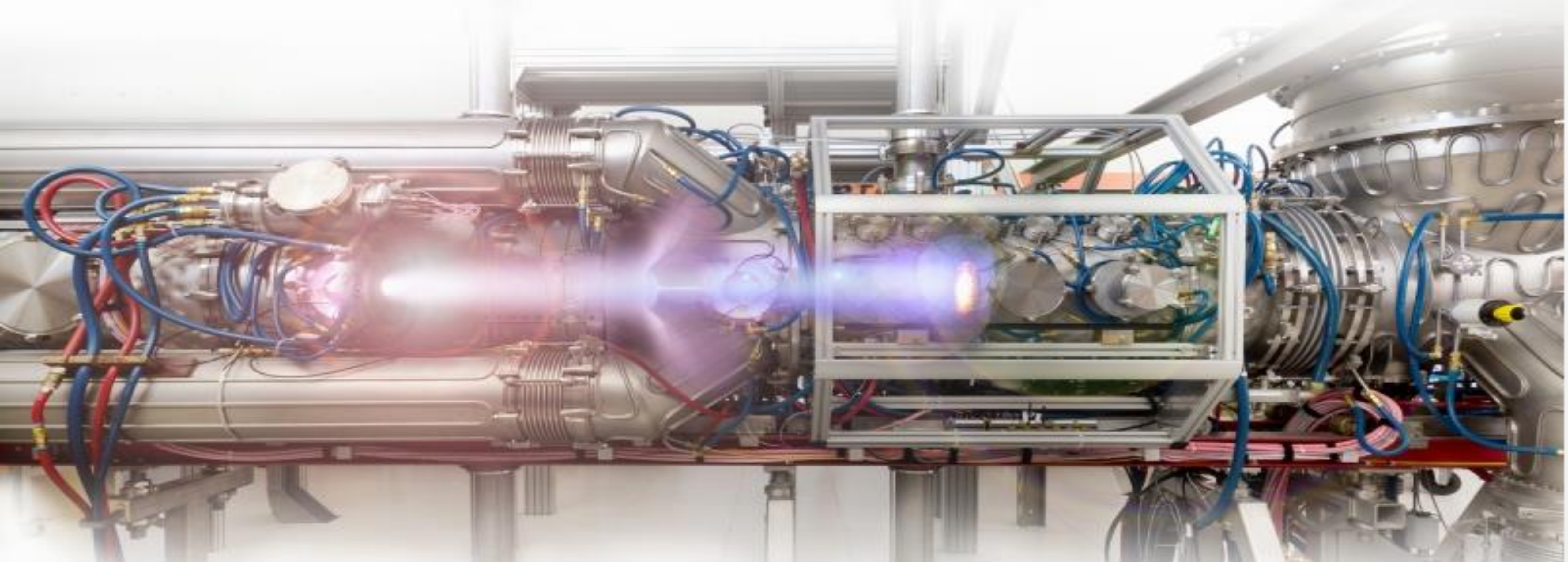
Liquid metal vapour shielding in linear plasma devices



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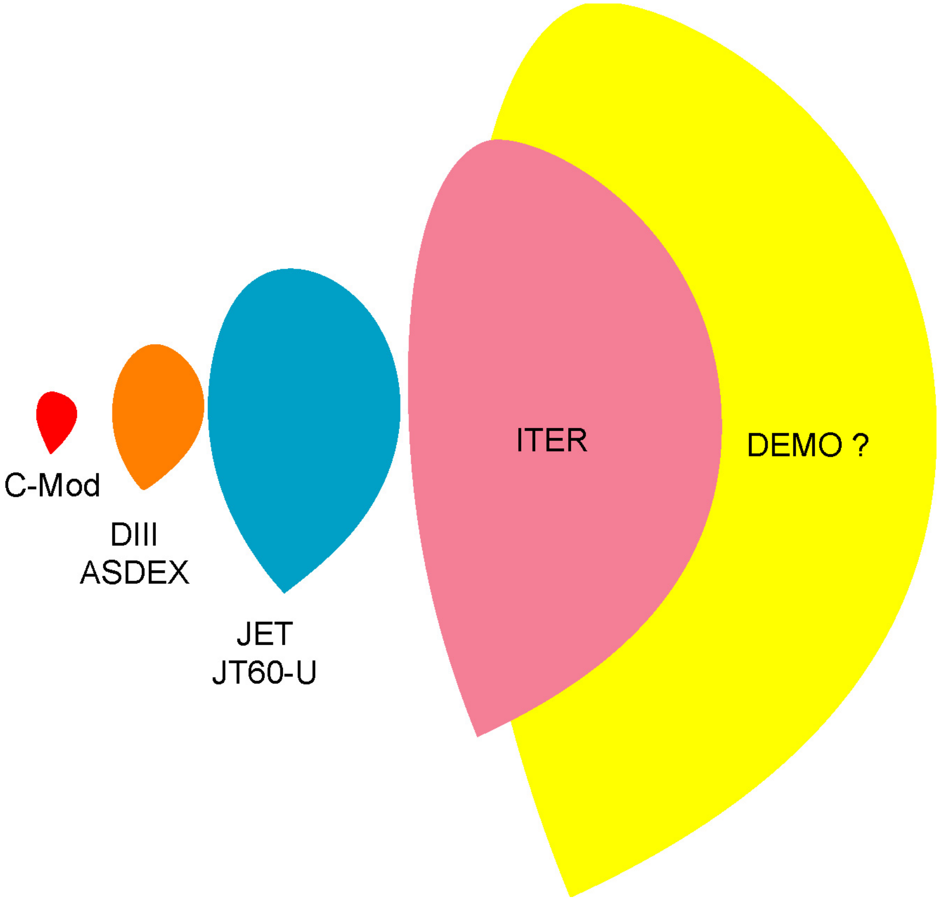
Dutch Institute for Fundamental Energy Research

Going from ITER to DEMO involves large jumps in several parameters



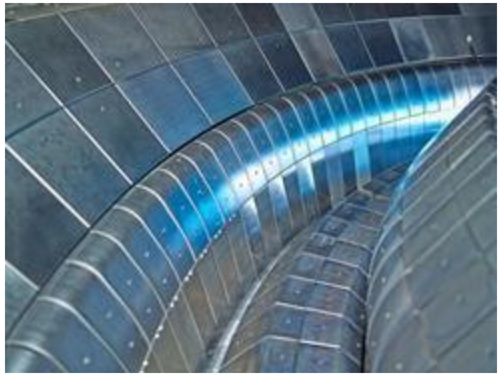
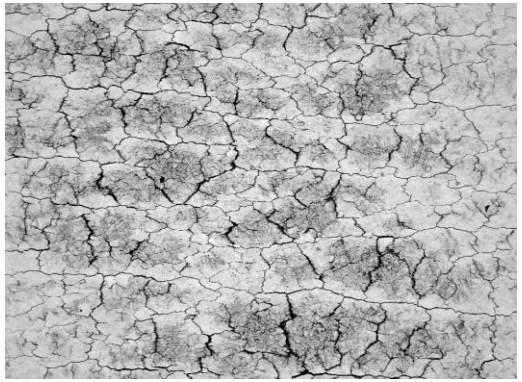
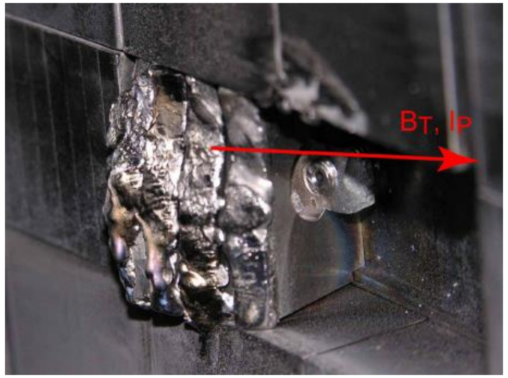
Courtesy G. Matthews

- Timescales/fluence much larger
- Neutron loading much higher
- Narrow path to avoid excessive exhaust power

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%**

Limiting factors for W in DEMO

Neutrons

High heat/particles	Thermal shock/fatigue	Big ELMs/VDEs/disruptions
		
Erosion For 5 mm W lifetime ~2 years[1]	Cracking (small ELM-like loading)[2] Progressive deterioration[3]	Melting- irreversible damage Runaway failure?

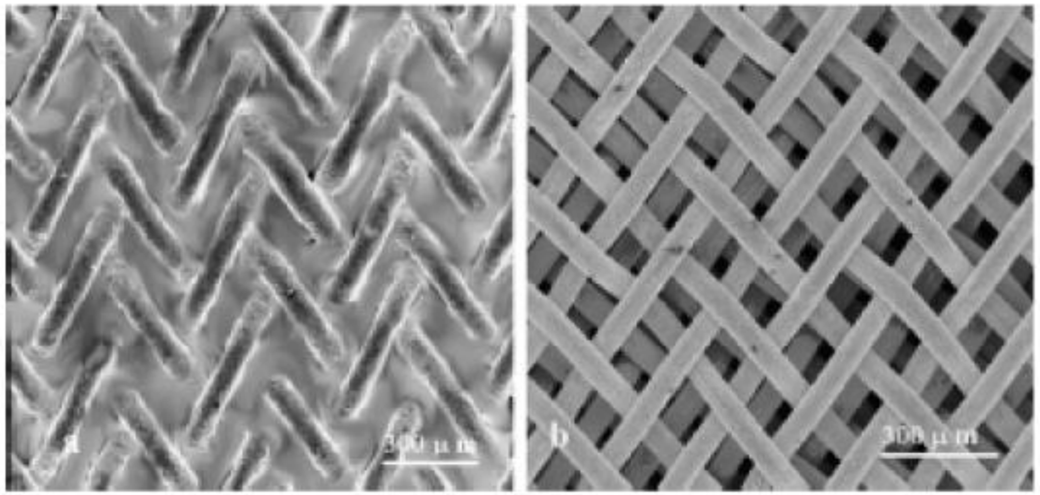
Transmutation, H+He creation, defects

Smaller operational temperature window

Increased brittleness

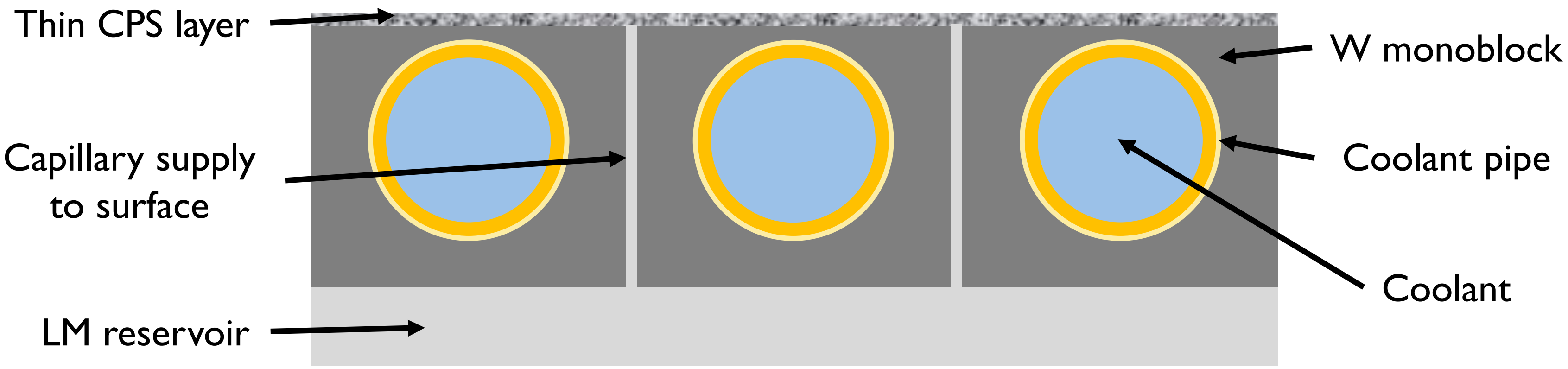
[1] *Maissonier NF 2007*
[2] *Linke NF 2011*
[3] *Loewenhoff FED 2012*

Capillary porous structures (CPSs) create conduction based stabilized PFCs



Evtikhin 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



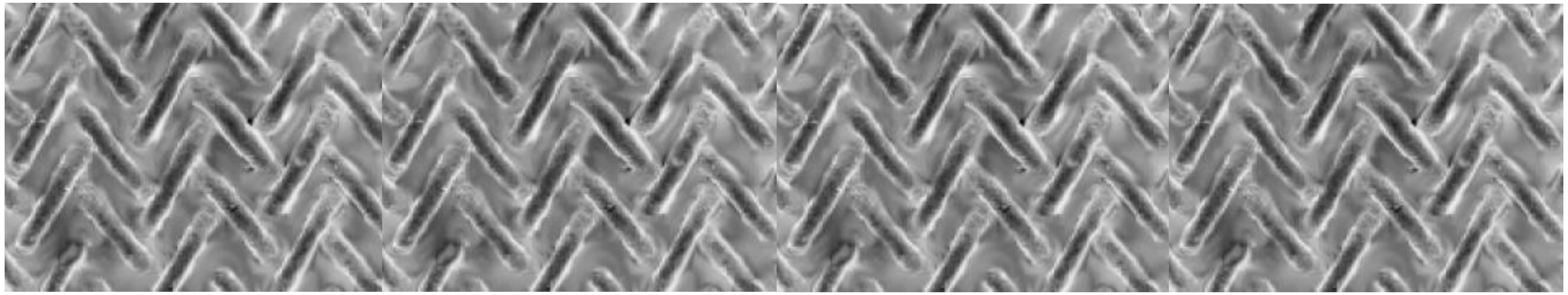
Benefits of liquid metals for DEMO

Neutrons

Sputtering

Thermal shock/fatigue

Big ELMs/VDEs/disruptions



Self replenishment

Higher heat fluxes

(see later)

No cracking

Lowered stresses substrate

ELMs possible(?)

Already molten

Vapour protection

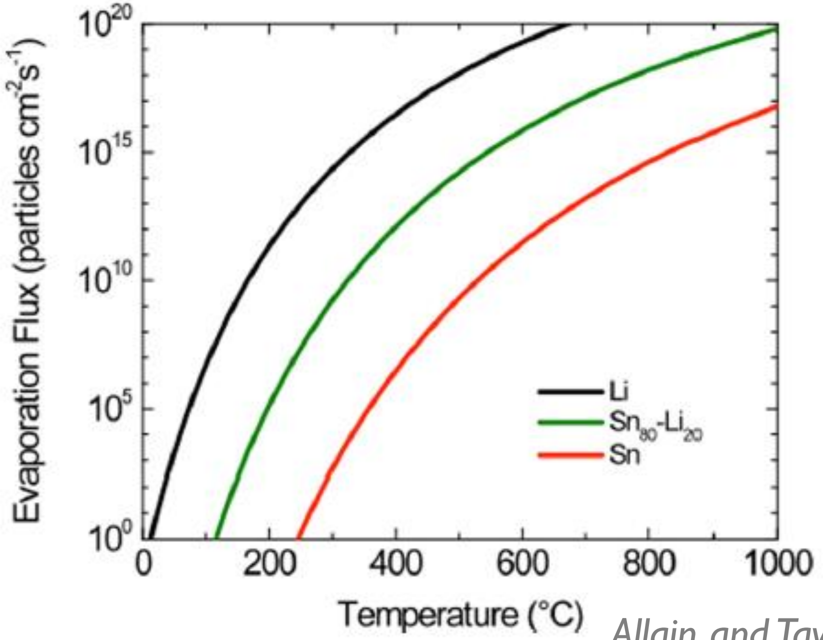
Only influences substrate

Separation of PSI from neutron issue

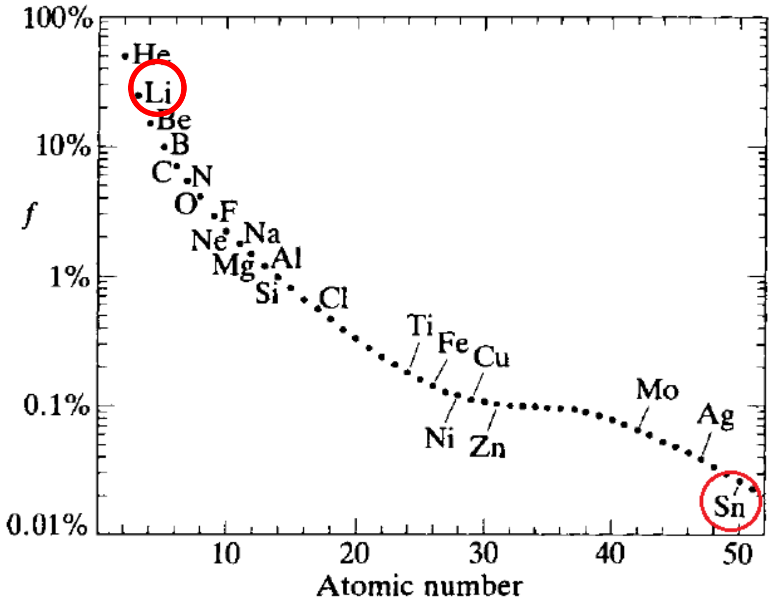
Material options of Li, Sn both have strengths and weaknesses

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

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

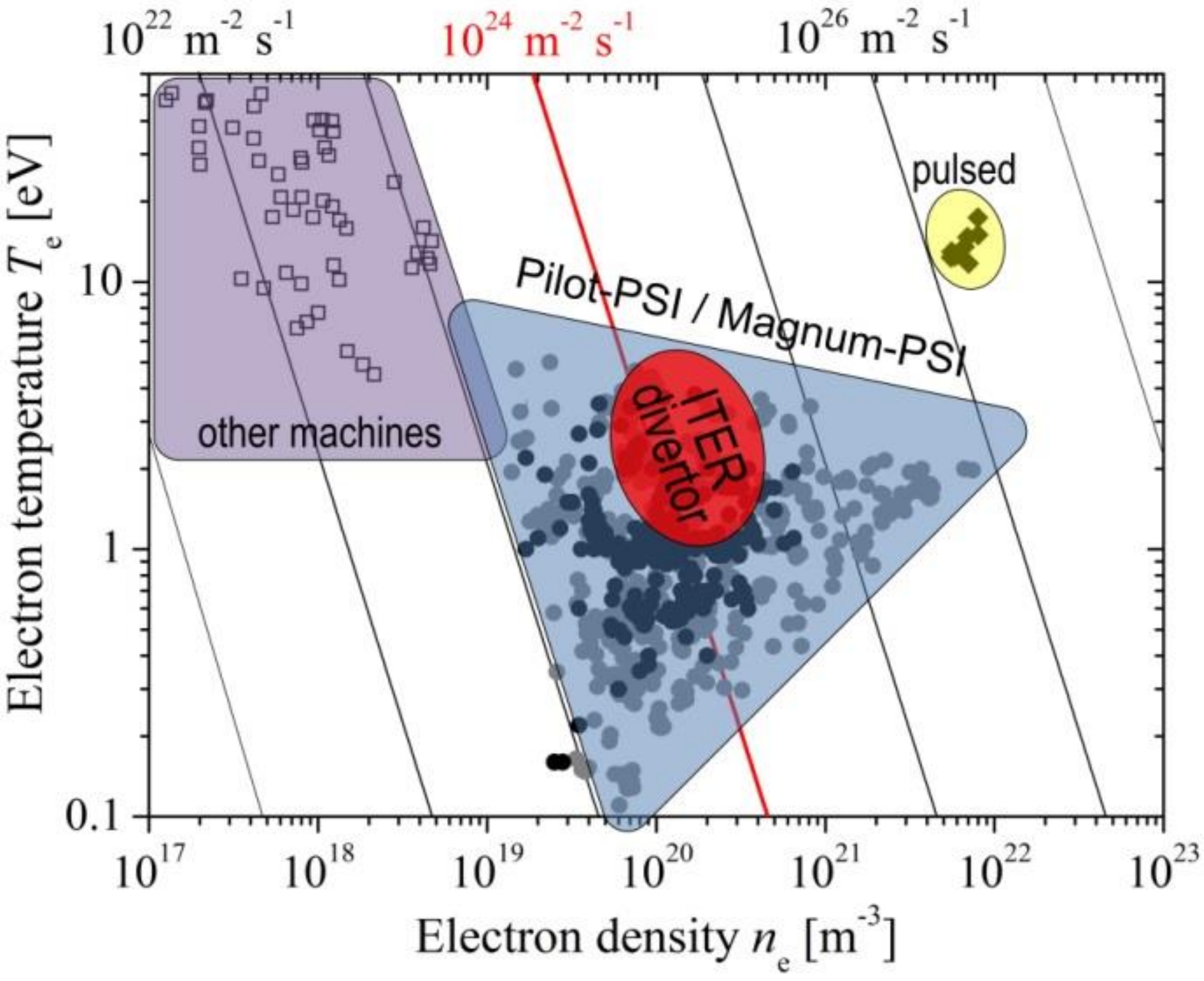


Allain and Taylor PoP (2012)

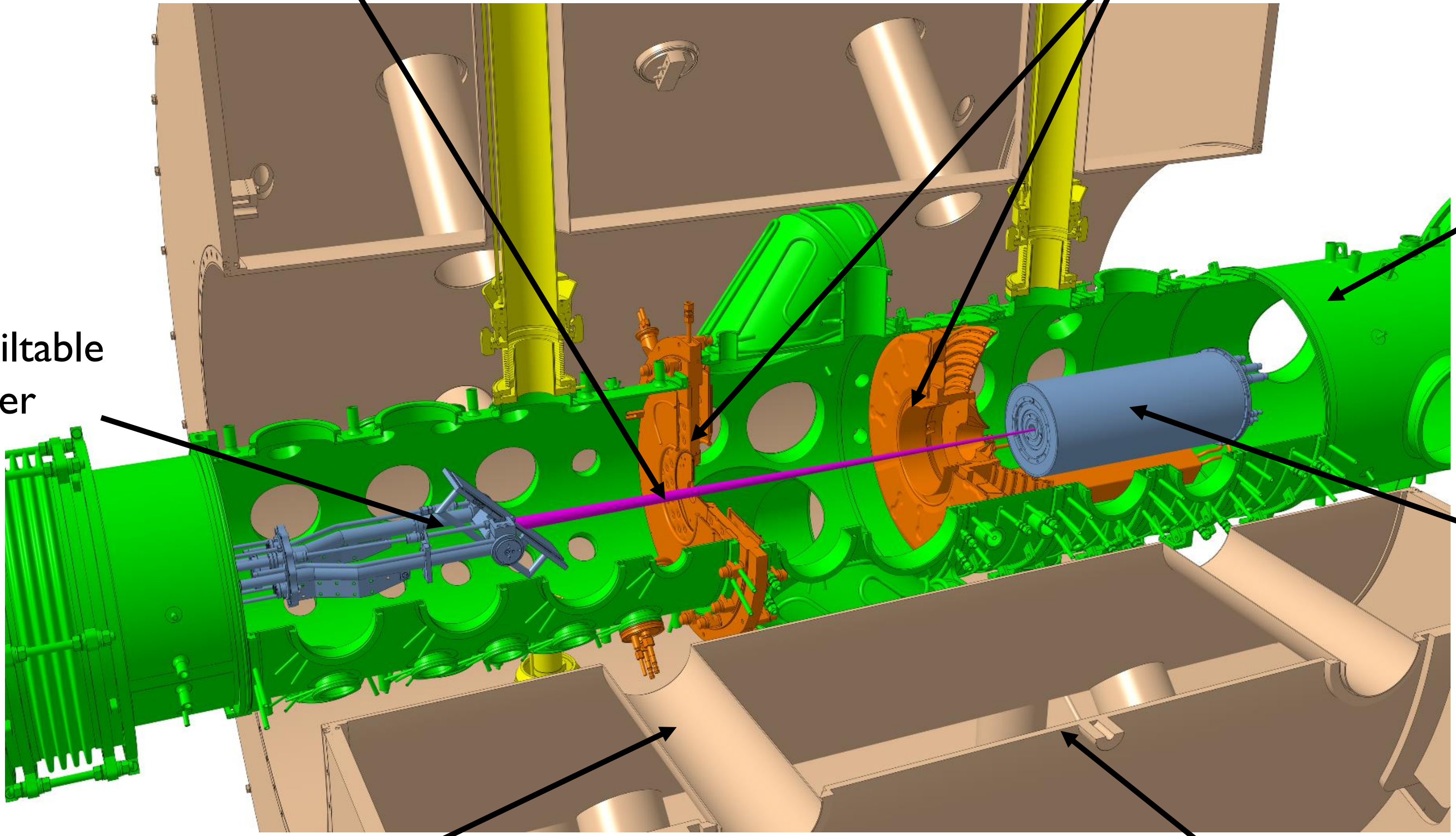


Wesson, Tokamaks (2004)

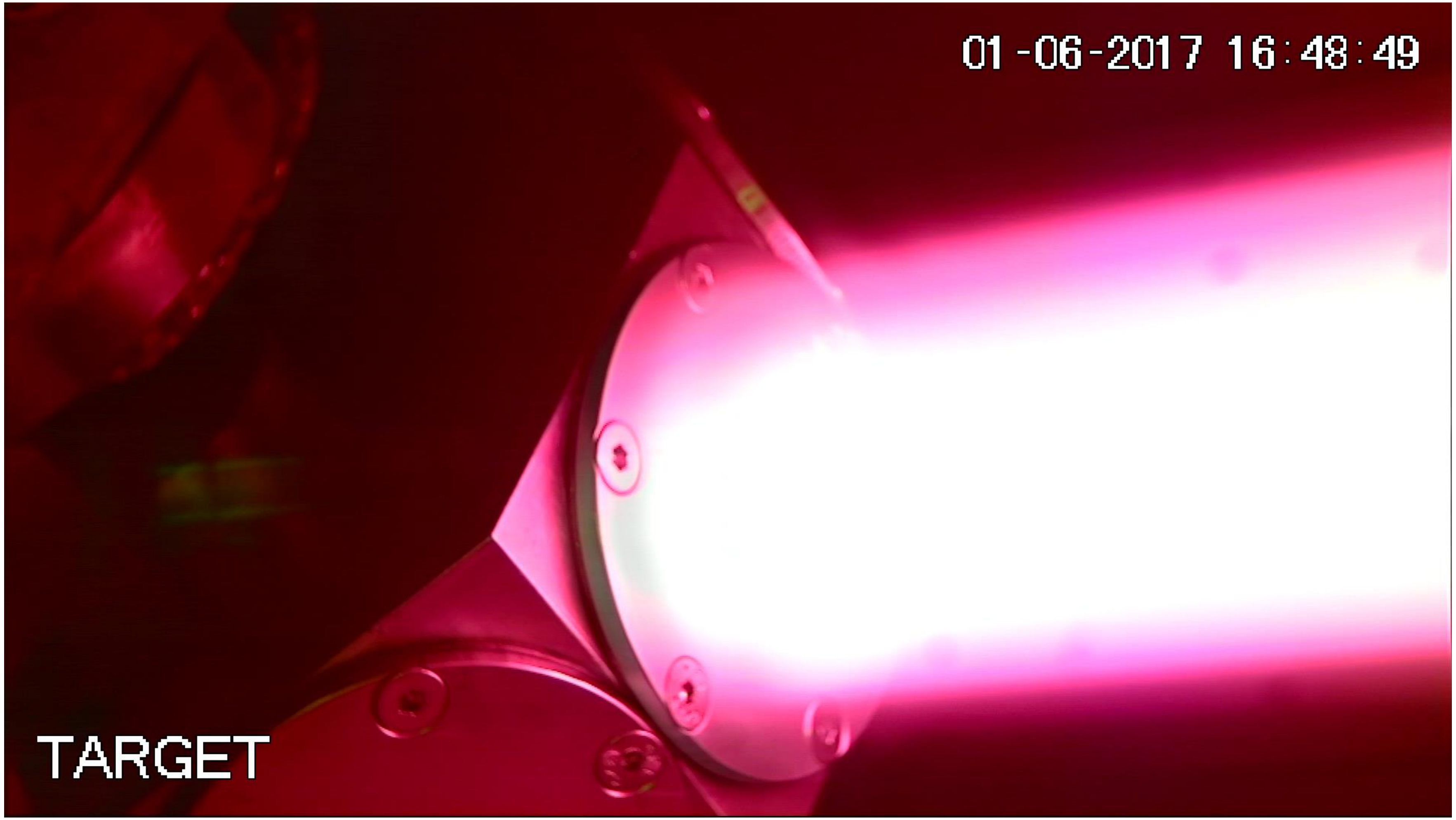
Magnum-PSI/Pilot-PSI utility for LM study due to DEMO relevant heat/particle loading



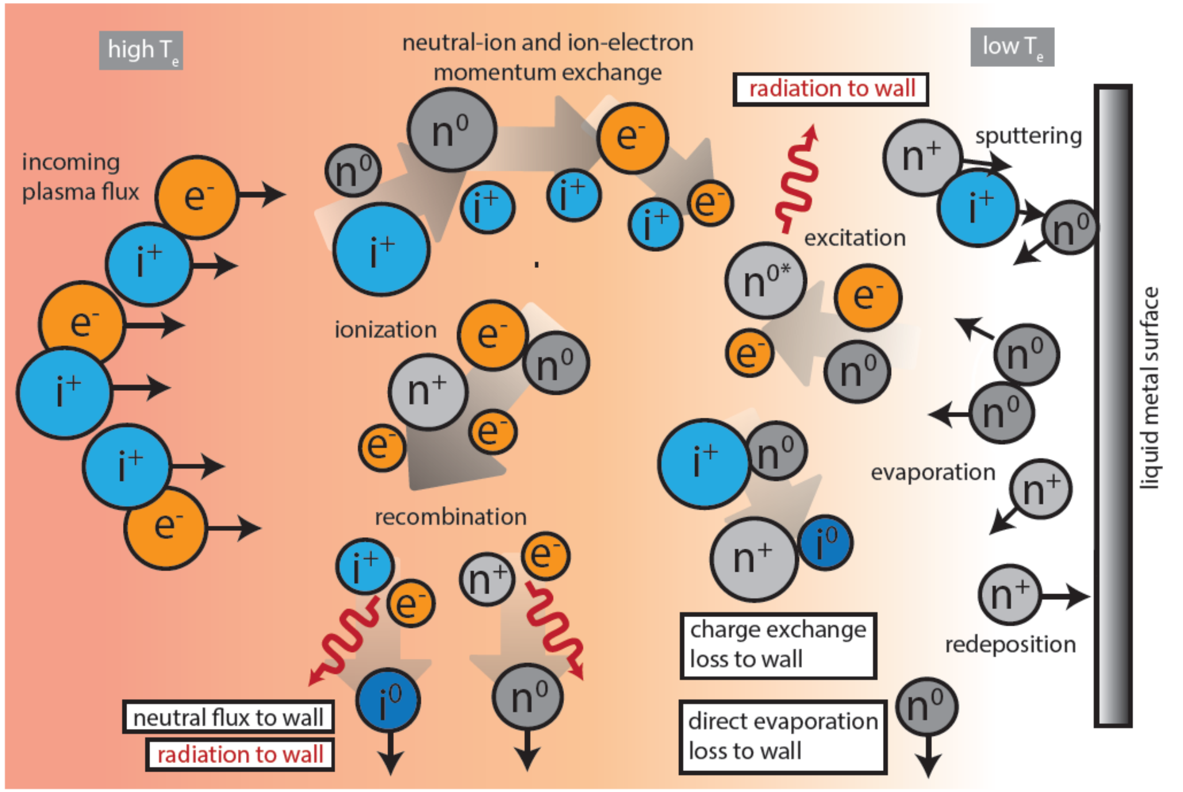
Linear devices have good flexibility and diagnostic access for basic physics and test module studies

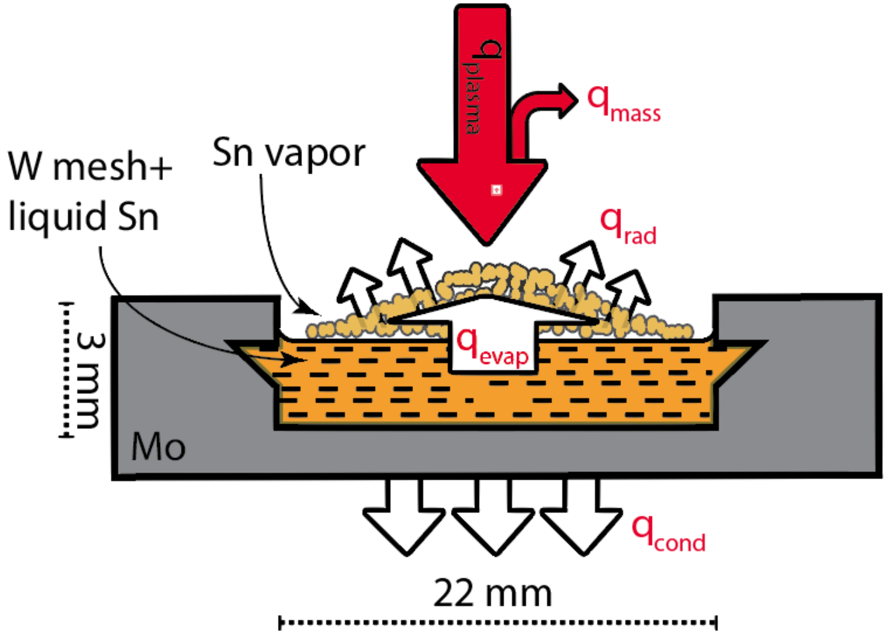


Linear devices have good flexibility and diagnostic access for basic and test module studies



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

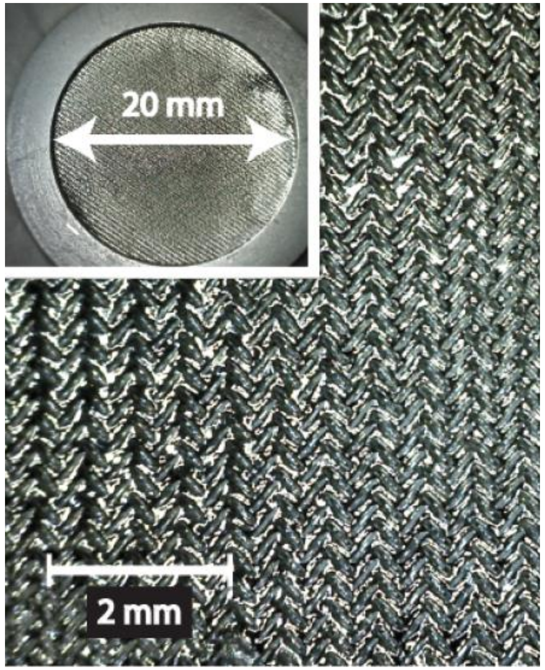


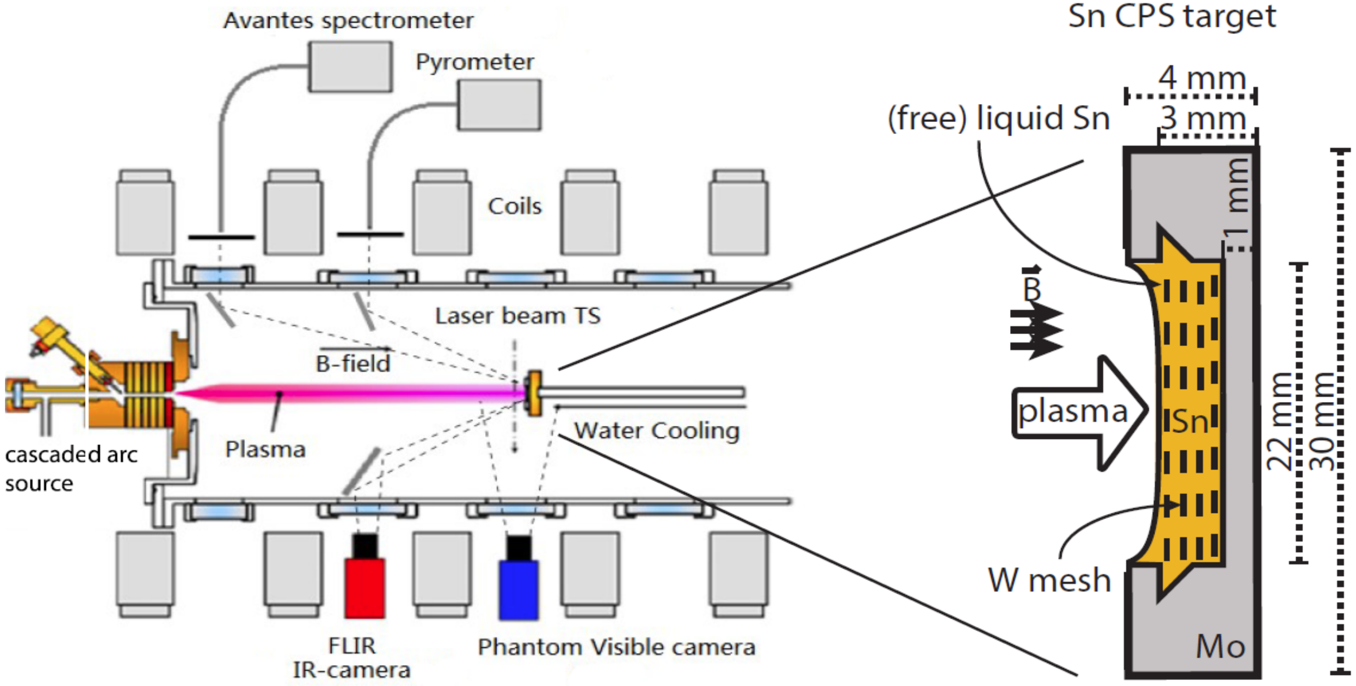


Solid metal: $q_{plasma} = q_{cond}$

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

Experiment compared performance of Sn CPS with solid Mo reference targets



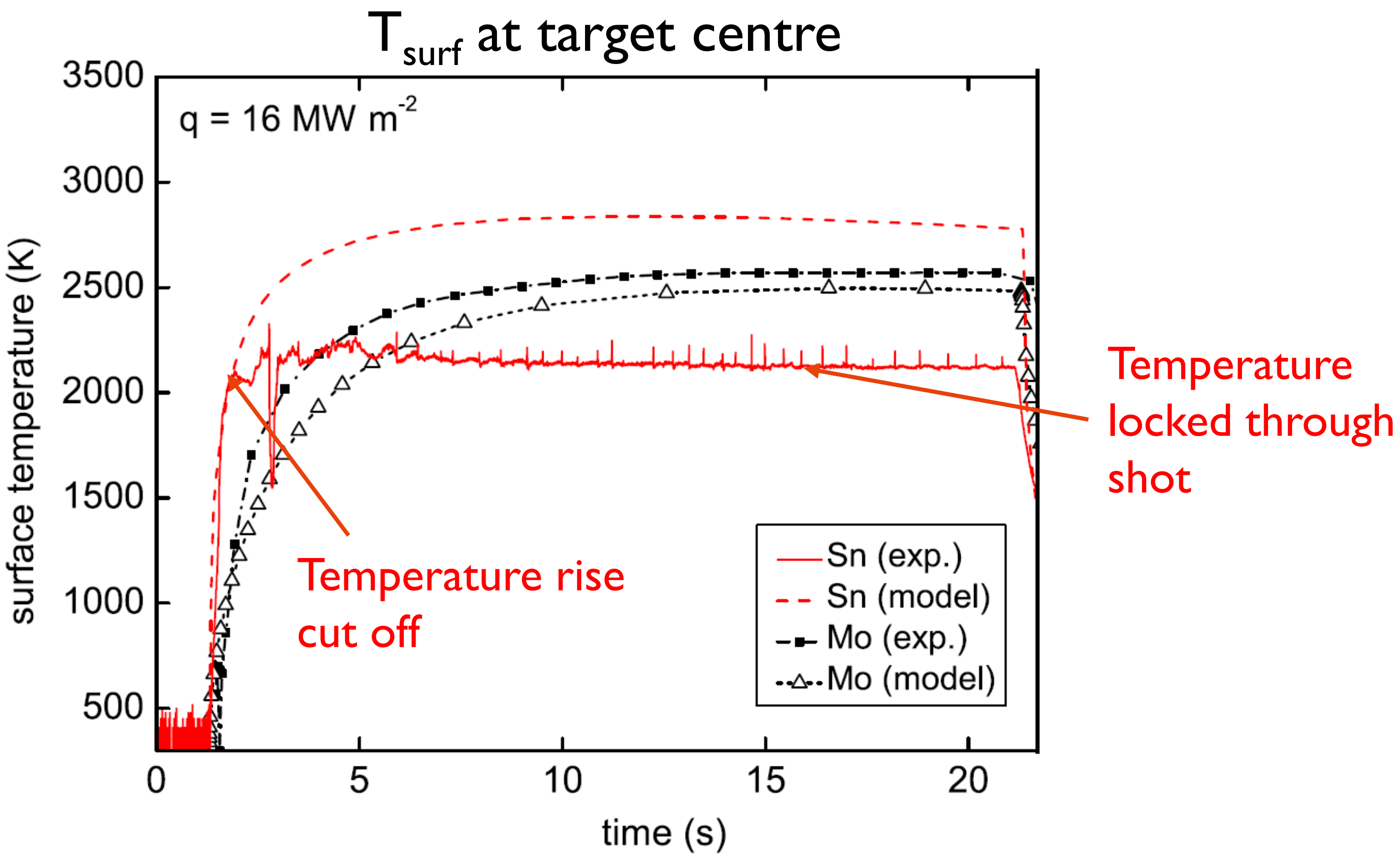


Ion species	T_e (eV)	n_e (10^{20} m^{-3})	Qref (MW m^{-2})
H or He	0.4-3.1	0.6-7.0	0.47-22

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

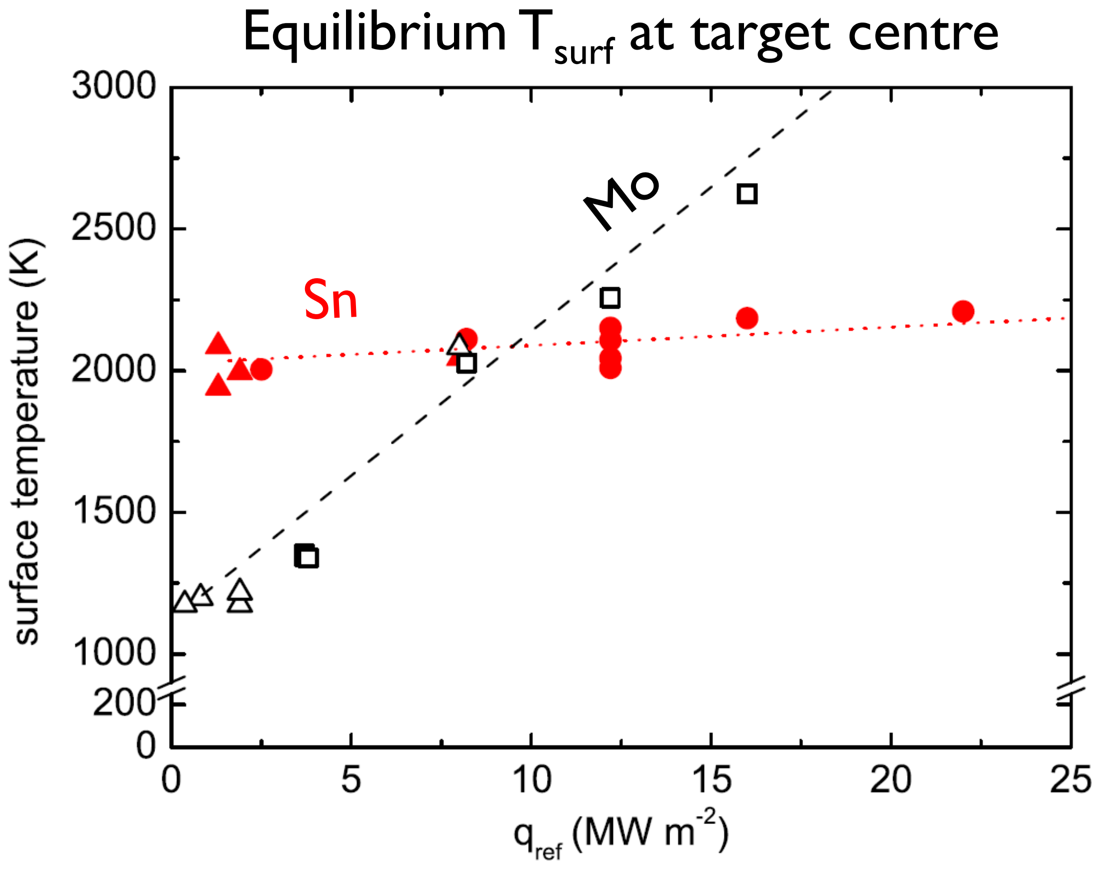
Vapour interaction with plasma decouples input power from surface temperature

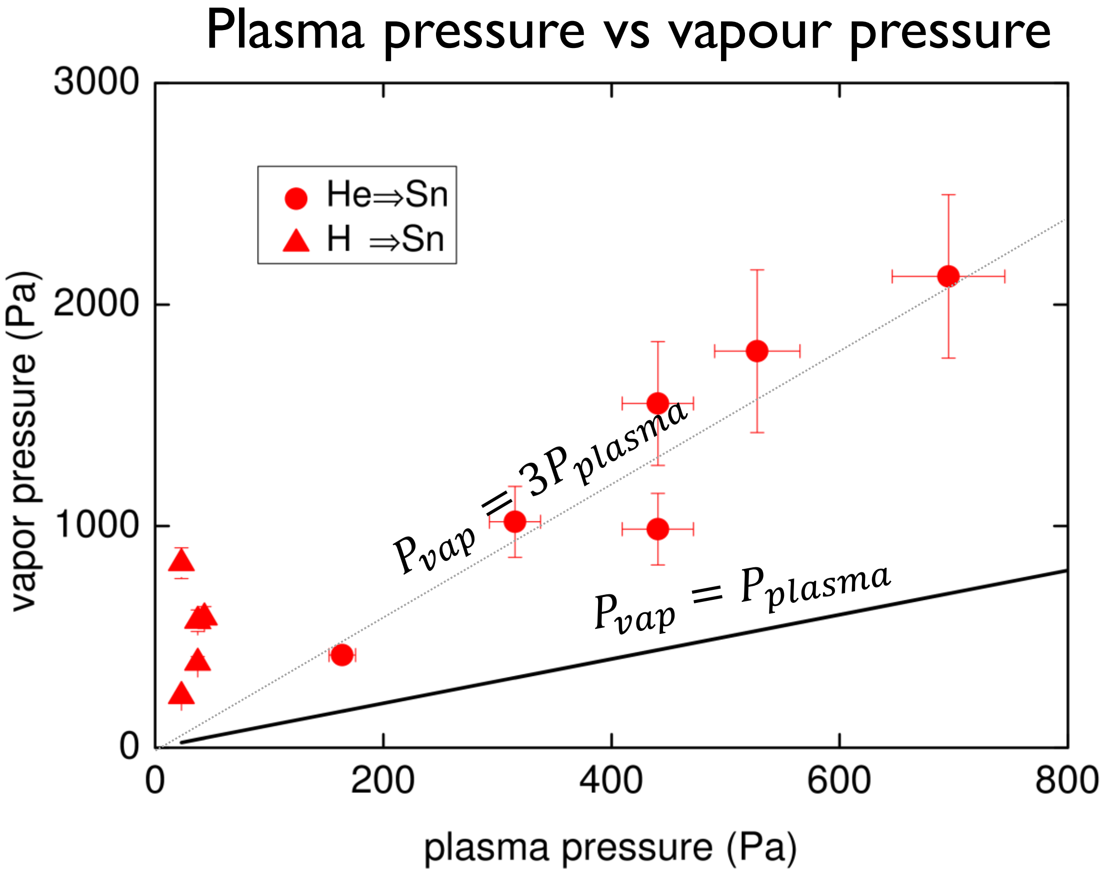
Poorly cooled Sn samples exposed to power load series in pilot-PSI



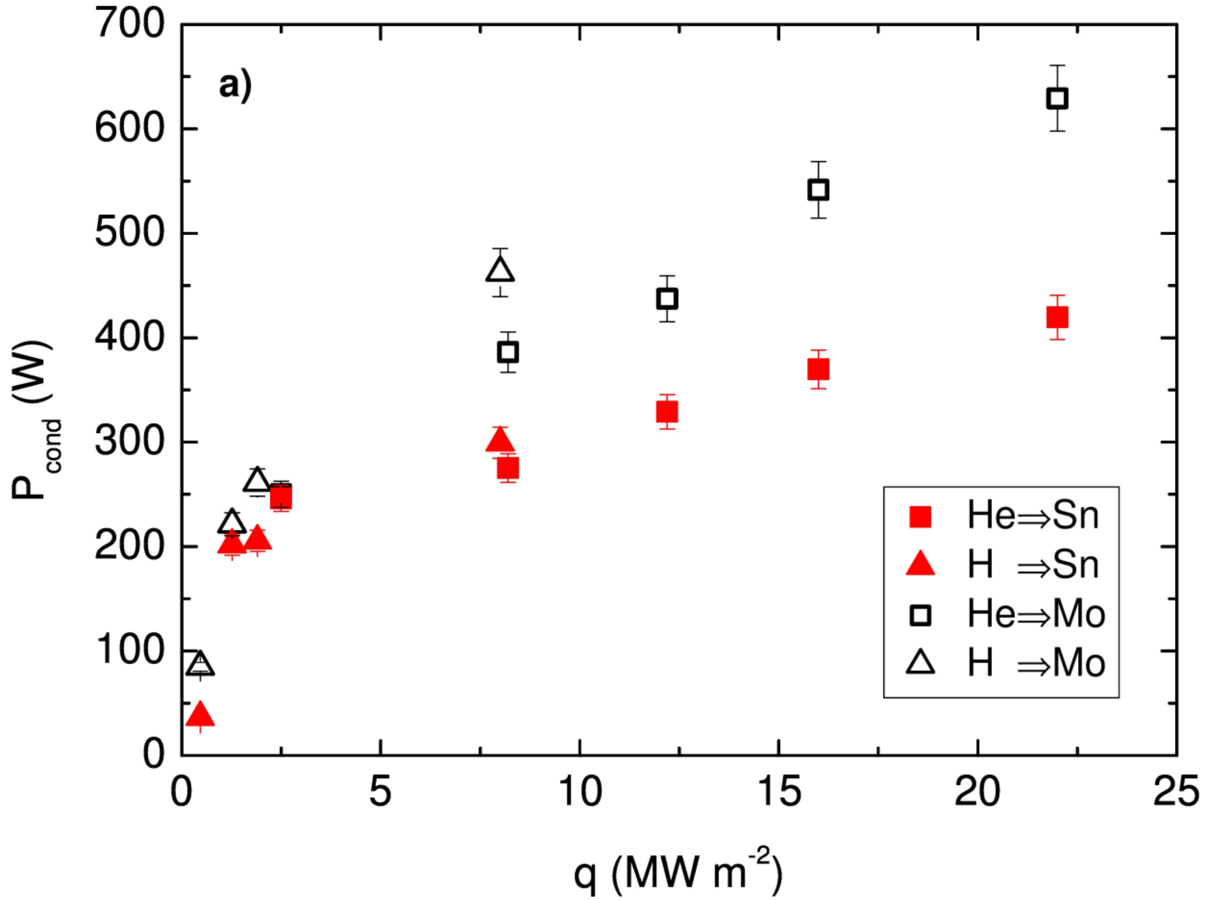
van Eden PRL 2016

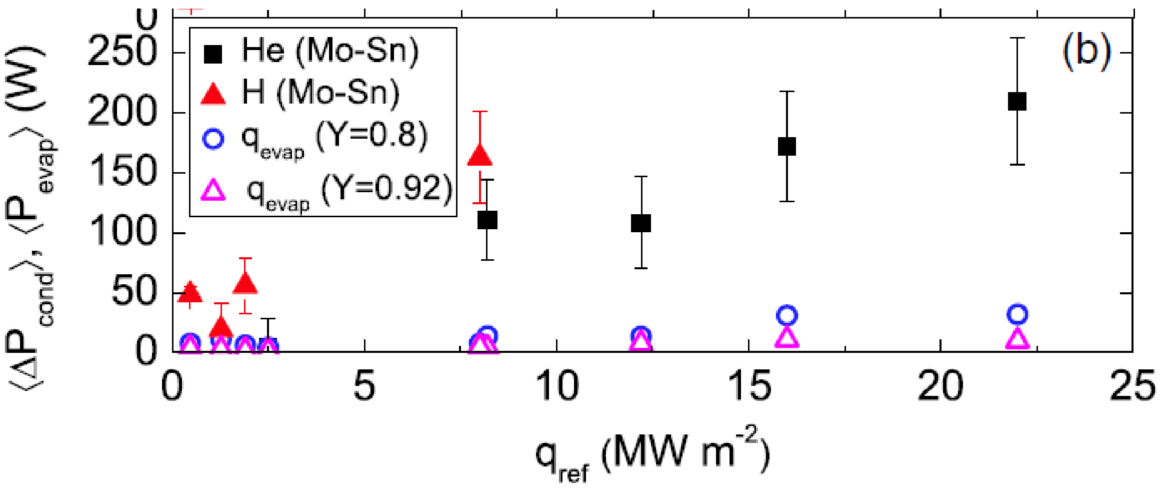
Temperature locking when vapour pressure and plasma pressure ~ matches





Overall reduction in power to cooling water of ~one third

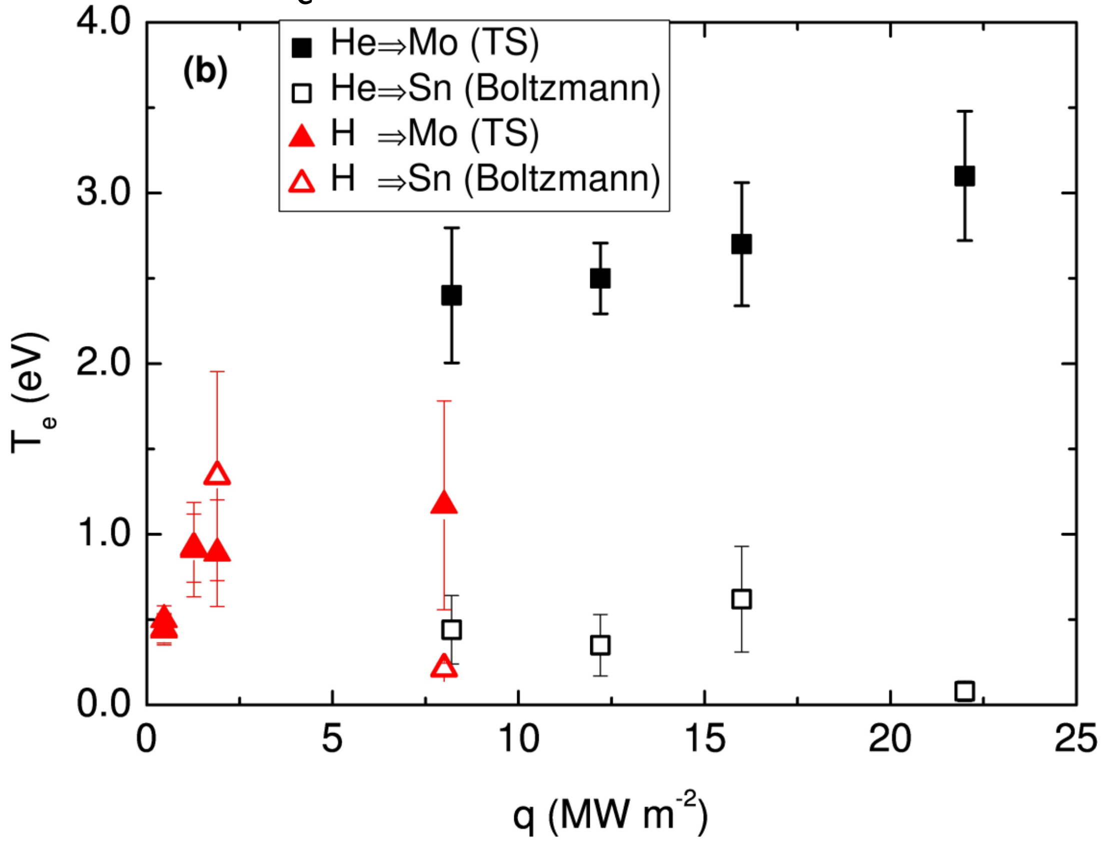




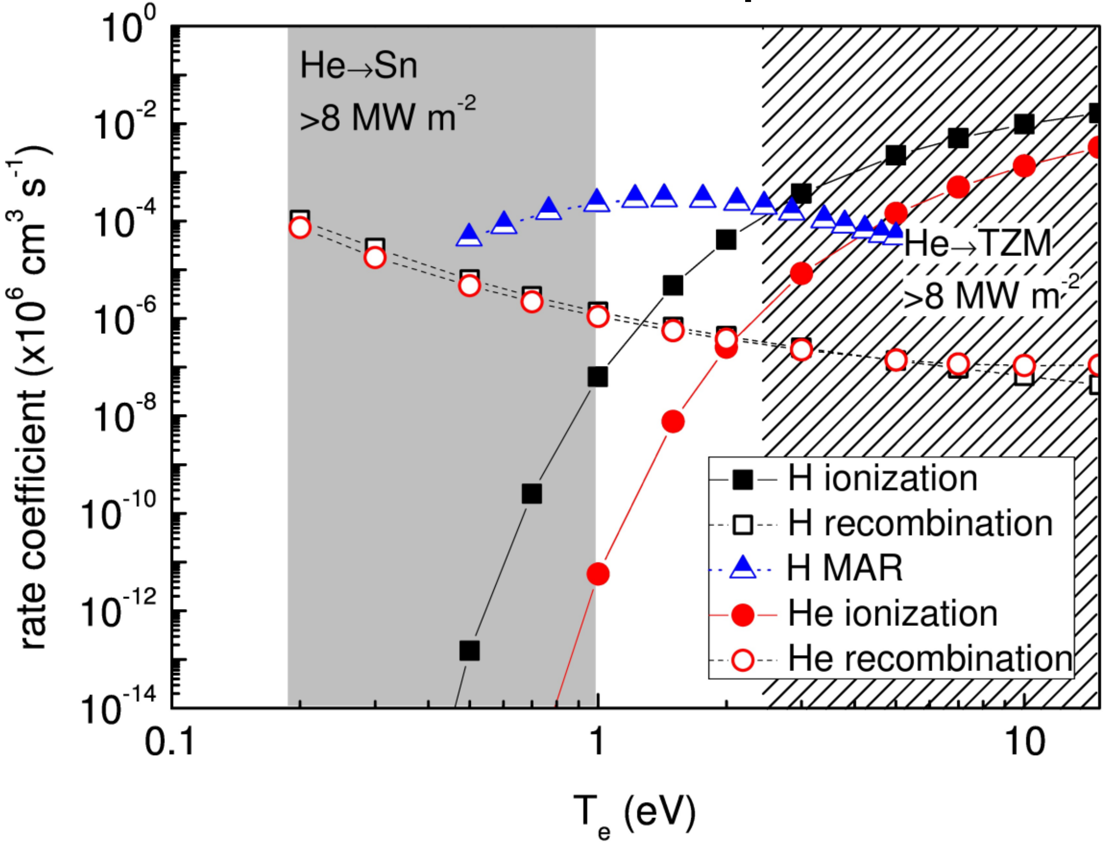
Evaporation alone cannot explain energy loss: relatively high re-deposition rate means most energy returns to surface

Strong recombination occurs due to lowered T_e

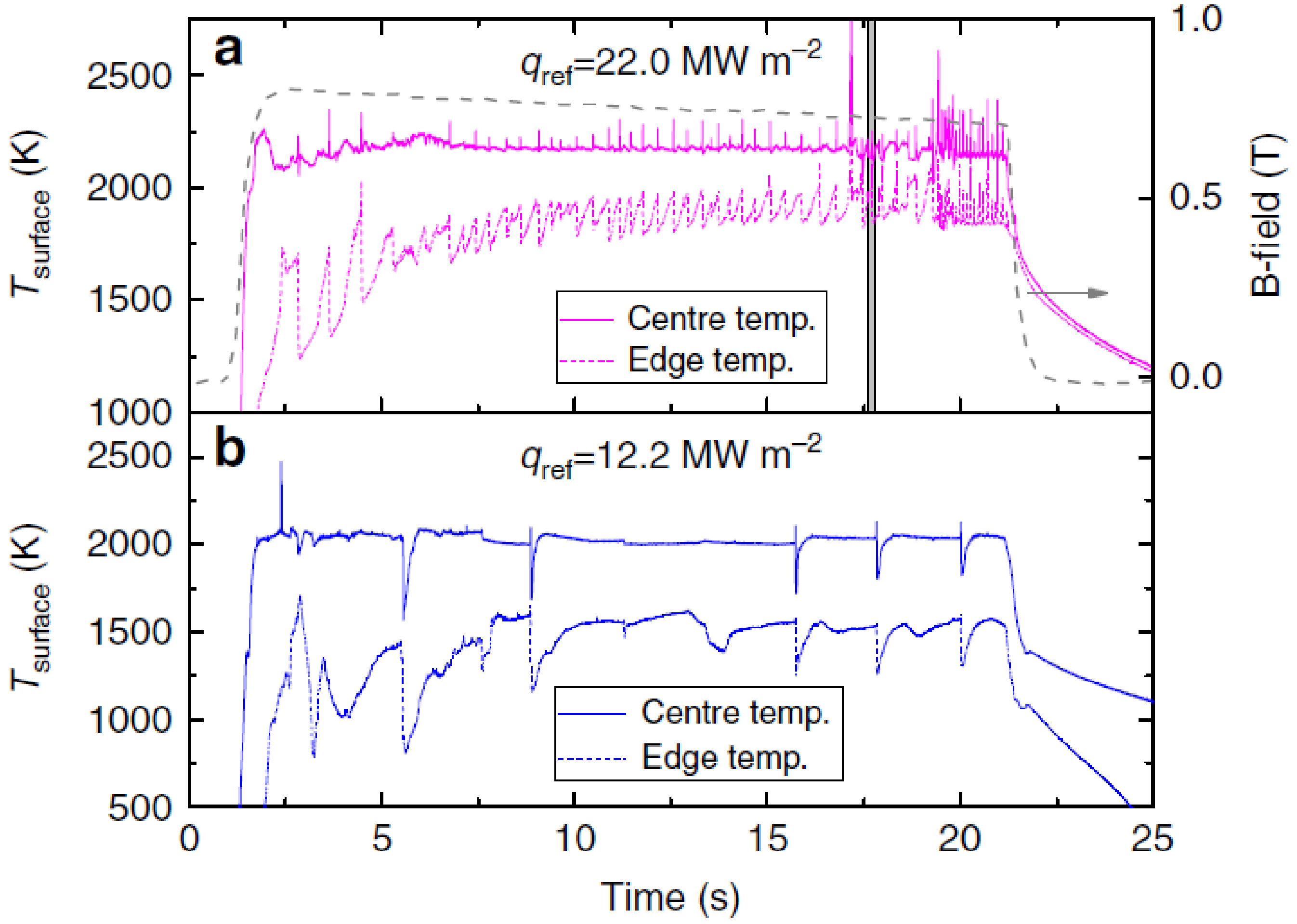
T_e Sn shots vs Mo shots

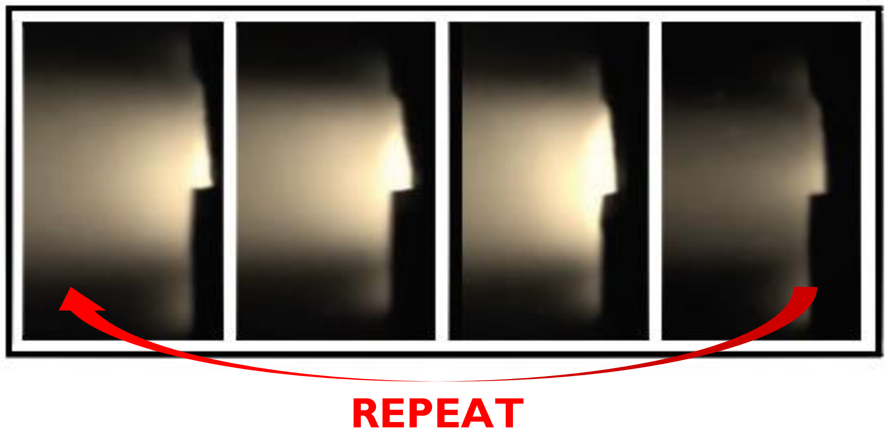


Atomic/Molecular processes

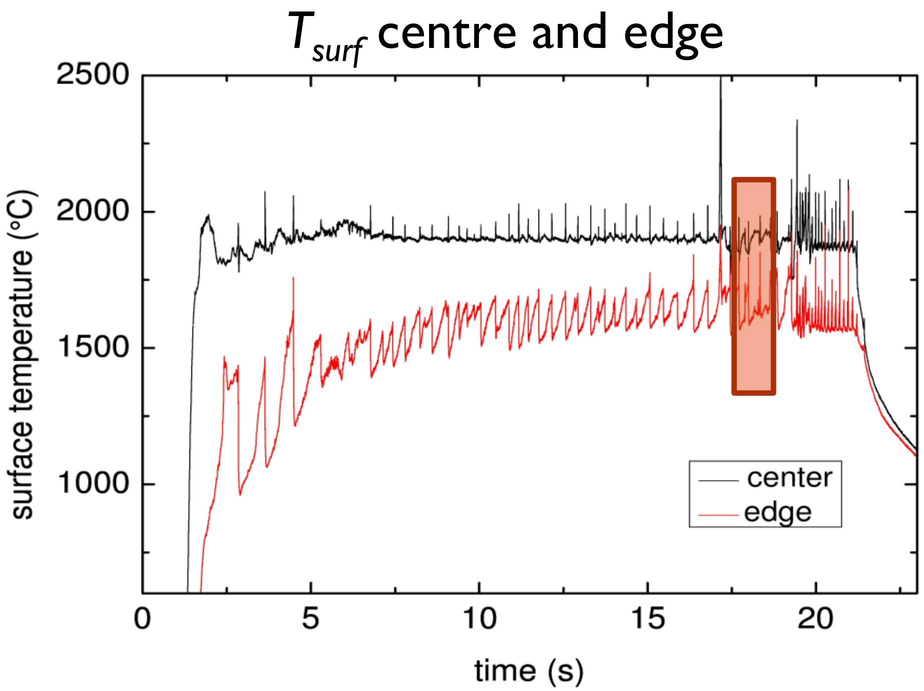


Oscillatory self-regulatory behaviour is observed: dynamical equilibrium

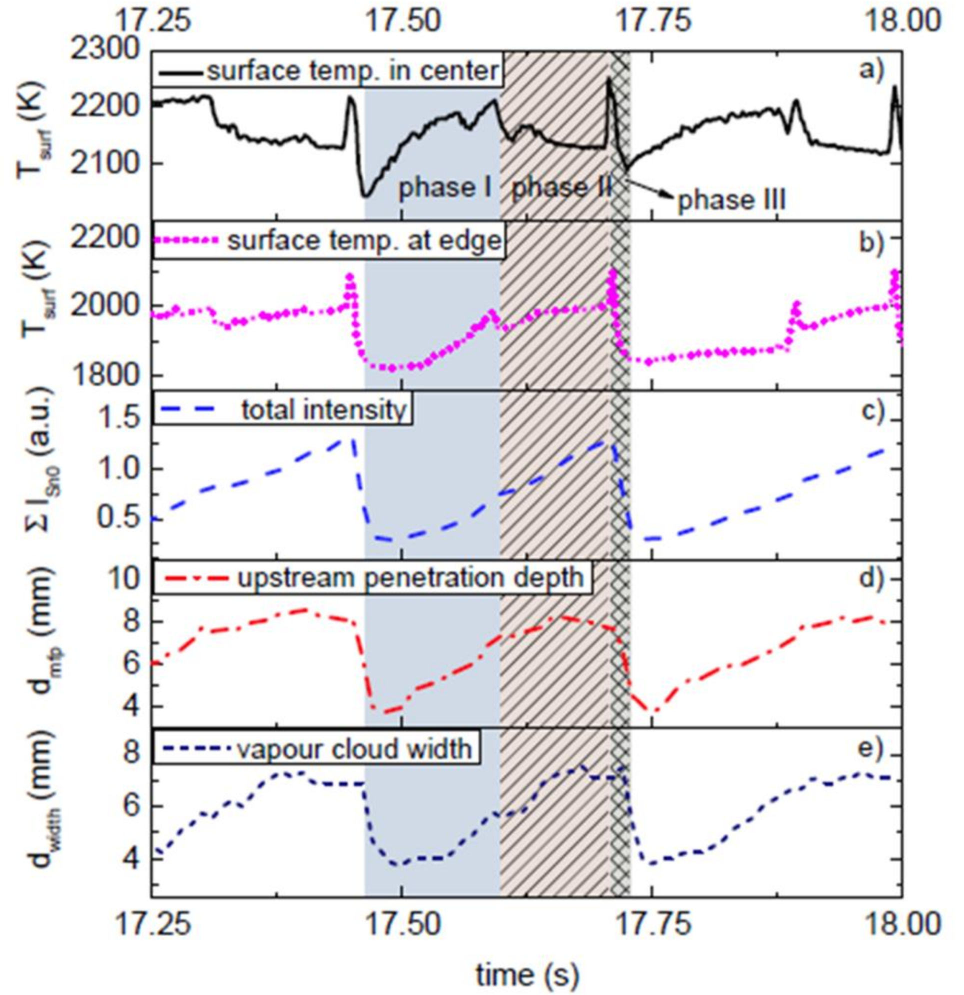




Shielding behaviour is oscillatory in nature

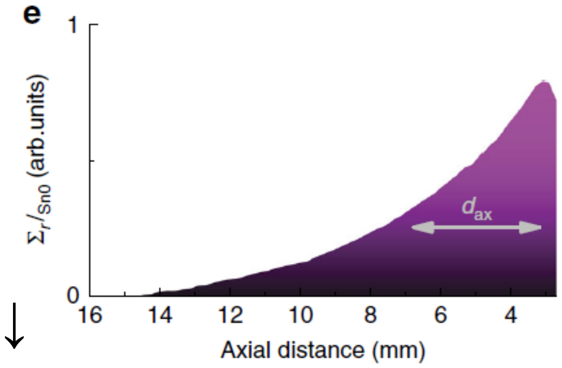


Emission and surface temp. correlated:



Sn⁰ emission @452 nm recorded at 10 kHz

$$I_{\mathrm{Sn0}} \propto n_{\mathrm{Sn0}} n_{\mathrm{e}} C_{\mathrm{exc}}(T_{\mathrm{e}})$$

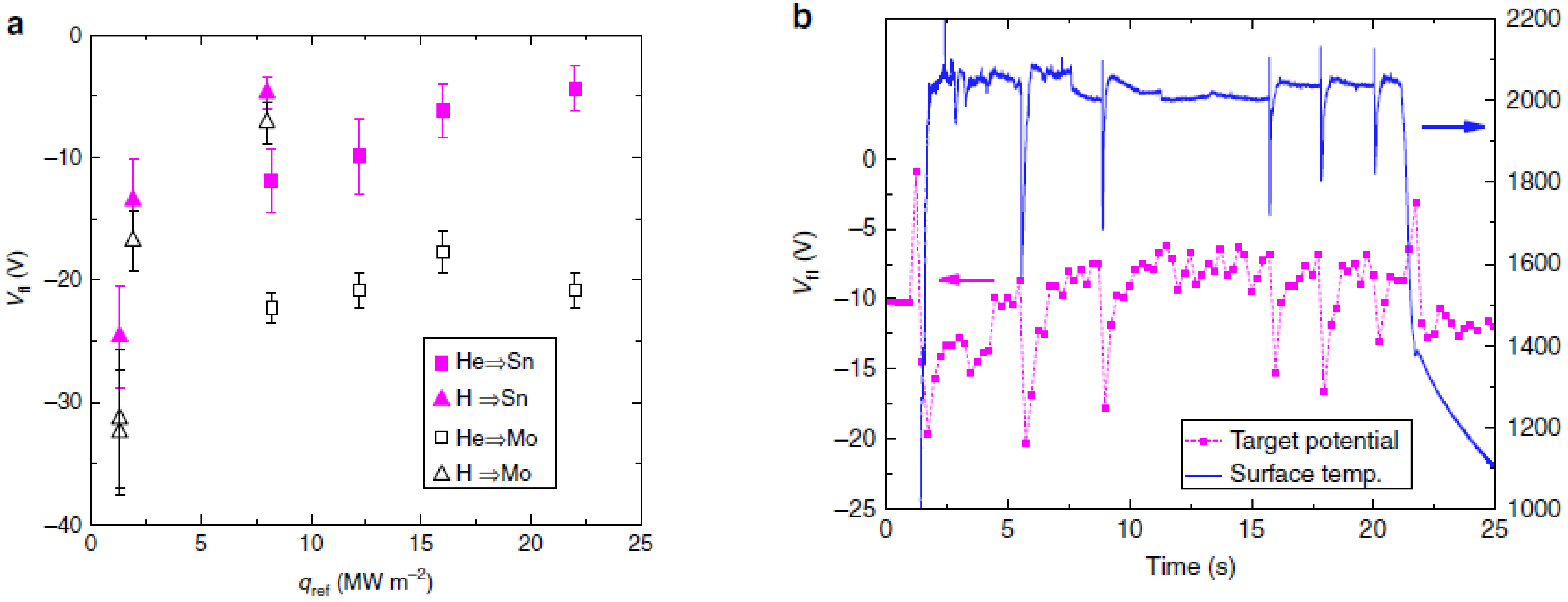


- Vapour cloud size and emission correlated to surface temperature
- $d_{mfp} \propto \frac{1}{\sigma n_e} \rightarrow d_{mfp} \uparrow$; T_e and/or $n_e \downarrow$

Oscillations in floating target potential indication of T_e variations

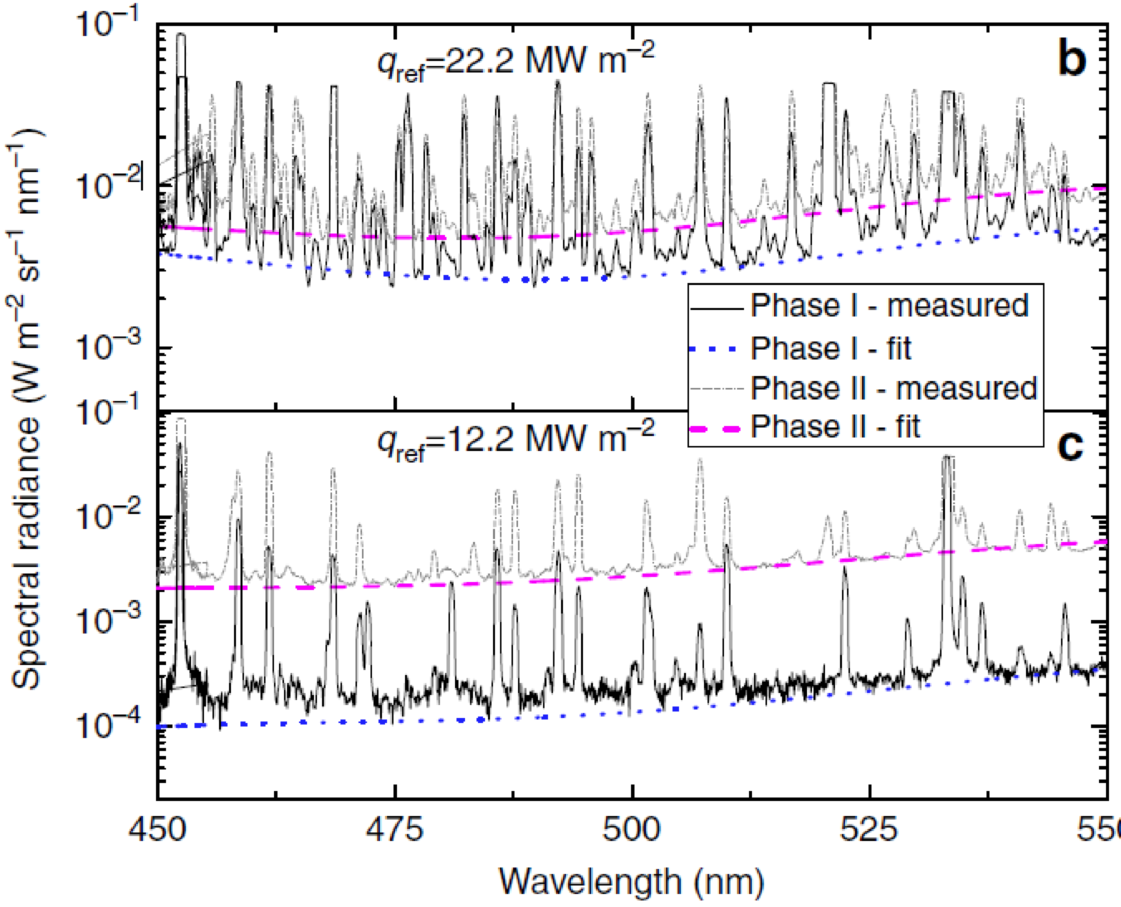
$$V_{fl} = V_p + V_{sh} + V_{ps}$$

$$V_{sh} \approx 2.5 k_B T_e / e$$



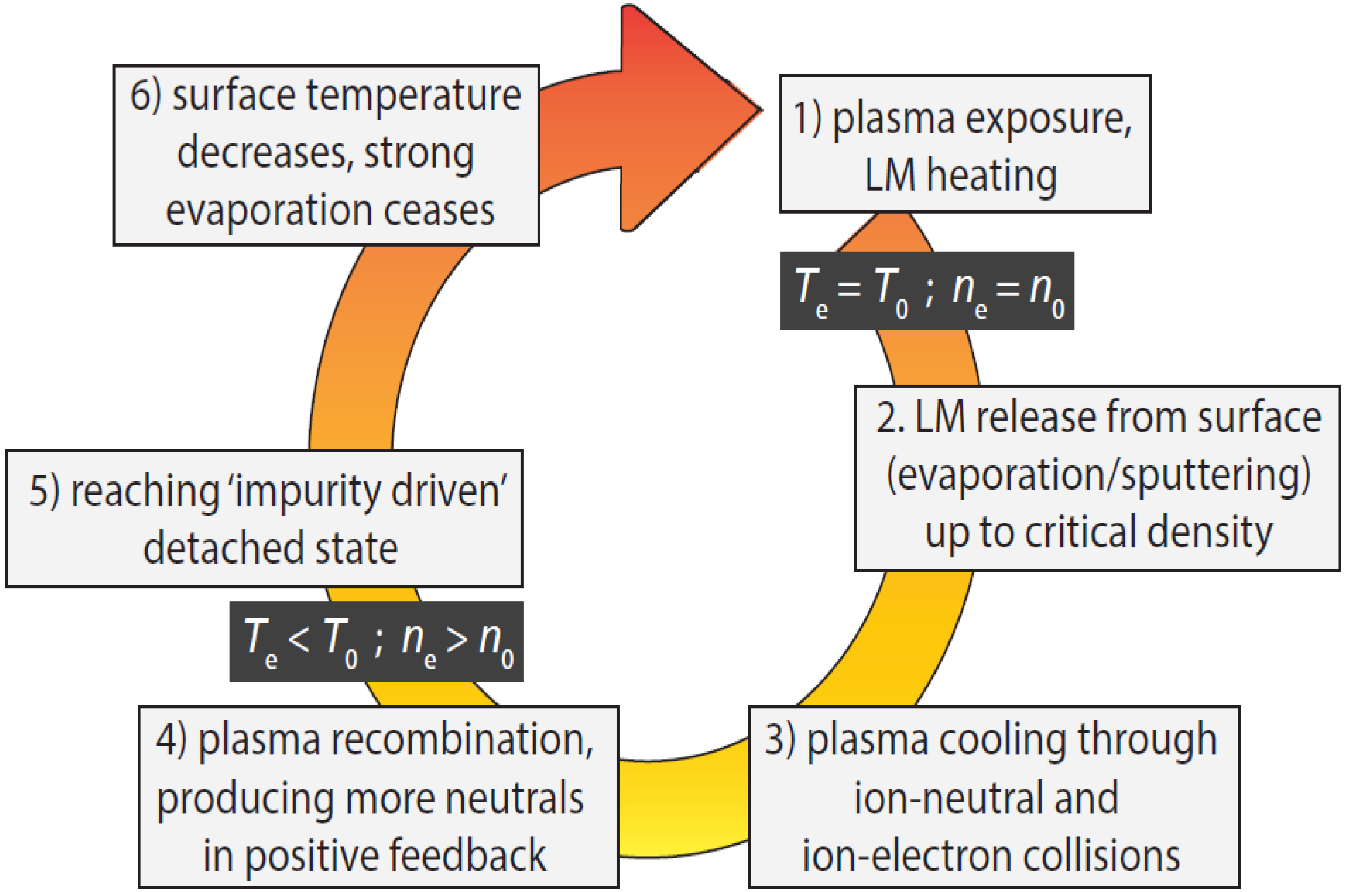
Oscillation in continuum emission – a sign of n_e variation

$$\epsilon_{\mathrm{cont}} \propto \sum_i \frac{n_\mathrm{i} n_\mathrm{e}}{\sqrt{T_\mathrm{e}}} = \frac{n_\mathrm{e}}{\sqrt{T_\mathrm{e}}}(n_{\mathrm{He}^+} + n_{\mathrm{Sn}^+}) = \frac{n_\mathrm{e}^2}{\sqrt{T_\mathrm{e}}}\,[\mathrm{Wm^{-3}sr^{-1}nm^{-1}}]$$



- Continuum emission increasing throughout cycle. n_e increases by factor 4
- Increased mean free path of Sn neutrals thus explained by reduced collision rate due to lower T_e
- Plasma pressure still ~conserved. ($\propto n_e T_e$)

Cyclical equilibrium leads to dynamic locking of temperature at pressure balance point

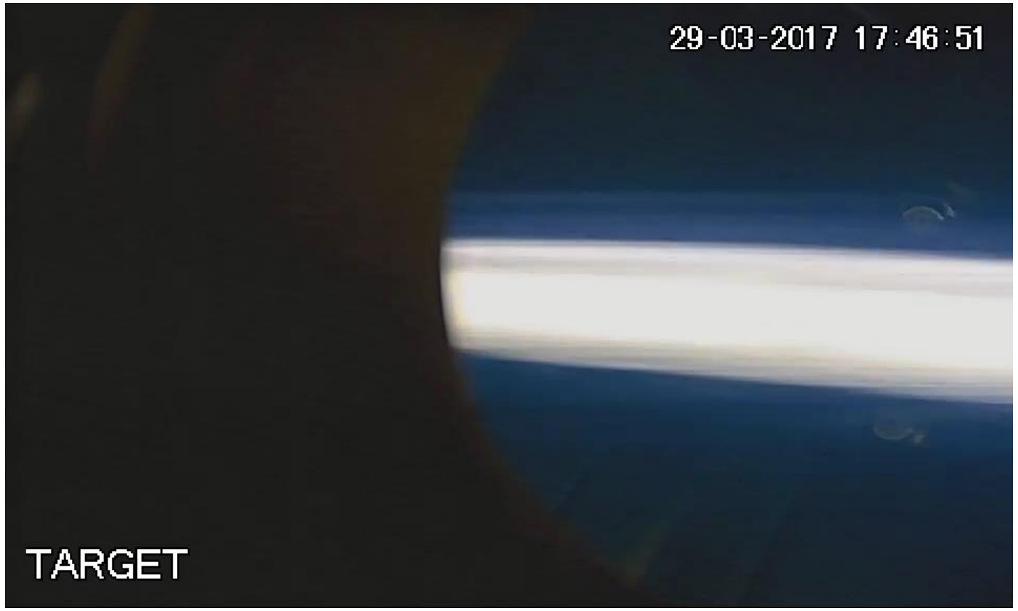


- Detachment timescale: $\tau_{ie} = \tau_{ei} = \tau_e\, m_{He}/2m_e$ ≈ **0.2 μs** (at 0.8 eV and $n_e = 10^{20}$ m^{-3})
- Vapour extinction timescale: $\tau_v = d_{ax}/\sqrt{(2\, kB\, T_{surf})/m}$ ≈ **16 μs**
- Cooling timescale: $T_{surf} = (T_0 - T_{cool})\, e^{-t/\tau_c} \rightarrow \tau_c$ ≈ **250 μs**
- Oscillation freq. (~10 Hz) set by thermal equilibrium timescale

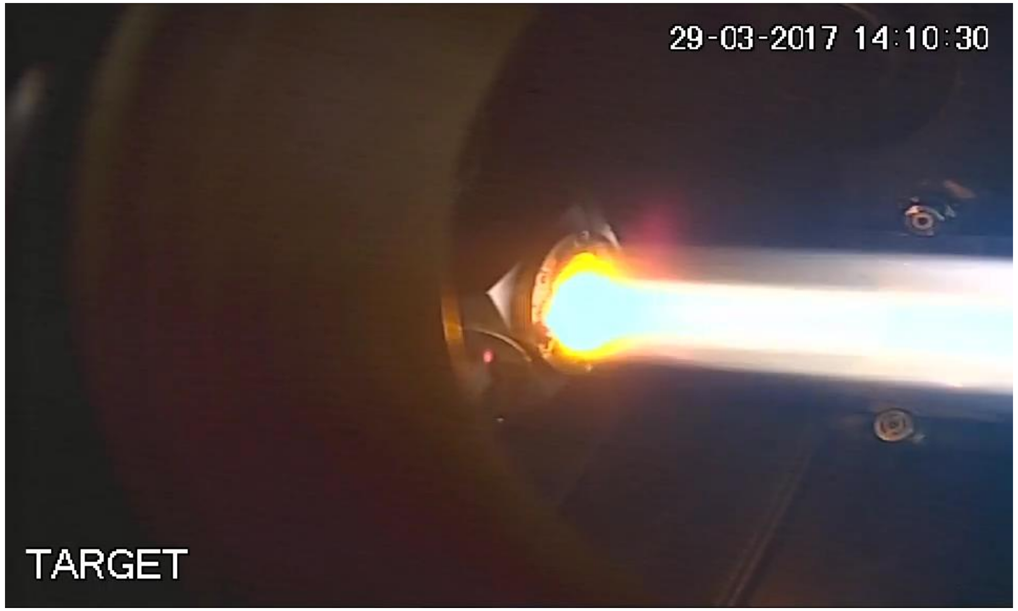
Increased (visual) emission near Li CPS target compared to solid reference

Applied conditions: 150 A, 14 slm He, 0.8 T → **11.4 MW m^{-2}**

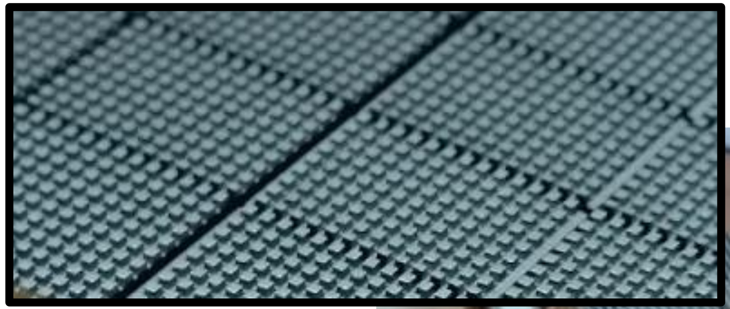
Mo reference:

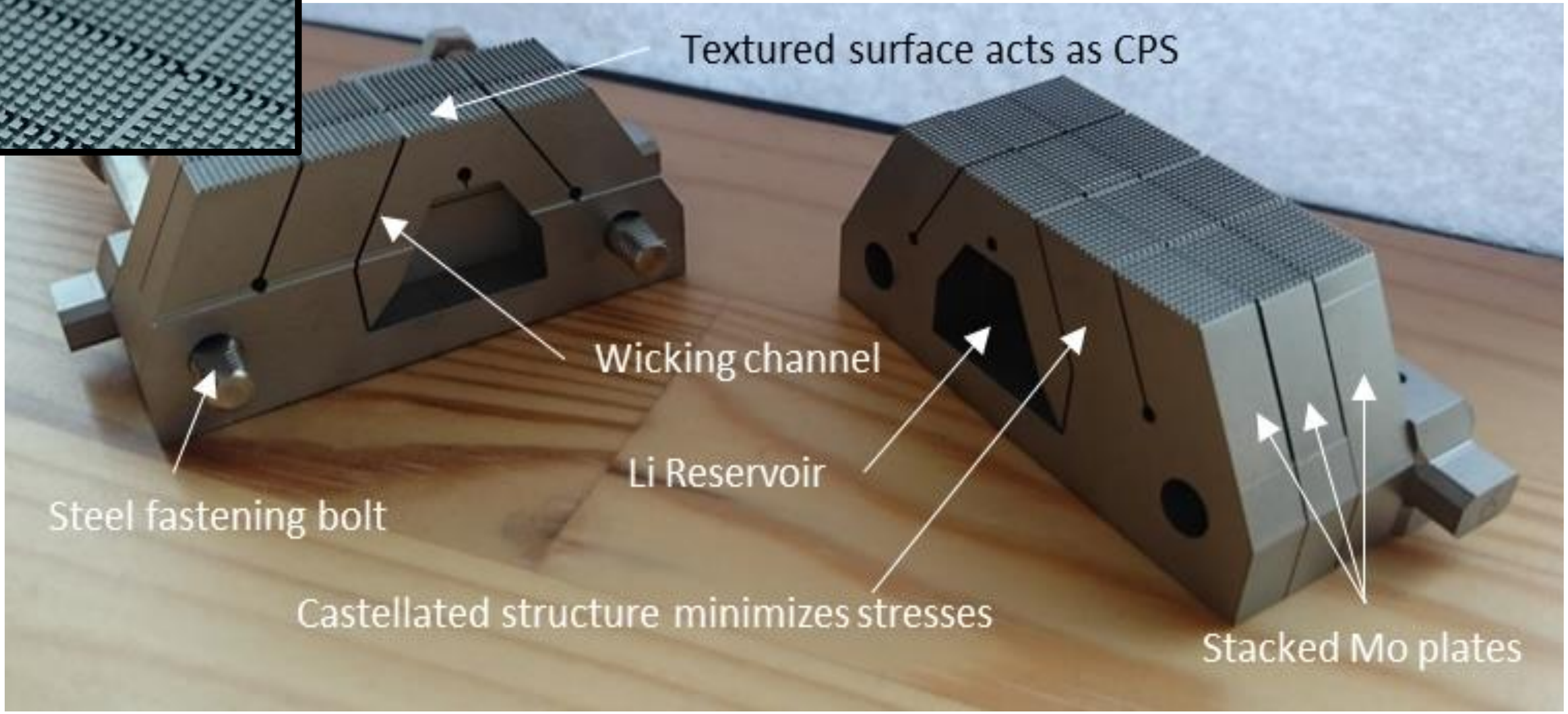


Li CPS



Technological challenge- performance on long timescales via surface replenishment

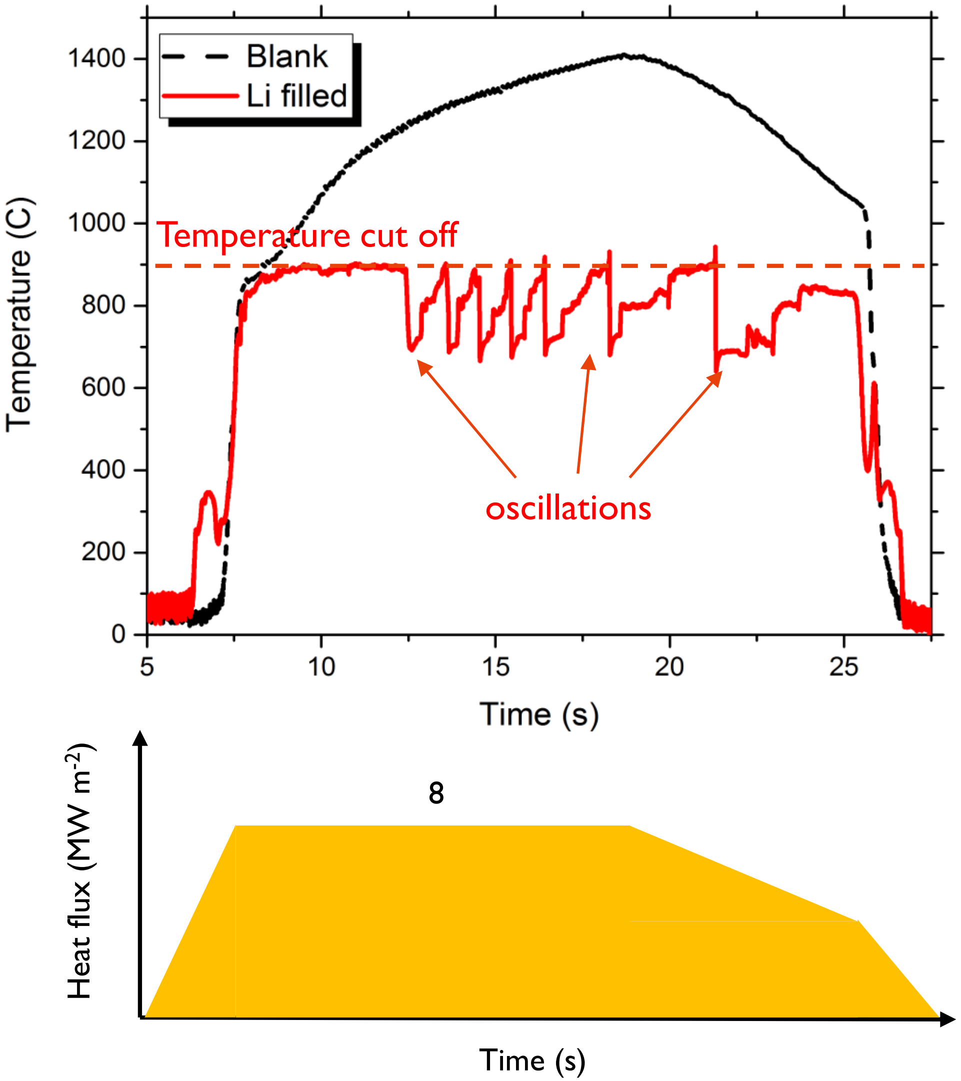




Component similar to and designed to test design for NSTX-U

Rindt FED 2016

Similar vapour shielding effect observed for Li as for Sn



- High heat load can be sustained (8 MW m^{-2} peak heat load)
- Sn vapour limit is ~1700 ° C (P_{vap}~$3P_{plasma}$)
- Prediction for Li is therefore ~700-900 ° C
- Prediction well matched by observation
- Similar oscillatory behaviour as for Sn

Analytical description of VS mechanism

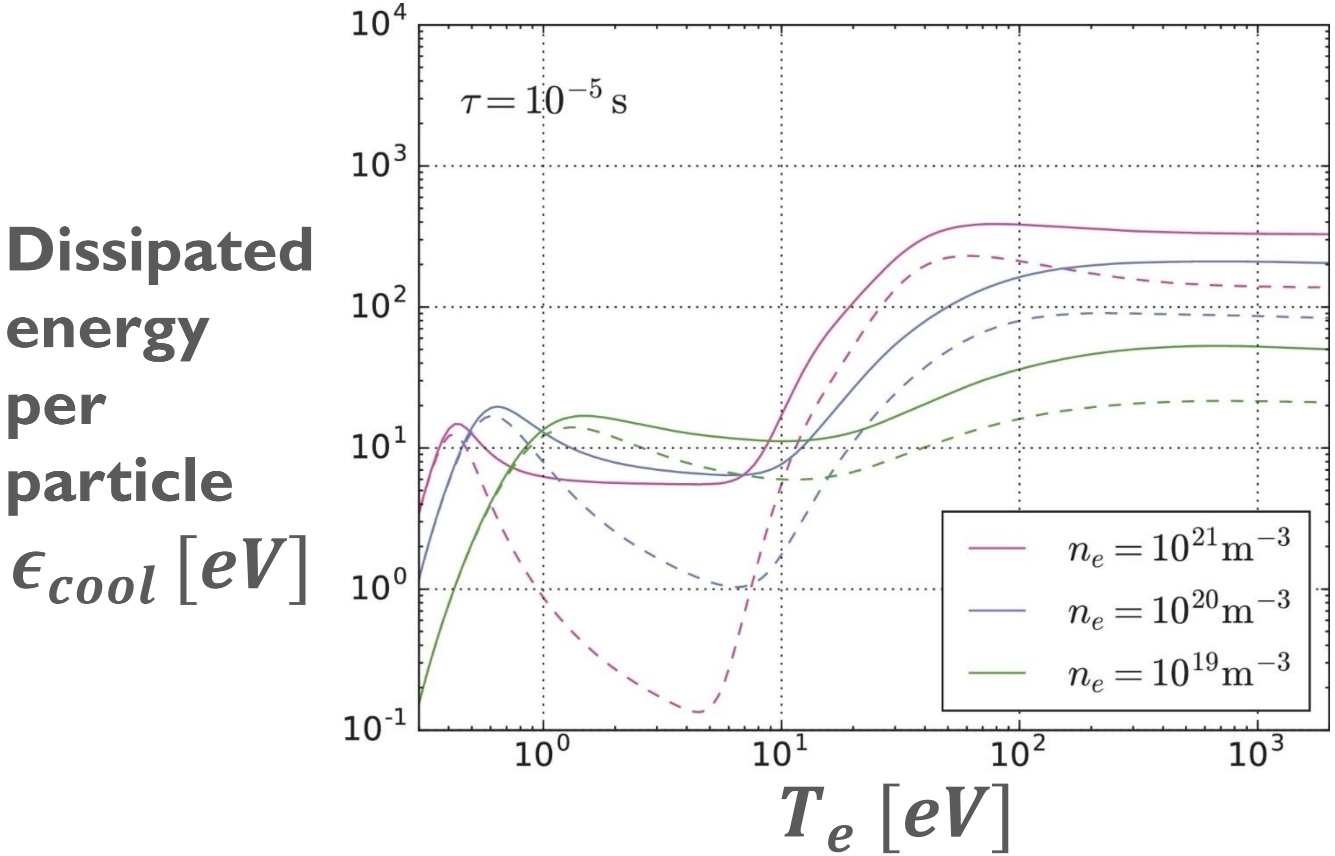
$$Q_{plasma} = \underbrace{\mathbf{Q}_{\mathbf{cond}}(T_{surf})}_{\text{Heat conducted through target.}} + \underbrace{\boldsymbol{\Gamma}_{\mathbf{Lithium\ Loss}}(T_{surf}, R) \cdot \boldsymbol{\epsilon}_{\mathbf{cool}}}_{\text{Power dissipated by lost Li.}}$$

$\boldsymbol{\epsilon}_{\mathbf{cool}} =?$

Net lithium loss rate.

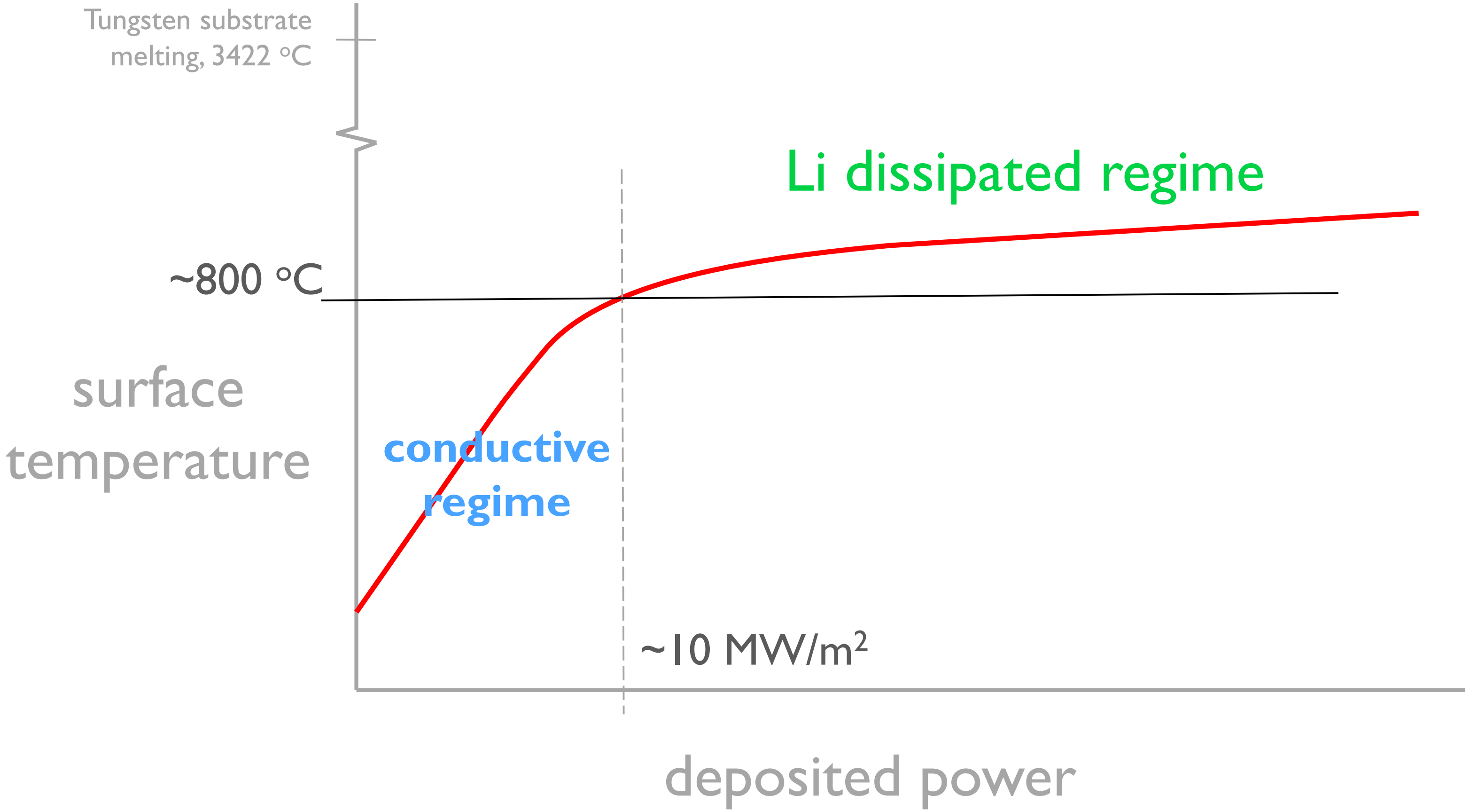
Limited by available supply

Lithium energy dissipation through ionization and radiation

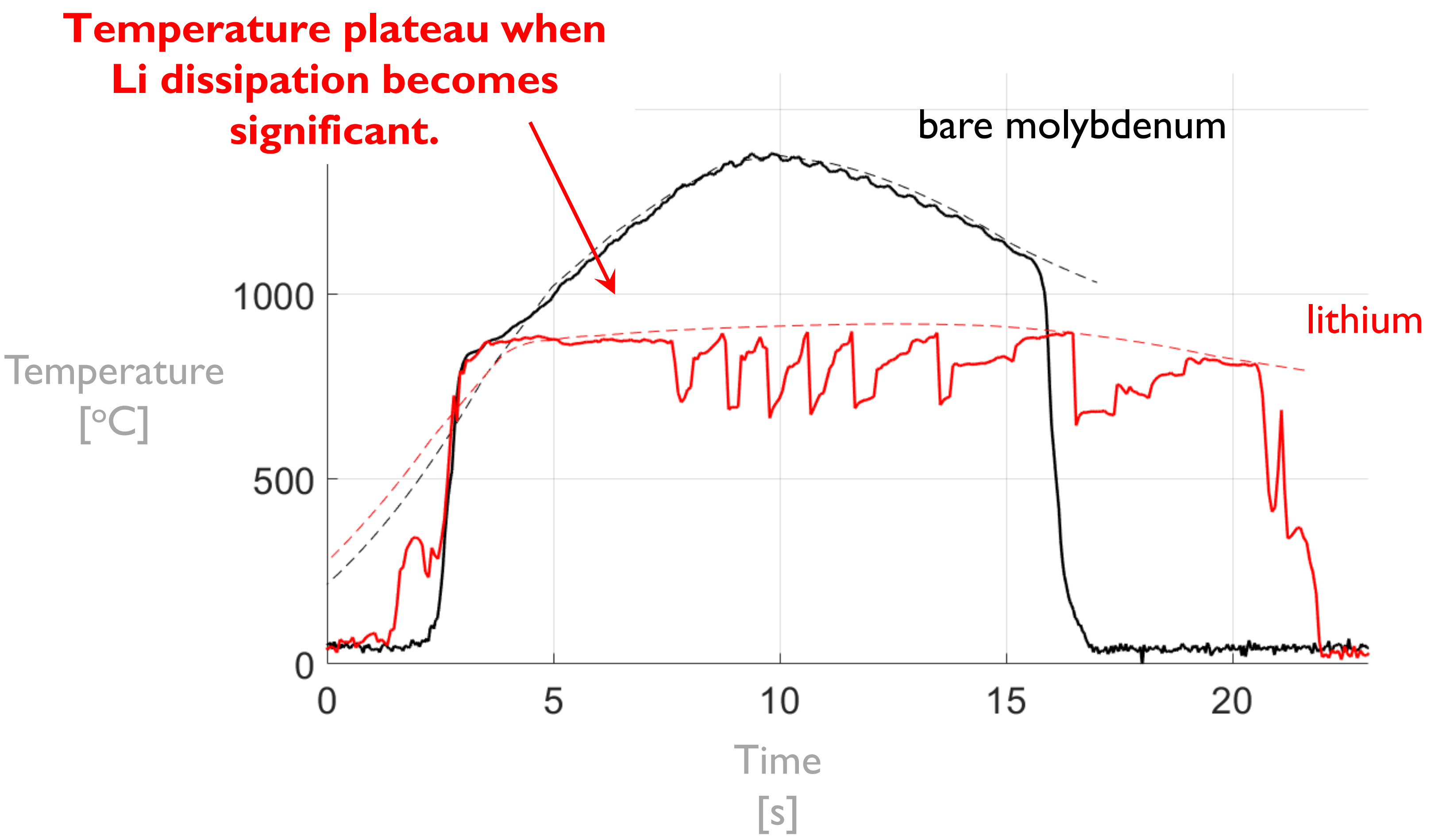


Calculated from collisional radiative modeling in:
Goldston et al., Nuclear Materials and Energy, 2017.

A temperature plateau occurs when dissipation via Li becomes dominant.



FEM shows good agreement with experiment



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

Requirements for atomic physics modelling of VS

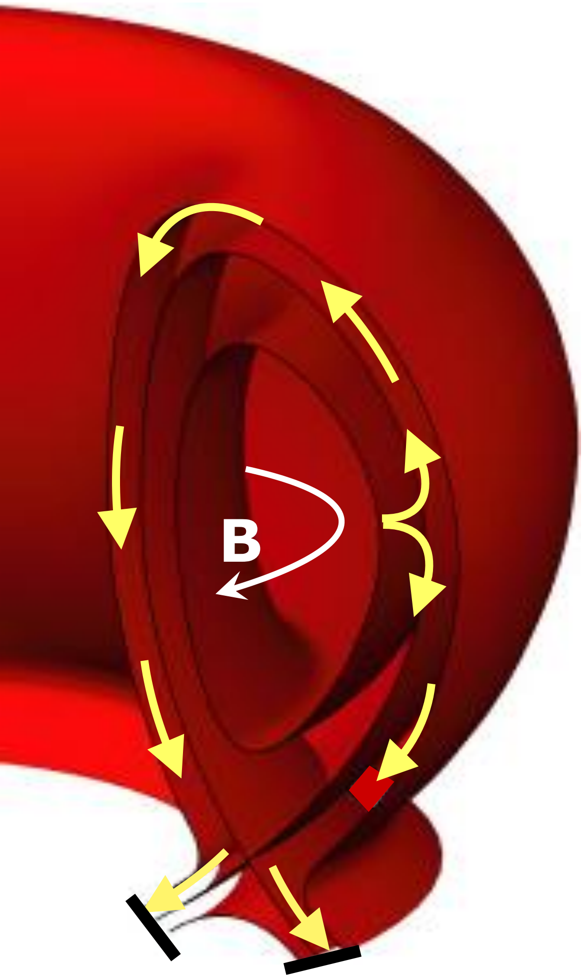
- cross sections for electron impact ionization and excitation for Sn (~0 - 5+)
- Improved low charge state modelling?
- cross sections for CX between Sn^0 or Li^0 and H+ or He+
- cross sections for momentum exchange between neutrals and ions (e.g. Sn^0 and H+)
- Lz curves for Sn

EXTRA SLIDES

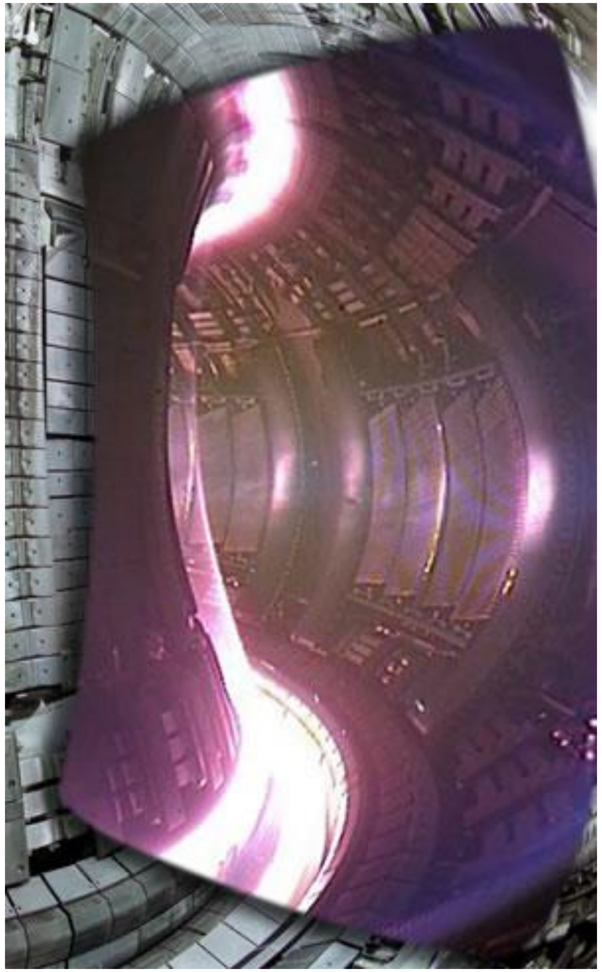
Conclusions

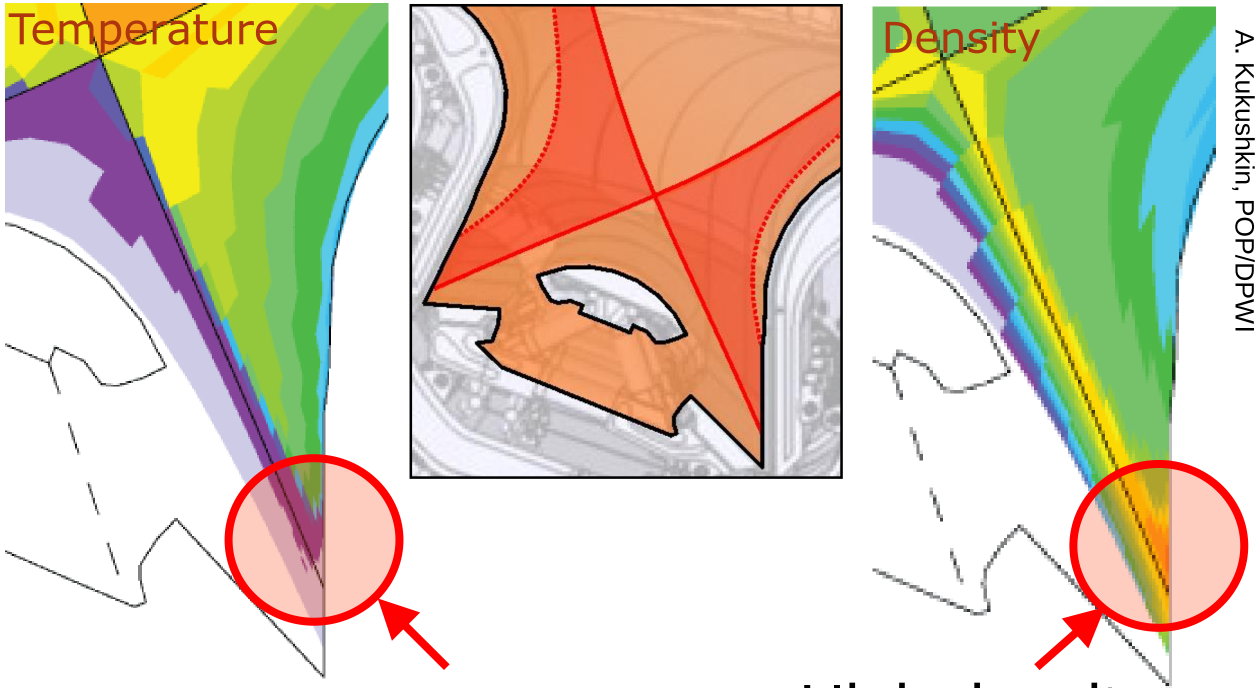
- **PFC design for DEMO unresolved issue**
- **LM-based PFC is a promising solution**
  - Can tolerate same/higher heat load than W-only PFC
  - Possible to operate at high power handling while staying below core impurity limits
  - VS and replenishment means more robust and forgiving against off-normal events
- **Physics rich and can be counter-intuitive**
  - VS, enhanced redeposition, radiative interactions…
- **Further engineering and physics required to reach maturity**

The heat exhaust challenge



Divertor





Low temperature (~10,000 °C)

High density (1/10,000 of an atmosphere)

Heat

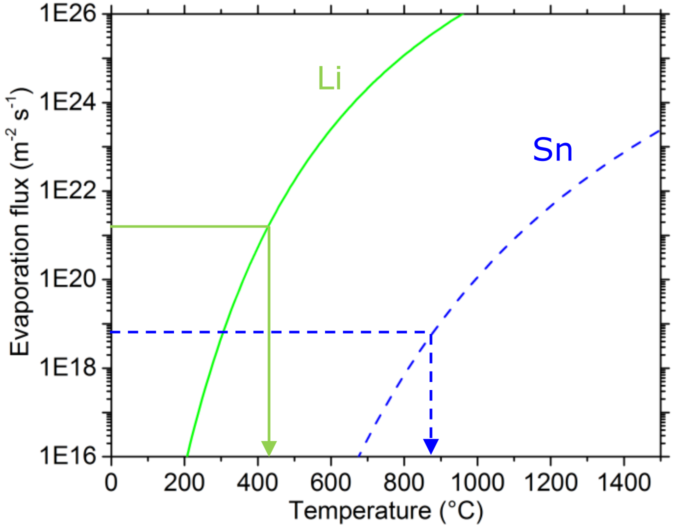
$10 MW.m^{-2}$ steady-state

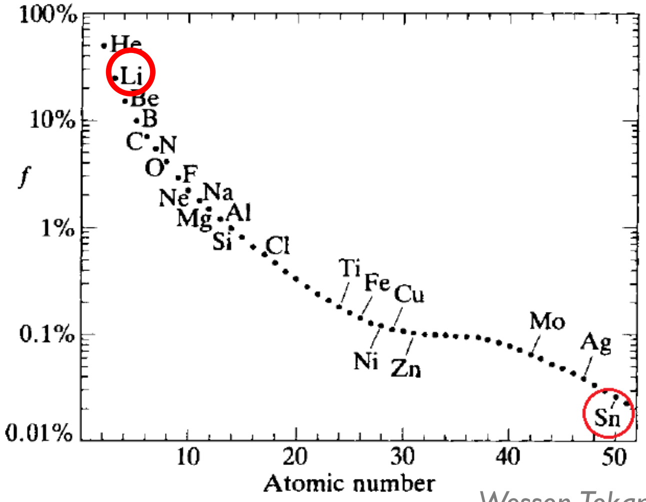
+

Particles

10^{24} $m^{-2}s^{-1}$ ($10^5 A.m^{-2}$)

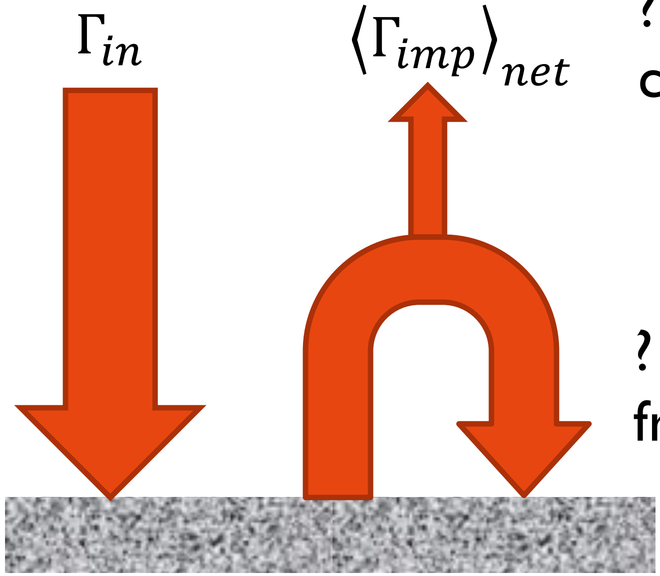
Power handling limit set by tolerable impurity concentration in core





Wesson, Tokamaks (2004)

$$\boxed{\langle \Gamma_{imp} \rangle_{net} = \frac{fV\langle n_e \rangle}{A_{div}\tau_p}}$$

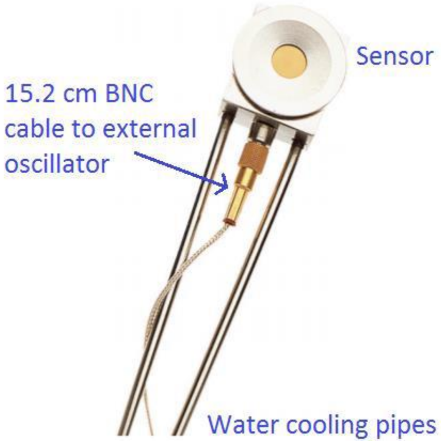


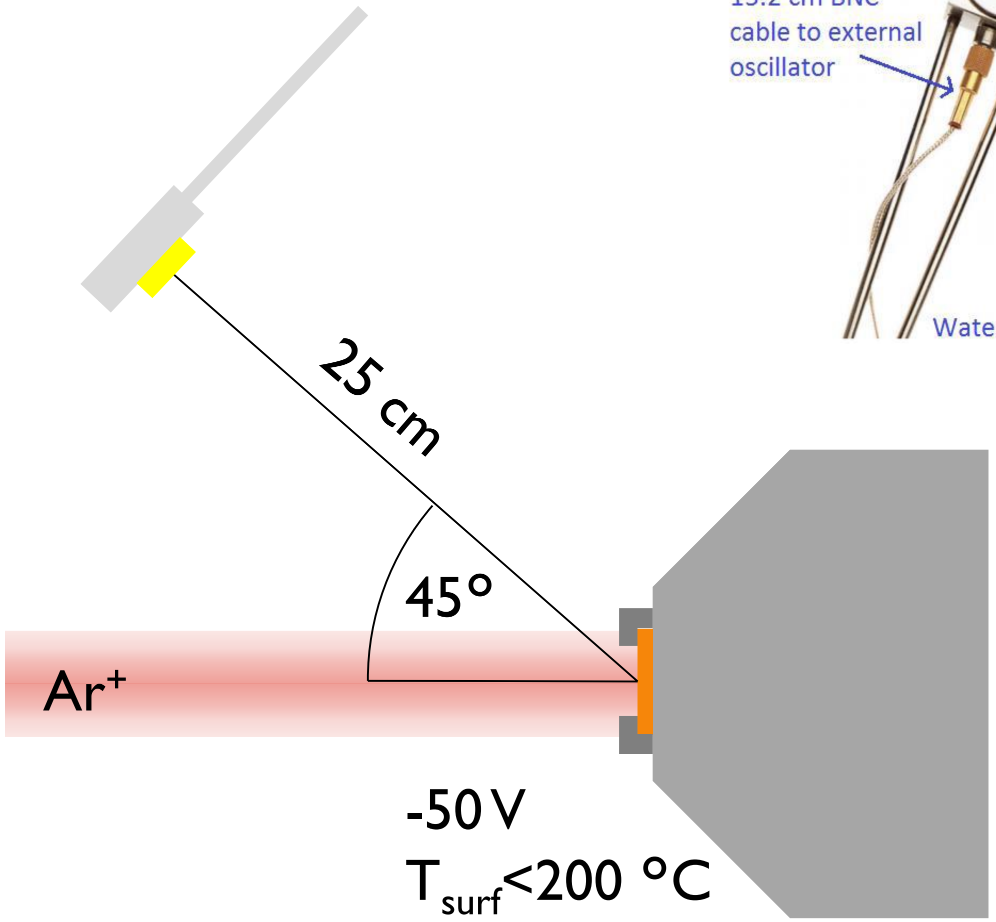
? Fraction going to core

? Redeposited fraction

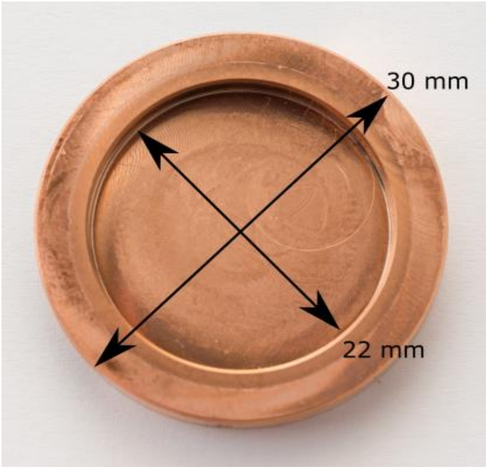
Experiments carried out in Magnum-PSI to study re-deposition rate directly

Measure mass gain (QMB)



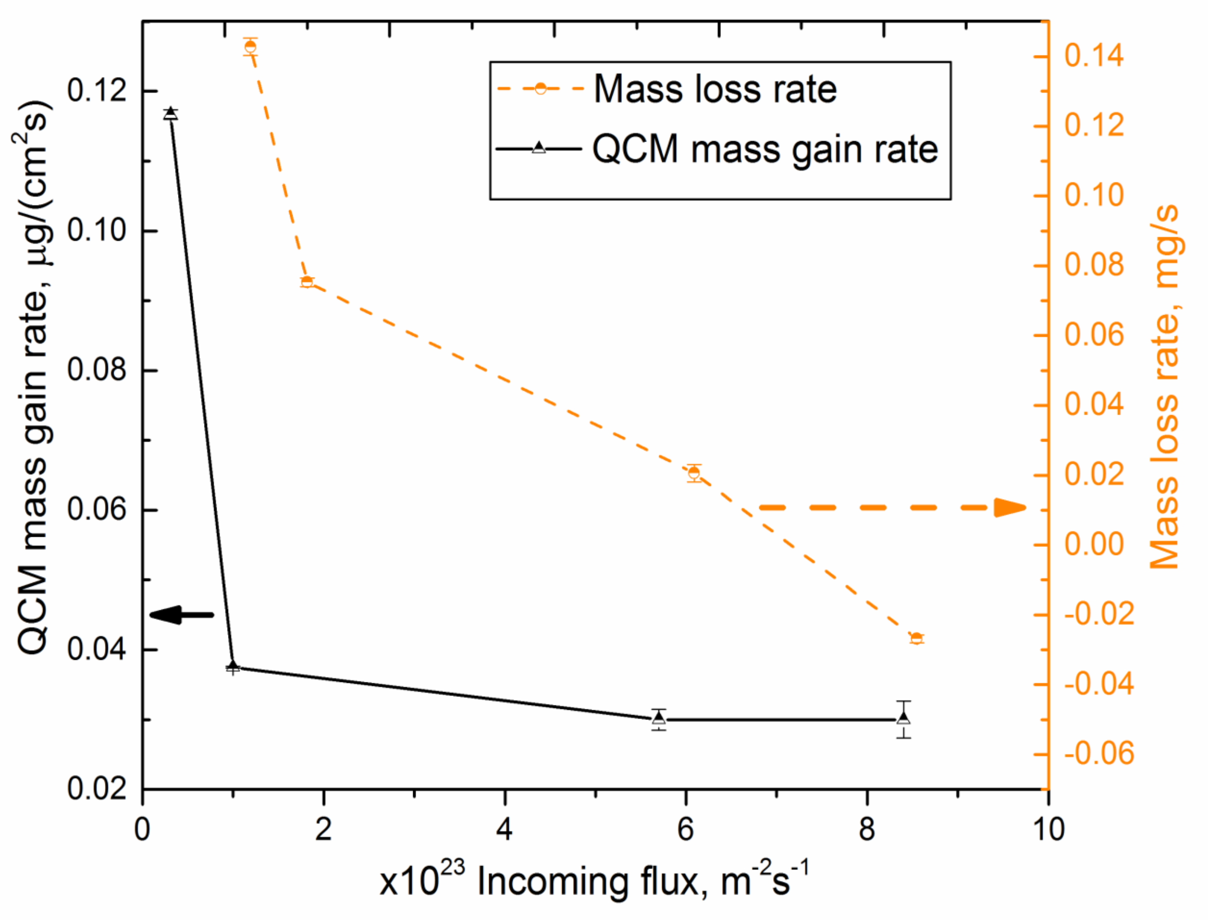


Measure mass loss (mass balance)



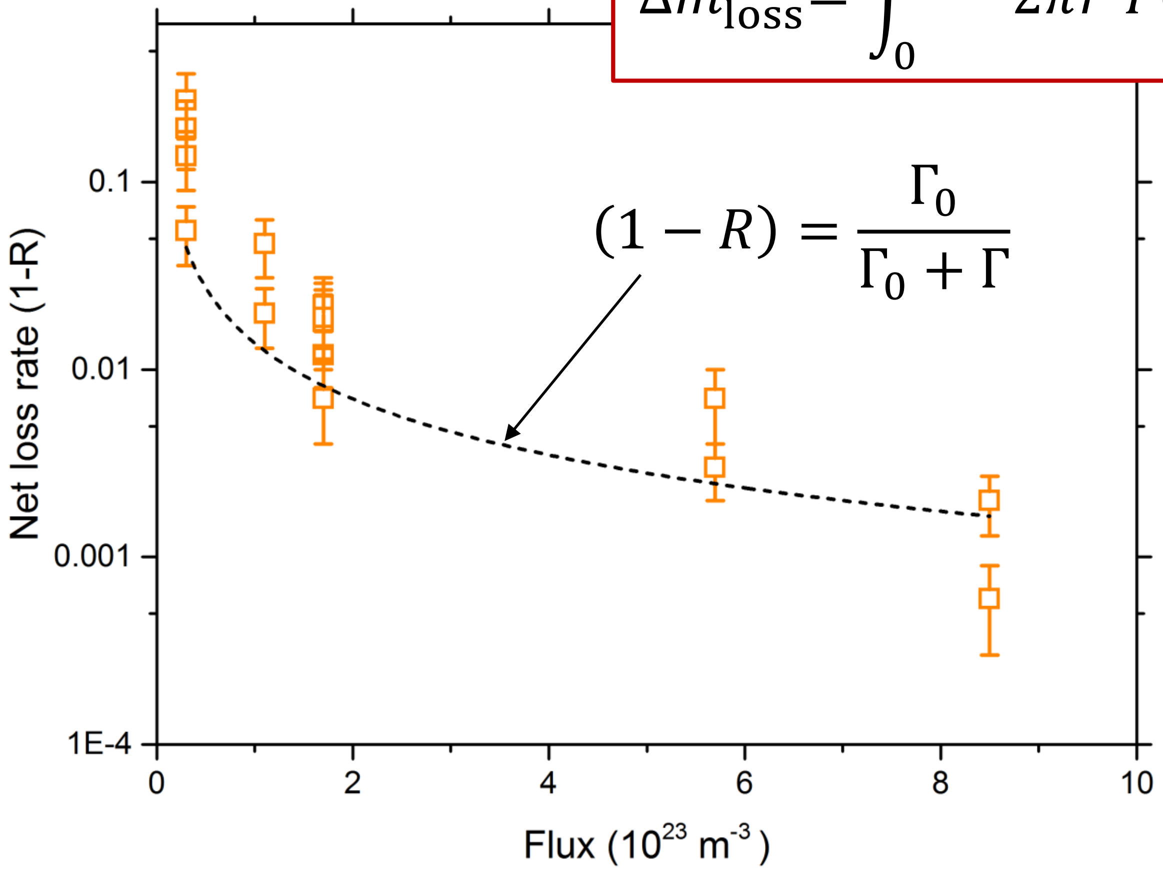
Sample	Flux ($\times 10^{23} m^{-2} s^{-1}$)
Cu1	0.3
Cu2	1.0
Cu3	5.7
Cu4	8.5

Mass loss rate goes down as a function of flux



Re-deposition rate strongly increases with flux, approaches 99.9%

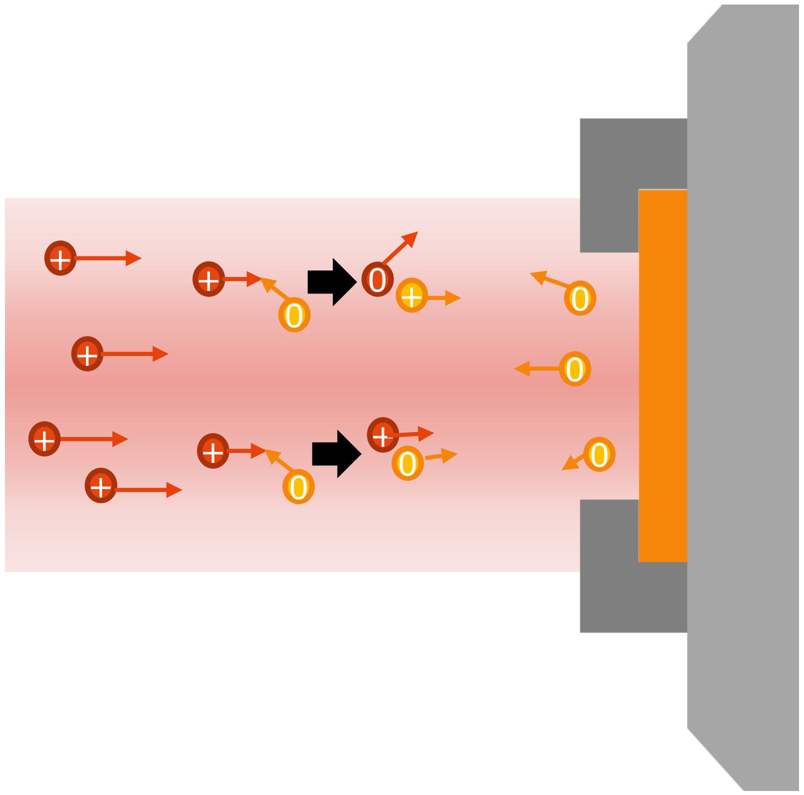
$$\Delta m^{\mathrm{e}}_{\mathrm{loss}} = \int_0^{r_{\max}} 2\pi r\, Y(E_{\mathrm{ion}}, i, z) * M_{\mathrm{z}} * \Gamma_{\mathrm{i}}(r) t\, dr$$



$$(1-R) = \frac{\Gamma_0}{\Gamma_0 + \Gamma}$$

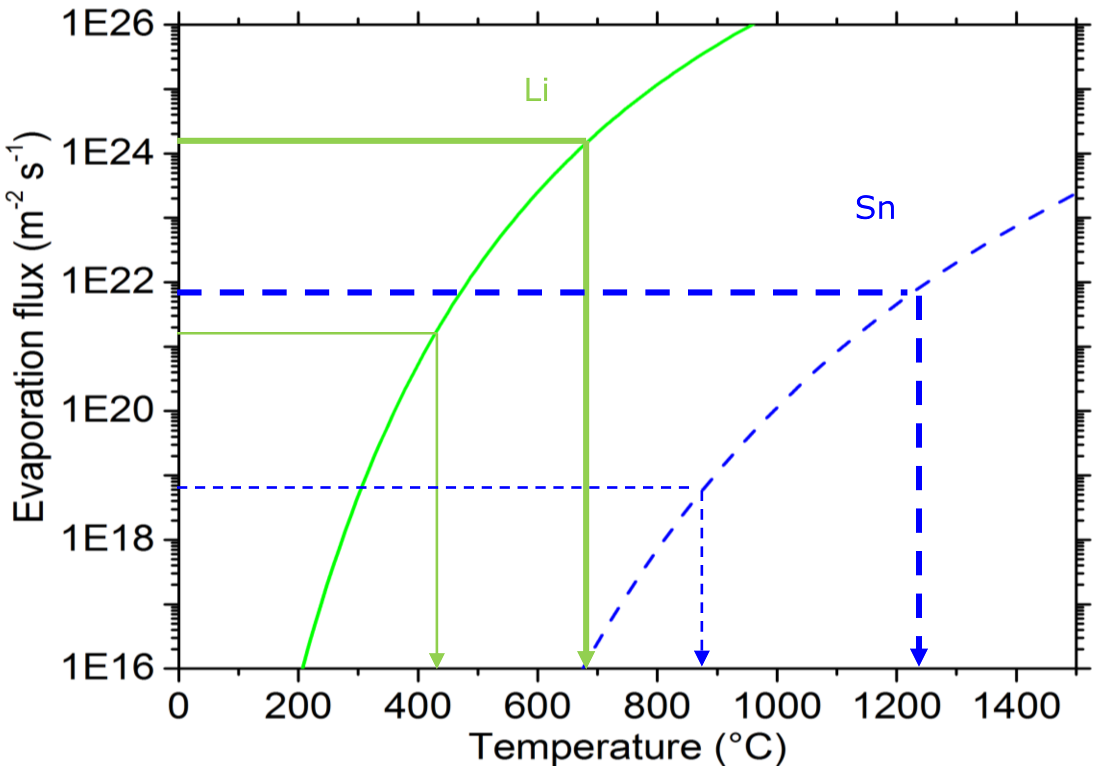
$\Gamma_0 = 1.4 \pm 0.3 \times 10^{21}$ m^{-2} s^{-1}

Mechanisms for strong redeposition



- Ionization rates negligible at these temperatures (<2 eV)
- Ion-neutral friction (and potentially CX) dominant with λ_{mfp} of a few mm (high n_e >10^{20} m^{-3})
- Particles promptly entrained in magnetized plasma and redirected to surface
- Such high density/flux plasma expected in DEMO divertor at strikepoints

Influences maximum evaporation rate and therefore upper limit of temperature window



Increase upper limit Li to ~700 °C*

Increase upper limit Sn to ~1250 °C

*Interaction of Li and D increases surface binding energy and can increase operational temperature further (Abrams NF 2015)

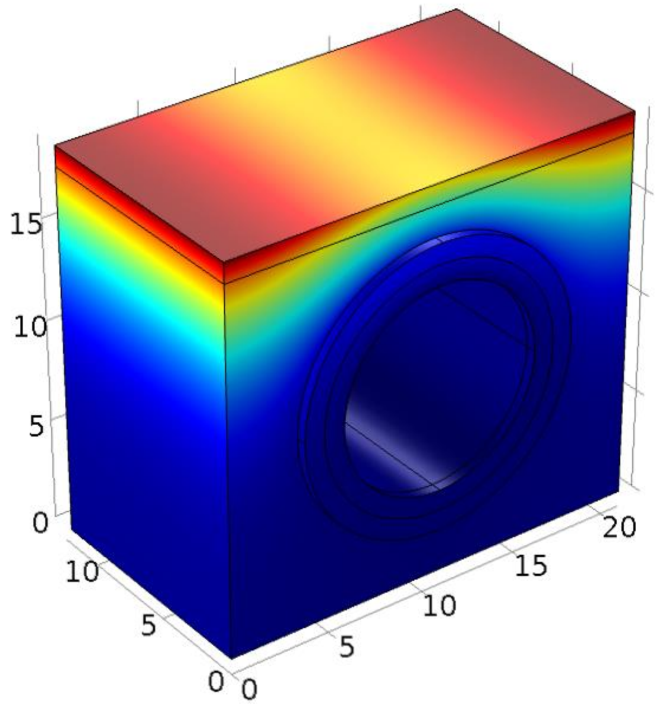
What is the power handling capability of liquid metals?

1. Overall temperature window

2. **Power handling limits**

3. Vapour shielding
    - Sn
    - Li

Finite element modelling can give estimate for power handling capability LMs



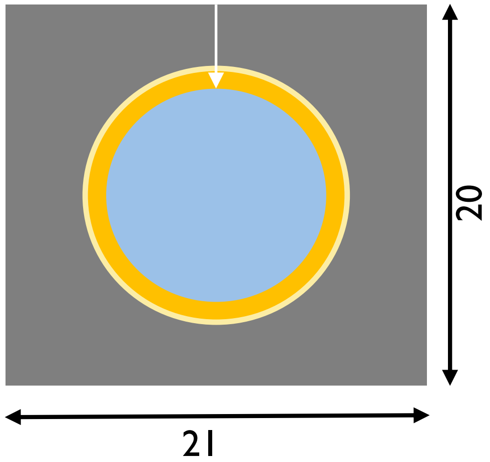
- Studies in Pilot-PSI demonstrated how to treat CPS as mixed material thermally[1]
- Modify existing DEMO designs[2] and use 3D FE modelling to determine max power load
- Determined from temperature limits of each component

Material	Limit	T_{max}
W	Recrystallization	1250 °C
Sn	**Evaporation (90% Redeposition)**	**1000 °C**
Cu/CuCrZr	Softening	300 °C
EUROFER	Softening	700 °C

[1] *Morgan NME (2017)*
[2] *Li-Puma FED (2013)*

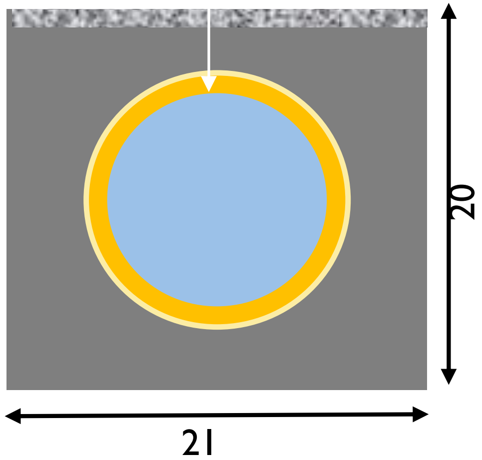
Different designs modelled to scope possibilities and limitations

DEMO Original



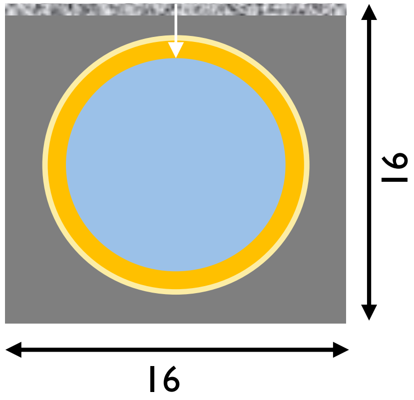
3.5 mm W
1 mm Cu
1 mm CuCrZr
200 °C water

CPS added



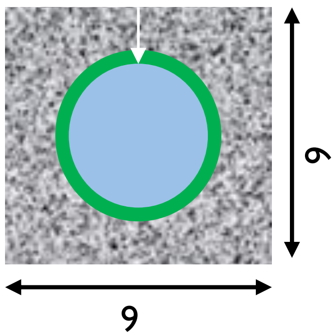
1 mm CPS
2.5 mm W
1 mm Cu
1 mm CuCrZr
200 °C water

Shrunken



0.5 mm CPS
1 mm W
1 mm Cu
1 mm CuCrZr
200 °C water

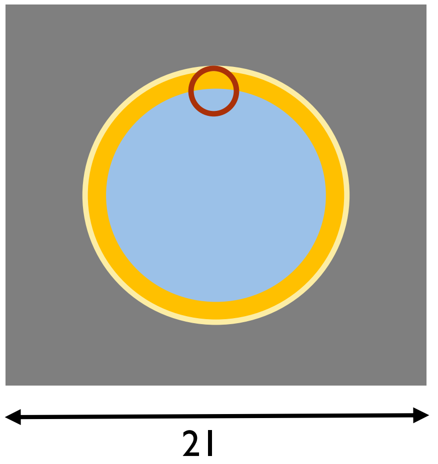
All CPS + EUROFER



1.1 mm CPS
0.42 mm EUROFER
325 °C water

Results show comparable/improved performance with additional advantages possible

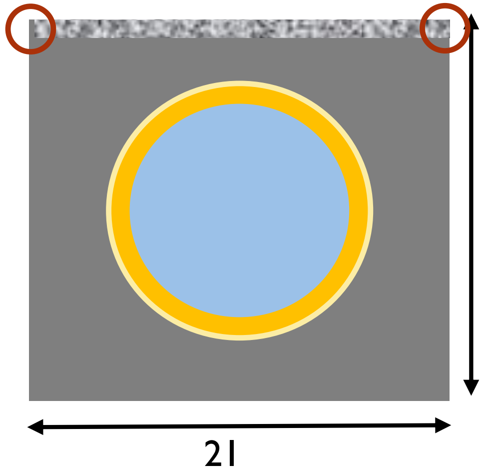
DEMO Original



q_{max}~18 MW m^{-2}

Lim: CuCrZr

CPS added

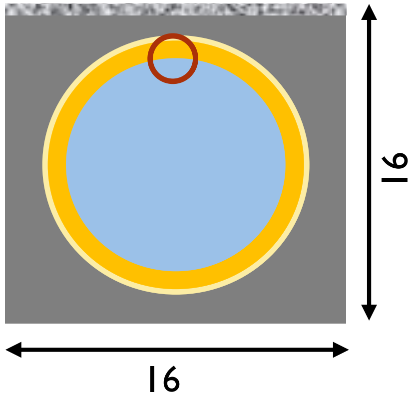


q_{max}~15 MW m^{-2}

Lim: Sn

- Minimum modification

Shrunken

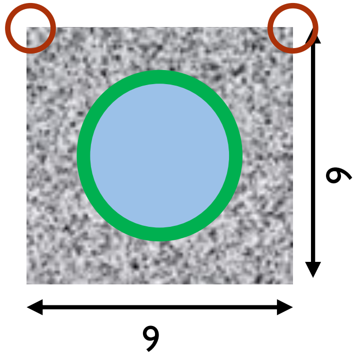


q_{max}~20 MW m^{-2}

Lim: CuCrZr

- Increased power handling

All CPS + EUROFER



q_{max}~15 MW m^{-2}

Lim: Sn

- Eliminate CuCrZr
- No interlayer
- Low stresses

What is the power handling capability of liquid metals?

1. Overall temperature window
2. Power handling limits
3. **Vapour shielding**
   - **Sn**
   - Li