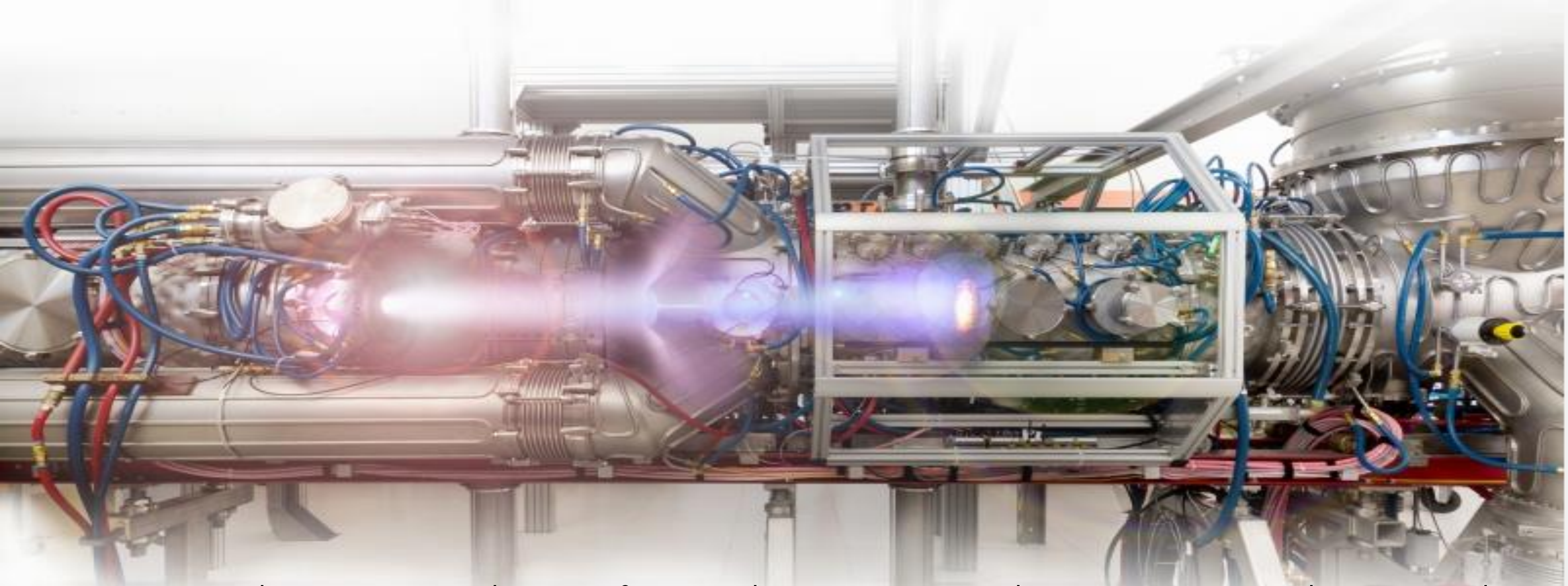
Liquid metal vapour shielding in linear plasma devices



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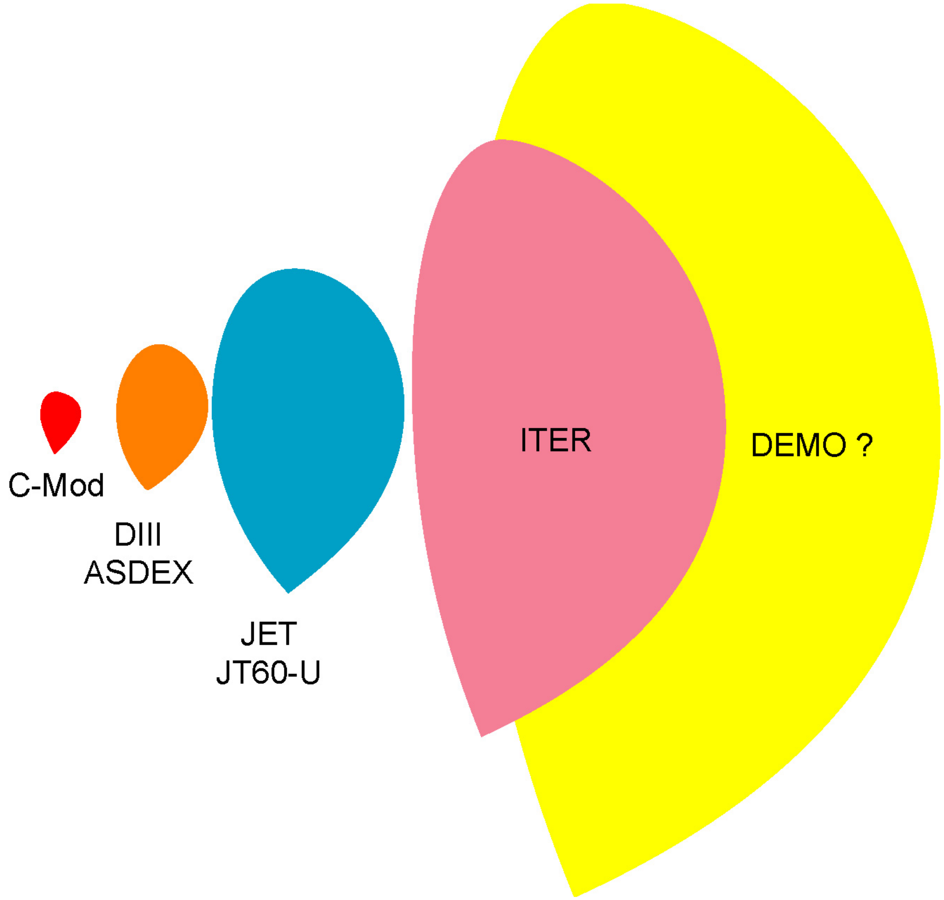
DIFFER
Dutch Institute for Fundamental Energy Research

Going from ITER to DEMO involves large jumps in several parameters



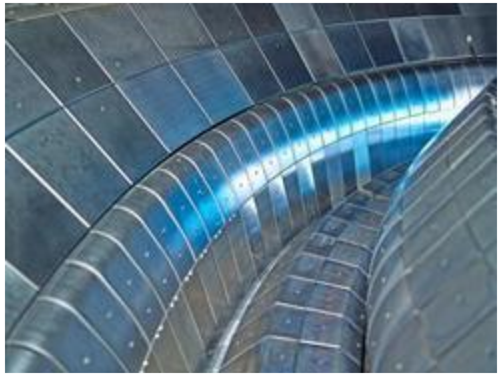
Property	ITER	DEMO[1]
Pulse length	~400 s	~7200 s
Duty cycle	**<2%**	**60-70%**
Neutron load	**0.05 dpa/yr**	**1-9 dpa/yr**
Exhaust power	150 MW	500 MW
Divertor area	~4 m^2	~6 m^2
Radiated power	**80%**	**97%**

Resilience to neutrons and power excursions becomes more important

Courtesy G. Matthews

Limiting factors for W in DEMO

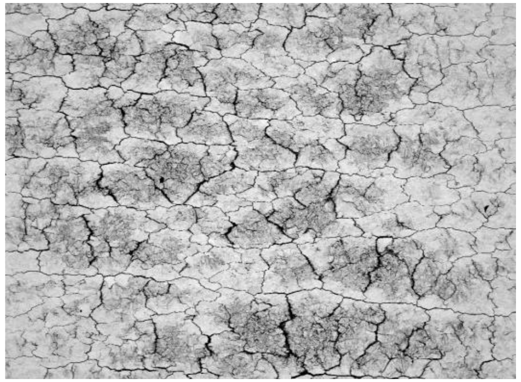
High heat/particles



Erosion

For 5 mm W lifetime ~2 years[1]

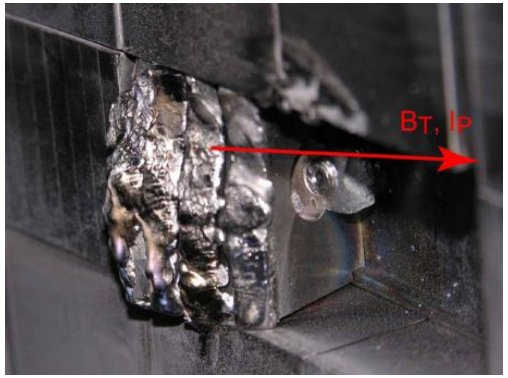
Thermal shock/fatigue



Cracking (small ELM-like loading)[2]

Progressive deterioration[3]

Big ELMs/VDEs/disruptions



Melting- irreversible damage

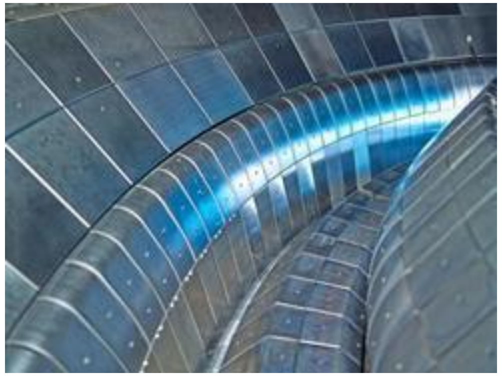
Runaway failure?

[1]Maissonier NF 2007
[2]Linke NF 2011
[3]Loewenhoff FED 2012

Limiting factors for W in DEMO

Neutrons

High heat/particles



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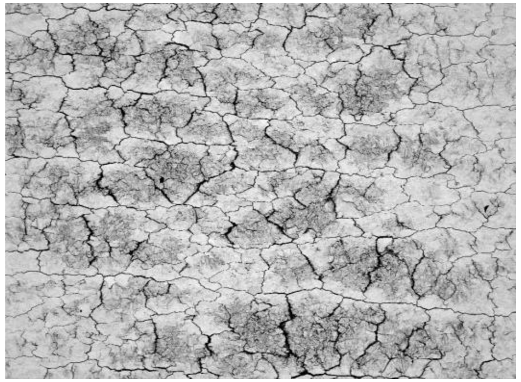

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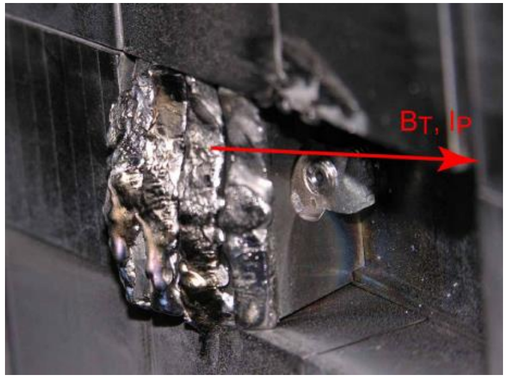


Erosion

For 5 mm W lifetime ~2 years[1]

Cracking (small ELM-like loading)[2]

Progressive deterioration[3]

Melting- irreversible damage

Runaway failure?

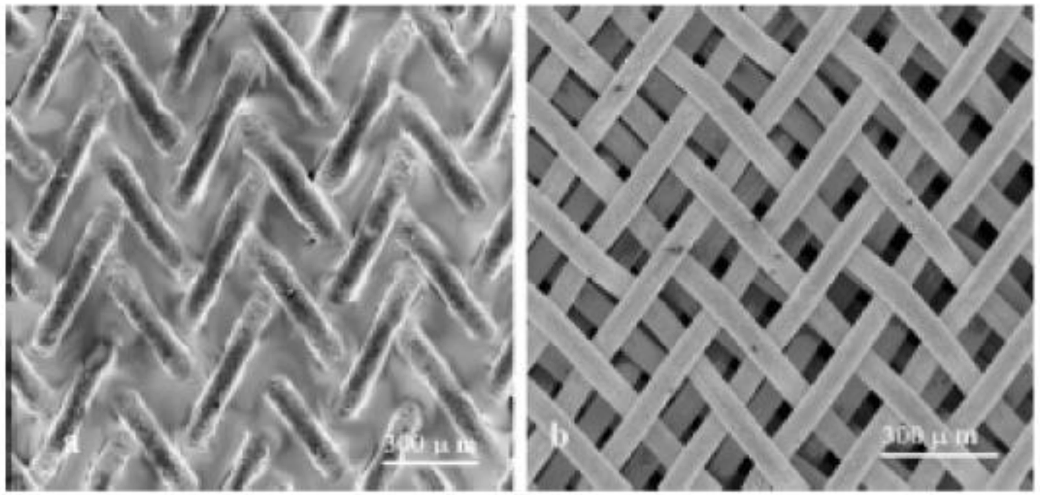
Transmutation, H+He creation, defects

Smaller operational temperature window

Increased brittleness

[1]Maissonier NF 2007
[2]Linke NF 2011
[3]Loewenhoff FED 2012

Capillary porous structures (CPSs) create conduction based stabilized PFCs to contain liquid metals



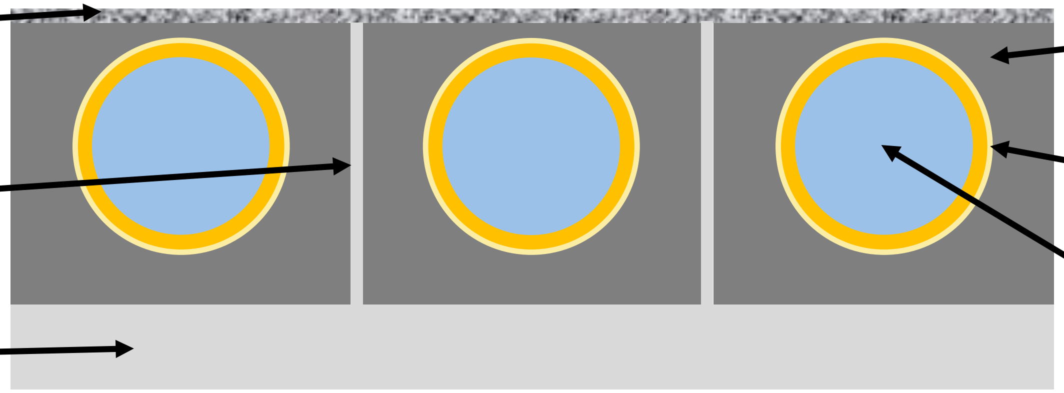
Evtikhin JNM 1999

Replace solid surface with liquid

MHD forces (j x **B**) destabilize liquids in tokamaks (droplets)

Use surface tension/capillary refilling

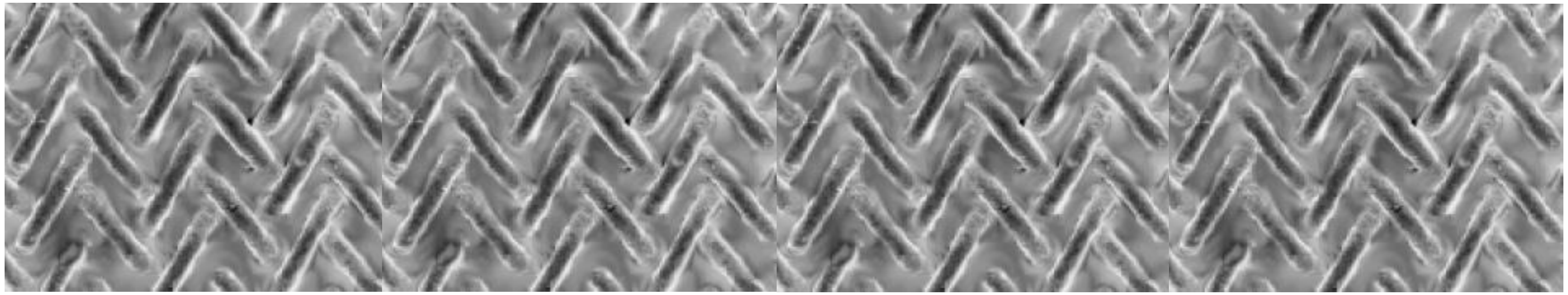
Replace top region with this combined material



Benefits of liquid metals for DEMO

Neutrons

Sputtering | Thermal shock/fatigue | Big ELMs/VDEs/disruptions



Self replenishment

Higher heat fluxes

No cracking

Lowered stresses substrate

ELMs possible(?)

Already molten

Vapour protection

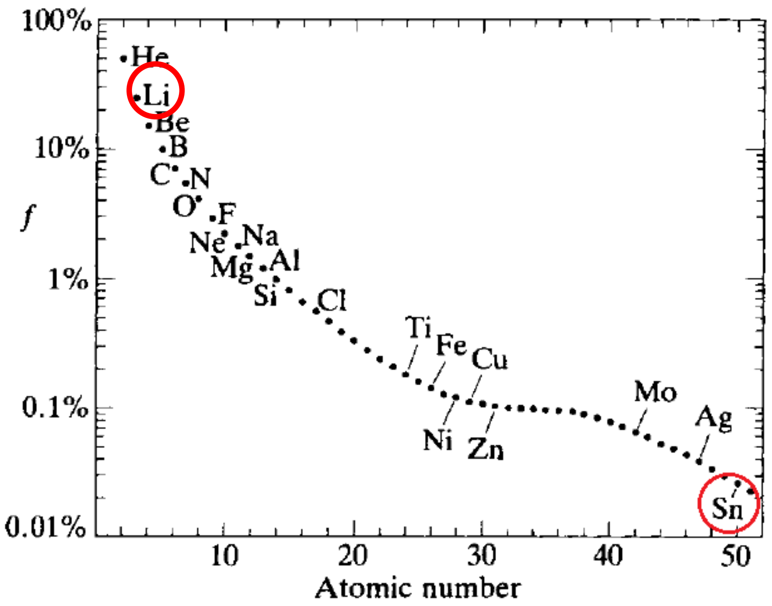
Only influences substrate

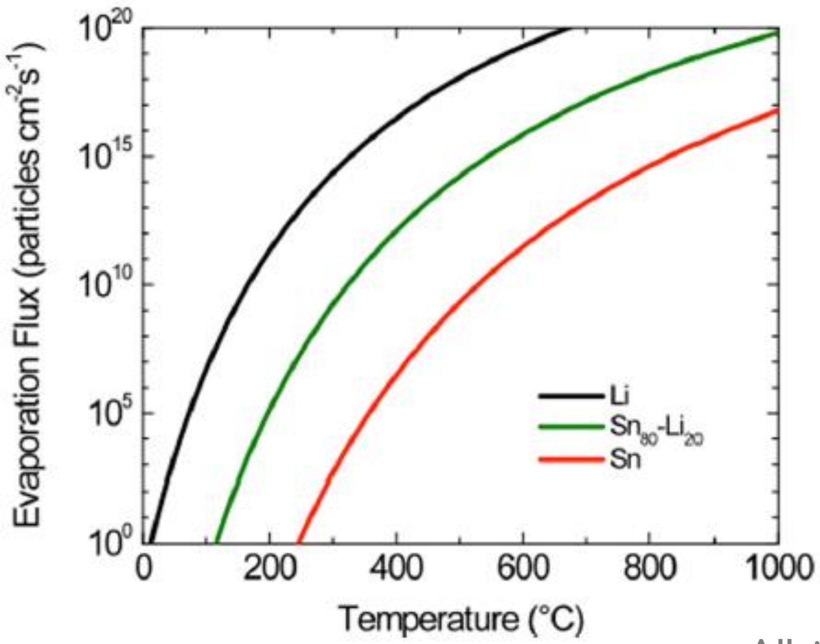
Separation of PSI from neutron issue

Material options of Li, Sn both have strengths and weaknesses

Choices once cost, availability, activation etc. taken into account

Lithium	Tin
Low Z	Higher Z
High vapour pressure	Lower vapour pressure
High T retention	Lower T retention

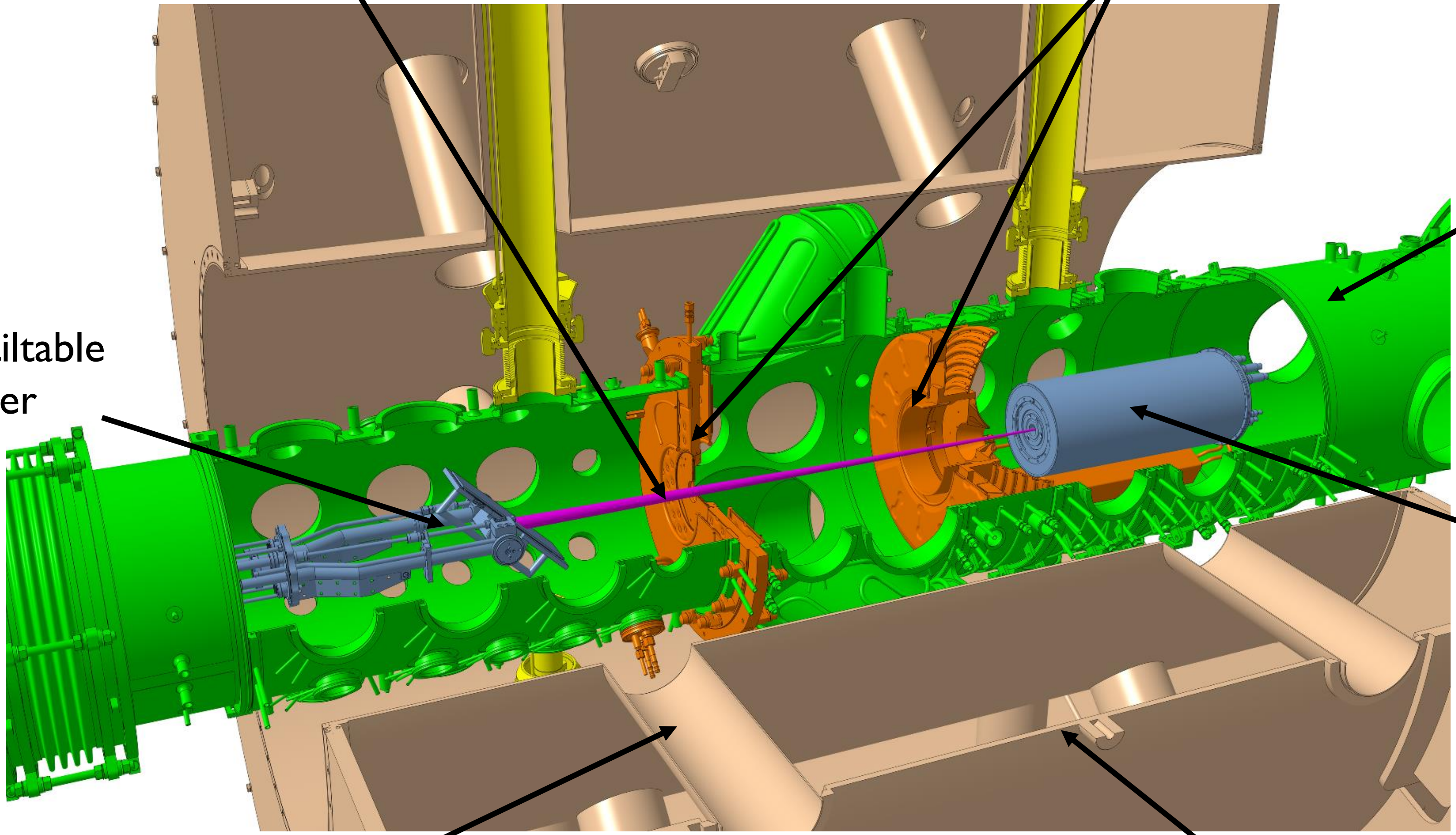




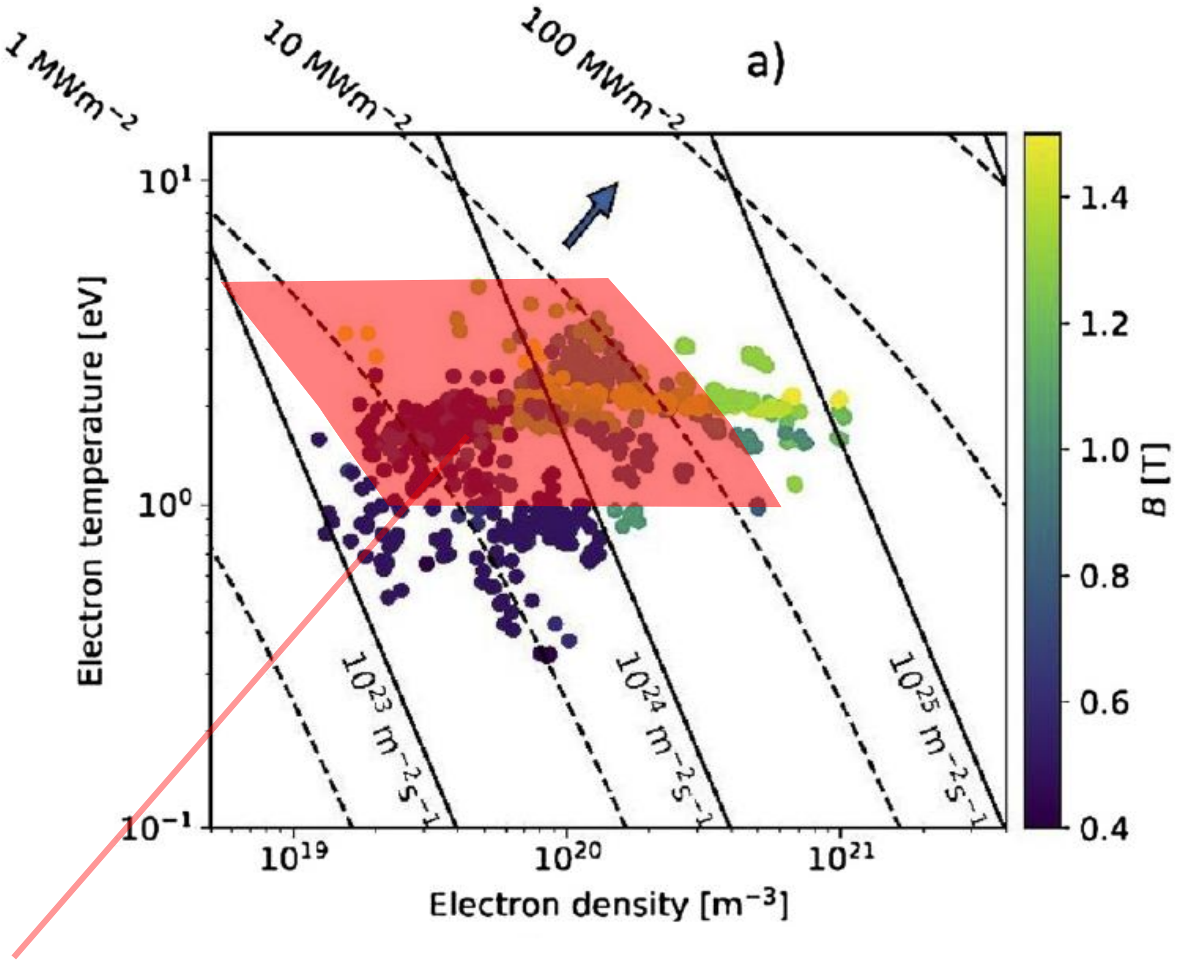
Wesson, Tokamaks (2004)

Allain and Taylor PoP (2012)

Linear devices have good flexibility and diagnostic access: good place to investigate vapour shielding



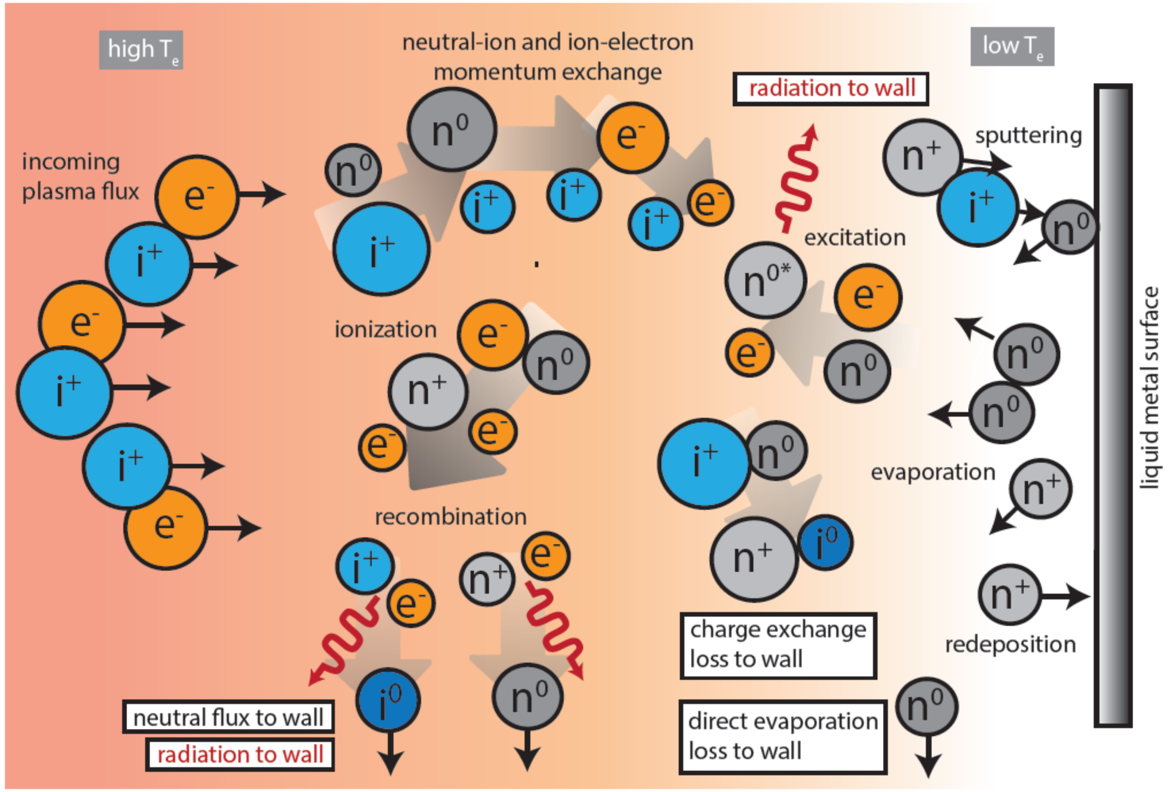
Magnum-PSI/Pilot-PSI good utility for LM study due to DEMO relevant heat/particle loading

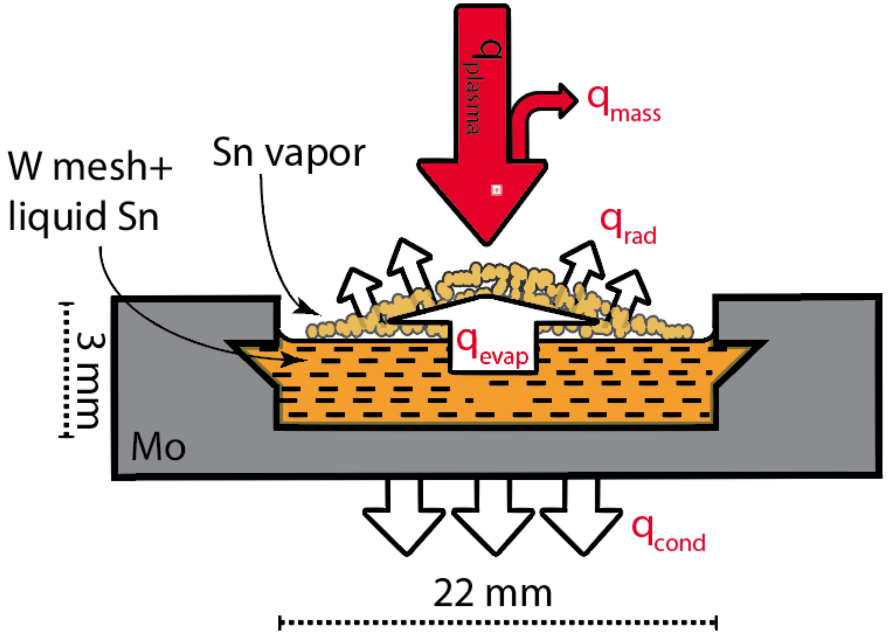


ITER/DEMO divertor strikepoint conditions (detached)

van Eck FED (2019)

Vapour shielding: additional loss channels for heat flux (impurity stimulated "detachment")

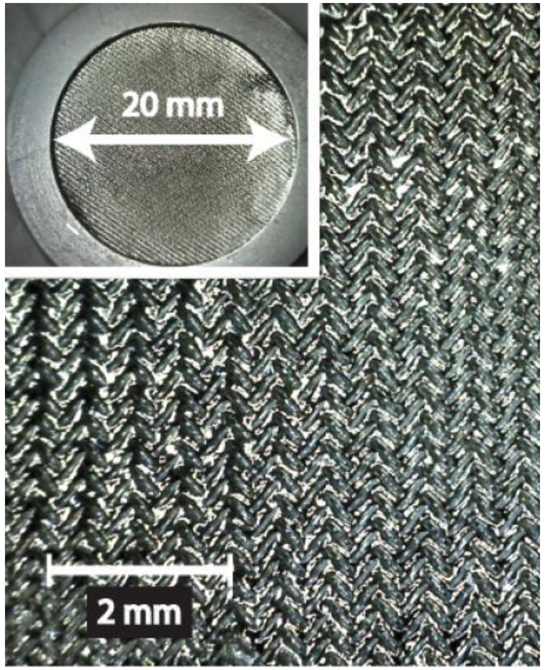


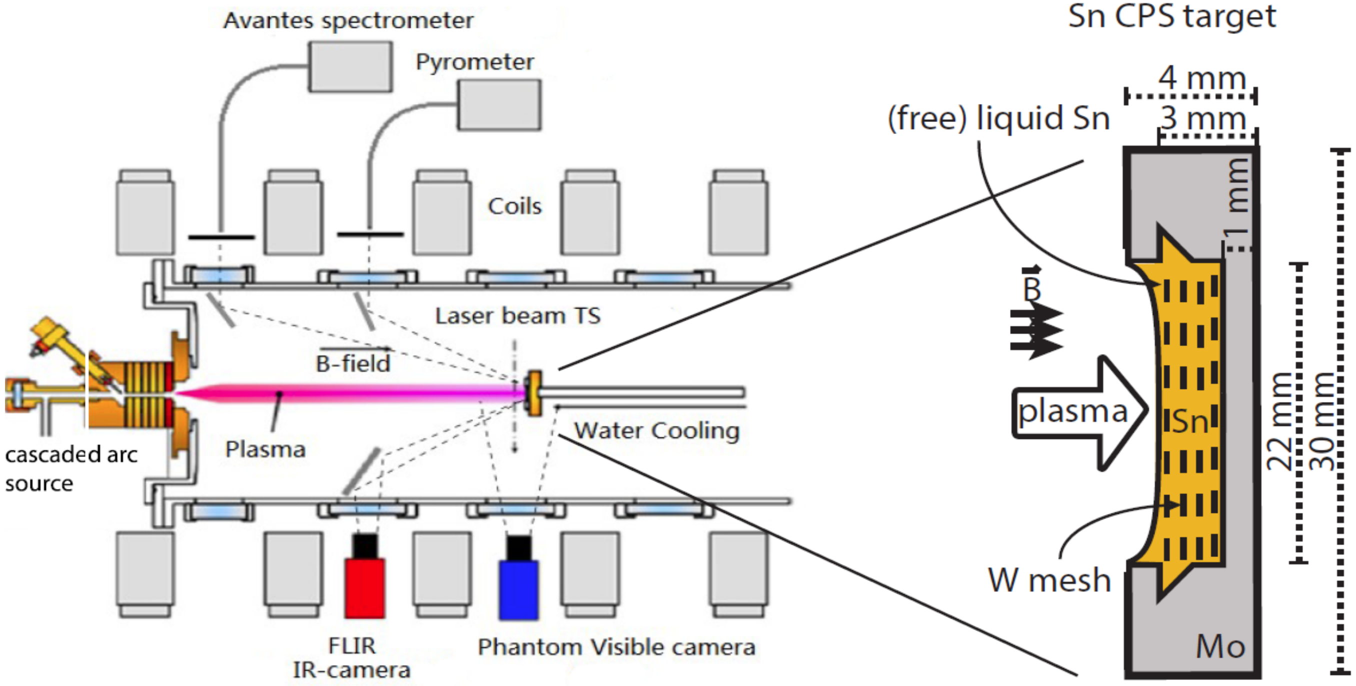


Solid metal: $q_{plasma} = q_{cond}$

Liquid metal: $q_{plasma} = q_{cond} + q_{evap} + q_{rad} + q_{mass}$

Experiment compared performance of Sn CPS with solid Mo reference targets





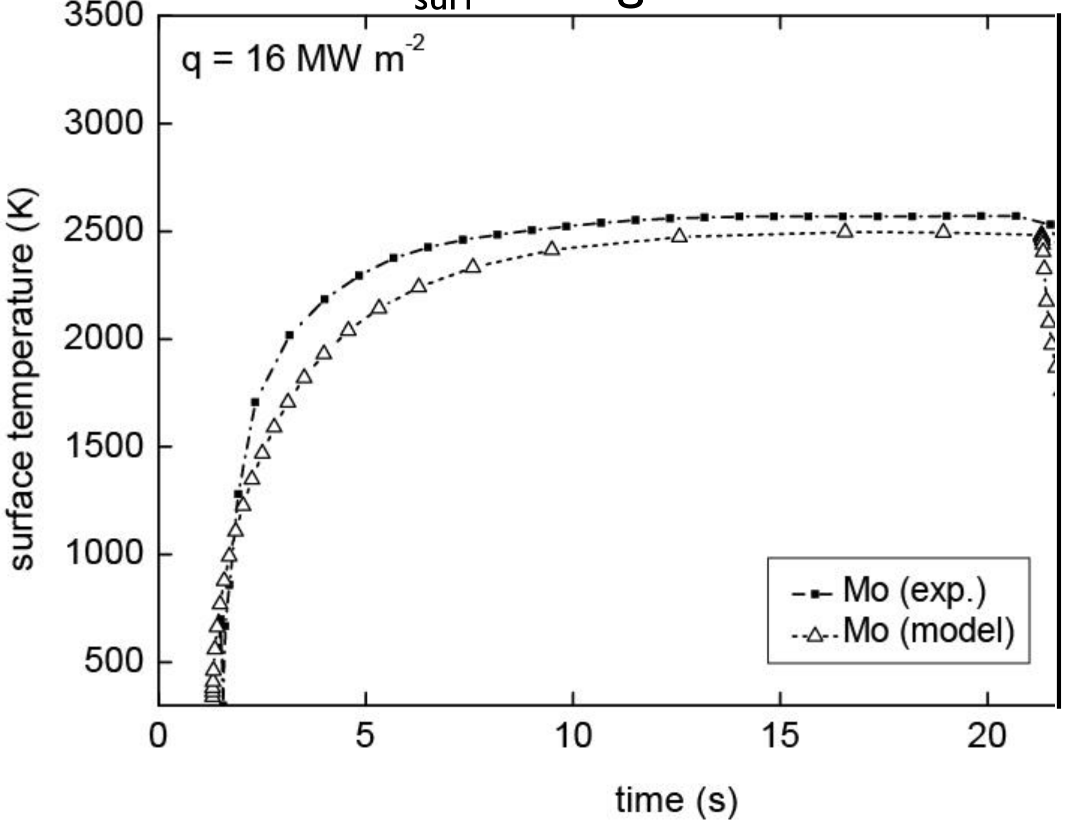
Ion species	T_e (eV)	n_e (10^{20} m^{-3})	q_{ref} (MW m^{-2})
H or He	0.4-3.1	0.6-7.0	0.47-22

n.b. Deliberately poorly cooled to reach VS temperature regime

Vapour interaction with plasma decouples input power from surface temperature

Poorly cooled Sn samples exposed to power load series in pilot-PSI

T_{surf} at target centre



van Eden PRL 2016

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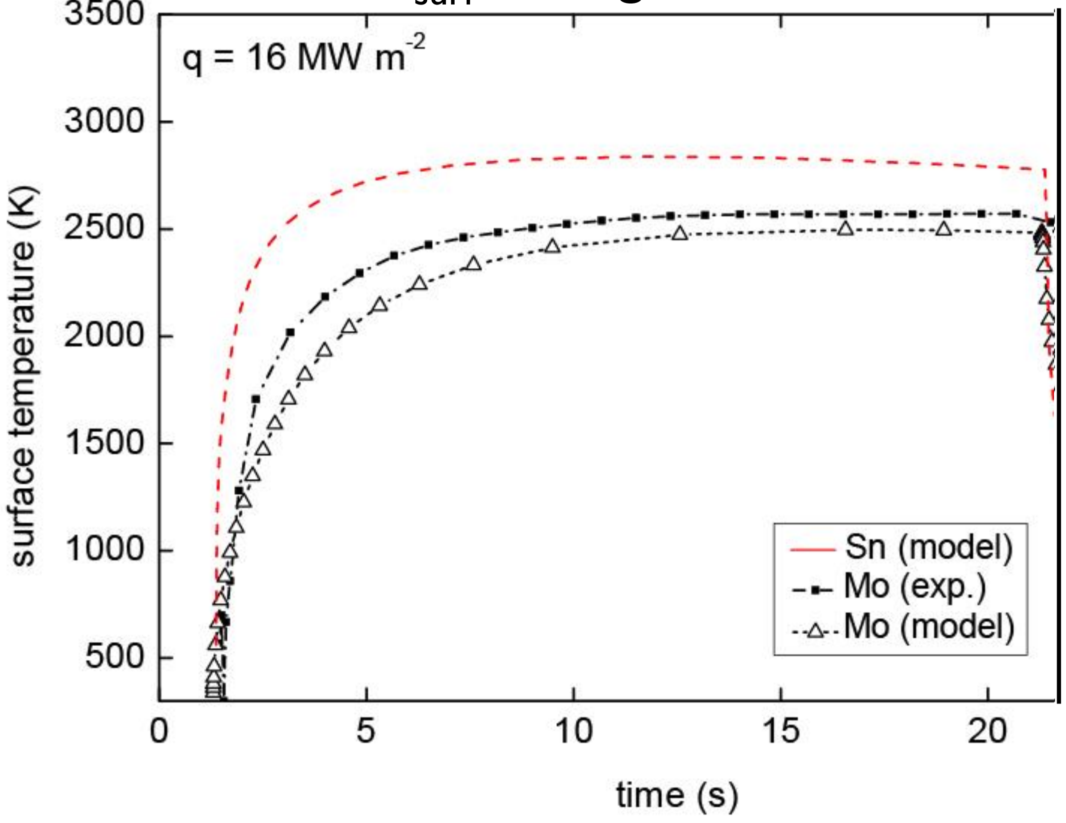

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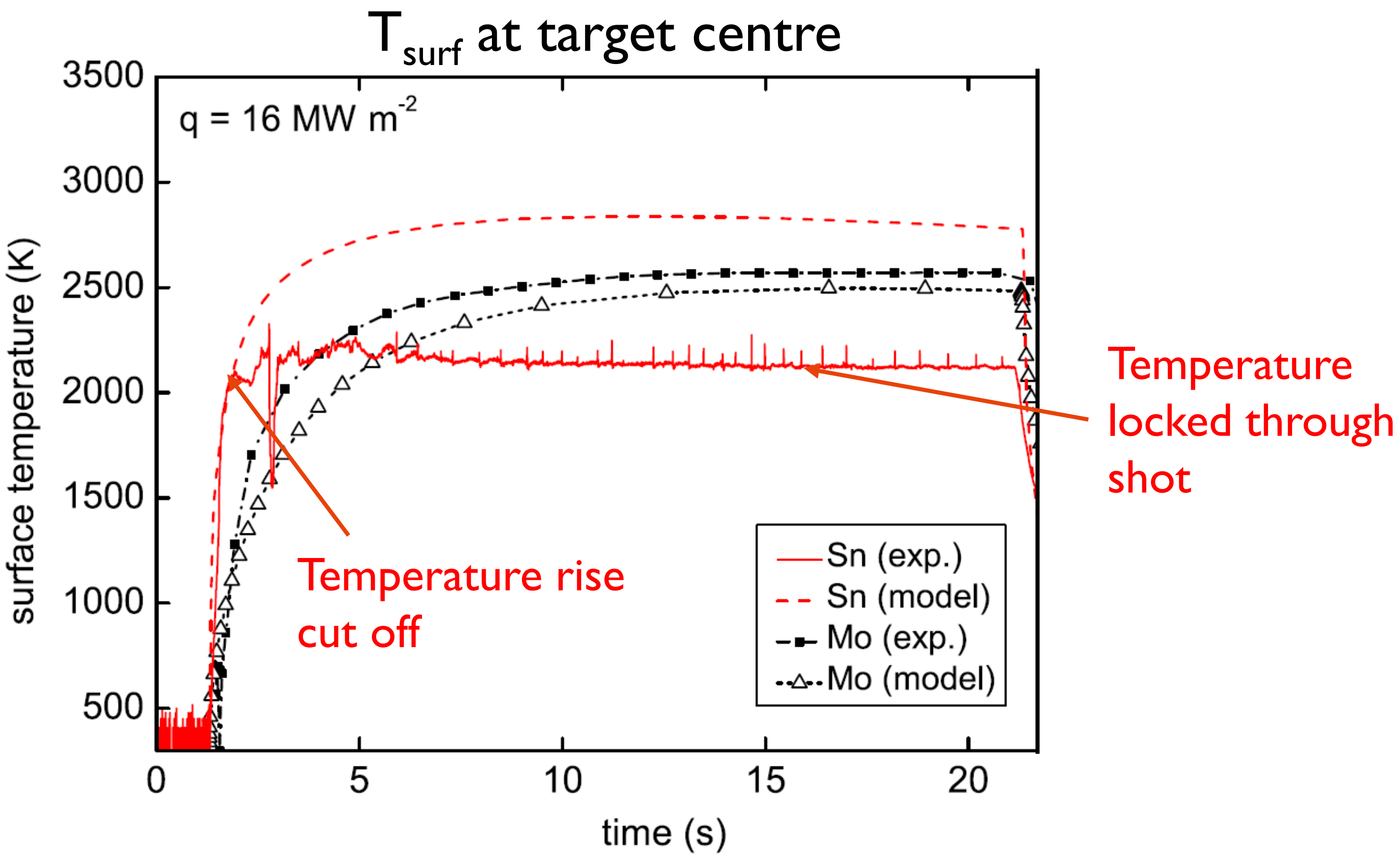
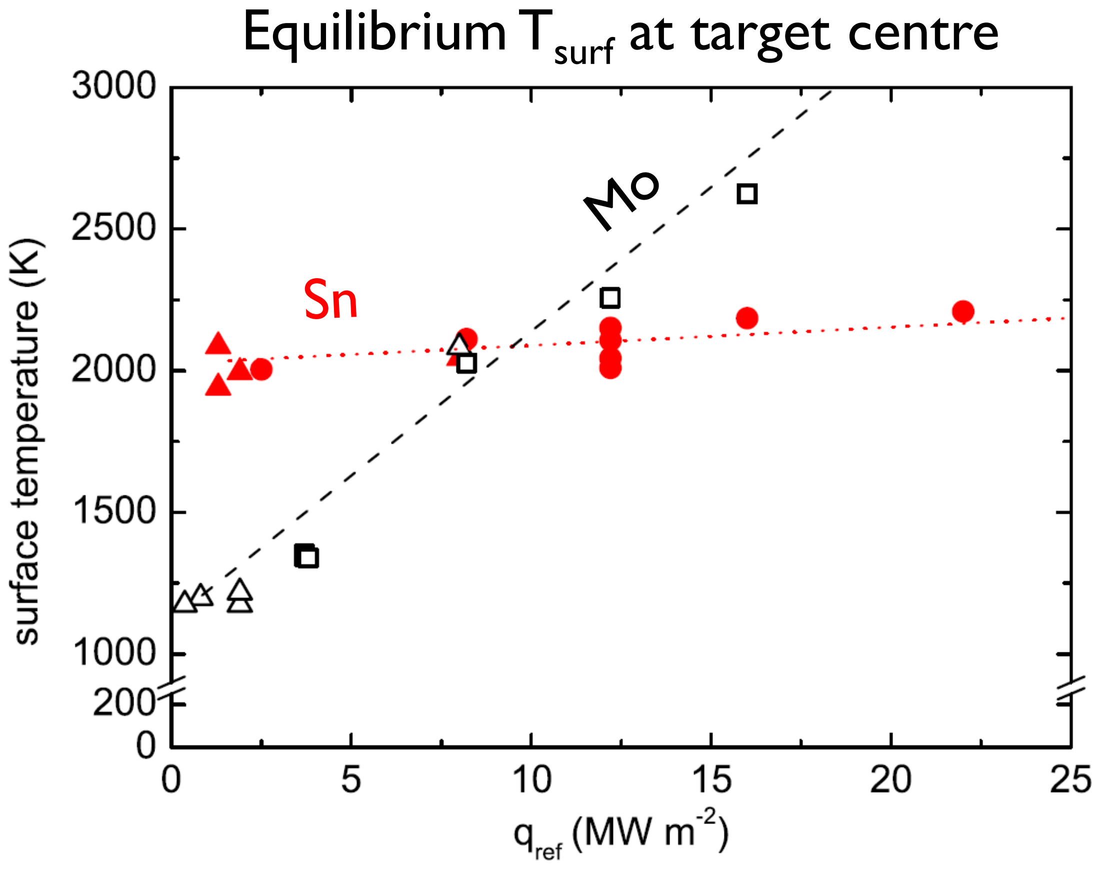
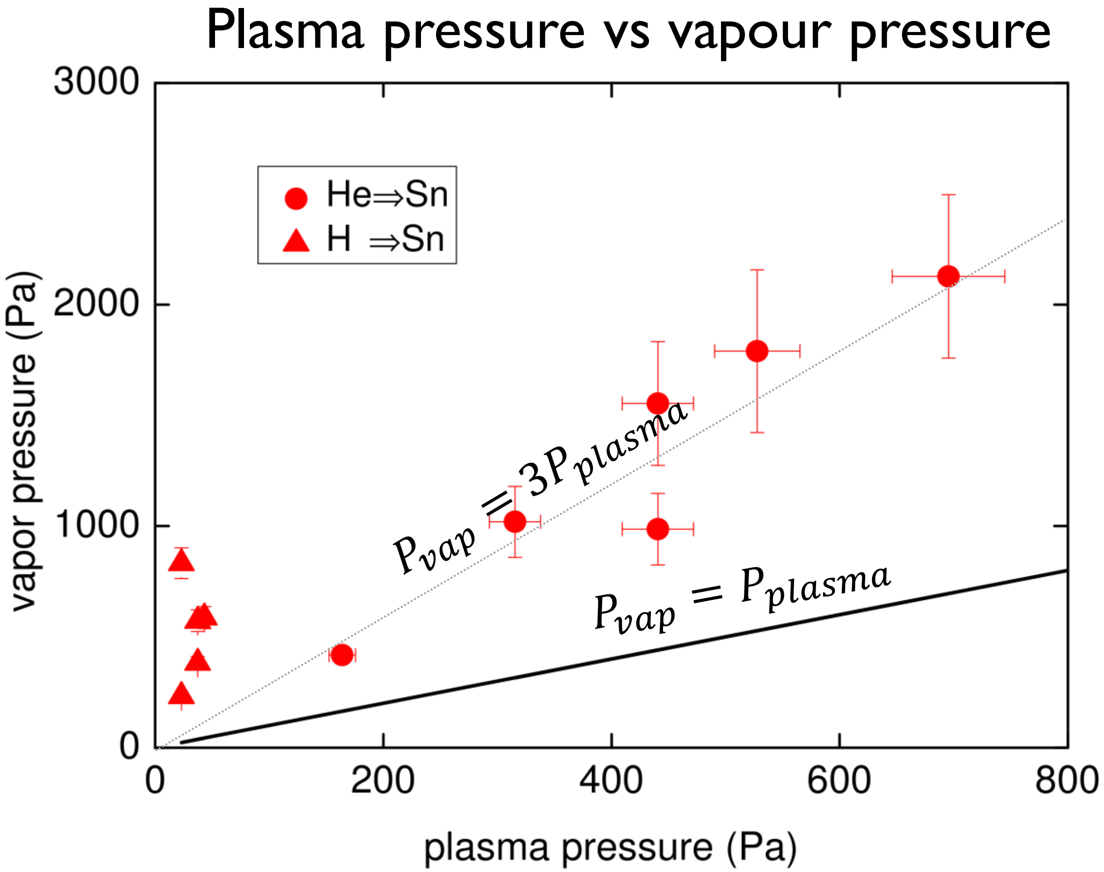


van Eden PRL 2016

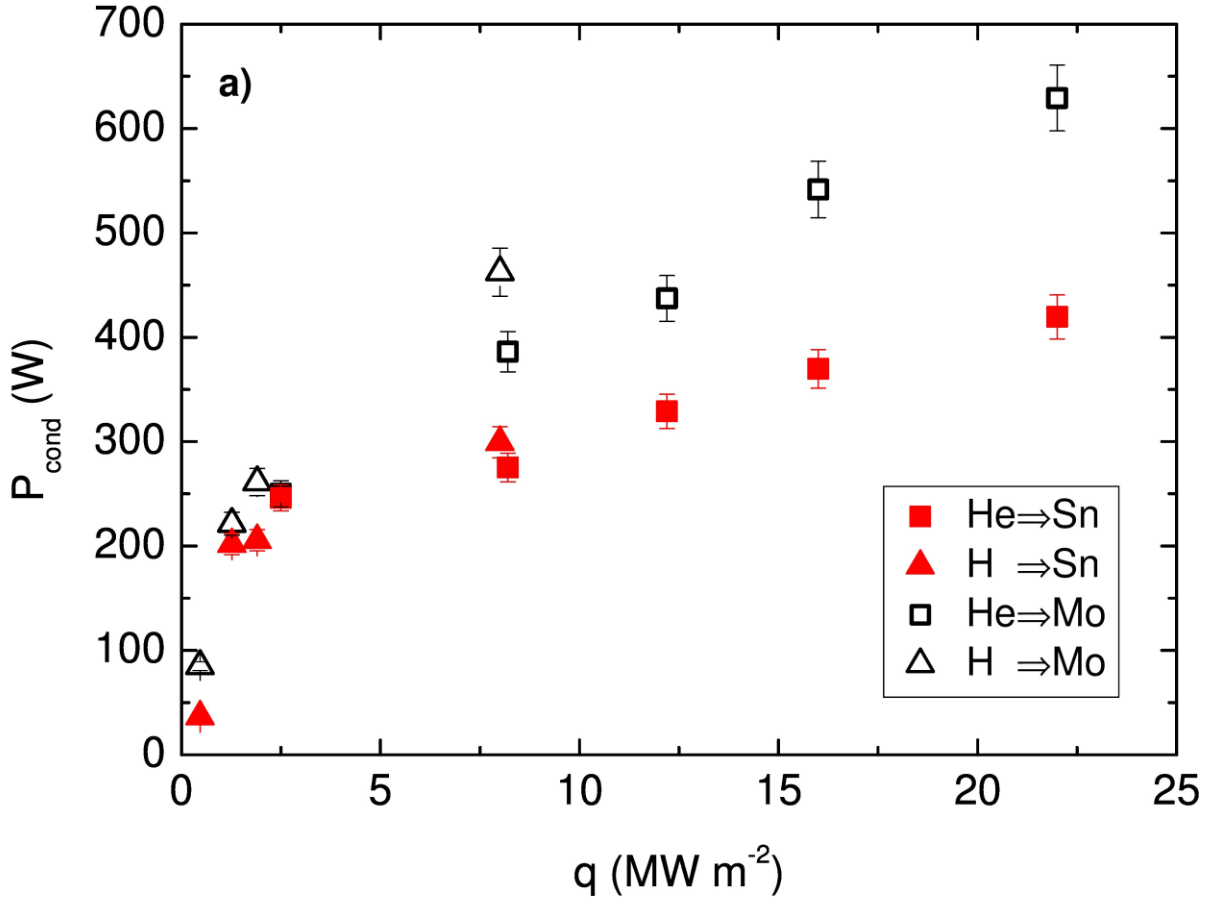
Temperature locking when vapour pressure and plasma pressure ~ matches

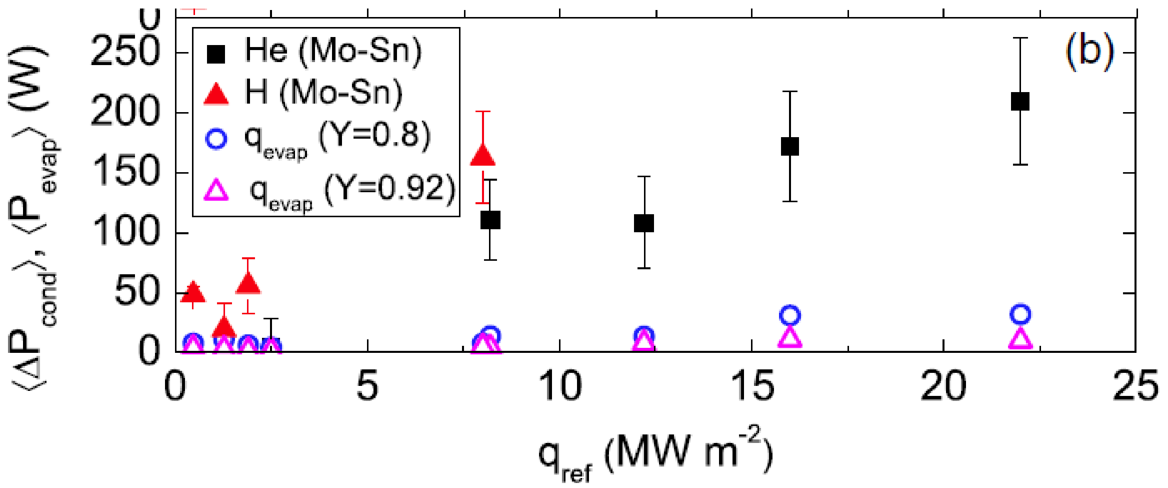




van Eden PRL 2016

Overall reduction in power to cooling water of ~one third



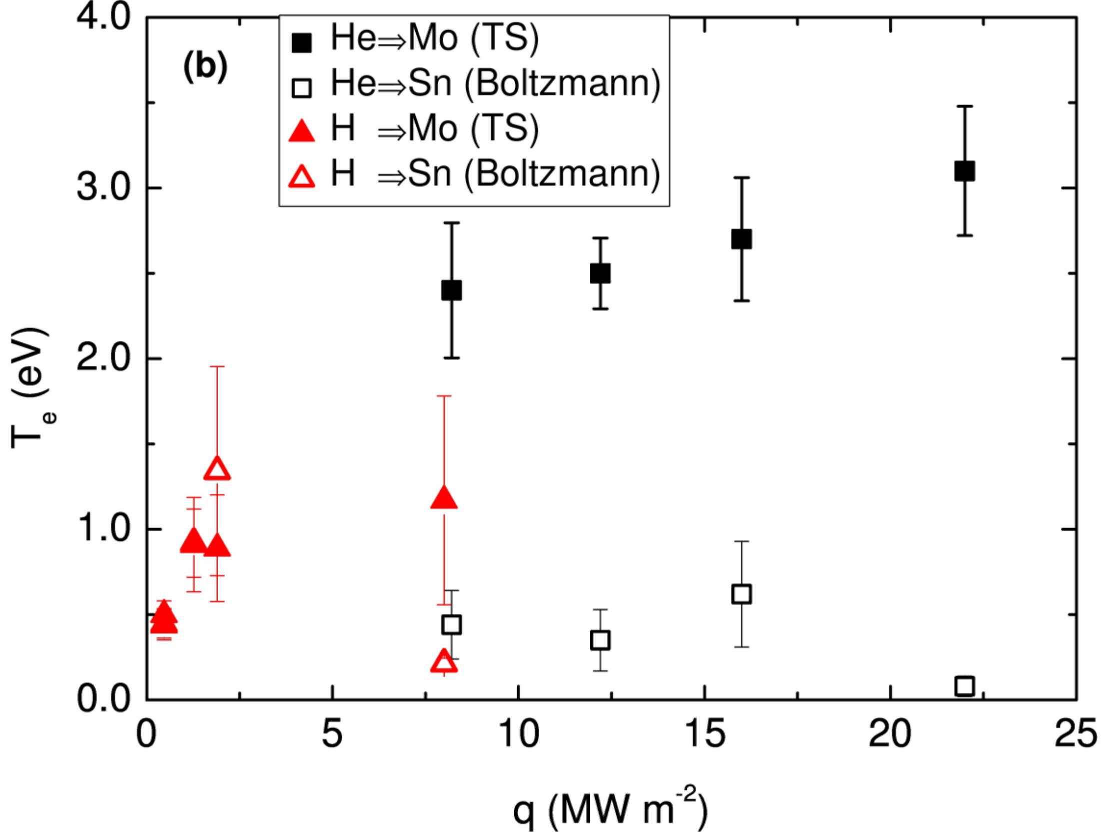


Evaporation alone cannot explain energy loss: relatively high re-deposition rate means most ε_{evap} returns to surface

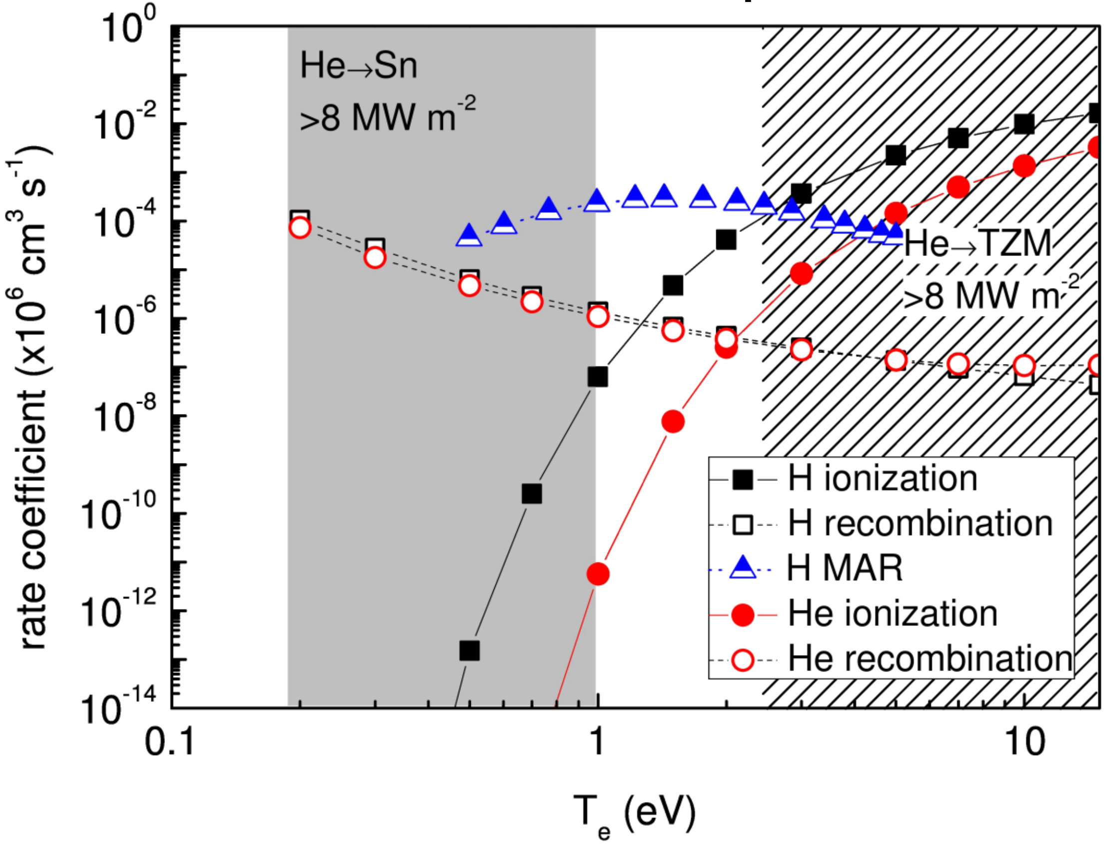
van Eden PRL 2016

Strong recombination occurs due to lowered T_e

T_e Sn shots vs Mo shots

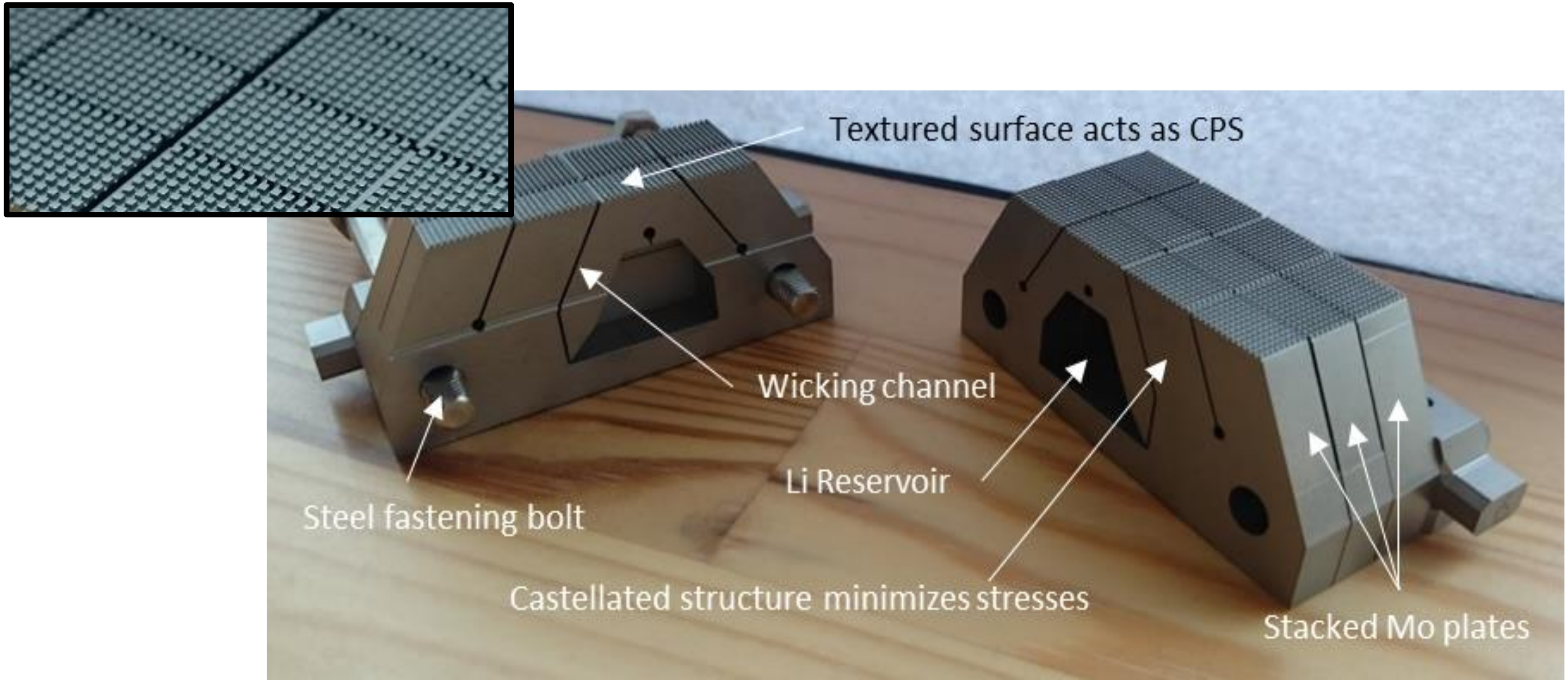


Atomic/Molecular processes



van Eden PRL 2016

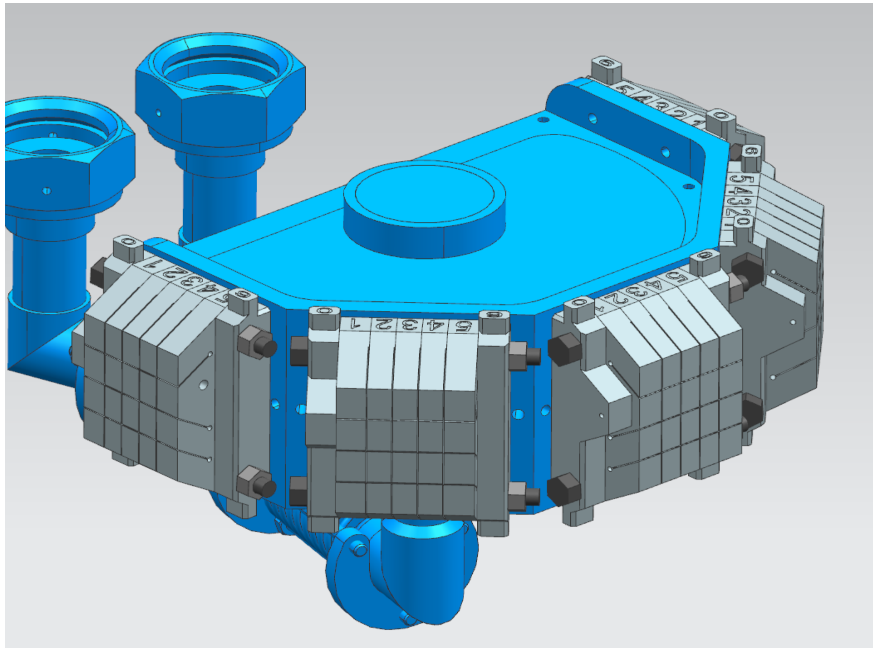
Li targets with a reservoir were used to permit long-timescale tests

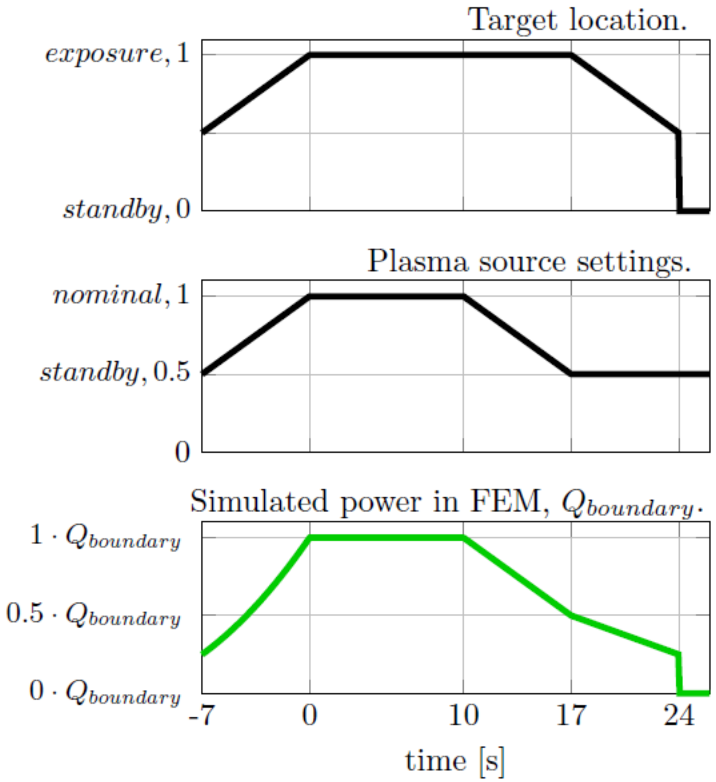


Component similar to and designed to test design for NSTX-U

Rindt FED 2016

Helium plasma loading to determine power handling limit in VS conditions

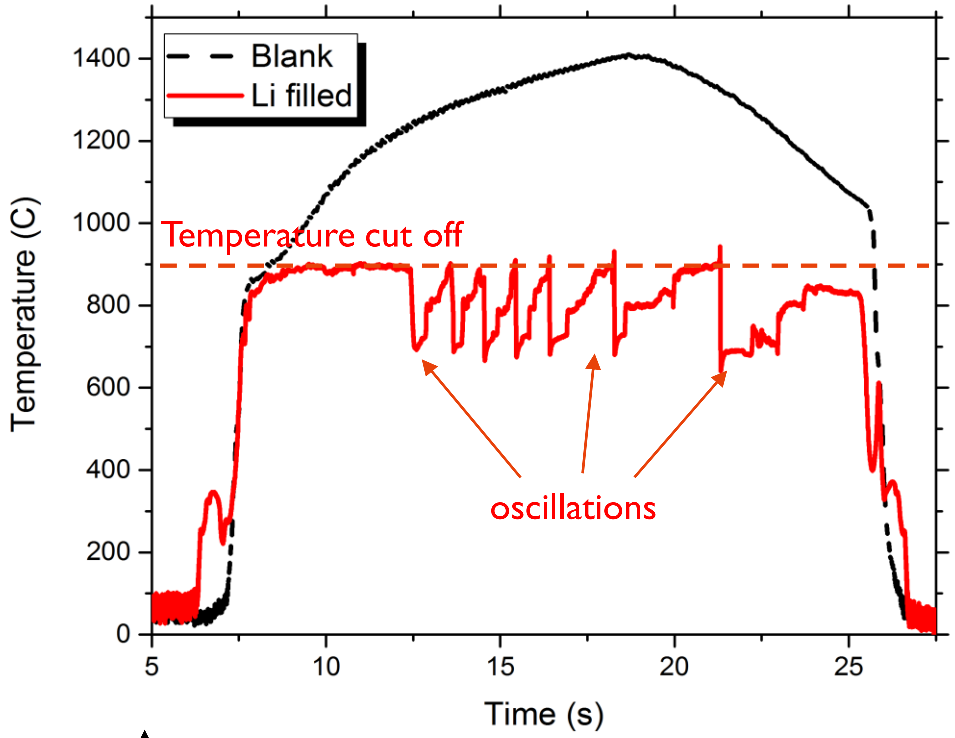


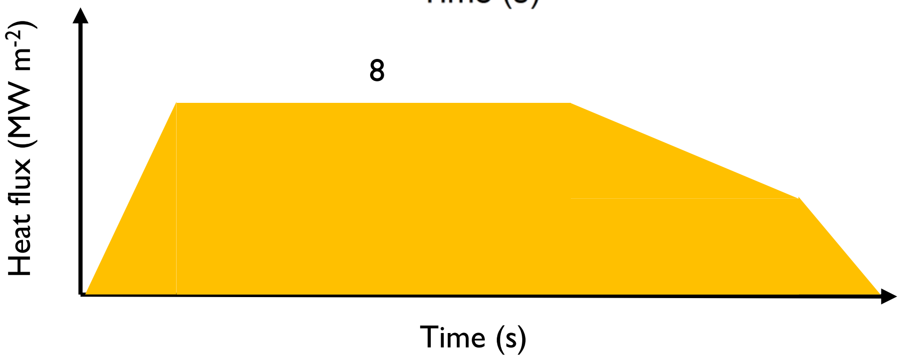


Parameter	Value
B	1.2 T
q_{ref}	8-10 MW m^{-2}
T_e	~4 eV
n_e	~4×10^{20} m^{-3}

Rindt NF (2019)

Similar vapour shielding effect observed for Li as for Sn





Rindt NF (2019)

High heat load can be sustained
(9 MW m^{-2} peak heat load)

Sn vapour limit is ~1700 ° C

Prediction for Li is therefore ~700-900 ° C

Prediction well matched by observation

Analytical description of VS mechanism

$$\underbrace{}_{}\mathbf{\mathit{Q}}_{\mathbf{\mathit{plasma}}} = \overbrace{\mathbf{Q}_{\mathbf{cond}}(T_{surf})}^{\text{Heat conducted through target.}} + \overbrace{(\mathbf{1} - \mathbf{\mathit{R}})\mathbf{\Gamma}_{\mathbf{evap}}(T_{surf}) \cdot (\boldsymbol{\epsilon}_{\mathbf{cool}} + \boldsymbol{\epsilon}_{\mathbf{\mathit{evap}}})}^{\text{Power dissipated by lost LM.}}$$

R=?

$\epsilon_{\mathbf{cool}}$ =?

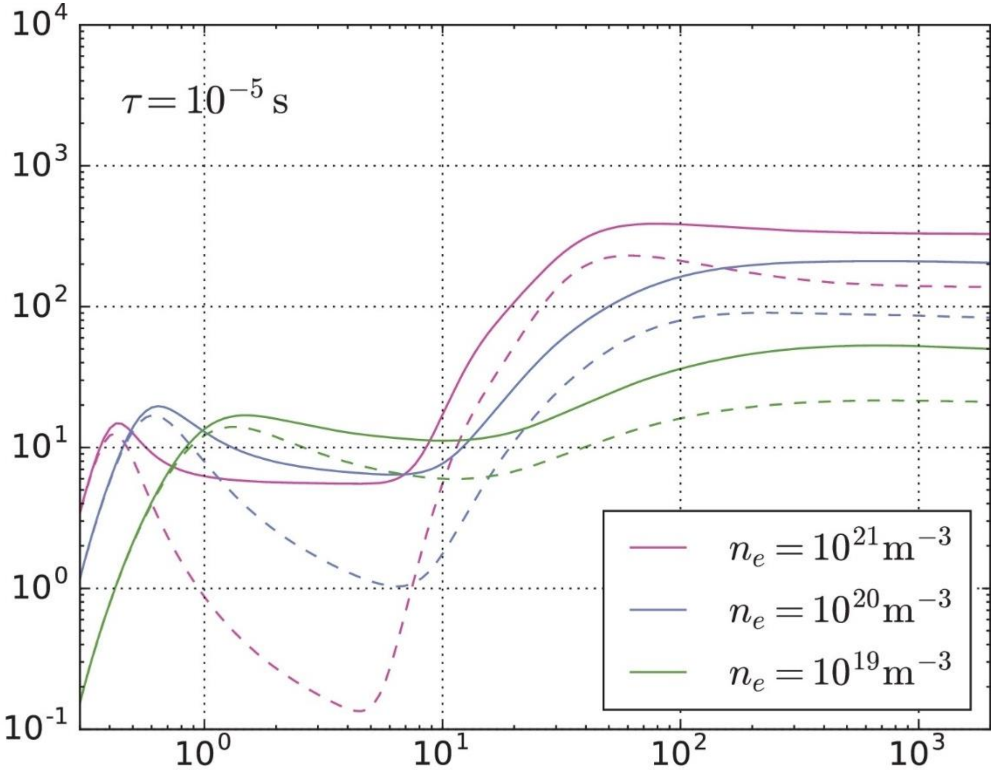
Net lithium loss rate.

Limited by available supply

Rindt NF (2018)

Lithium energy dissipation through ionization and radiation can be estimated as ~ 5 eV

Dissipated energy per particle ϵ_{cool} [eV]



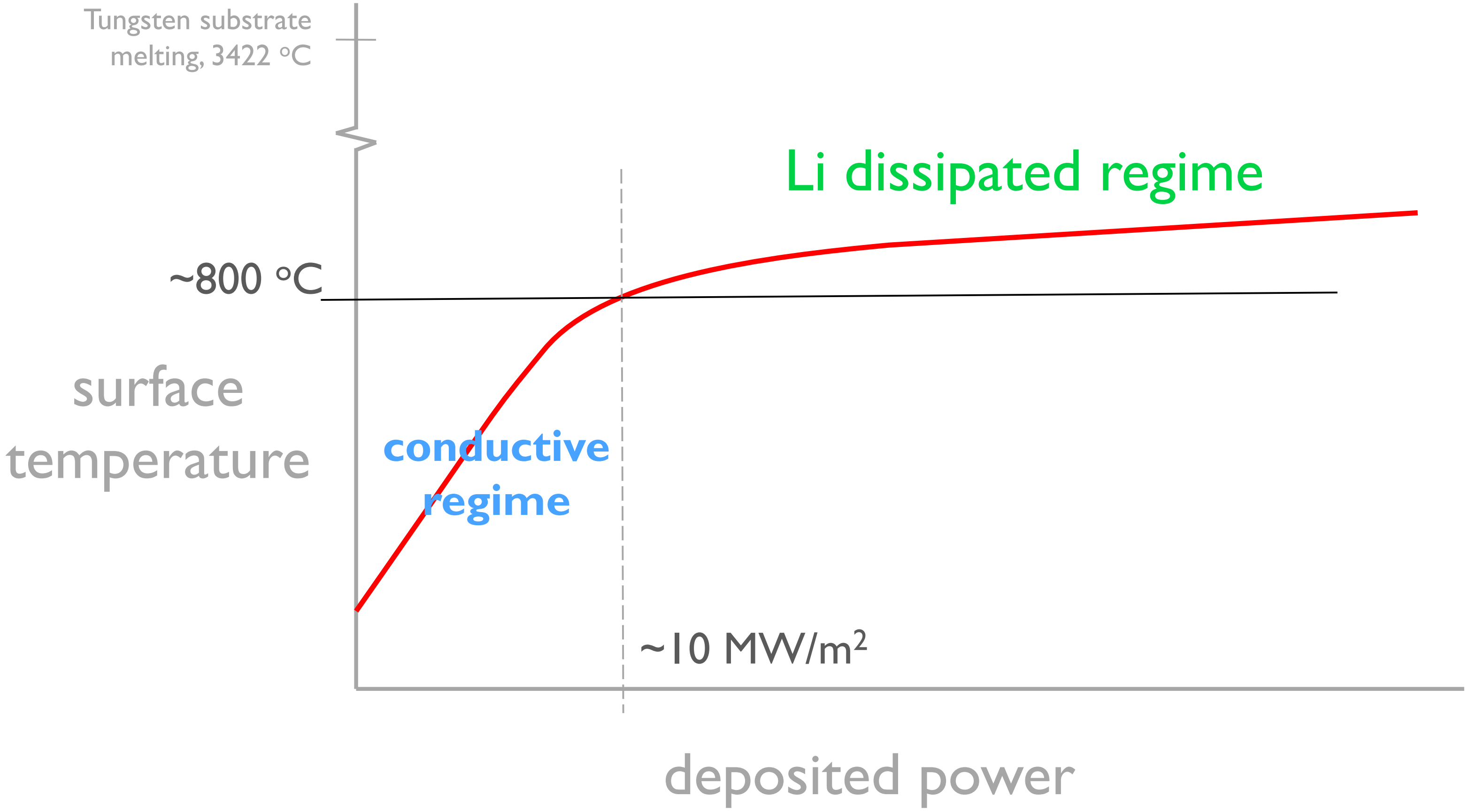
T_e [eV]

Based on lifetime of Li samples R~0.9 is measured

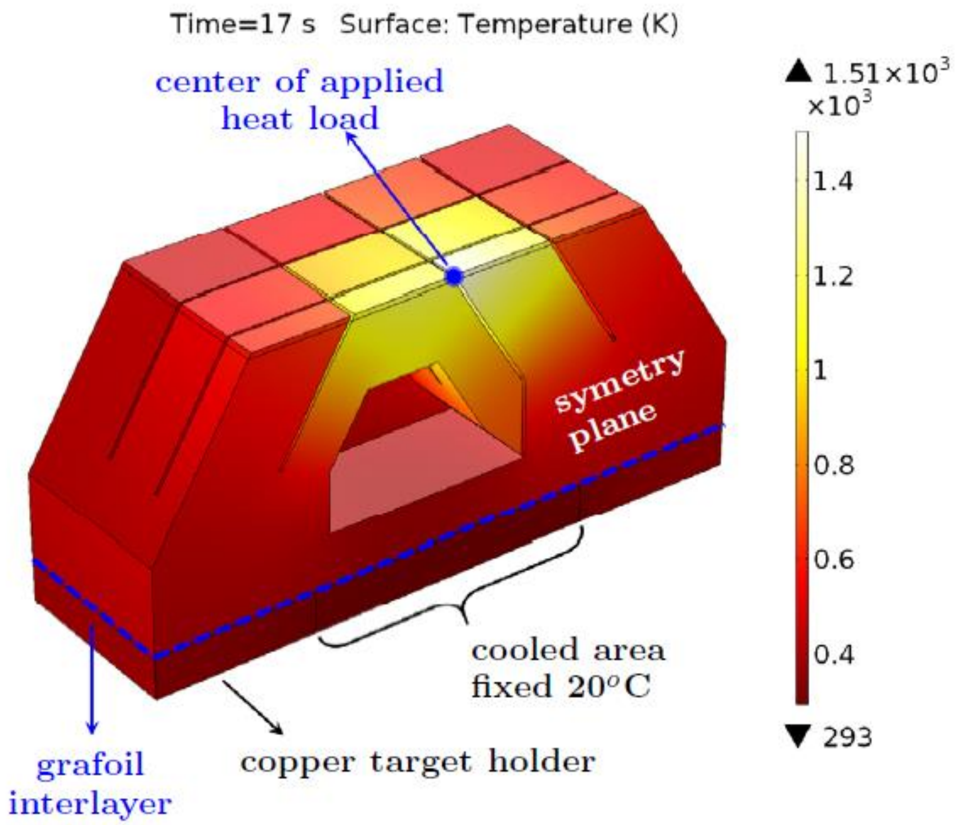
Taking into account energy dissipation via ionization and radiation from non-promptly redeposited Li we get ϵ_{cool}~5 eV for Magnum-PSI experiments

Goldston NME (2017)

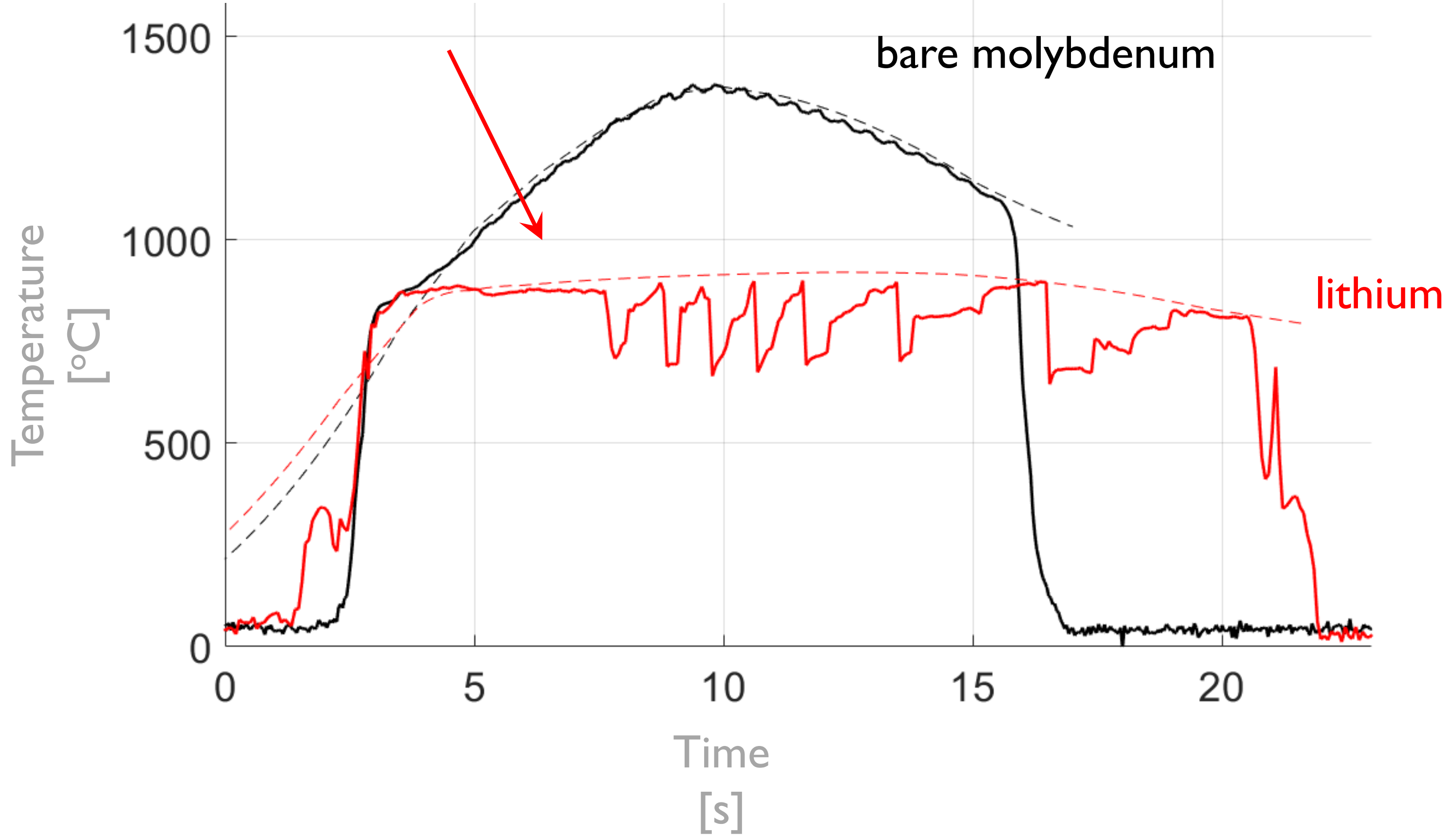
A temperature plateau occurs when dissipation via Li becomes dominant.



FEM shows good agreement with experiment



Temperature plateau when Li dissipation becomes significant.

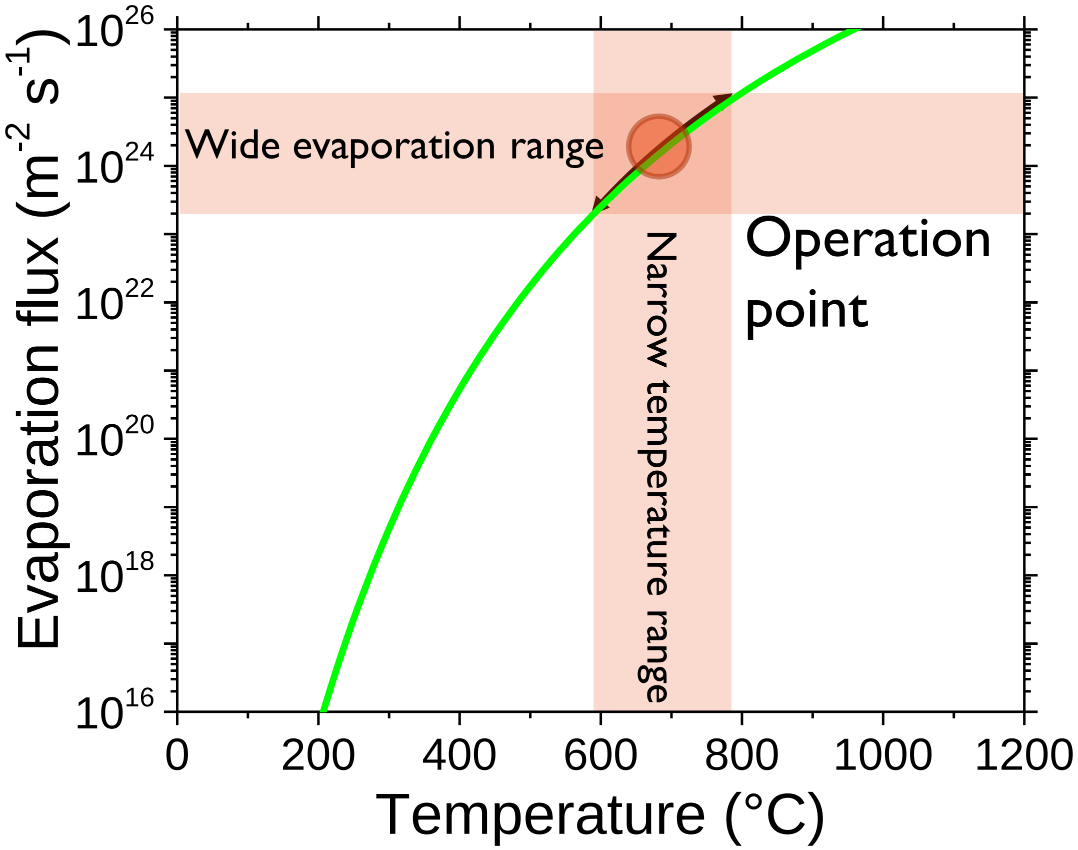


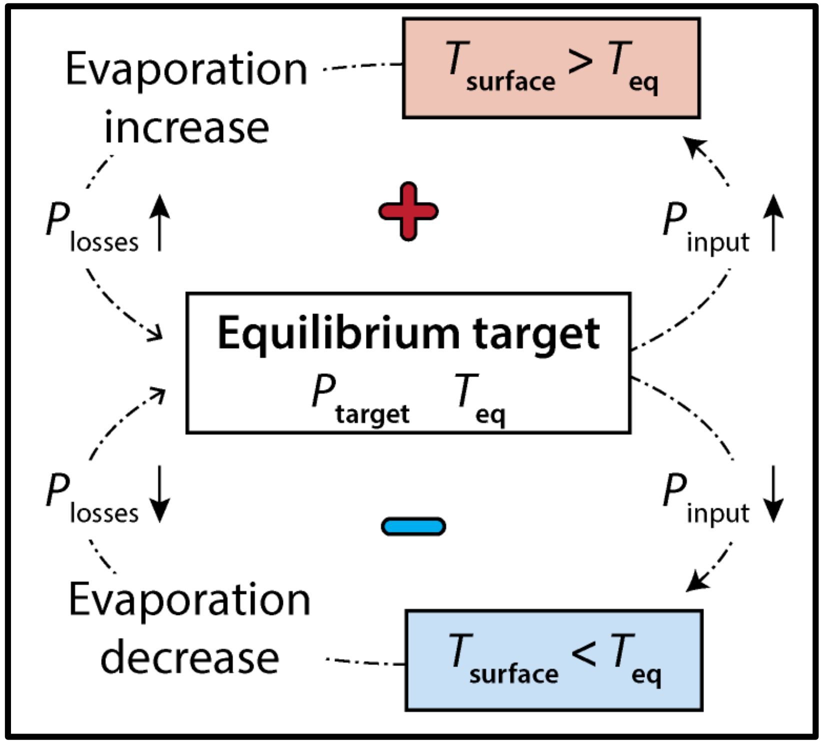
Rindt NF (2018)

Benefit for DEMO of vapour shielding

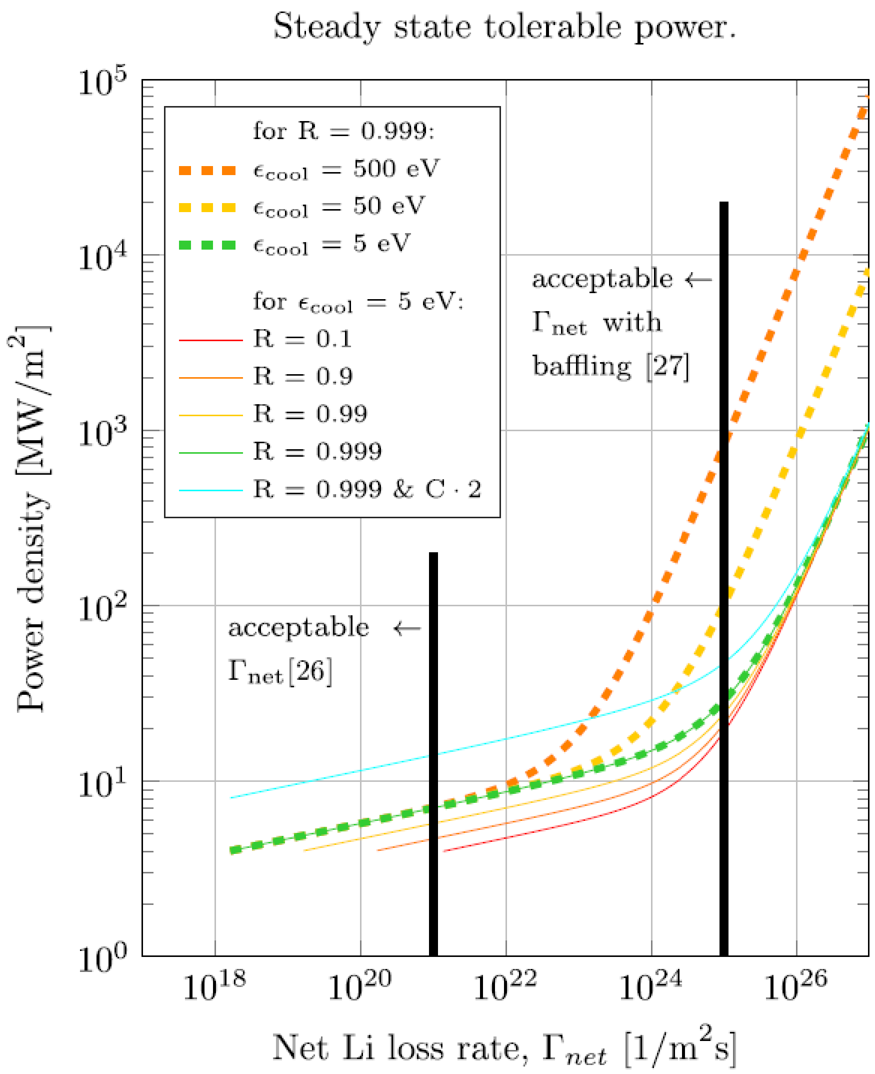
- **Decouples** incoming heat load from surface temperature and reduces cooling requirements
- Maximum **impurity influx ~fixed**
- For Sn adds **protection** for off-normal events: adds **robustness** and is more **forgiving**
- For Li **constant operation** could be possible

Vapour shielding leads to stable power reduction to target over wide P_{input} due to natural negative feedback





Steady state operation with a Li divertor in DEMO can handle very large heat loads



Rindt NF (2019)

Want to determine potential of Li VS for DEMO

Assume a target with same thermal conductance (C) as ITER monoblocks

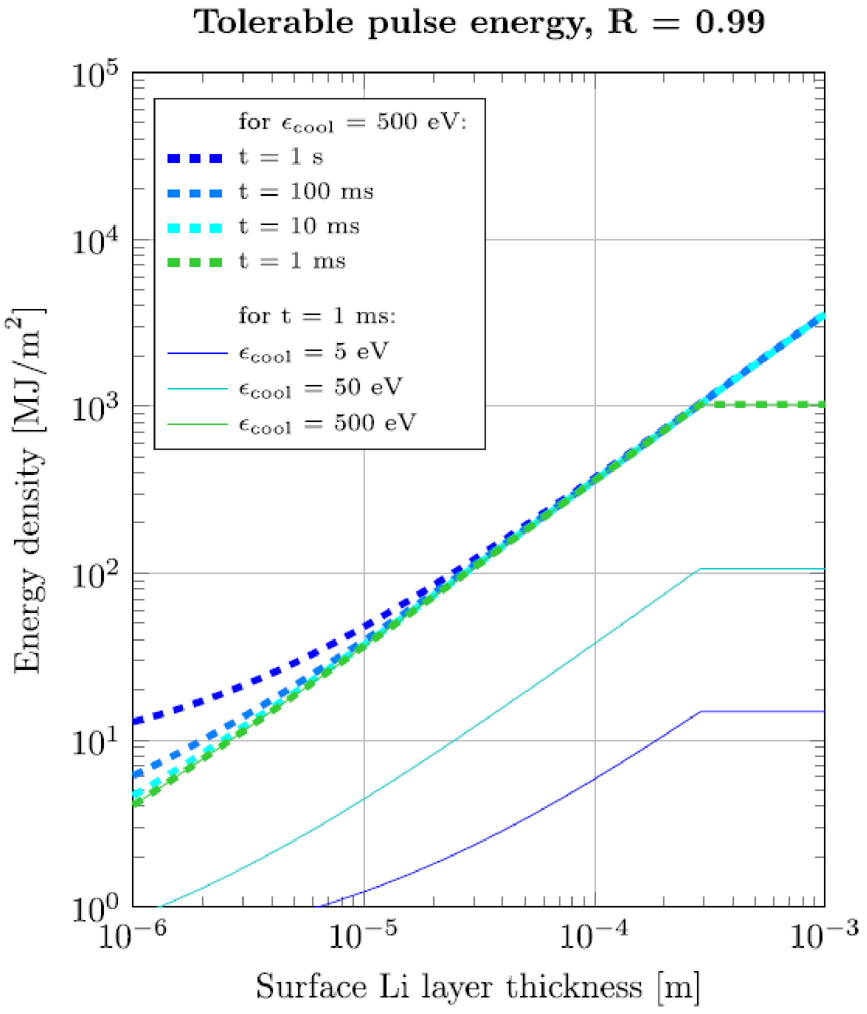
For steady state detached conditions tolerable power density dominated by conduction

For e.g. slow transients ϵ_{cool} is larger and can in principle handle very large power densities

Requires strong baffling however (vapour box*) to limit core influx to tolerable levels

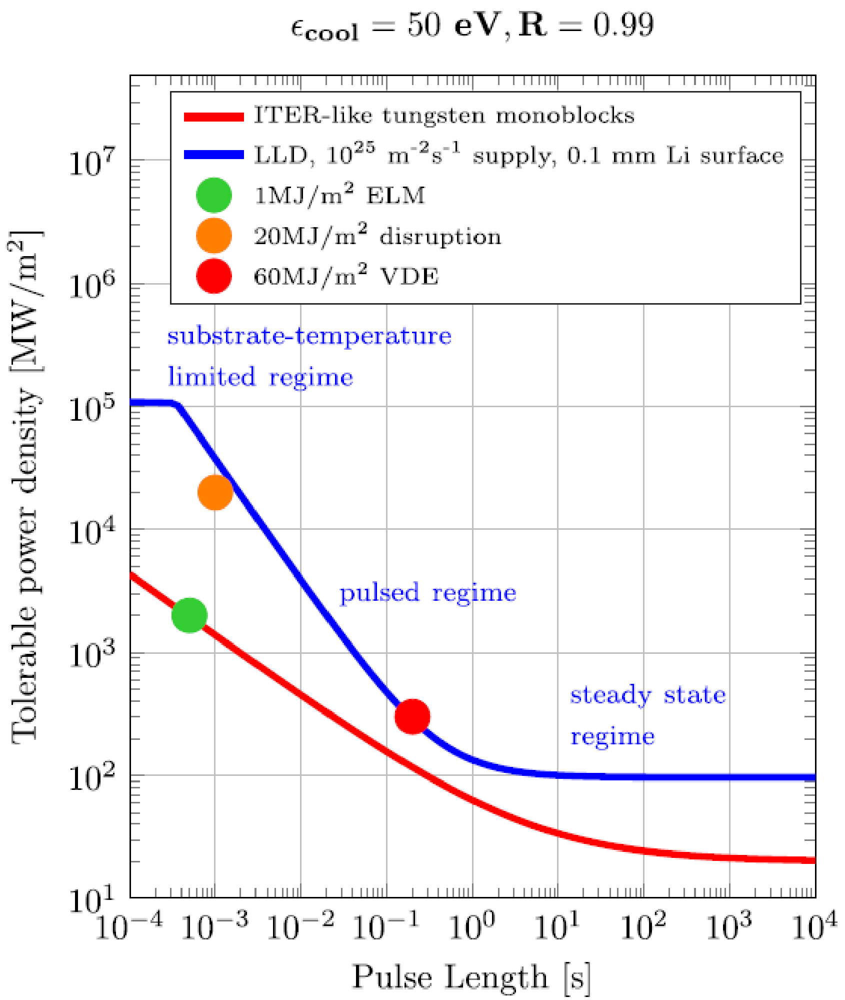
*Goldston Phys. Scr. (2017)

An LM-coated surface is also very resilient to transient events



Survival without substrate damage is defined only by loss of all LM surface layer

An LM-coated surface is also very resilient to transient events

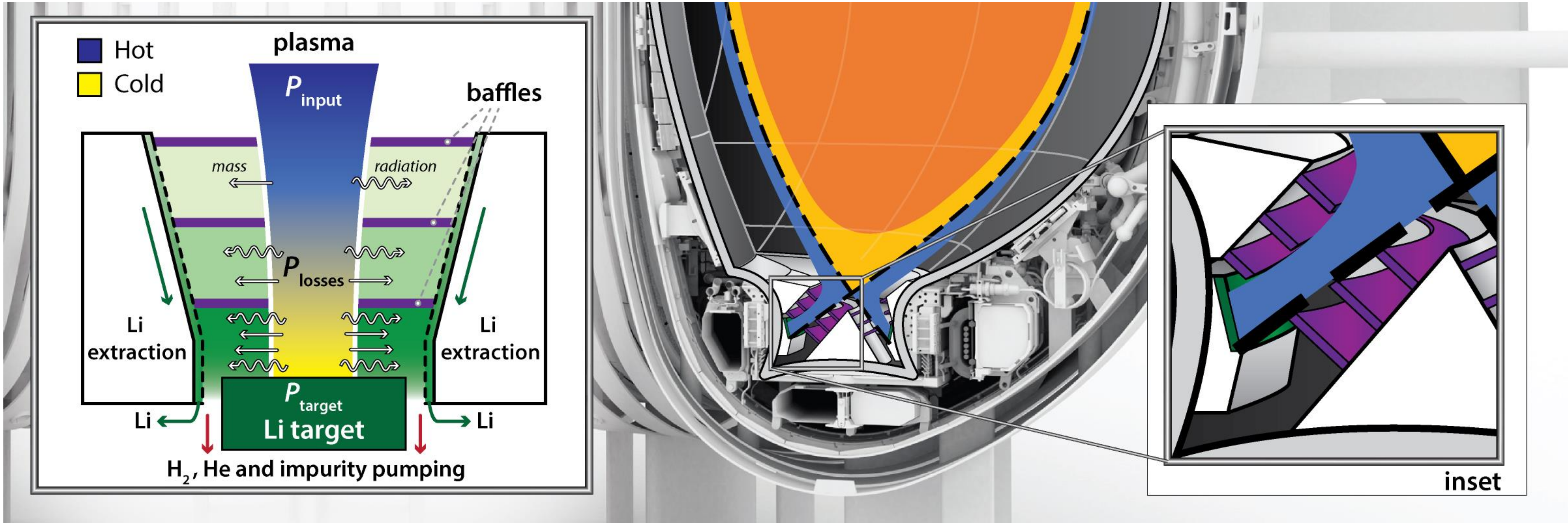


Survival without substrate damage is defined only by loss of all LM surface layer

Divertor can withstand ELMs, VDEs, disruptions

Evaporation temporarily above tolerable load but should be seen as damage mitigation during loss of control events and can tolerate small ELMs

Main challenge is to engineer closed divertor and ensure efficient and effective Li extraction



Conclusions

Strong interactions between impurities and plasma leads to strong cooling and energy loss during high evaporation: vapour shielding

Leads to a natural negative feedback with temperature locking at pressure balance point

Extrapolation to DEMO indicates high heat loads can be tolerated with Li if a vapour box divertor can be successfully engineered