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NSTX-U

Design and construction of a lithium vapor box similarity experiment

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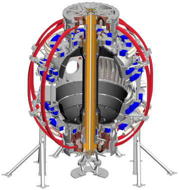
PPPL



Abstract

Future fusion devices will require handling extreme heat fluxes. The lithium vapor box divertor is a concept to manage this heat flux. The divertor plasma impinges on a dense cloud of lithium vapor, leading to volumetric cooling, radiation, and recombination. The vapor is localized by baffles and condensation on the divertor slot walls upstream of the target, limiting the lithium reaching the main chamber. A series of test stand experiments will study vapor confinement and plasma plugging in a simplified baffled-pipe geometry. A first experiment without plasma will validate a DSMC model for evaporation, flow, and condensation of lithium vapor. Three stainless steel cylindrical cans will be heated to 550°C, 600°C, and 650°C respectively inside a vacuum chamber. Lithium flow will be measured by weighing the cans before and after heating and by calorimetry of the latent heat of the vapor. Progress on the experiment will be presented.

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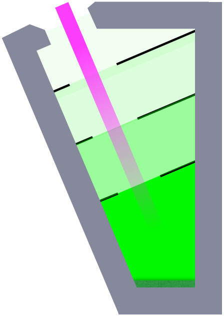
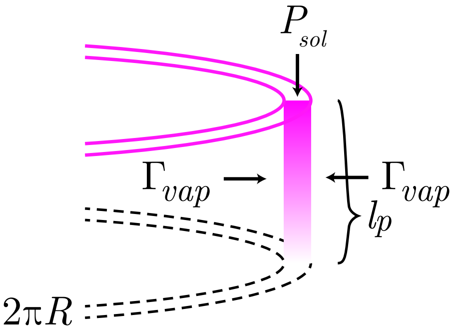
Lithium Vapor Box Divertor seeks stabilized detachment

- Need to dissipate $\sim$100MW of power in ITER.
- Li vapor radiates plasma power in bottom chamber
- Additional chambers, baffles condense escaping vapor
- Increasing vapor density along field line aims to stabilize detachment front.



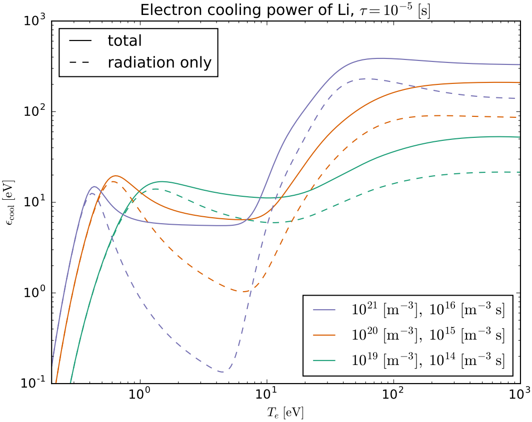
Required vapor density determined by radiation per atom



$\Gamma_{vap} = n_{vap}\sqrt{T_{vap}/2\pi\, m_{Li}}$. $P_{sol} = 2\pi R\, l_p\, \epsilon\, \Gamma_{vap}$.

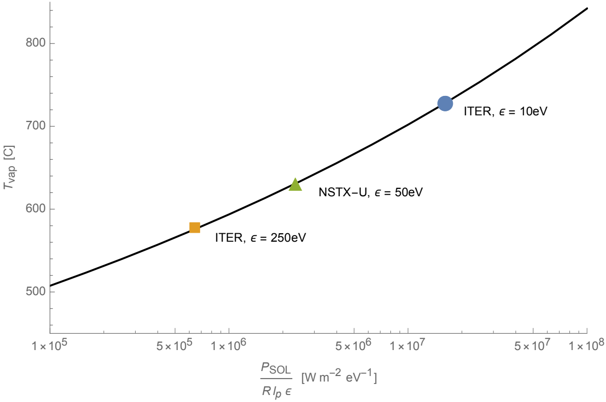
- Γ_{vap} matches plasma power
- Use additional $n * l$ as ELM buffer

Li cooling per atom calculated with ADAS collisional radiative model



Electron cooling energy of a single injected neutral atom at $n_e = 10^{19}\ \mathrm{m}^{-3}$ to $10^{21}\ \mathrm{m}^{-3}$ and a specified T_e and over a lifetime of $\tau = 10^{-5}$ s.

NSTX-U, ITER require reasonable vapor temperatures for wide range of ϵ



Temperature required to generate enough Li vapor such that the entire P_{SOL} is radiated by Li atoms entering the plasma, as a function of $P_{SOL}/Rl_p\epsilon$. Three example points are given: ITER ($P_{SOL} = 100$ MW, $R = 6.2$ m, $l_p = 10$ cm) at $\epsilon = 10$ eV and $\epsilon = 250$ eV, and NSTX-U ($P_{SOL} = 10$ MW, $R = 0.85$ m, $l_p = 10$ cm) at $\epsilon = 50$ eV.

Test concept using scaled experiments at PPPL and Magnum-PSI

- 6 cm diameter experiment at PPPL.
  - Test vapor flow and condensation

  this poster

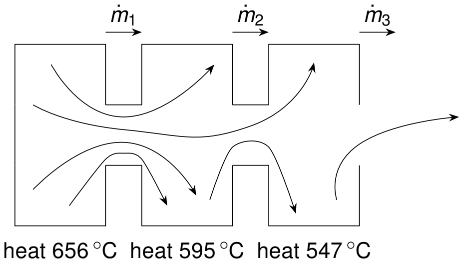
- 15 cm diameter experiment at Magnum-PSI.
  - Plasma plugging
  - Detachment
  - Power redistribution

Experiments scaled to match flow regime of NSTX-U-sized LVBD, to validate code

- Use cylindrical cans instead of toroidal slot
- Select wall temperatures to match Knudsen Number λ_{mfp}/L.
- Compare experiment to Direct Simulation Monte Carlo neutrals code.

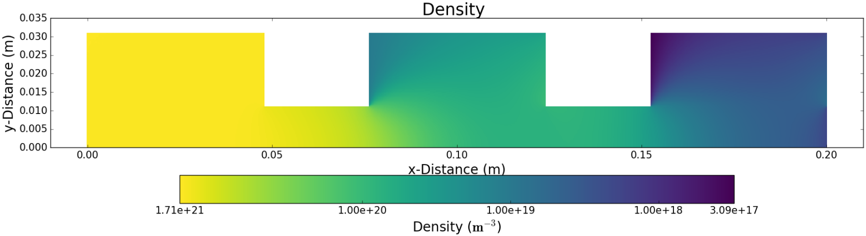
	NSTX-U	Kn		PPPL	Magnum-PSI
T_3[°C]	350	0.44	T_3 [°C]	547	520
T_2[°C]	475	0.14	T_2 [°C]	595	563
T_1[°C]	625	0.045	T_1 [°C]	656	617

Measure vapor transport without plasma



1. Place 10 g Li in first chamber.
2. Hold constant T_{wall}.
3. Wait 1 hour.
4. Measure masses in each chamber to 0.01g.

Direct Simulation Monte Carlo code predicts vapor flow



Simulation by E. Emdee. See his poster **PP11.00094**.

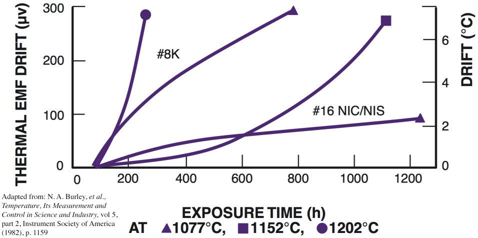
Lithium vapor flowing out of each box:

PPPL box	T[°C]	$\dot{m}$[mg/s]	m [g/hour]	Δm [g]
3	300	0.016	0.057	+0.47
2	450	0.15	0.53	+8.6
1	650	2.5	9.1	-9.1

Vapor flow model validation by measuring mass changes vs temperature

- ±3.6 K temperature measurement corresponds to ±10% mass flow rate.
- Use ***Type N*** thermocouples: avoid drifts of Type K. Will use an RTD to calibrate.

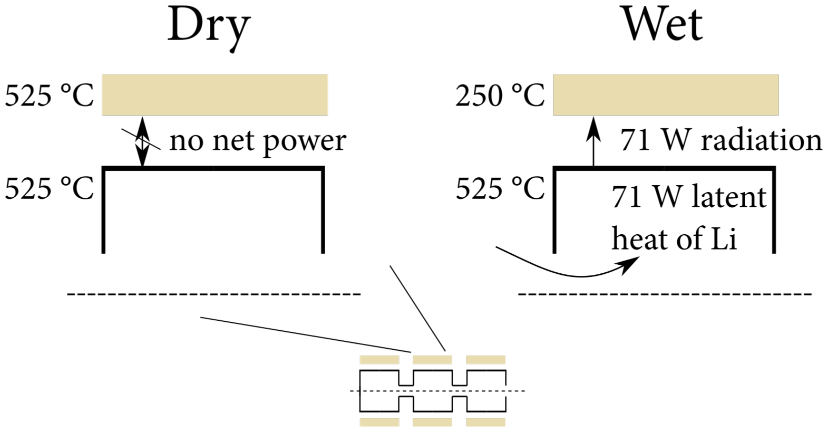
Type N may reduce drifts by 0.5-2K



Adapted from: N. A. Burley, *et al.*, *Temperature, Its Measurement and Control in Science and Industry*, vol 5, part 2, Instrument Society of America (1982), p. 1159

Use calorimetry as second check on vapor flow model

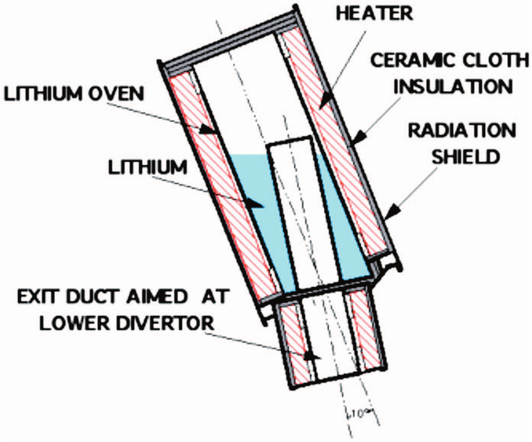
Different heater temperatures for box at same temperature:



Future Work

- Better understand thermocouple measurement technique; limits of accuracy..
- Construct experiment to study vapor flow at PPPL.
- Develop thermal (radiative and conductive) model to support DSMC model validation.
- Validate DSMC model by studying vapor flow: a tool for designing toroidal-experiment or reactor-scale vapor box schemes.
- Design and construct 15-cm scale experiment for Magnum-PSI or another linear plasma divertor simulator device.
- Test whether vapor can effectively redistribute plasma's power, spread heat footprint.

Construction and safety issues similar to LITER



from Kugel et al, Physics of Plasmas **15**, 056118 (2008).

Using same type of mullite ceramic heaters as LITER.


1) In glovebox, fill first box with 10g Li
Argon glovebox with nitrogen scrubbers prevents Li contamination
Fill fraction of 20g Li
2) Move to experimental chamber
Transfer Assembly in glovebox antechamber
3) Ramp up box temperature to 650 °C
Temperature history during heating
°C
1000
800
600
400
200
0.0
0.1
0.2
0.3
0.4
0.5
hours
Heater
Shield
Box
Overcoming latent heat loss due to Li efflux
Radiation power ~ T4
Radiative heating simulation
using simple cylindrical geometry, assumed emissivities, heat capacities, 'choked flow' Li vapor flow model
4) Hold for one hour
ONE HOUR
Li flowed expected to be ~9g: greater than the ~0.75g during heating and ~0.3g during cooldown
5) Turn on He gas feed to cool
Temperature history during cooling
°C
1000
800
600
400
200
0.0
0.1
0.2
0.3
0.4
0.5
0.6
hours
Heater
Shield
Box
Convective cooling plus radiation and Li latent heat flow (as in heating simulation)
6) Transfer to glovebox to weigh change of Li in each box
MS603TS weighs up to 620g with repeatability 0.001g. Through subtraction, this allows measuring Li that has exited the third box to 2%.
PPPL box
Δm [g]
'Efflux out of 3rd nozzle'
0.057g
3
+0.47
2
+8.6
1
-9.1
Predictions
Box dry mass 400g
Vapor box detail
Graphite spray coating on nozzles and box front walls increases emissivity to keep joints hotter than boxes by a ~few K
Box body
2.5" OD seamless tube, 0.049" wall
Nozzle
1" OD tube
2
1
vapor flow
Stopper
inserted for transfer from vacuum vessel to glovebox. 100nm of oxidation (~mg mass changes) would not ruin measurement, though.
Welded construction
vacuum welds prevent dripping
Inner nozzle
prevents liquid Li from 'walking' into nozzle
Reflective heat shields
Keeps nozzle hotter, closer to temperature of box 1
Demountable butt joint wrapped with shimstock. Boxes disassemble for weighing.
Thermocouple feedthrough
Supports up to 25 thermocouples via 50-pin D-sub. Uses copper pins.
Possible future site for QCM / real-time Li deposition monitor
Supporting rods
Proper positioning and retrieval of boxes; support for T/C wires
Drip tray & Li catcher
Prevents wires and flanges from being directly coated
8" CF flange
unbolted to move Transfer Assembly into glovebox
Temperature measurements
Example thermocouple locations
Use Type N thermocouples for increased stability over Type K: decreases error ~0.5-2K
Macor UHV D-sub connectors
Allow disassembly for weighing.
Operates to 300 °C
15 pins: 7 T/C pairs each
Uses Type K pins rather than copper: temperature gradients likely here.
Type N pins not found.
Additional boxes
12-T/Cs for temperatures of Heater Assembly
Error due to copper pins estimated to be < 1K.
25-T/C feedthrough.
Copper pins.
2 x NI 9213
total 32 T/C channels
PC with LabView
Gas feed system
Helium and argon: cooling and backfilling.
Designed to fill chamber to 1 atm at 80 L / minute: fill in 120s.
30psi regulators, 1/4" tube
He
Ar
Shutoff and regulator valves
Swagelok SS-4H bellows-sealed valve
Should hold vacuum.
Gas feedthrough
25 pin D-sub feedthrough, copper pins
For thermocouples on heater assembly
Power feedthrough
for 2160 W of heaters
Radial build
Vapor box nozzle
Vapor box body
Support rods 1/8" steel
space for cooling gas
Ceramic heaters to 1200°C
Alumina spacer
Heat shield+support stainless steel
1/4" stainless tube cooling gas feed
8020 aluminum supports
cantilevered from 16.5" flange
16.5" CF flange
unmounts for maintenance
Vacuum chamber
Volume of 0.2 cubic meters. Desired base pressure 10-6 torr. Has turbo backed by roughing pump, with a bypass of the turbo to allow a continuous 80 L / min gas feed.
Transfer Assembly
Heater Assembly
Vacuum vessel