

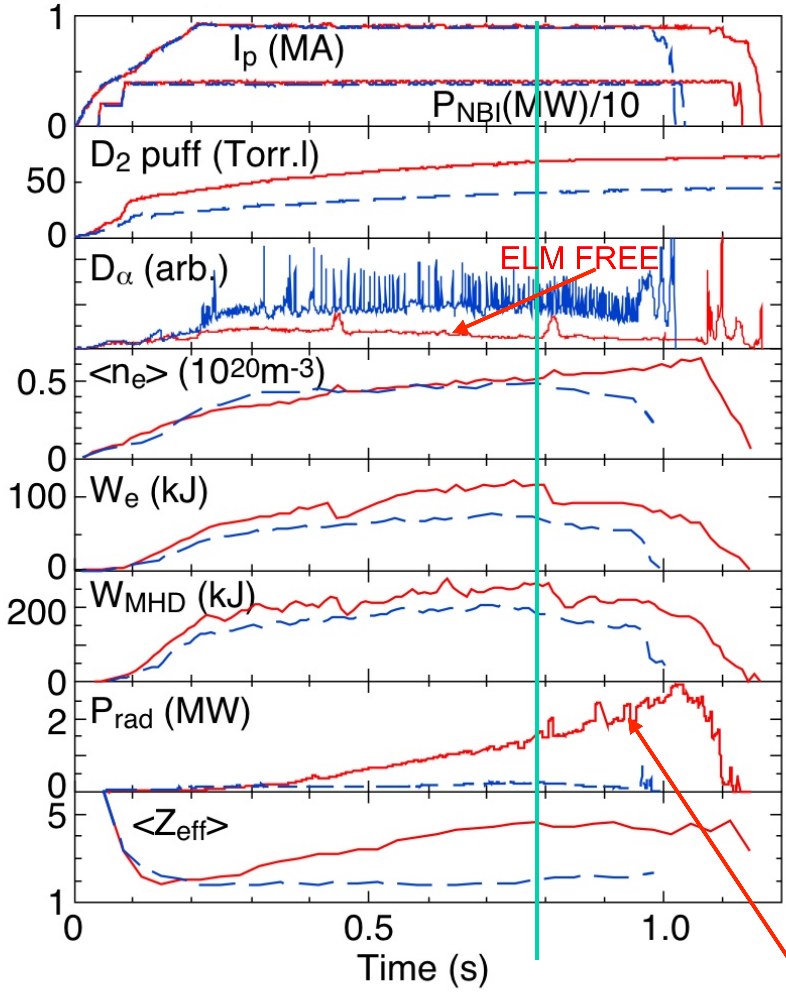
- Lithium transported over broad area by wings of LITER distribution and plasma migration.



- After exposure to air (2009), 600g Li deposition converts to white ceramic lithium carbonate (Li_2CO_3).
  - Li_2CO_3 removed prior to evacuation with 5% solution of acetic acid (CH_3COOH) to convert Li_2CO_3 to water soluble lithium acetate ($LiC_2H_3O_2$)

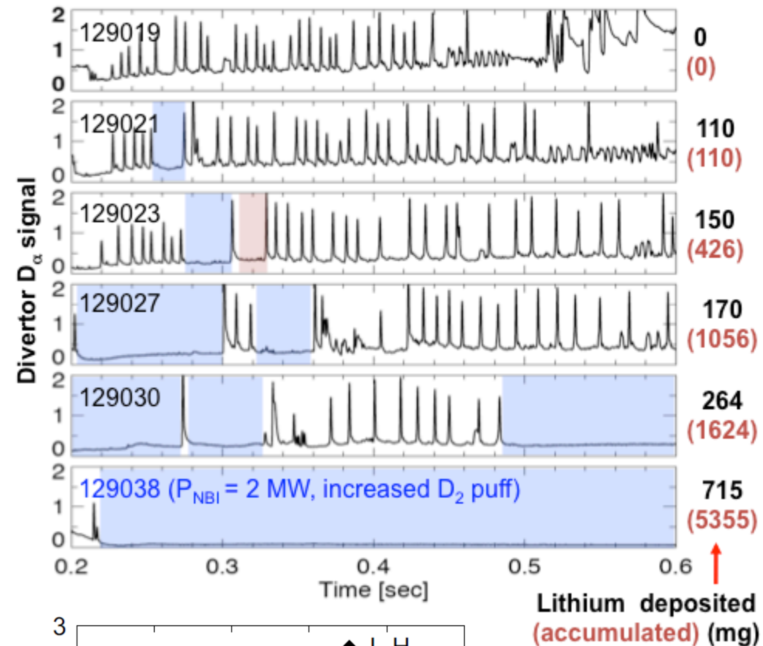
Lithium Coating Reduces Deuterium Recycling, Reduces P_{L-H}, Suppresses ELMs, Improves Confinement

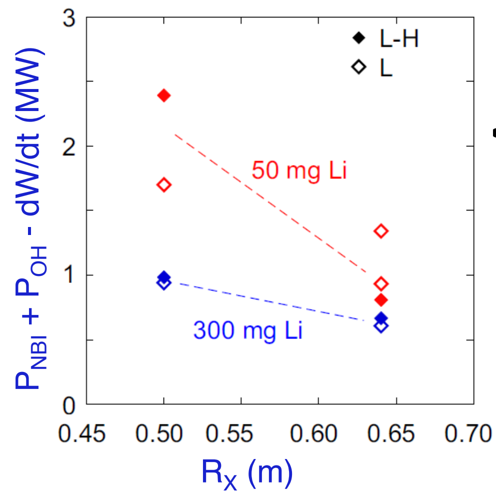
No lithium (129239); **260mg lithium** (129245)



Without ELMs, impurity accumulation increases radiated power and Z_{eff}

- ELMS reduced as lithium increases

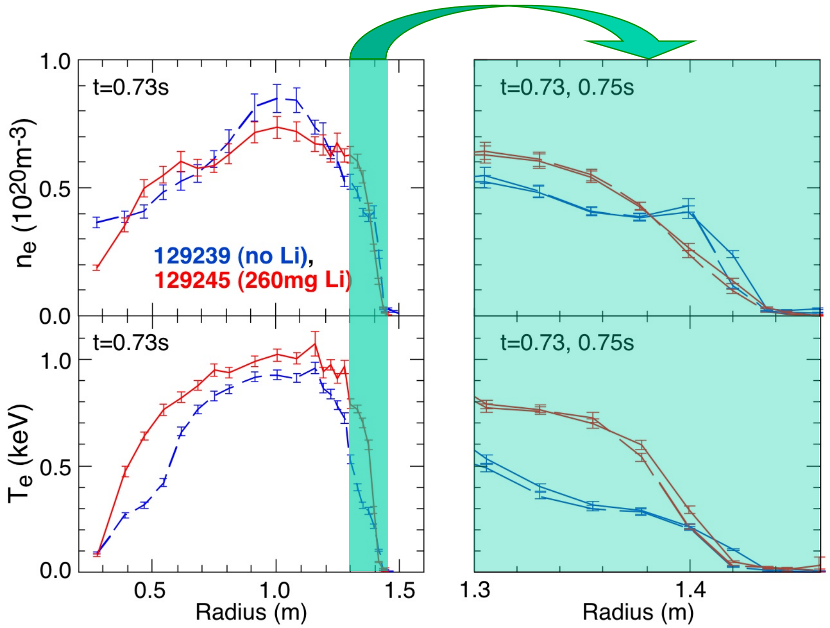




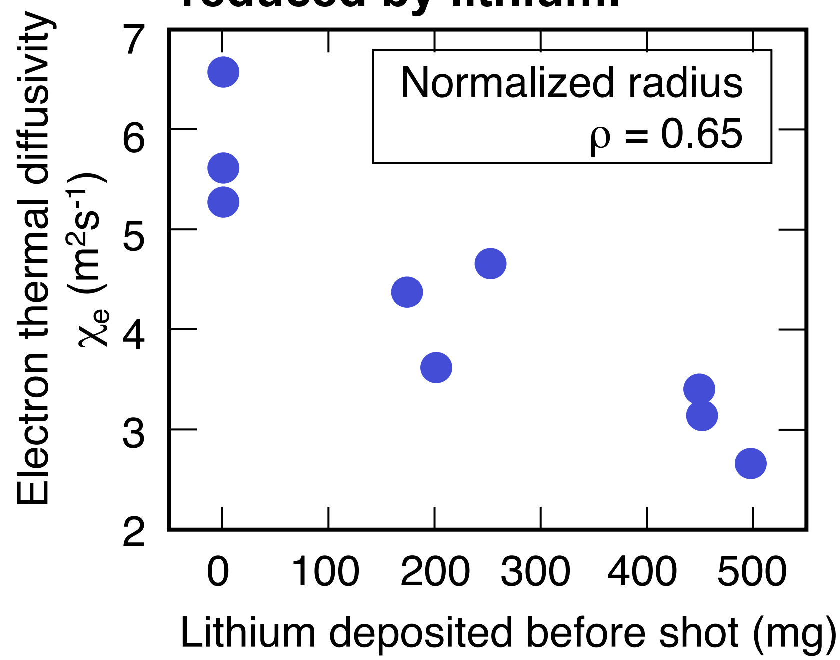
- **Lithium lowers H-mode threshold at both radii.**

Lithium Evaporated on Divertor Broadens Electron Temperature Profiles and Decreases Electron Thermal Diffusivity

- **Edge electron density decreases and electron temperature increases.**



- **TRANSP analysis confirms electron thermal transport in outer region progressively reduced by lithium.**



- **Fast-ion contribution to total energy ($\propto T_e^{3/2}/n_e$) also increases**

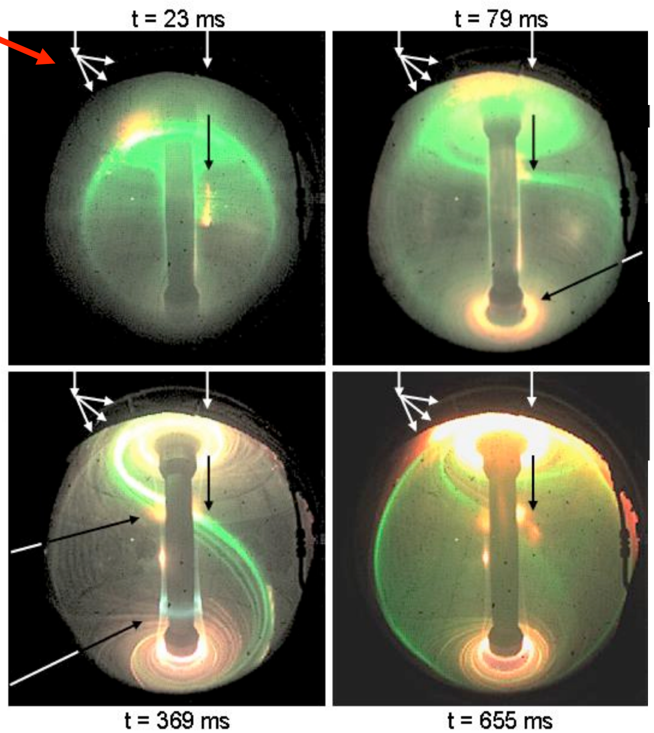
Lithium Powder Injection in Progress to Test Increased Rate of Lithium Delivery to Plasma Wetted Areas

• **Particle delivery rates up to 80 mg/s (LITER ~10-20 mg/min per unit)**

44 mm Li spheres enter SOL

ELM filaments strike lithium in SOL flow.

Diffuse plasma edge and MARFE (blue).

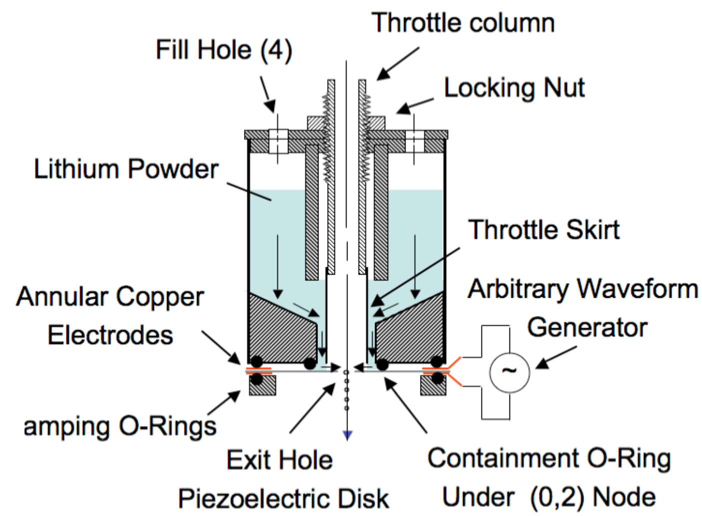


As NBI starts, lithium is swept toroidally in SOL flow

Lower single null strike points evaporate Li.

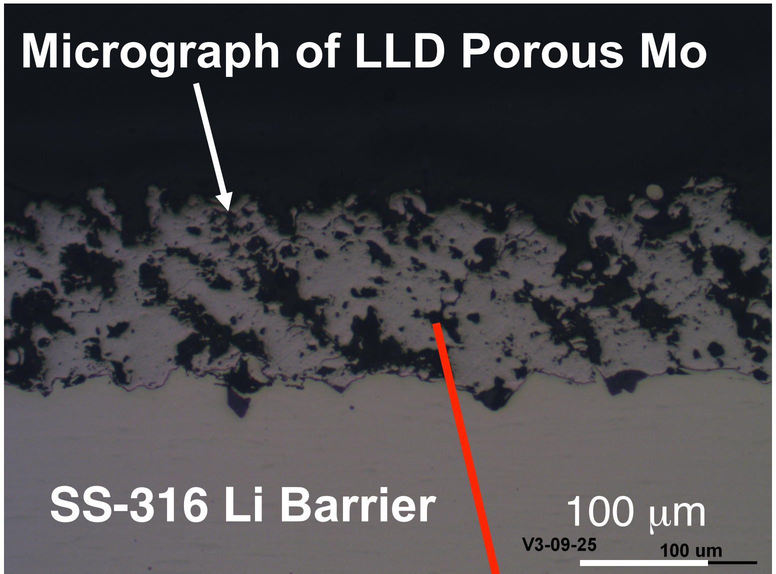
ELMS and MARFES vanish by t~500ms. Sharp plasma edge and Li radiative mantle

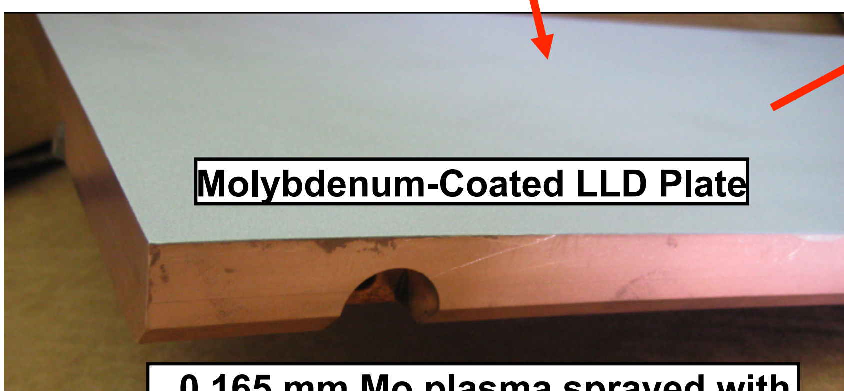
Schematic of Lithium Powder Piezoelectric Acoustic Injector



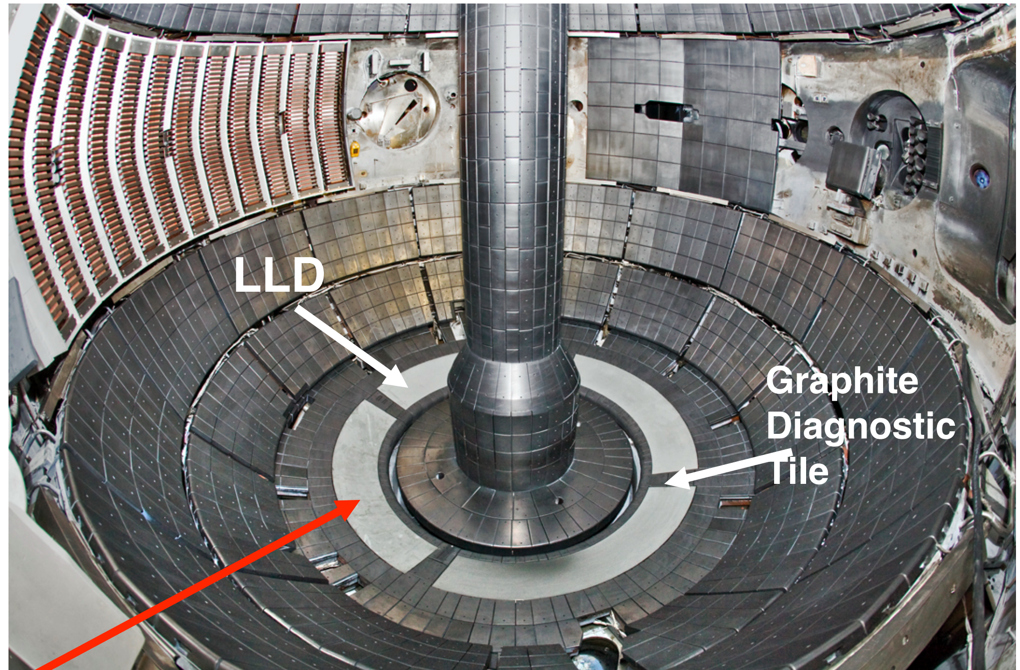
• **Lithium particles can be delivered before t=0 and during discharges.**

Liquid Lithium Divertor (LLD) Installed in NSTX with Porous Molybdenum Face to Hold Lithium



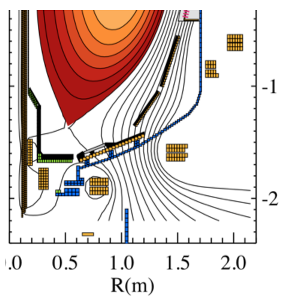


0.165 mm Mo plasma sprayed with 45% porosity on a 0.25 mm SS barrier brazed to 22.2 mm Cu.

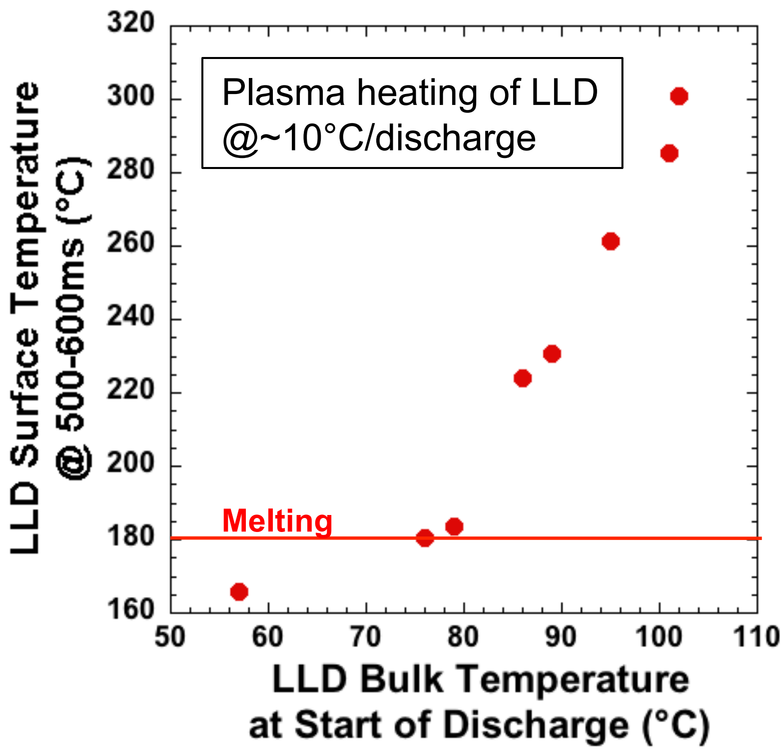


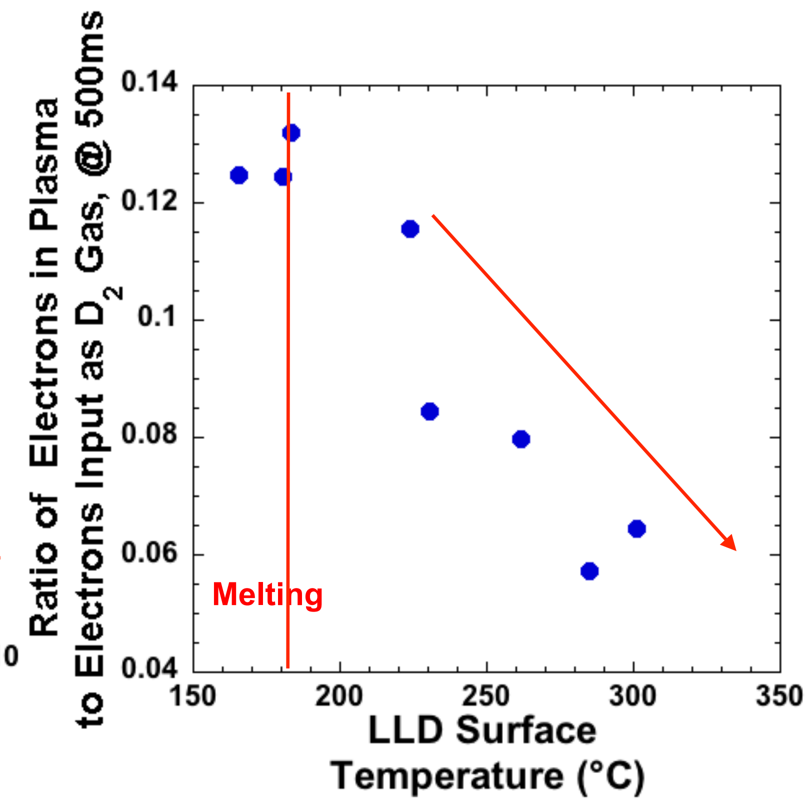
- **4 heated plates (80°each) separated by graphite diagnostic tiles. Each section electrically grounded at one location to control eddy currents**
- **LLD loaded by LITER evaporation**
  - **5% of LITER output reaches LLD**
  - **initial tests with up to 35% full**

An Observed Plasma Density Decrease Despite Deuterium Fueling Increase as Lithium Surface of LLD Liquefied



I_p = 0.8MA,
P_{NB} = 4.0MW
B_T = 0.48T
R_{OSP} = 0.73m
LLD ~%5 full
(~0.5μm)





- **In other LLD tests, the amount of required fueling was similar to that for solid lithium coatings. Work is in progress to investigate these differences, e.g.,**
  - **liquid lithium can pump impurities and effect density**
  - * **liquid lithium surface impurities (C,O,…) from sputtering and gettering can reduce the formation of LiD and decrease pumping.**

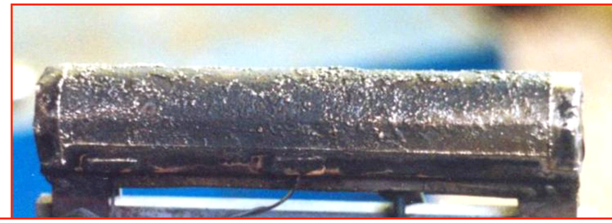
Alternate Approaches for Limiters and Divertors:

Capillary-Porous Systems (CPS)

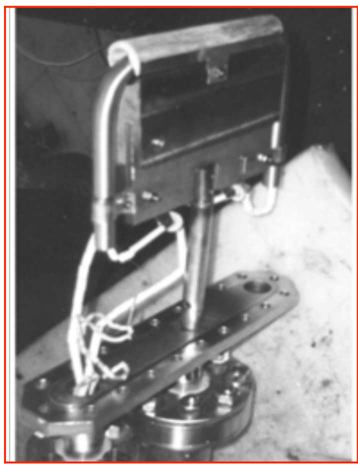
- **CPS use surface tension forces in capillary channels to retain liquid lithium in the presence of changing magnetic fields**
- **CPS has been used to confine and redistribute liquid lithium on surfaces with several profiles and orientations**
  - **e.g. horizontal, angled, and vertical**
- **Self-sustaining systems supplying liquid lithium by capillary forces can compensate for lithium removal by evaporation and sputtering**
- **Eroded lithium can be condensed and captured on the CPS surfaces outside plasma interaction and returned via flow without special pumping**
  - **Lithium will not accumulate as dust**
- **The lifetime of CPS applied in current experiments can be increased by**
  - **redistribution of high heat loads over a larger area,**
  - **evaporation-condensation mechanisms**
  - **re-radiation in the lithium edge vapor cloud**

Experiments in T-11M with lithium rail limiters (1998-2009)

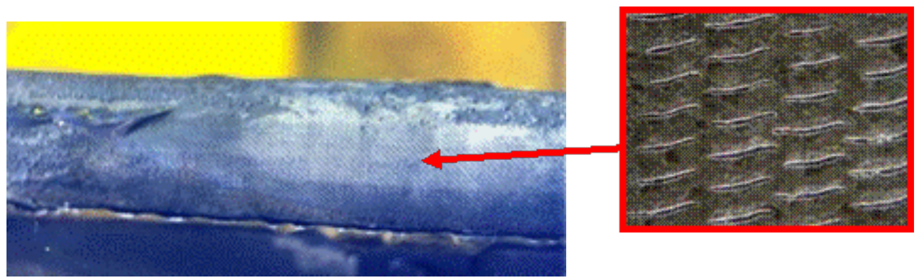
Experiments with five versions of rail limiters based on lithium CPS have been performed to prove compatibility with boundary plasma and confirm Li CPS stability



Limiters from SS mesh with pore size of 15 -50 μm



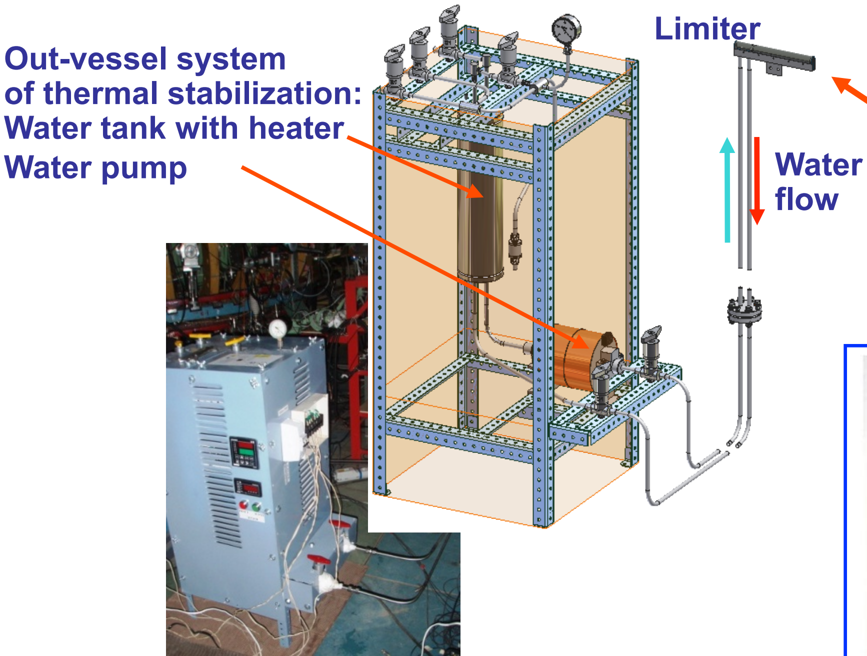
Limiter from Mo mesh with pore size of 75 μm



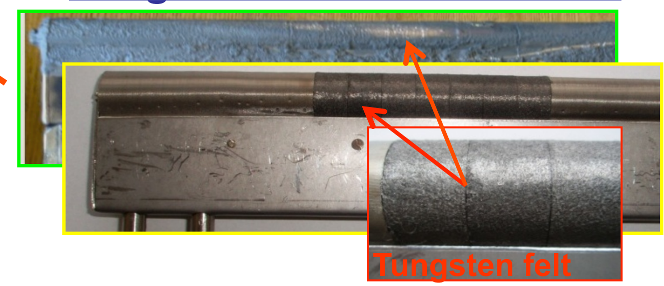
View of limiter surface after 2000 plasma shots

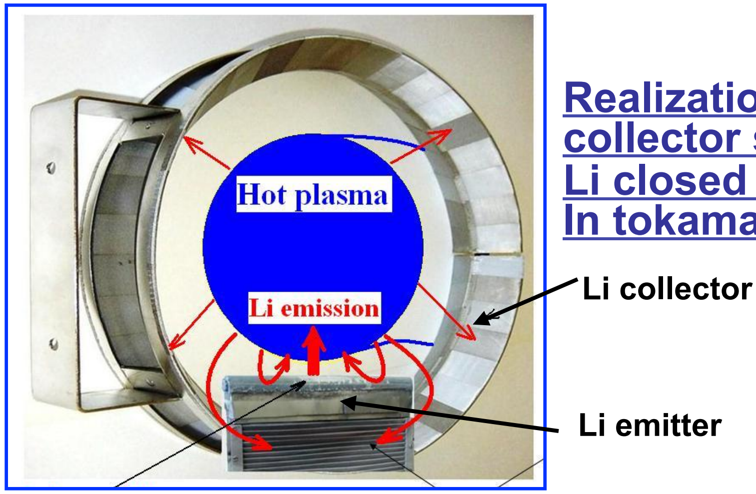
- **Li CPS demonstrated excellent potential for higher power applications.**
- **No damages, no Li splashing, no plasma contamination, high resistance to power fluxes up to 10 MW/m^2 and to disruptions.**

W-based lithium limiter with active cooling for T-11M (2009-2010)



Tungsten felt based limiter





Realization of emitter-collector scheme for Li closed circulation In tokamak

CPS – W felt (wire Ø30 μm, pore size 30 μm)
Structural material – Mo and SS
Coolant – water (T ≤230°C P~25 atm.)

Power flux	up to 15 MW/m^2
Discharge duration	up to 0.3 s
Li surface area	~ 100 cm^2
Initial Li temperature	≥ 200°C
Max. Li surface temperature	< 550°C

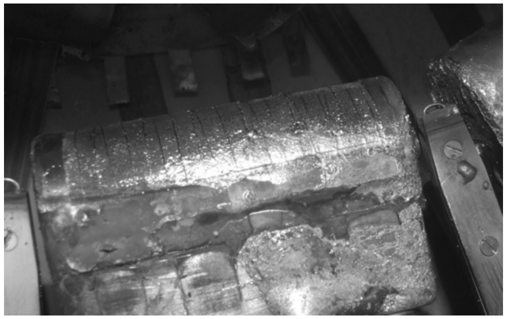
T-11M experiments have demonstrated:

1. *Clear advantage of W-based limiter compared to SS-based system.*
2. *Possibility of collecting about 80% of injected Li.*

Experiments in FTU with lithium SS and W-based limiters (2005-2010)

- **Key stage in validation of lithium CPS performance for fusion application**

SS Limiter after tests



W-based Limiter after 2009-2010 tests

Power flux	**up to 5 MW/m^2**
Toroidal magnetic field -	**up to 6 T**
Discharge time –	**1.5 s**
Total lithium area -	**~200 cm^2**
Total amount of lithium -	**≅ 80 g**
LI surface temperature -	up to 550^{o}C
CPS -	**SS mesh, and W-based**

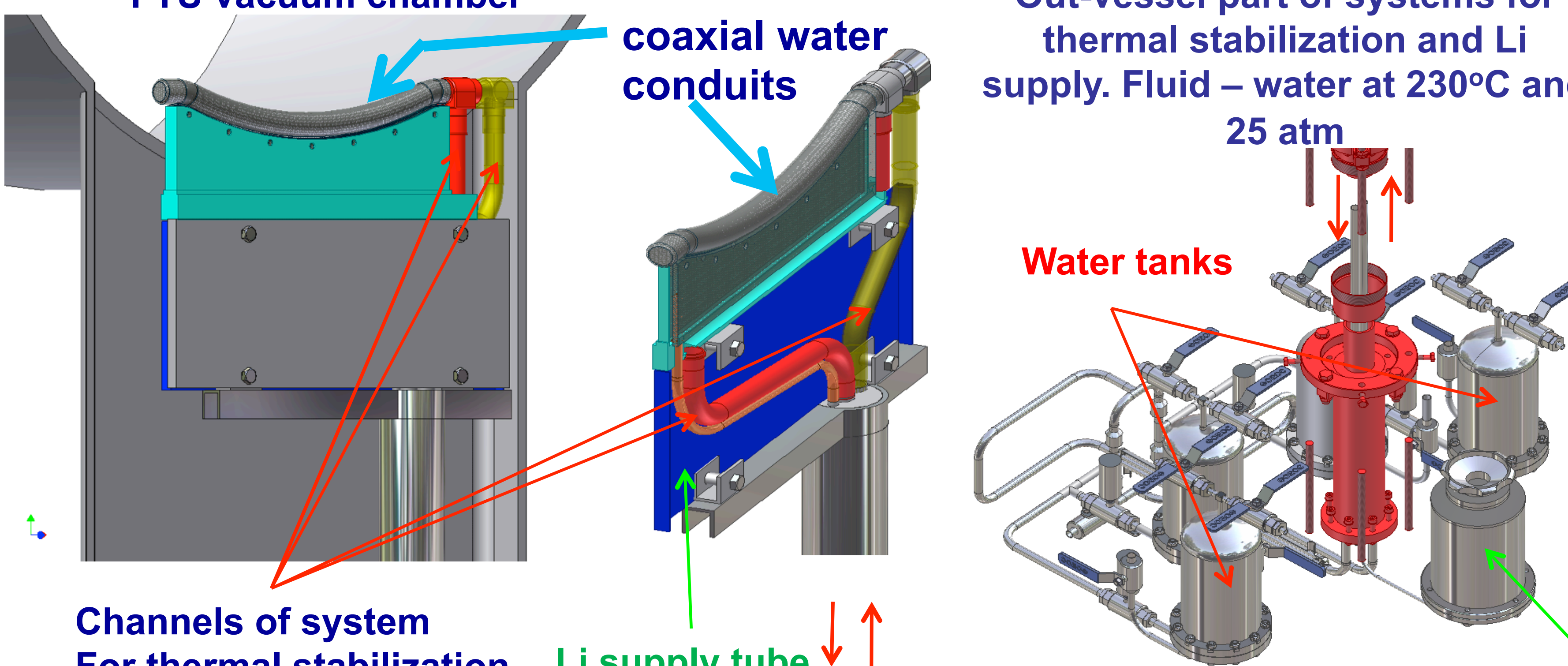
Main technological issues:

- **SS CPS for Li surface renewal and liquid Li confinement are confirmed for**
  - **high magnetic field up to 6 T**
  - **power load exceeding 5 MW/m^2.**
  - **lithium temperature range of 200-600 ^{o}C.**
  - **no indications of (Fe, Cr, Ni) in UV spectra**
  - **SS mesh has shown the basic advantages of Li CPS but is not suitable for a long operating times operation.**

- **Recent Work with W-based limiter found**
  - **no changes on CPS surface after long-term operation at > 5 MW/m^2**

New single element Li limiter for FTU (in progress)

- **Limiter will provide lithium surface temperature stabilization in a range of 450-550°C under power flux up to 10 MW/m² during 5 s and permanent Li supply.**



Liquid Lithium Limiter for stellarator TJ-II (2010)

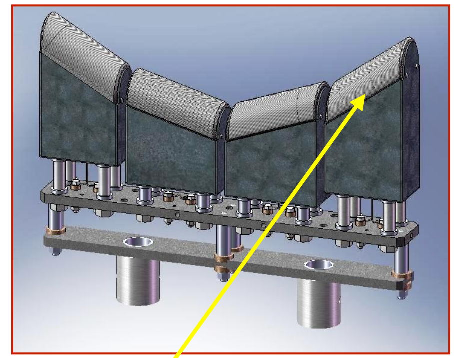
Background: stellarator is basically free from extreme thermal load events.

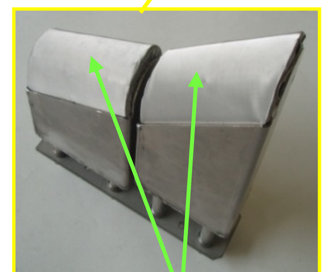
Problem – tendency for impurity accumulation.

Solution - application of lithium for PFC or wall conditioning for progress in effective impurity and particle control.

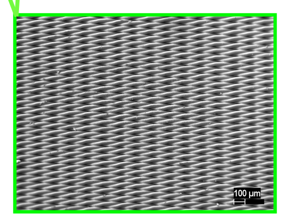
Technical approach: Two CPS based Liquid Lithium Limiters in opposite sections of TJ-II.

Experimental possibilities: Variable position, lithium supply, preliminary heating, gas puffing, biasing, surface temperature stabilization, gas sorption/release study.





Lithium Elements



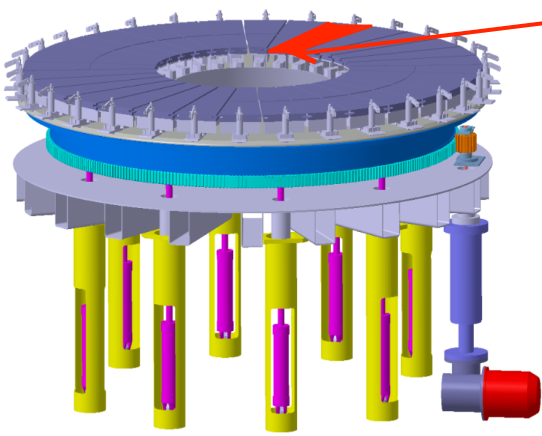
SS-based CPS

Dimensions L x D x H	324 x 44 x 225 mm
Lithium surface area	$2.24{\cdot}10^{-4}$ m^2
Power load	up to 10 MW/m^2
Initial temperature	200 - 550 ^{o}C
Amount of lithium	~ 80 g (20 g x 4)
Pore size / Capillary pressure	30 μm / ~5 10^4 Pa
Power of heater	up to 300 W
Total weight	5 kg
Operation campaign	> 1000 discharges

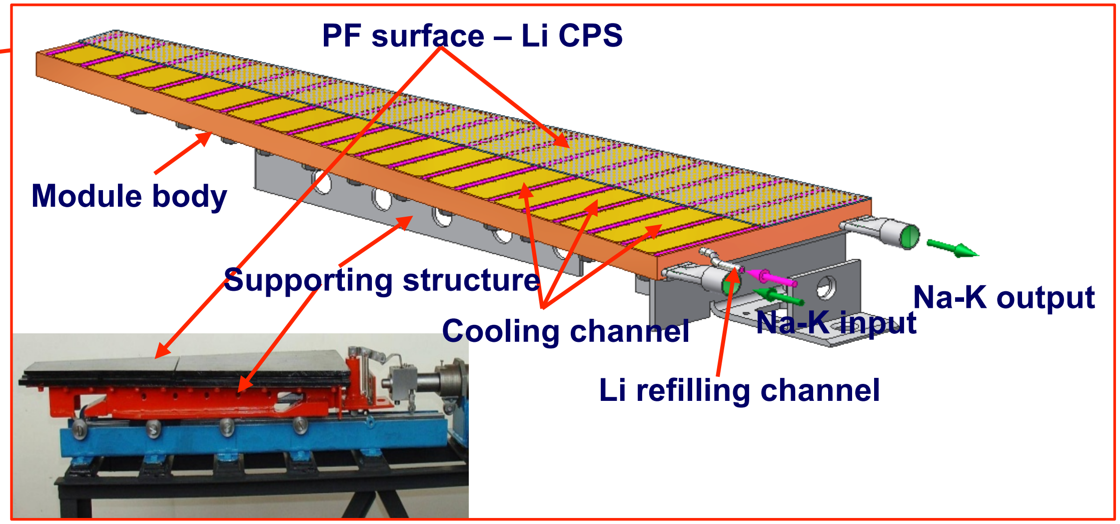
Installation to TJ-II is expected in 2011

Project of Li divertor module for KTM (in progress)

Changeable module (1/32 part) for steady-state operation with thermal stabilization by Na-K flow and permanent Li supply



Graphite divertor of KTM with CPS Module



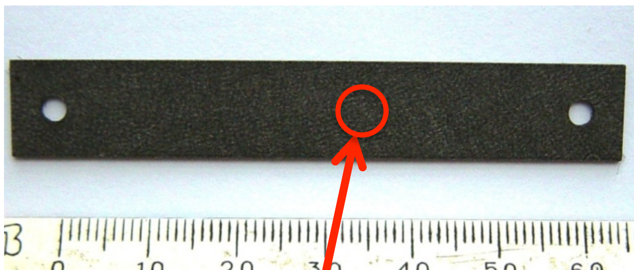
Power flux	up to 10 MW/m^2
Discharge duration	Up to 5 s
Surface temperature	200-550°C
Material CPS / module body	SS mesh and W felt / SS
Heat transferring fluid	Na-K eutectic alloy

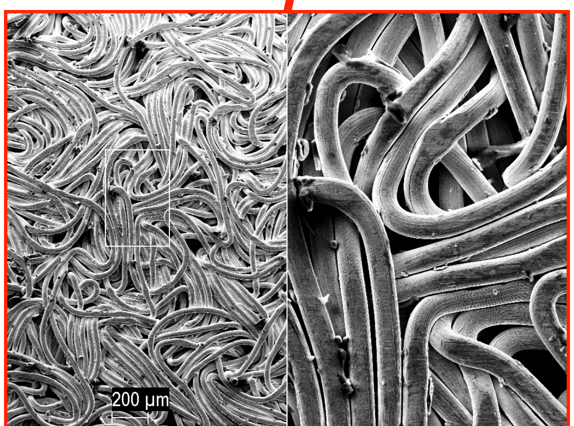
Aimed at lithium divertor development for a DEMO fusion reactor

Development Strategy for CPS-based Plasma Facing Element

1. **New CPS –based on suitable plasma facing materials**
2. **Plasma facing elements for steady-state, long-time operation**

Tungsten fiber based CPS with wire diameter and pore size of 30 μm have been developed and manufactured

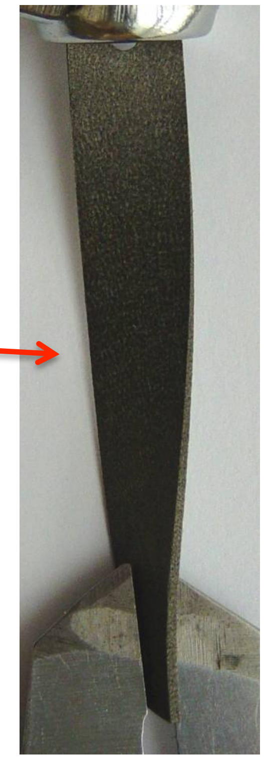




Microscope photo

- **Porous W mat has a high heat conductivity (~6 time) and strength (~5 time) comparing to SS mesh mat.**

- **Good flexibility.**



Conclusions

- **Significant improvements in NSTX NBI heated divertor H-mode discharges result from lithium depositions**.
  - Lithium evaporated on divertor suppresses ELMs and improves confinement

- **Under some conditions, experiments with the NSTX liquid lithium divertor indicated a plasma density decrease, as lithium surface of LLD liquefied, despite deuterium fueling increase. In other cases, the pumping was about the same as with solid lithium coatings.**
  - Impurities on the liquid lithium surface may reduce the formation of LiD and decrease pumping relative to that of clean lithium.

- **In limiter tokamaks using lithium Capillary-Pore Systems, very similar behavior has been found for the lithium effect on plasma performance.**
  - No catastrophic events leading to lithium injection over the range 20-600^{o}C
  - The energy confinement times are increased.
  - Decrease in recycling, Zeff (to 1.1 - 1.2)
  - Decrease in radiation losses.
- **The application of lithium Capillary-Pore Systems is a promising path toward development of plasma-facing elements for the next generation, high power, steady-state, fusion experiments.**