A lithium vapor box test stand experiment

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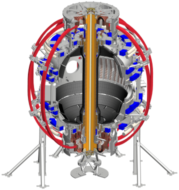
APS DPP, San Jose, CA, Nov 3rd



Motivation

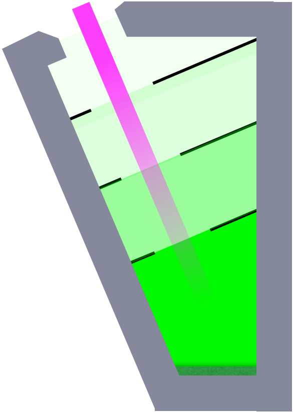
- Solid divertors can only work with $> 90\%$ volumetrically radiated power
  - SOL widths appear not to scale with reactor R, leading to very high parallel heat fluxes
  - angles between $\vec{B}$ and a divertor plate are limited by engineering tolerances, preventing arbitrarily low heat fluxes on a plate.
- Detached divertors with gas puffing can lead to MARFEs when the detachment front is unstable[1] [2] .

It is desirable for a divertor technology to have a large stability window, or a physics-based feedback mechanism.

The lithium vapor box divertor (VBD)

- A chamber filled with lithium vapor with margin in *nl* to extinguish the maximum expected heat flux.
- Lithium evaporates from the lowest chamber and is redeposited at upper chambers.
- To prevent efflux of vapor, create shocks by making baffles reflecting: have the baffle temperature greater than the local vapor density's saturation temperature:

$$n_{\mathrm{eq}}(T_{\mathrm{baf}})\sqrt{T_{\mathrm{baf}}} > n_{\mathrm{vap}}\sqrt{T_{\mathrm{vap}}}$$



Vapor box comparison to gas puff

In contrast to gas puffing detachment schemes, with the vapor box divertor,

- gas must be pumped, but vapor is condensable by cool surfaces.
- a strong gradient of impurity density may yield stable detachment.
- higher power input should quickly evolve more vapor.
- controlling wall temperatures provides control over heat extraction as a function of position

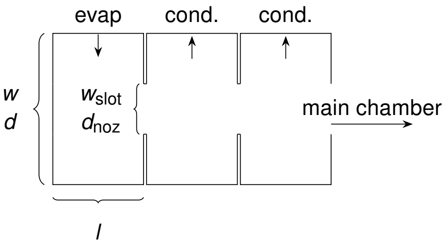
Validating this concept before tokamak use

Open questions with the VBD:

1. Can the Li cloud be contained by baffles and condensing surfaces, both without and with plasma?
2. What Li vapor density yields detachment?
3. Can the plasma power be transmitted to latent heat of Li to spread heat over large areas?
4. When detached operation is reached, how much Li is advected/diffused upstream in the plasma toward the core?

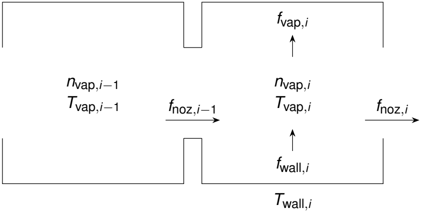
A cylindrical-geometry test stand with similar T_{vap}, n_{vap}, n_e can test this concept.

Li vapor flow without plasma determines possible operating mode



- Specify geometry and wall temperatures
- Choked flow through nozzles/slots
- Assume that vapor in the center of the boxes is homogenized by standing shocks.

Simple model describes 0-D solution for n boxes



This model solves for $n_{\text{vap},i}$ and $T_{\text{vap},i}$ from flows f of vapor into and out of the ith chamber. Only the geometry and $T_{\text{wall},i}$ must be specified. Model from [3].

$$f_{\text{wall},i}\ [\text{s}^{-1}] = A_{\text{wall},i}\Gamma_{\text{Lang},i} \qquad f_{\text{noz},i}\ [\text{s}^{-1}] = 0.6288 A_{\text{noz},i} n_{\text{vap}}\sqrt{\frac{kT_{\text{vap},i}}{2\pi m_{\text{Li}}}}$$

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Implementation for an NSTX-U sized device

Geometry $R = 1\,\mathrm{m}$, $l = 10\,\mathrm{cm}$, $w = 15\,\mathrm{cm}$, $w_{\mathrm{slot}} = 5\,\mathrm{cm}$.

	1	2	3
T_{wall} °C	625	475	350
T_{vap} °C	625	617	617
n_{vap} m^{-3}	8.09×10^{20}	2.42×10^{20}	6.86×10^{19}
p_{vap} Pa	10	2.98	0.843
Mass flow kg/s	1.91×10^{-3}	5.69×10^{-4}	1.61×10^{-4}
Mass flow kg/h	6.87	2.05	$\boxed{0.580}$
Latent heat flow kW	40.7	12.1	3.43
Enthalpy flow kW	5.14	1.52	0.43
Kn	0.0356	0.119	$\boxed{0.42}$

Efflux from last box $>$ 300g/h indicates that vapor box **should not** be kept hot between shots. Knudsen number in the 'transitional' regime (0.01-10) means a fluid model is not strictly applicable.

A simple detachment model

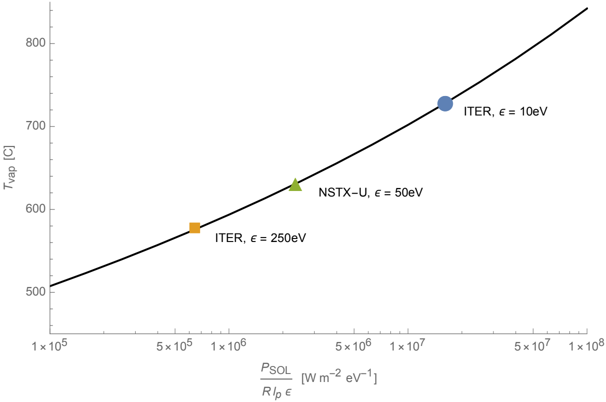
Estimate the Li vapor temperature requried to dissipate energy of the divertor plasma in the final vapor box chamber.

- Lithium vapor flux into each side of the plasma sheet is $n_{\mathrm{vap}}\sqrt{kT_{\mathrm{vap}}/(2\pi m_{\mathrm{Li}})}$
- Each Li atom dissipates ϵ eV of energy.
- Two-sided area of plasma sheet is $2 * 2\pi R\ l$.

$$P_{sol} = 4\pi R\ l\ n_{\mathrm{vap}}(T)\sqrt{\frac{T_{\mathrm{vap}}}{2\pi\ m_{\mathrm{Li}}}}\ \epsilon$$

Limitations: value of ϵ is not well understood: not constant for each atom, and varies by divertor conditions. **2D effects** such as the thickness of the divertor plasma could prevent neutral Li from cooling the center.

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 ($P_{SOL} = 100\,\mathrm{MW}$, $R = 6.2\,\mathrm{m}$, $l_p = 10\,\mathrm{cm}$) at $\epsilon = 10\,\mathrm{eV}$ and $\epsilon = 250\,\mathrm{eV}$, and NSTX-U ($P_{SOL} = 10\,\mathrm{MW}$, $R = 0.85\,\mathrm{m}$, $l_p = 10\,\mathrm{cm}$) at $\epsilon = 50\,\mathrm{eV}$.

Radiative cooling estimated with CR ADAS database

Can estimate ϵ using a collisional-radiative model:

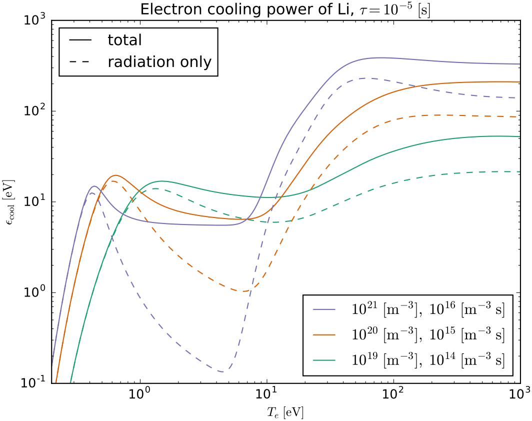
- Specified n_e, T_e for a hydrogen plasma.
- Li atoms enter as neutrals and ionize, radiate.
- Li particles are lost with a characteristic decay time τ.

$$\begin{aligned}\frac{\partial n_{(i)}}{\partial t} &= n_e n_{(i-1)}\,\mathrm{SCD}_{(i-1)} - n_e n_{(i)}\,\mathrm{SCD}_{(i)} \\ &+ n_e n_{(i+1)}\,\mathrm{ACD}_{(i+1)} - n_e n_{(i)}\,\mathrm{ACD}_{(i)} \\ &- n_{(i)}/\tau\end{aligned} \qquad \frac{\partial n_{(0)}}{\partial t} += 1/\tau$$

$$L_z = \left(\mathrm{PLT}_{(i)} + \mathrm{PRB}_{(i)}\right) \qquad \epsilon = L_z n_e \tau$$

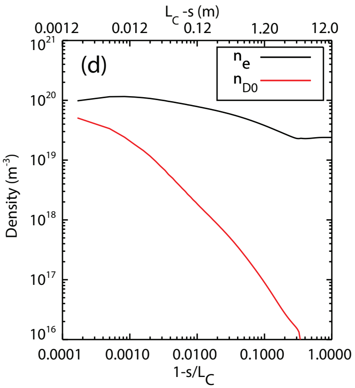
Rates SCD, ACD, PLT, PRB(n_e,T_e) from ADAS. Does not account for transport: local density and temperature change over time, and the decay time τ can only be estimated.

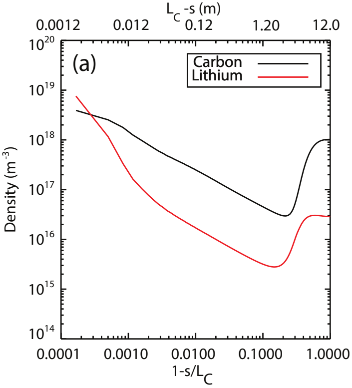
Cooling per ion strongly varies with plasma parameters



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

Li concentration varies by ×800 in simulations





Simulations along the SOL of NSTX, from F. Scotti's thesis [4]

c_{Li} varies from 0.08 to 10^{-5} $\Longrightarrow$ Include this effect in models.

Theory for Li transport in a low-impurity-fraction plasma

Forces on impurities in a hydrogen-dominated plasma: [5, 4]:

$$m_z \frac{d}{ds_\parallel}\left(n_z v_z^2\right) = m_z n_z \frac{v_i - v_z}{\tau_s} + Zen_z E + n_z(\alpha_e + \beta_i)\frac{dT}{ds_\parallel}$$

- Electric force $F_E = Zen_z E$
- Temperature gradient force $F_{\boldsymbol{\nabla} T} = n_z(\alpha_e + \beta_i)\frac{\partial T}{\partial s_\parallel}$
- Friction force $F_f = m_z n_z \frac{v_i - v_z}{\tau_s}$
- No impurity pressure force — trace impurity limit

Where $\alpha_e = 0.71 Z^2$; $\quad \beta_i = \frac{3(\mu + 5\sqrt{2}Z^2(1.1\mu^{5/2} - 0.35\mu^{3/2}) - 1)}{2.6 - 2\mu + 5.4\mu^2}$

$$\mu = \frac{m_z}{m_z + m_i}; \quad \tau_s = \frac{1.47\times 10^{13}\frac{m_z}{m_p} T_z \left(\frac{T_i}{m_i/m_p}\right)^{1/2}}{\left(1 + \frac{m_i}{m_z}\right) n Z^2 \log(\Lambda)}$$

A test-stand experiment

Without plasma at PPPL, and then *with* plasma on Magnum-PSI at DIFFER.

- Several vapor box chambers to study the flow of Li
  - coupled by valves, so that the first chamber can be heated without introducing Li into the second.
  - be able to be disassembled
    - measurement of mass change due to Li buildup
  - outfitted with thermocouples
    - to measure temperature at several points on their surface
    - infer radiated power
  - with heating power of a few kW per chamber
  - and similar amounts of cooling power, for steady-state experiments on Magnum-PSI
    - with cooling-fluid calorimetry to measure energy transport

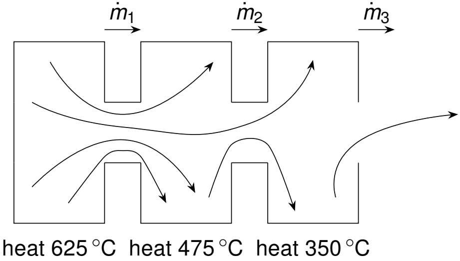
Test stand with matched Kn is reasonable size

3 boxes of $l = 15\,\mathrm{cm}$, $d = 15\,\mathrm{cm}$, $d_{\mathrm{noz}} = 5\,\mathrm{cm}$.

T_{wall} °C	617	561	514
T_{vap} °C	617	569	522
n_{vap} m^{-3}	8.01×10^{20}	2.43×10^{20}	6.94×10^{19}
p_{vap} Pa	9.84	2.82	0.762
Mass flow kg/s	1.18×10^{-5}	3.47×10^{-6}	9.64×10^{-7}
Mass flow g/15min	$\boxed{11}$	3.1	0.87
Latent heat flow W	251	73.9	20.5
Enthalpy flow W	3.14×10^{1}	8.75	2.3
Kn	3.59×10^{-2}	1.18×10^{-1}	4.15×10^{-1}
ϵ for $\epsilon A_{\mathrm{wall}} \sigma T^4$ assumed	0.03	0.2	0.1
$\epsilon A_{\mathrm{wall}} \sigma T^4$ W	85.7	334	133
Heating power req'd W	517	300	41

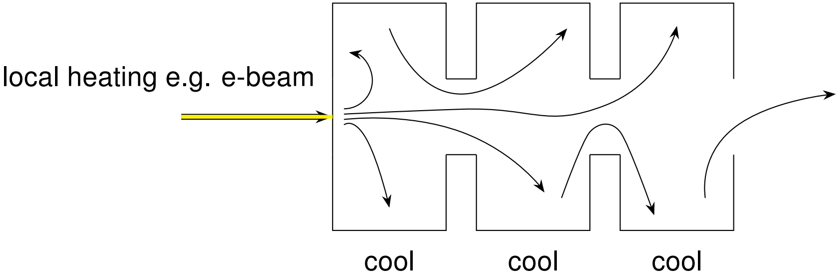
Experiment with heating walls

1. Hold constant T_{wall}.
2. Wait.
3. Measure masses.



- Test the condensation of Li on surfaces to limit efflux
- Validate DSMC models of neutral flow.
- Provides a comparison to the box *with* plasma
  - test plasma plugging of the vapor.

Experiment with non-uniform heating



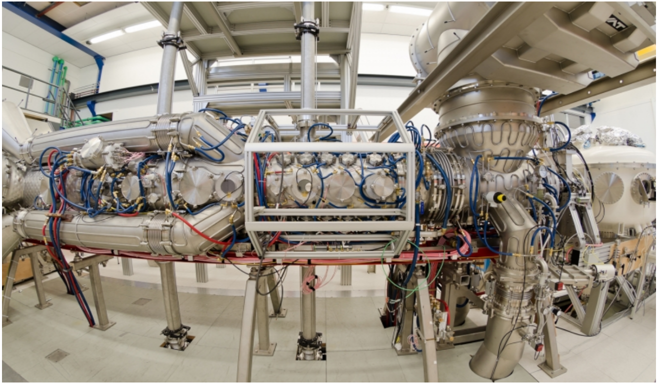
- Test response of the vapor box to localized heating:
  - heating profile should be similar to that of an attached plasma.
- Test for local dryout of Li by measuring the temperature close to heating point

Interpretation and validation: DSMC code

- Typical Knudsen number for flow in the vapor box is between 0.01-1, the ‘transitional’ regime between fluid dynamics and rarefied gas dynamics.
- Traditional fluid code is not appropriate.
- The Direct Simulation Monte Carlo (DSMC) method is suited for this regime[6]:
  - Model Li surfaces as emitting Maxwellian-distributed particles
  - Particles hitting those surfaces are absorbed
  - Surfaces with specular or random-direction reflection

The OpenFOAM code implements a DSMC model that should be suitable.

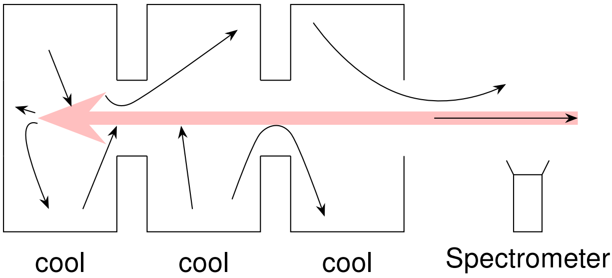
Magnum-PSI provides suitable plasma



Pic from `https://www.differ.nl/magnum_plasma_en`

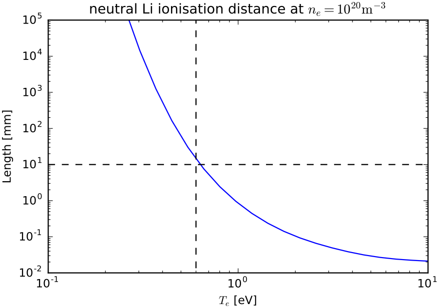
$q_{||} \approx 10\,\mathrm{MW/m^2}$ over a 3 cm diameter, $n_e \approx 2 \times 10^{20}\,\mathrm{m^{-3}}$, $T_e \approx 3\,\mathrm{eV}$.

Experiments at Magnum-PSI



- changes in Li neutral transport with plasma
- vapor box start-up heating by plasma
- the vapor density and temperature required for detachment
- upstream contamination by transport of Li through the plasma
- power deposition profiles

Li ionization length in Magnum-PSI



Typical ionization distance for a Li atom moving at 1km/s at $n_e = 10^{20}\ \mathrm{m}^{-3}$ as a function of T_e.

Li vapor atoms will still ionize in Magnum-PSI as long as $T_e \gtrsim 0.6\,\mathrm{eV}$ and $n_e L \gtrsim 10^{18}\ \mathrm{m}^{-2}$.

Plasma pressure for detachment is OK

Magnum-PSI plasma cylinder $l = 15\,\text{cm}$, $r = 1.65\,\text{cm}$.

Input power [kW]	$n_e[\text{m}^{-3}]$	T_e [eV]	$n_e T_e$ [Pa]
8.5	1.75×10^{20}	3	$\boxed{84}$

ϵ [eV]	Flux $[\text{m}^{-2}\text{s}^{-1}]$	$T_{\text{vap}}[^\circ\text{C}]$	p_{vap} [Pa]
0.95^R	3.6×10^{24}	734	115
6.0	5.7×10^{23}	640	$\boxed{19}$

Calculations for vapor temperature in the 1st chamber to dissipate the plasma input power in Magnum. ^{R} represents cooling energy from radiation only; else includes ionisation energy.

$p_{\text{plasma}} > p_{\text{vap}}$ so the plasma is plugging the vapor.

Experiments inform future models

Perhaps a 1D multi-fluid model with

- radiation and ionization ϵ
- main ion and impurity fluids
- + DSMC neutral vapor transport (loosely coupled)

Or a 2D model like UEDGE or SOLPS if finite SOL width or flow reversal are important.

Summary

- The lithium vapor box divertor is a potential solution to future tokamaks' high SOL power and heat flux.
- We plan to build and test a vapor box simulator to study
  - vapor efflux from the box.
  - redistribution of heat by lithium vapor.
  - necessary lithium vapor density and temperature to create a detached plasma.
  - lithium contamination of plasma upstream of the box.
- The first two of these will be characterized without plasma here at PPPL, and all of them will be studied with plasma input at Magnum-PSI.

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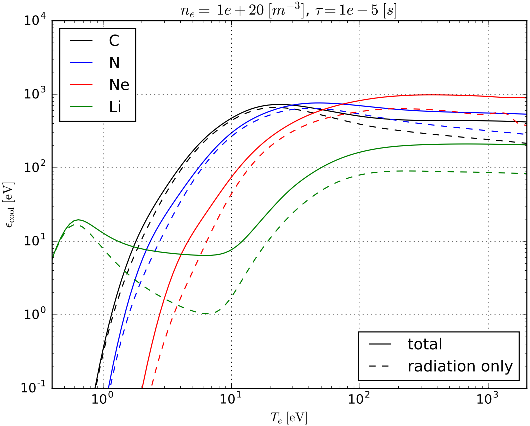
Acknowledgements

Thanks to Chris Jagoe for work OpenFOAM's relevance for VBD design.

This work supported by supported by U.S. DOE Contract No. DE-AC02-09CH11466.

Li is a better coolant than C, N, Ne at low T_e

At this density and lifetime, Li is a stronger electron coolant than C, N, Ne at $T_e < 1.5$eV.



Electron cooling power of C, N, Ne, and Li at $n_e = 10^{20}\ \mathrm{m}^{-3}$ and a specified temperature and over a lifetime of $\tau = 10^{-5}$ s.