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NSTX-U Near Term Lithium Options

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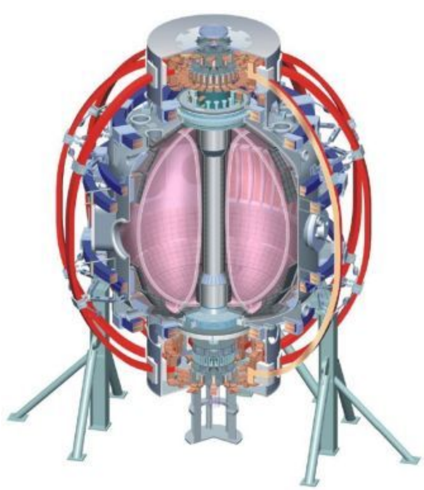
H. W. Kugel

LRTSG
Feb. 06, 2012



Culham Sci Ctr
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ENEA, Frascati
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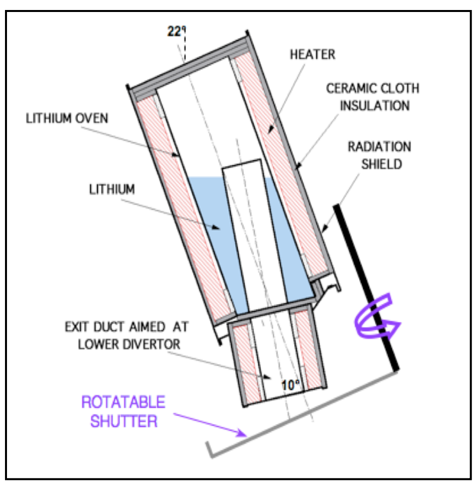
IPP, Garching
ASCR, Czech Rep
U Quebec

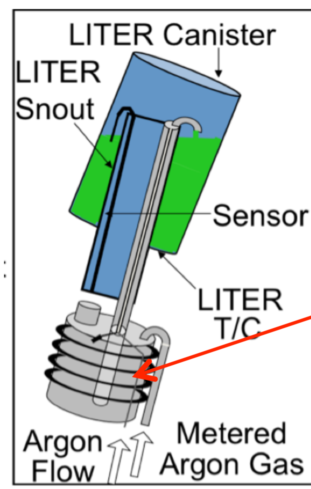
Candidate NSTX-U Baseline Year-1 Lithium Plan
- for Noteworthy Results Early in the Campaign

- Install ATJ Graphite tiles on Lower, Inner & Outer Divertor
- Install subset of existing tile diagnostics on Lower Outer Divertor
- Mount the 2011 Molybdenum tiles on Upper Inner Divertor
- Mount the 2011 LITERs on Upper Divertor
- Mount suitable Lithium Technology for coating Upper Divertor
- Take 6 shots without lithium
- Start lithium deposition, and obtain research grade shots within 10 discharges (Kugel, PSI 2010, Fig.7), or do 3 TMBs and take 6 weeks (M. Bell, Startup Calendars, 2006-2010)
- Proceed to qualify Upgrade & initiate characterization of NBI current drive

Near Term Option-1:
Coat Lower Divertor using 2 Upper LITERs

- Coat Lower Divertor using 2 Upper LITERs
  - \+ 4 LITERs available: allows 2 spares for reloading and uninterrupted service
  - \- will not allow Upper Divertor coverage for USN and DND discharges
  - \- will not allow extension of the "*more lithium coverage is better*" database
  - \- reinstallation concerns
    - Inspect port covers and adjust the LITER shutters
    - Reinstall LITER Fill Stands to allow trial-alignments and filling
    - Test and align Bay-F and Bay-K LITERs for BBQ rail clearance
    - Reinstall LITER control rack and cables
    - Test LITER controls (computer, PLC, Shot Clock)

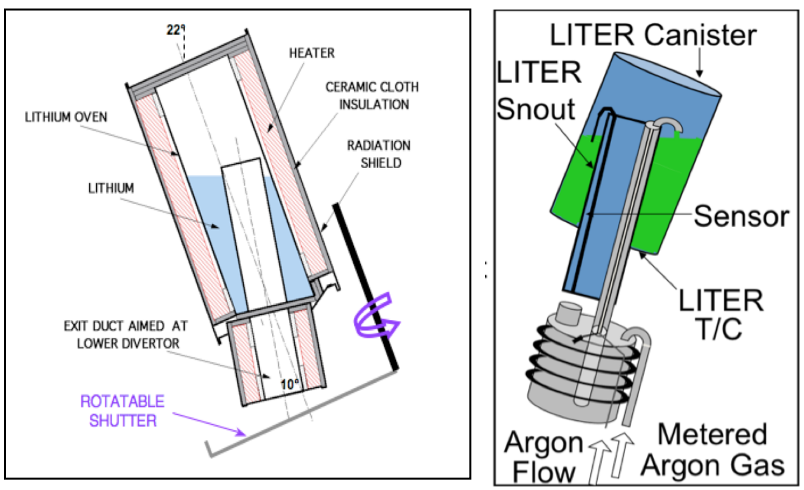




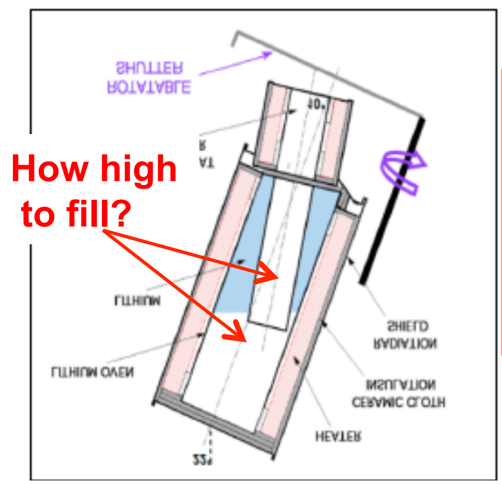
Empty and clean before each full

Near Term Option-2:
Coat Lower and Upper Divertors Using 4 LITERs

- Coat Lower and Upper Divertors using 2 Upper LITERs aimed at Lower Divertor and 2 lower LITERS aimed at Upper Divertor
  - \+ provides twice the lithium coverage for extension of Li coverage database
  - \+ allows coating on Upper divertor for USN and DND studies
  - \- allows no spares for reloading; will result in episodes of no-LITER during reloading
  - \- need to allocate 2 lower divertor ports
  - \- need to fabricate 2 additional port cover and shutter assemblies
  - \- need to purchase 2 additional sets of power supplies and controls
  - \- need to upgrade computer and PLC control software
  - \- need to solve LITER upside-down loading and operating issues



LITER AIMED DOWN



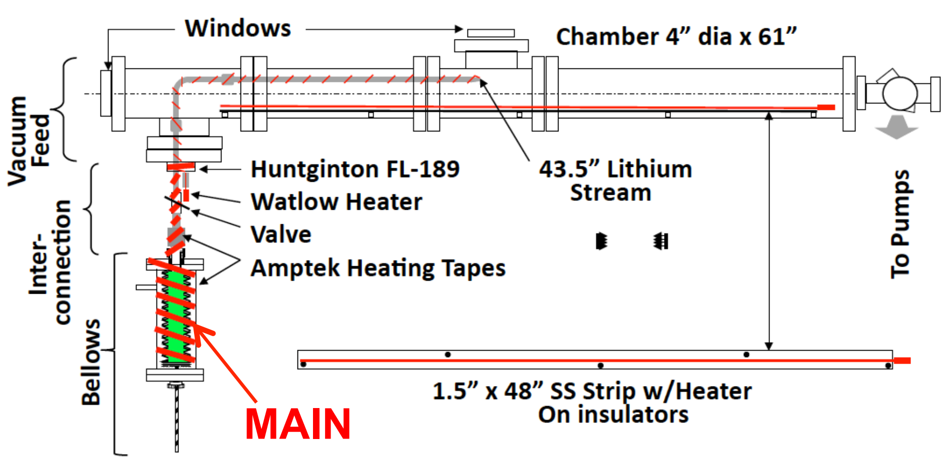
LITER AIMED UP

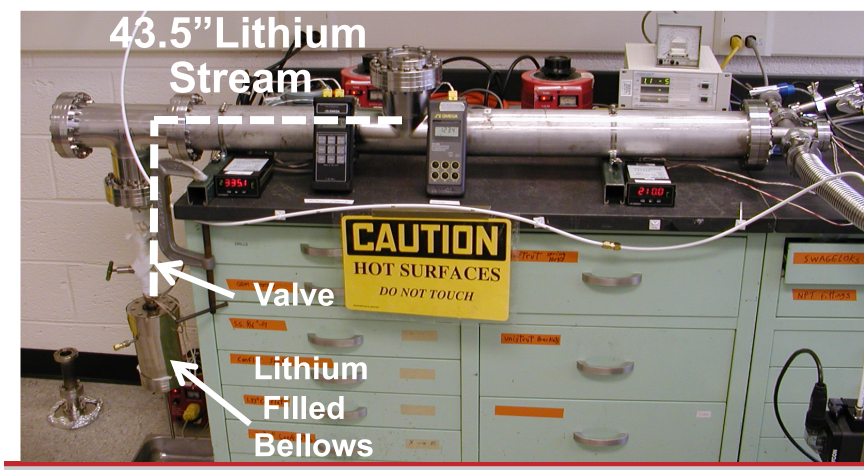
- Loading LITER–Up using LIFTER requires new Fill Stands

Near Term Option 3a:
Coat Upper Divertor Using LITER-Fast

- Use 2 Upper LITERs for coating Lower Divertor, and a new technology, LITER-Fast for coating Upper Divertor
- Requirements for LITER-Fast
  - + to eliminate the thermal inertia of a large reservoir of liquid lithium, perform directed 1-2 min, flash evaporation of 200mg of lithium from suitable crucible
  - + to eliminate shutters and associated failure modes provide for fast cool-down(~5 min) using a suitable coolant
  - - Requires precise refill of fast-crucible from outside the vessel using e.g., LIFTER, MAIN, EM injector, or other method
- Issues:
  - - requires R&D
  - - requires ports, controls,..

LIFTER = Liquid LIthium Filler for LITER
MAIN FILL = MAnaged INjection FIller for Liquid Li

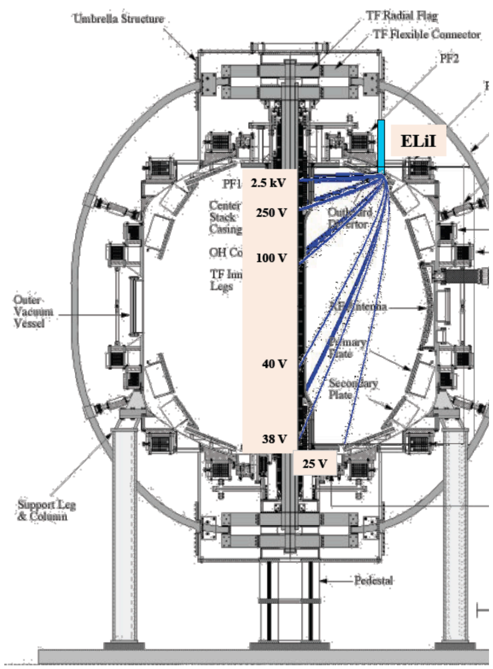




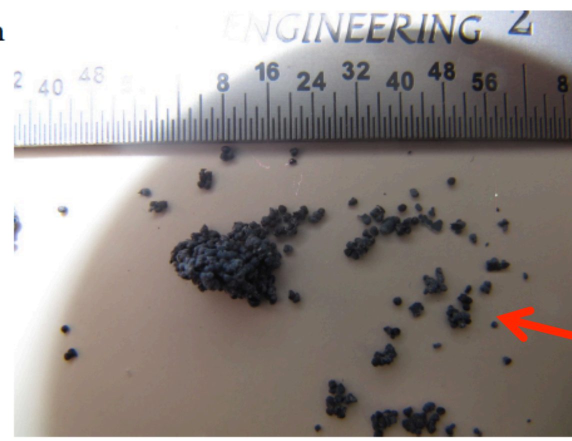
Near Term Option 3b:
Coat Upper Divertor Using Electrostatic Injection

- Electrostatic Lithium Injector (ELiI) is under development at UIUC (Andruczyk et al)
  - Charged 200 μm lithium droplets are formed and accelerated to a biased target
    - \+ might be relatively simple
    - \- present embodiment requires biasing the target
    - \- 200 mm granules propelled; uniform surface coatings need to be demonstrated

DROPLET TRAJECTORIES TO BIASED CS



- Parameters:
  - Li temperature $T_{Li} \approx 220$ °C
  - Backing pressure $P_o = 3.5$ atm
  - Initial velocity measured $v \approx 60$ cm/s
- The particles that sprayed out collected on the wall and plates.
- The particles were small:
  - D ≈ 50 μm -1000 μm



Above: Lithium particles that have deposited on the wall of vacuum vessel.

Left: Some examples of the sprayed particles from ELiI.

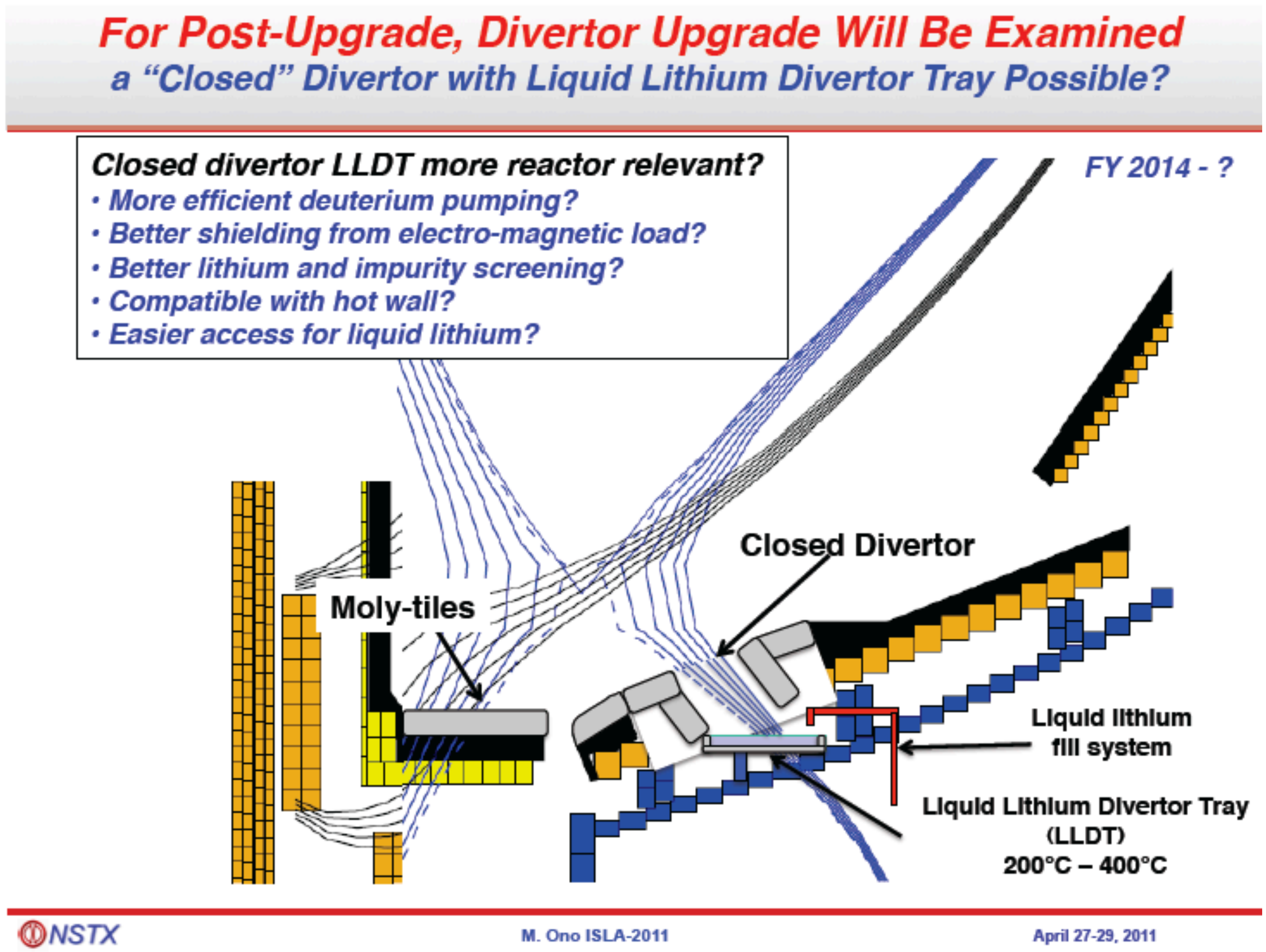
Research and Development Procedure for LLD-2

- An analysis in progress of 5 proposed flowing liquid concepts indicates common questions that impact the selection fabrication, installation, and operation of a reliable flowing liquid divertor system for NSTX-U
  - Proposed concepts.
    1. Toroidal Closed Divertor Lithium Tray on Outer Divertor (M. Ono)
    2. KTM Lithium CPS (I. Lyublinski)
    3. Flowing Liquid Lithium System (FLiLi, L. Zakharov)
    4. Steady-State Soaker Hose (J. Goh)
    5. Lithium/Molybdenum Infused Trenches (LiMIT, D. Ruzic)

- Questions resulting from this analysis are being used to derive the proposed 2012-2014 experiments and testing.

Concept-1: Toroidal Closed Divertor Li Tray on Outer Divertor - A Location and Geometry Concept

- Several embodiments are possible to minimize installation issues and experimental constraints
- Needed 2012-2014 experimental data:
  - what is optimum D retention Li surface
  - Li rate of flow
  - Li inlet design
  - Li drain design
  - Li external heating
  - Li external metering
  - Li external purification
  - will it restart after cooling



M.Ono

Concept-2: KTM Lithium Capillary Porous System (CPS)

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РОСАТОМ

Location of the lithium divertor module

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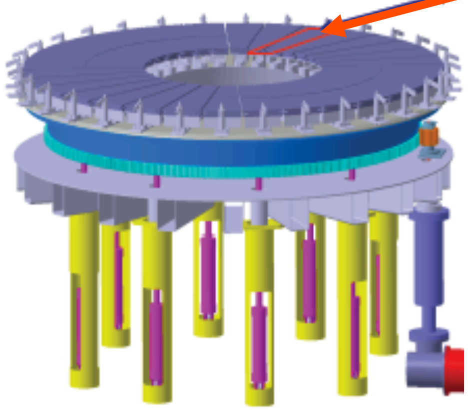
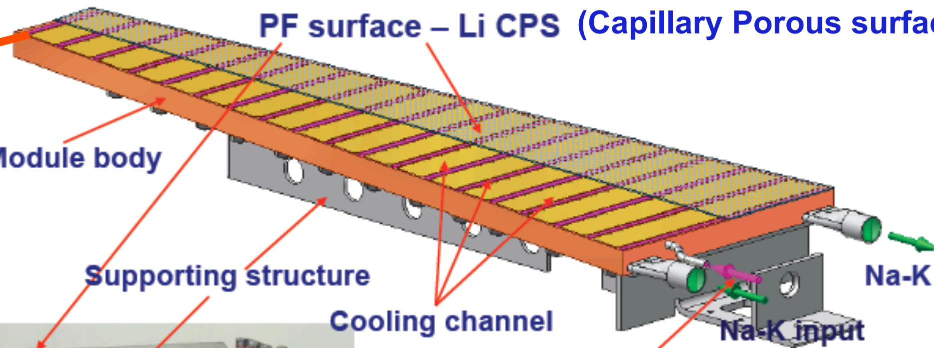
РОСАТОМ

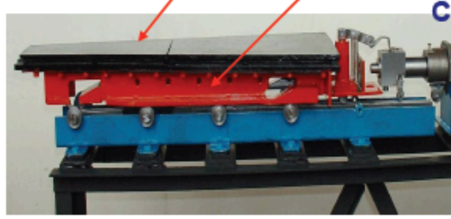
Design and location of the lithium divertor module for KTM

In-vessel unit

Module of lithium divertor will be placed on supporting structure of KTM







The 2[nd] International Symposium on Lithium Application for Fusion Devices
Princeton, New Jersey, USA, April 27 – 29, 2011

I. Lyublinski

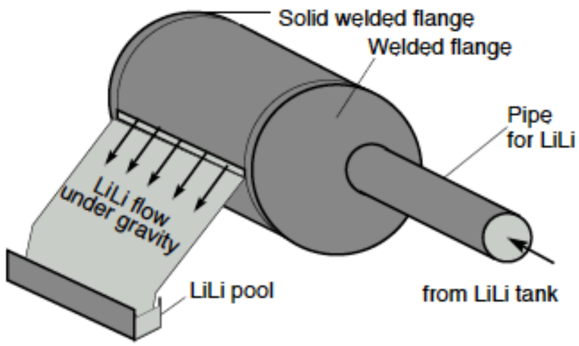
The 2[nd] International Symposium on Lithium Application for Fusion Devices
Princeton, New Jersey, USA, April 27 – 29, 2011

- what is optimum D retention Li surface
- Li rate of flow
- Li external metering
- Li external purification
- will it restart after cooling

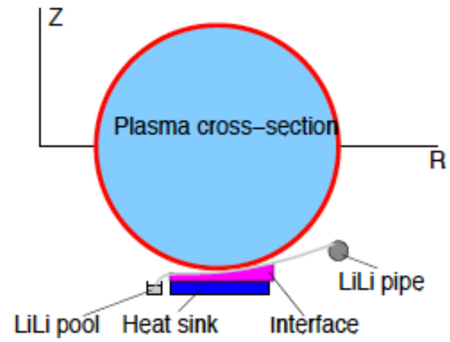
Concept-3: Flowing Liquid Lithium System

FLiLi R&D path

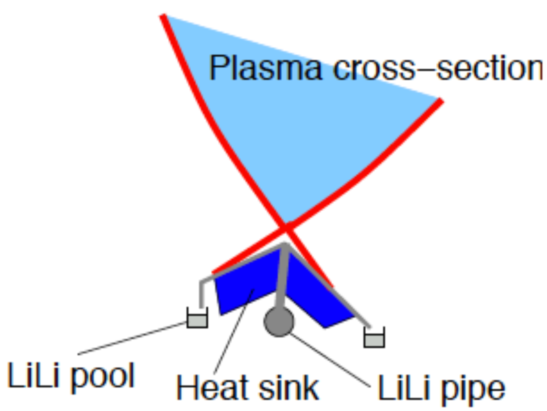
11/13



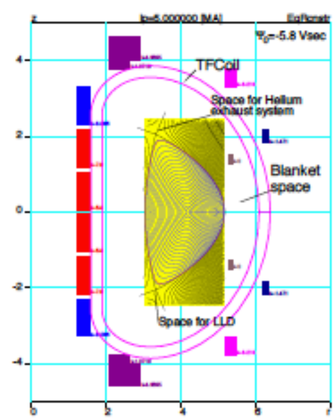
(a) workbench prototype



(b) Toroidally extended SSS-FLiLi on HT-7



(c) FLiLi for EAST



(d) From EAST to 100 MW FFRF

Thin layer FLiLi is consistent with vision on fusion development

Leonid E. Zakharov, HT-7 Data Meeting and Workshop, July 19-20, 2011, ASIPP, Hefei, Anhui, China

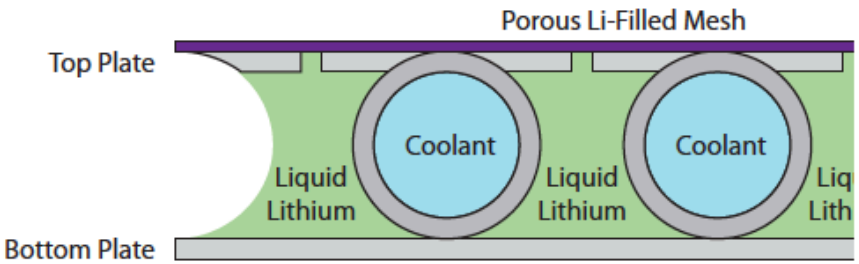
PPPL THEORY

- Requires either a toroidal or radial conic section flow surface with heat sink. Could be applicable at the Concept-1 location.

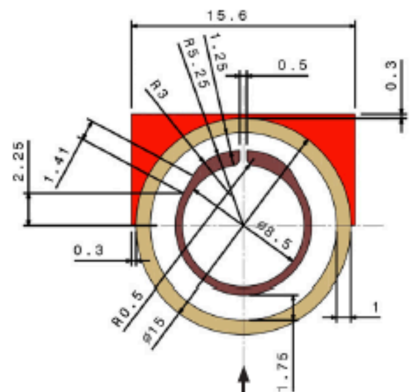
- Needed 2012-2014 experimental data:
  - optimum surface for Li wetting
  - optimum substrate for survivability during disruptions
  - Li rate of flow
  - Li input design
  - Li drain design
  - Li external heating
  - Li external metering
  - restart after cooling

L. Zakharov

Concept-4: Steady-State Soaker Hose



Ihli et. al: *Design and performance study of the helium-cooled T-tube divertor concept*



'Soaker Hose'-Style Liquid Lithium Divertor
'Coolant': Simple Turbulent Pipe Flow or ARIES T-Tube

- Actively-cooled liquid-Li divertor feasible for NSTX-U type heat flux
- 9% heat flux to evaporation with complex solution (T-Tubes)
- 37% heat flux to evaporation w/ simple solution (CO2 pipe flow)
- Li evaporation effectively clamps system temperatures
- Protects divertor from very high heat fluxes: safety factor/temps O.K.

PRINCETON UNIVERSITY

Concept Development and Engineering Considerations of a Steady-State Lithium-Coated Divertor
2nd International Symposium on Lithium Applications for Fusion Devices, 29th April 2011

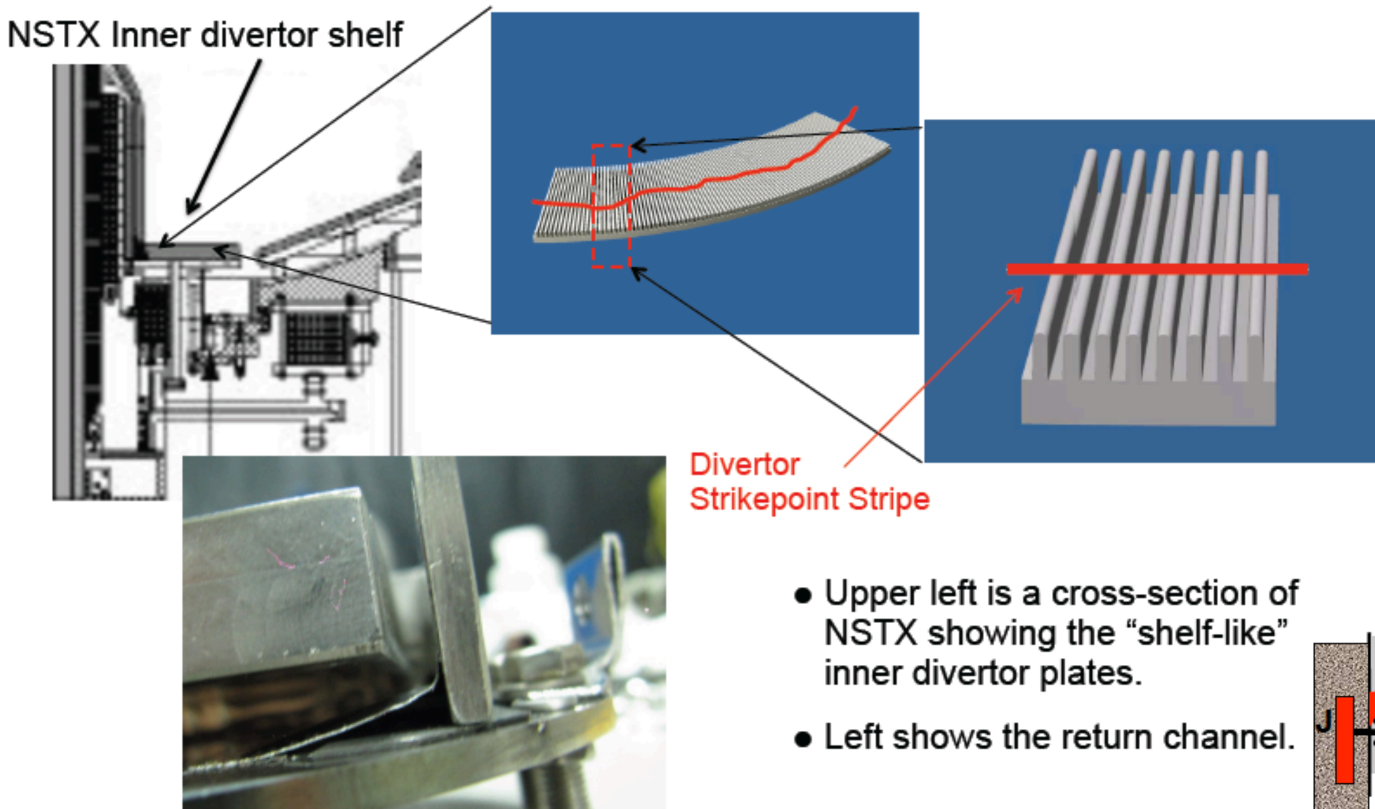
PPPL

- Could be applicable at the Concept-1 location.
- Needed 2012-2014 experimental data:
  - Li compatible bonding of mesh surface to edge supports & tubes needed
  - optimum surface for Li wetting & restart after cooling
  - Li rate of flow
  - Li input design
  - Li drain design
  - Li external heating
  - Li external metering
  - restart after cooling

J.Goh

Concept-5: Lithium/Molybdenum Infused Trenches on Inner Divertor

Heat-Flux Removal: “LiMIT” Design in NSTX [1]



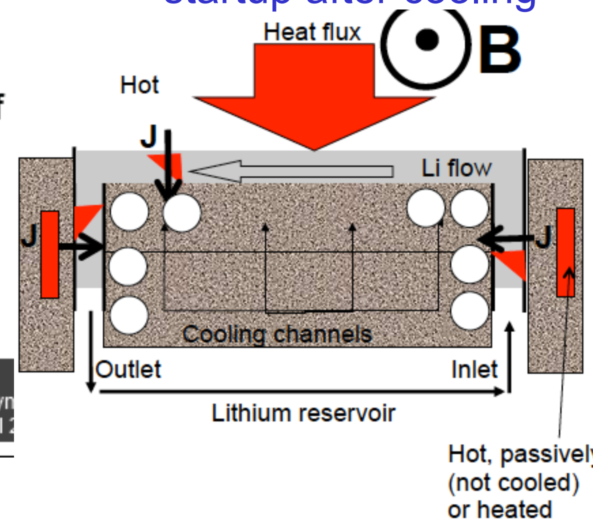
- Upper left is a cross-section of NSTX showing the “shelf-like” inner divertor plates.
- Left shows the return channel.

CPMI http://cpmi.uiuc.edu
Center for Plasma-Material Interactions

PPPL Lithium Syn
April 2

D.Ruzic

- Needed 2012-2014 experimental data:
  - propulsion in 1-2T?
  - disruption forces?
  - optimum D retention
  - Li surface wetting
  - Li rate of flow
  - Li input design
  - Li drain design
  - Li external heating
  - Li external metering
  - startup after cooling



2012-2014 Laboratory Experiments at PPPL, & Machine Experiments at EAST, FTU, KTM,.. Could Provide Guidance for Design of NSTX-U Flowing Liquid Divertor System

- Analysis of 5 proposed flowing liquid concepts indicates common questions that impact the selection, fabrication, installation, and operation of a reliable flowing liquid divertor system for NSTX-U.

- How does D retention in CPS mesh behave in presence of high power densities?

- How does the selected liquid lithium substrate wet, accumulate impurities, effect D retention versus vacuum impurities, discharge impurities, and operating temperature.

- Will continuous impurity buildup impede restart after cooling? What is the required maximum system temperature for restart? Is it is best to drain system before cooling?

- What is the range of Li flow rates as determined by D retention, impurity accumulation, and long term reliability.

- What is the optimum substrate, heating fluid, and technique for the NSTX-U environment?

- How to provide diagnostics for real-time Li surface quality indication, internal and external Li flow measuring, reliability during operations.

- Power-handling *versus* particle control: How does the selected liquid lithium substrate wet, accumulate impurities, effect D-retention *versus* vacuum impurities, discharge impurities, and operating temperature.

Summary and Conclusions

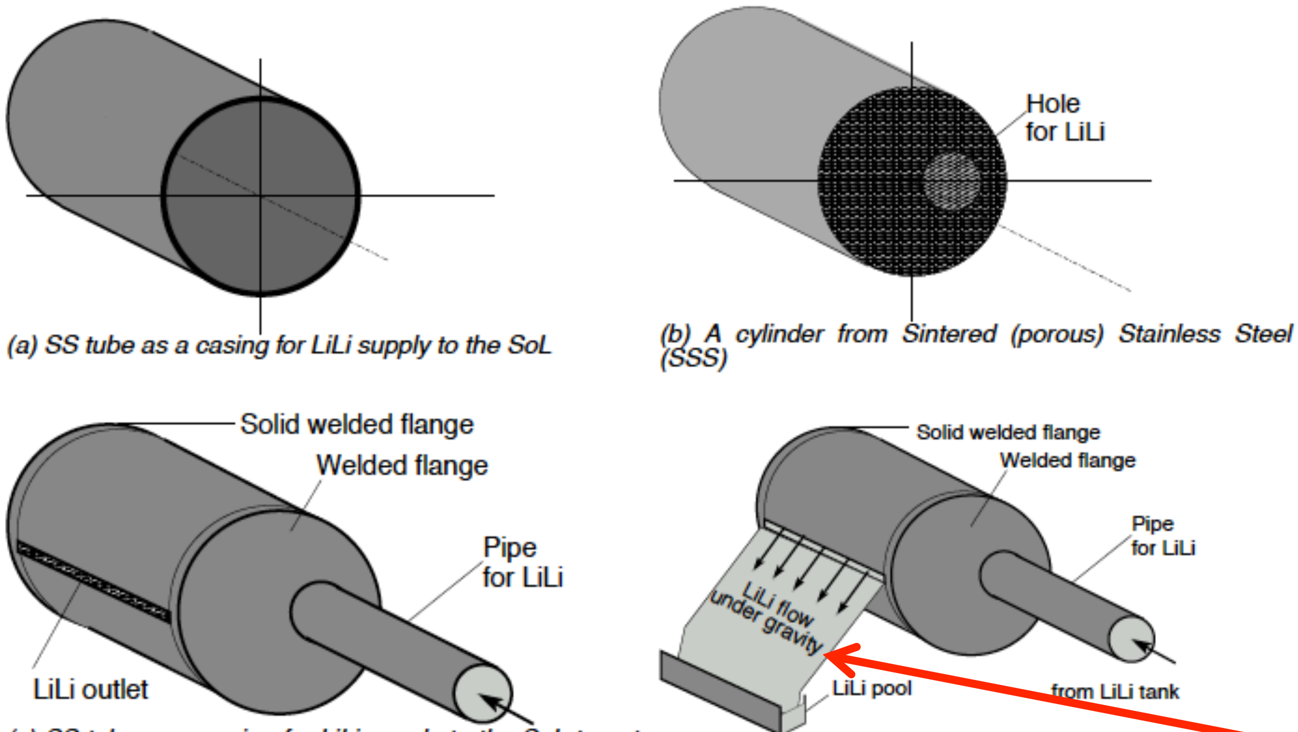
- Year-1 Lithium Startup Options
  1. Coat Lower Divertor using:
     2 Upper 2011-LITERs (this provides 2 spares)
  2. Coat Lower Divertor and Upper Divertor using:
     2 Upper 2011-LITERs for Lower Divertor
     and 2 Lower 2011-LITERs for Upper Divertor (provides no spares)
  3. Coat Upper Divertor using new technologies:
     2 Upper 2011-LITERs for Lower Divertor
     and new technologies for Upper Divertor
     a. LITER-Fast (200mg flash w/fast cool-down)
     b. Electrostatic Injection (UIUC)

- NSTX-U research progress beyond present lithium coatings and passive liquid lithium surfaces requires:
  - maintain a chemically-active, moving, liquid lithium divertor surface
  - capability to be solidified and re-liquefied for recirculation many times
  - diagnostic capability to measure flow and surface quality between discharges

Backup

Concept-3: Flowing Liquid Lithium System

5 Sintered SS filter for FLiLi system



(a) SS tube as a casing for LiLi supply to the SoL

(b) A cylinder from Sintered (porous) Stainless Steel (SSS)

(c) SS tube as a casing for LiLi supply to the SoL target surface

(d) LiLi flow from a tank to a pool (heaters not shown)

Mo or SS bonded to heat sink

Heaters should be engineered, everything else is straightforward.

Leonid E. Zakharov, HT-7 Data Meeting and Workshop, July 19-20, 2011, ASIPP, Hefei, Anhui, China

PPPL THEORY

L.Zakharov

Concept-5: KTM Lithium Capillary Porous System (CPS)

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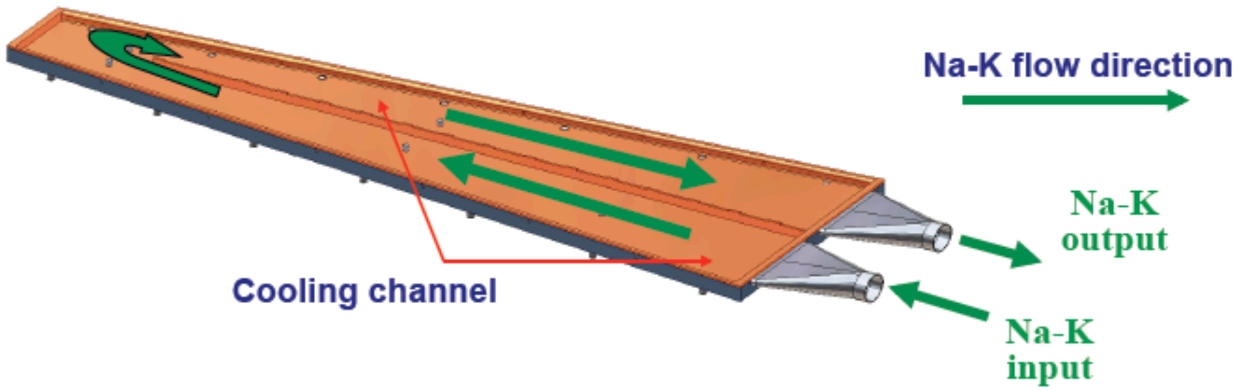
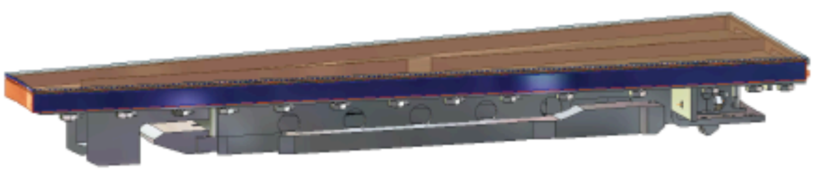
РОСАТОМ

In-vessel unit

Internal structure of module

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





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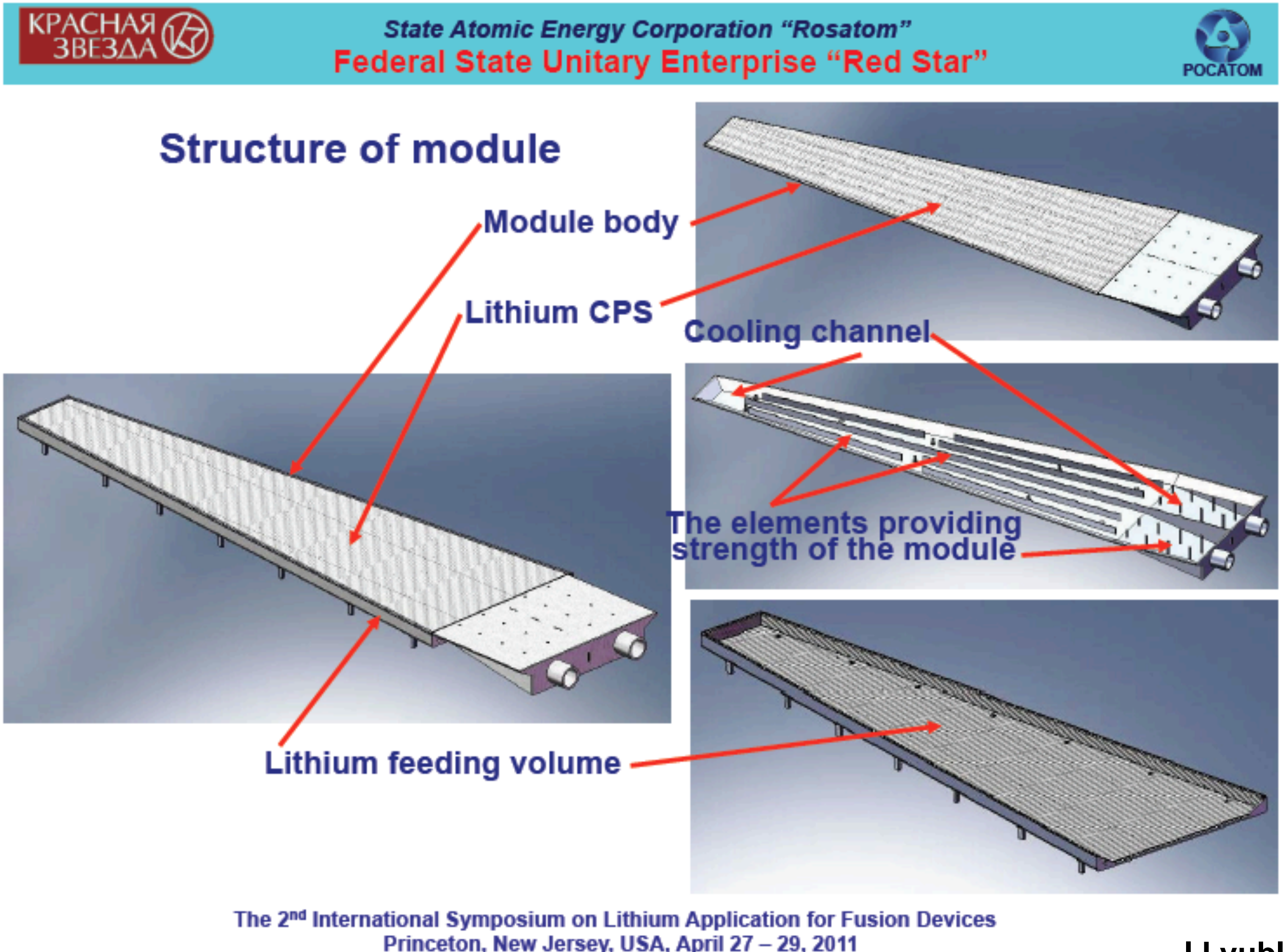
Concept-5: KTM Lithium Capillary Porous System (CPS)



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РОСАТОМ

Lithium divertor module manufacturing

Lithium module in the process of electron beam welding

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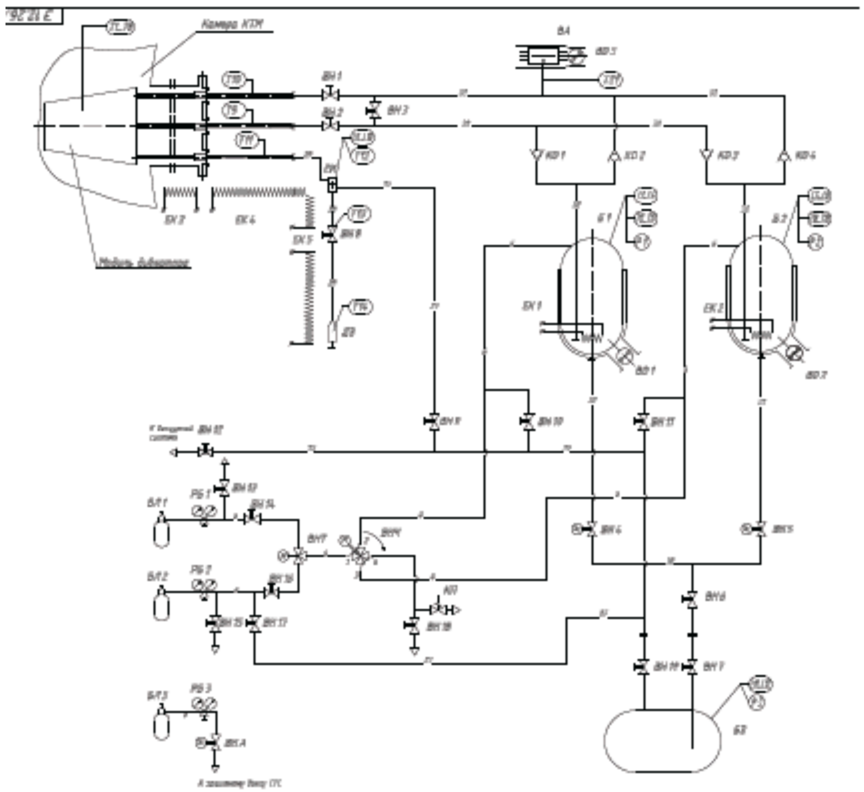
РОСАТОМ

Cooling of lithium divertor module in-vessel unit will be provided by thermal stabilization external (out-vessel) system



Heat transfer media is Na-K eutectic alloy with melting point - 11°C

Scheme of thermal stabilization external (out-vessel) system including all elements of liquid metal system

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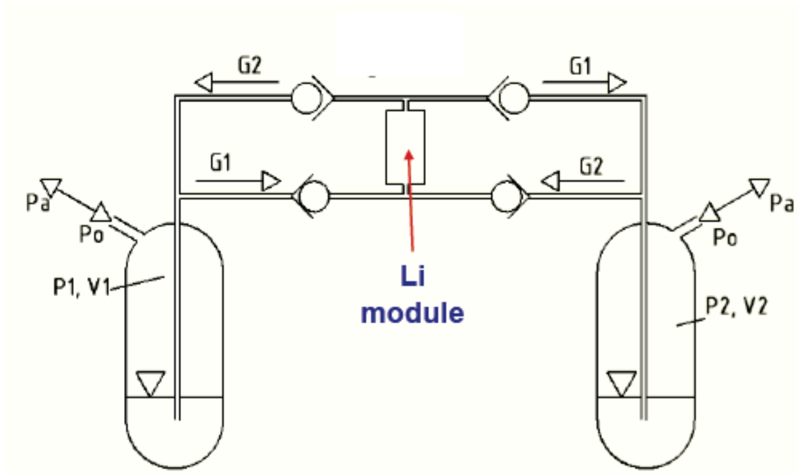
РОСАТОМ

Circulation of liquid metal in the module occurs by means of cyclic pump of the limited quantity of metal from tank in tank. The system of check valves provides a metal flow in only one direction



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PNEUMATIC PUMP

I.Lyublinski

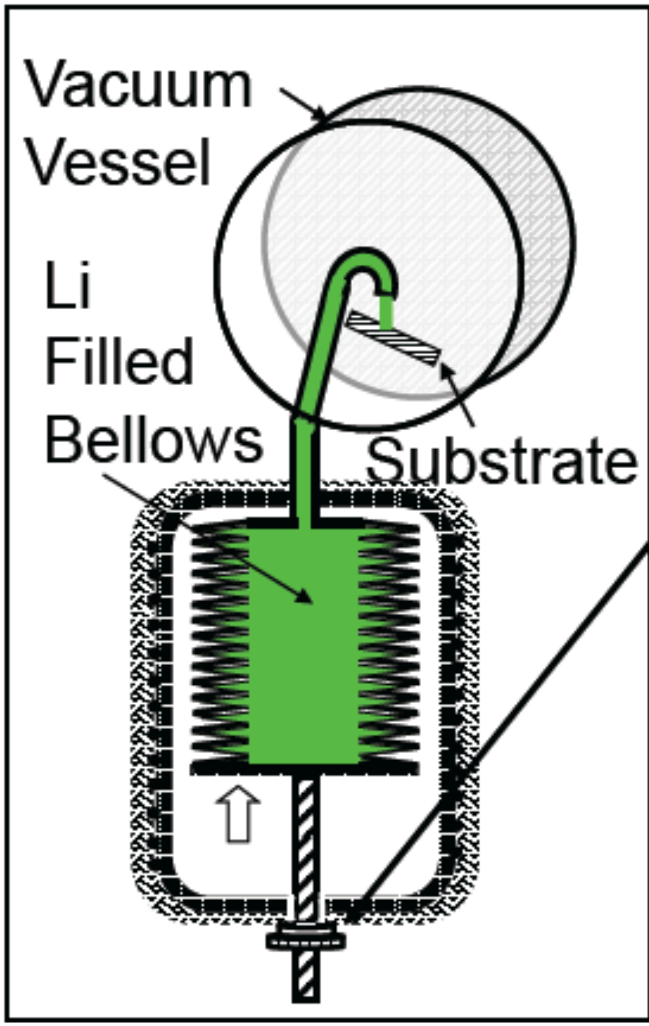
Pathway for Development of a Clean, Continuously Moving, Liquid Lithium Divertor Surface for NSTX-U

- The R&D pathway to develop this capability could proceed as follows:
  1. Test simple-as-possible Single-Pass and Cyclical Flow concepts
  2. Characterize simple-as-possible operation in tokamak-like vacuum
  3. Characterize behavior in vacuum of candidate NSTX PFC prototypes
  4. Move portable candidate PFC to high power density source & characterize
  5. Characterize PFC in applied magnetic fields with high power densities

- The Proposed R&D
  - The goal would be to assemble a simple facility to accomplish R&D Steps 1, 2, and 3
  - The developed system should be portable enough to enable the performance of Steps 4 and 5 on a suitable Test Stand

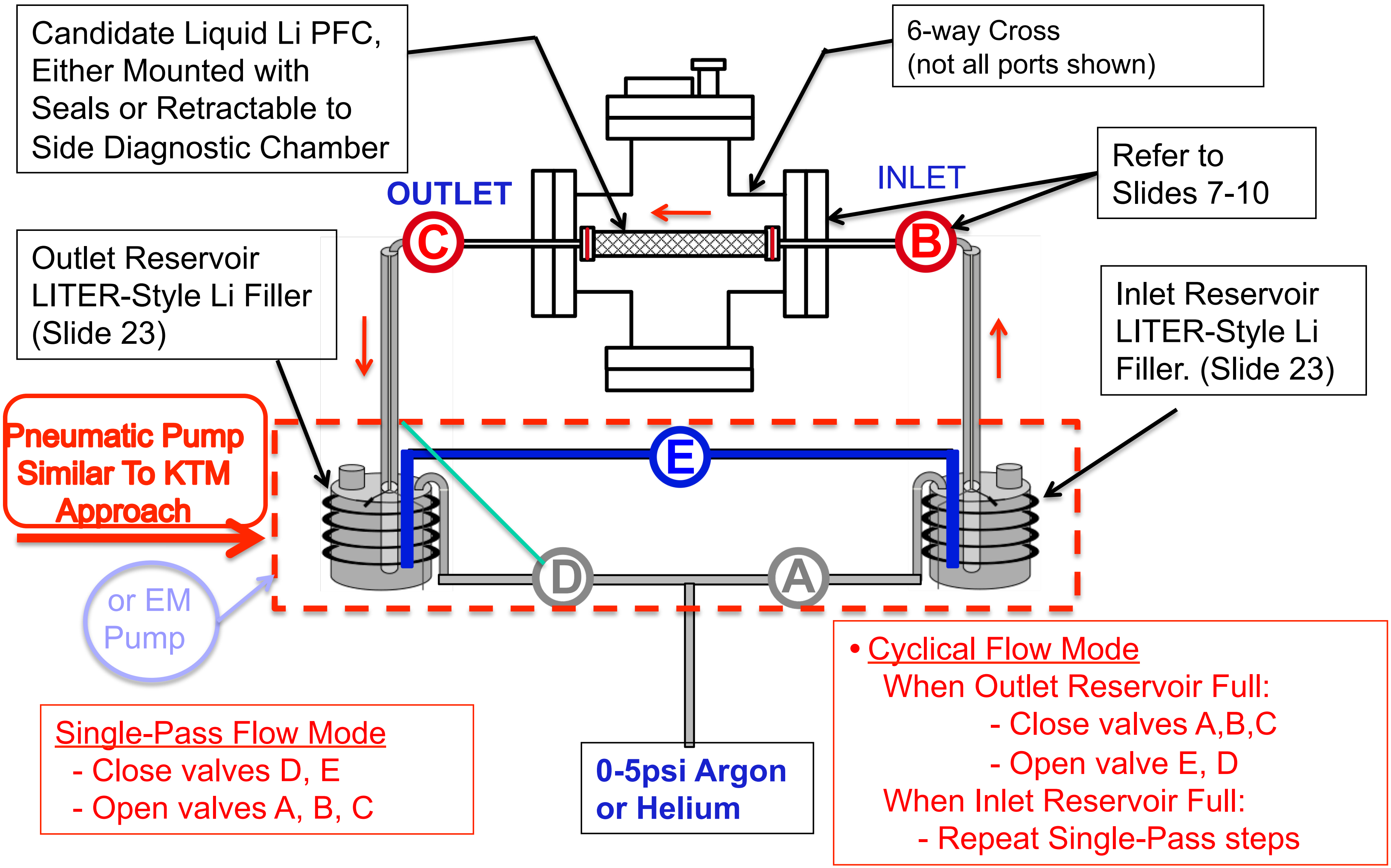
Existing Technology and Capability to be Leveraged to Implement this Work - LITER Loader developed in 2010

- MAnaged INjection FIller for Liquid Li



In this simplified cartoon, the MAIN FILL method consists of a bellows filled with molten lithium and compression using a precision threaded rod and nut for controlled amounts of liquid lithium to be applied to a substrate in vacuo – argon gas not required to move lithium as in LIFTER.

Schematic of Possible Near Term Liquid Lithium Test Facility
- Pump Port, Heating, GDC, Instrumentation, and Diagnostics Not Shown



XP-1: Test Simple-as-Possible Single-Pass and Cyclical Flow Concepts

- Single-Pass Liquid Lithium Flow Testing at Best Achievable Vacuum
  1. Using micro-grooved Mo(TZM) tray, measure flow rates at 250,300, 350, 400°C versus He and Ar propellant pressures
  2. At each temperature, record RGA (H_2O, CO, CO_2, C_xH_y ...), and e-beam induced surface luminosities for surface characterization
  3. Cool and restart 3 times at temperature and propellant pressure for fastest and most uniform flow rate from Step 1

- Cyclical Liquid Lithium Flow Testing at Best Achievable Vacuum
  1. Using grooved Mo(TZM) tray, measure flow rates at 250-400°C versus He and Ar propellant pressures
  2. At each temperature, record RGA (H_2O, CO, CO_2, C_xH_y ...), and e-beam induced surface luminosities for surface characterization
  3. Cool and restart 3 times at temperature and propellant pressure for fastest and most uniform flow rate from Step 1

XP-2: Characterization of Vacuum Interactions

- LiqLi Cyclic Flow Testing Using Variable Vacuum
  1. Using grooved Mo(TZM) tray, select temperature and propellant pressure for fastest and most uniform flow rate as determined from XP-1
  2. Using the controllable leak, raise vacuum pressure from baseline to 10^{-7} Torr, and then to 10^{-6} Torr using H_2O
  3. At each pressure, record RGA(H_2O, CO, CO_2, $C_xH_{y\,...}$), and e-beam induced surface luminosities for surface characterization
  4. Repeat steps 2 and 3 using CO
  5. Repeat steps 2 and 3 using CO_2
  6. Repeat steps 2 and 3 using CH_4

XP3: Characterize Vacuum Interactions and Restart Capabilities of Candidate NSTX-U Prototypes

1. Using the temperature and propellant pressure for the conditions providing the fastest and most uniform flow rate from XP-1 and XP-2 for the Mo(TZM) micro-groove tray, repeat XP-1 and XP-2 using the following candidate PFCs
   - Mo(TZM) CPS candidate (mesh on tray)
   - Mo(TZM) LIMITS grooved tray (e.g., 2mm wide x 10mm deep grooves)
   - 304SS reference grooved tray
2. Using the temperature and propellant pressure for the conditions providing the fastest and most uniform flow rate from XP-1 and XP-2 , and the above steps, investigate the ability of ArGDC to facilitate restarting the flow from room temperature conditions. Compare the use of the PFC as either the anode or cathode for the GDC. Also vary the PFC temperature.
3. Investigate comparing the above results by replacing the propellant reservoirs with a suitable EM pump.