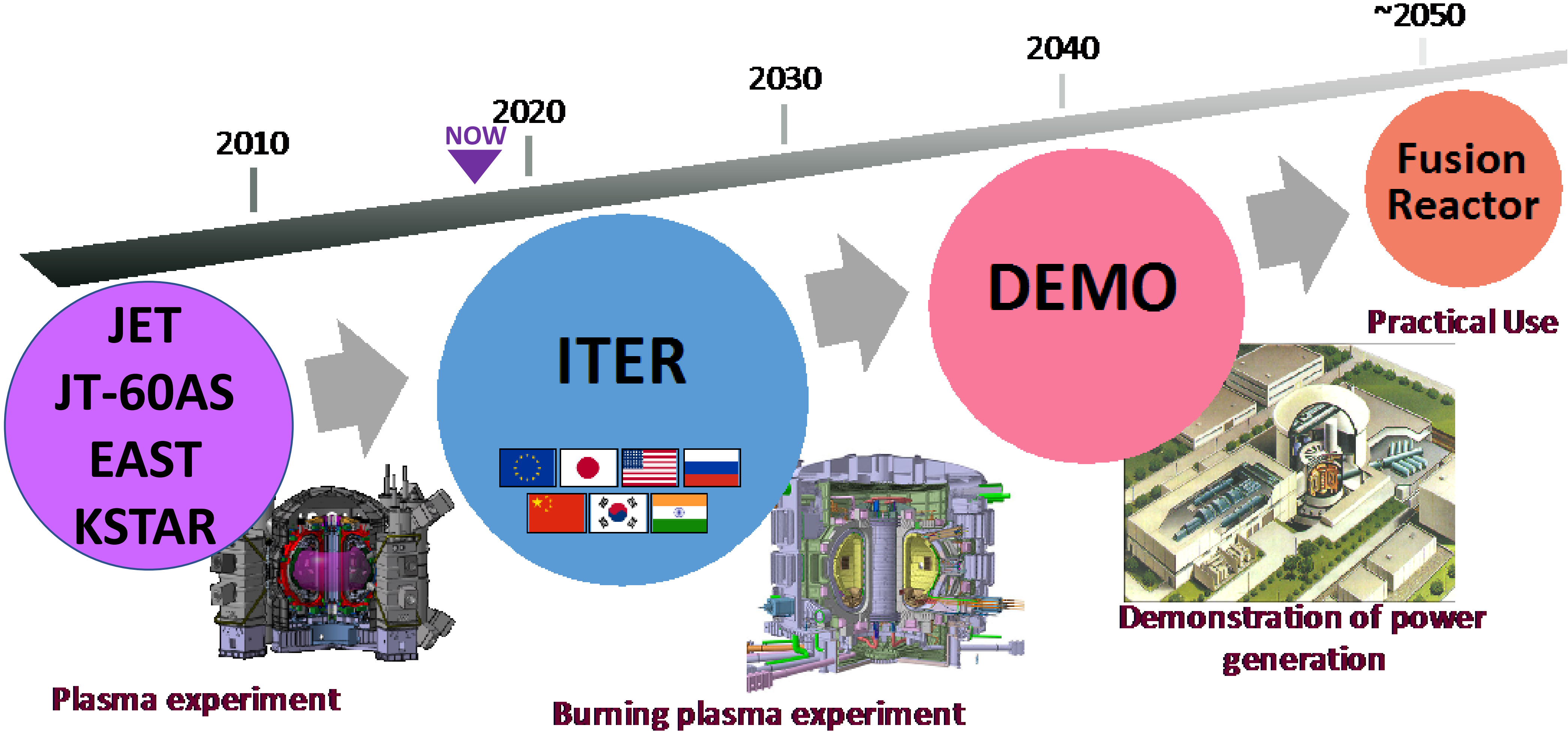
Plasma Facing Components Beyond ITER – Liquid Materials

Daniel Andruczyk

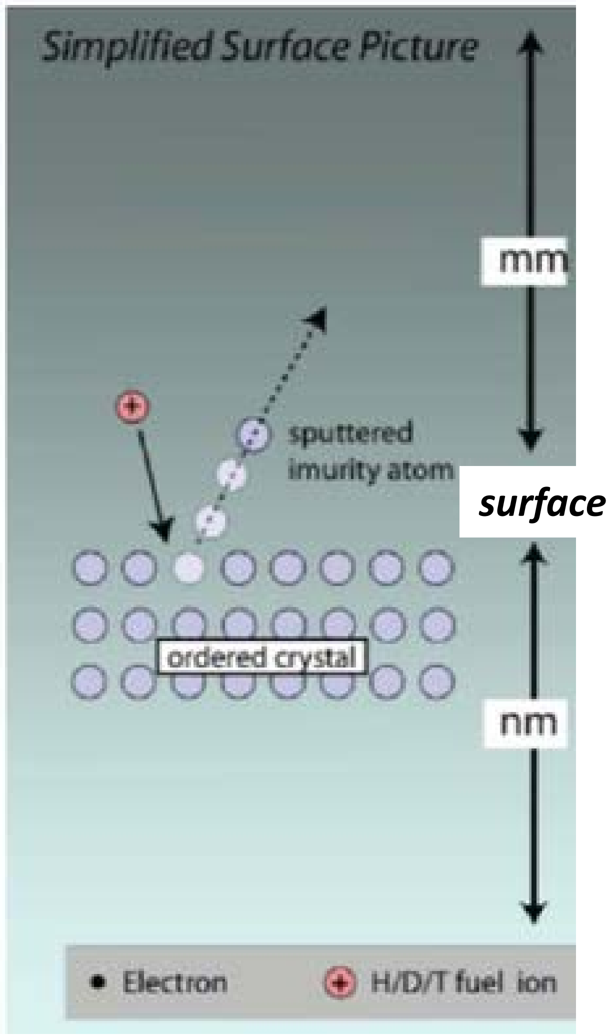
Assistant Research Professor

Hybrid Illinois Device for Research and Applications (HIDRA), Center for Plasma Material Interactions (CPMI), Department od Nuclear Plasma and Radiological Engineering (NPRE), University of Illinois Urbana-Champaign (UIUC), Urbana IL, 61801 USA

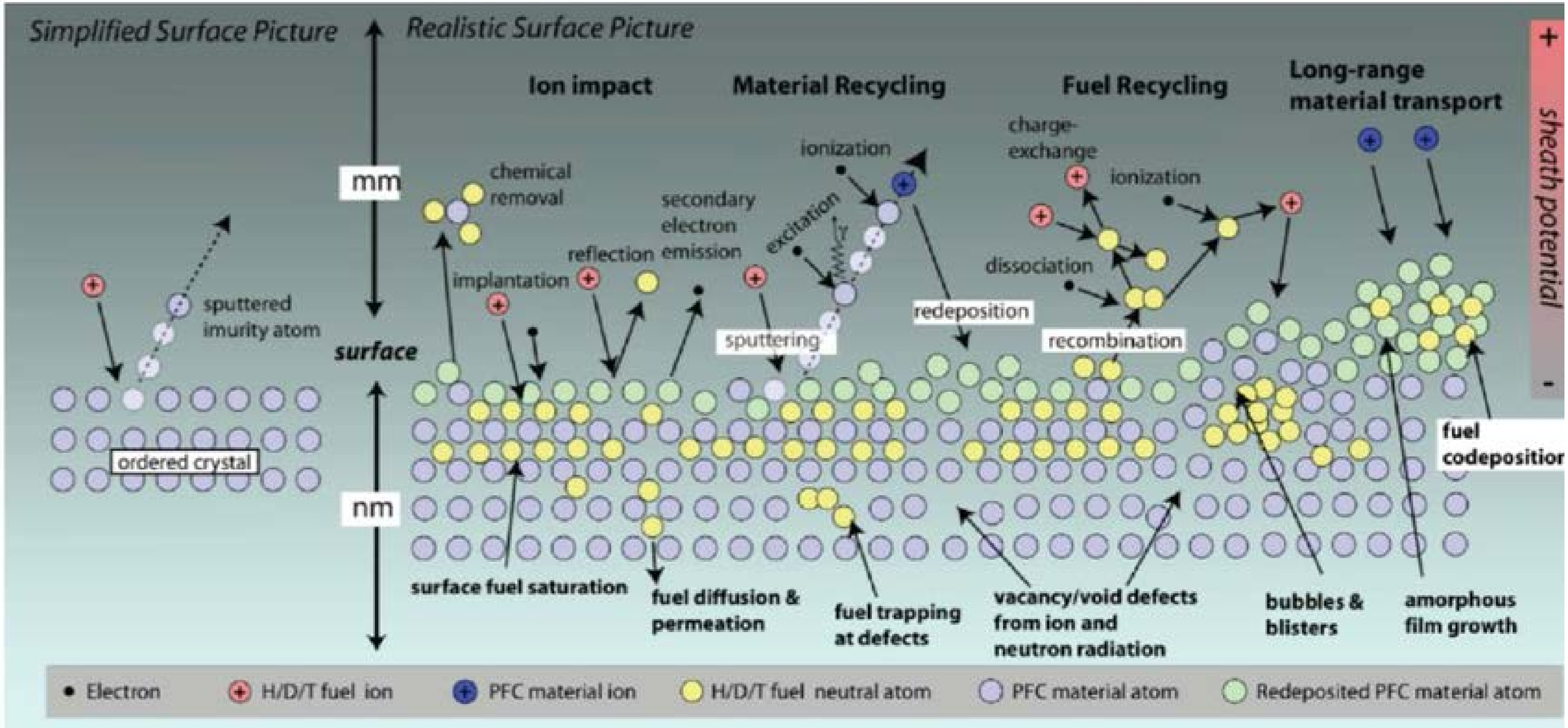
The Path Towards Commercial Fusion Power

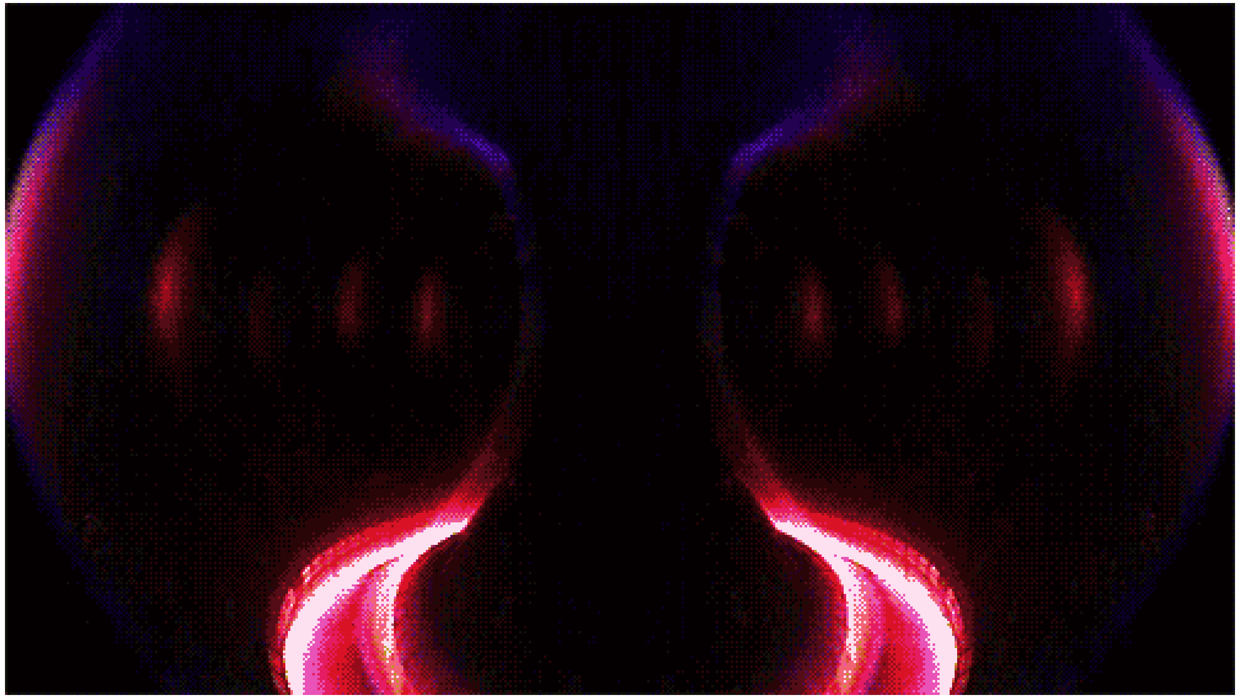


Plasma Material Interactions are Extremely Complex!

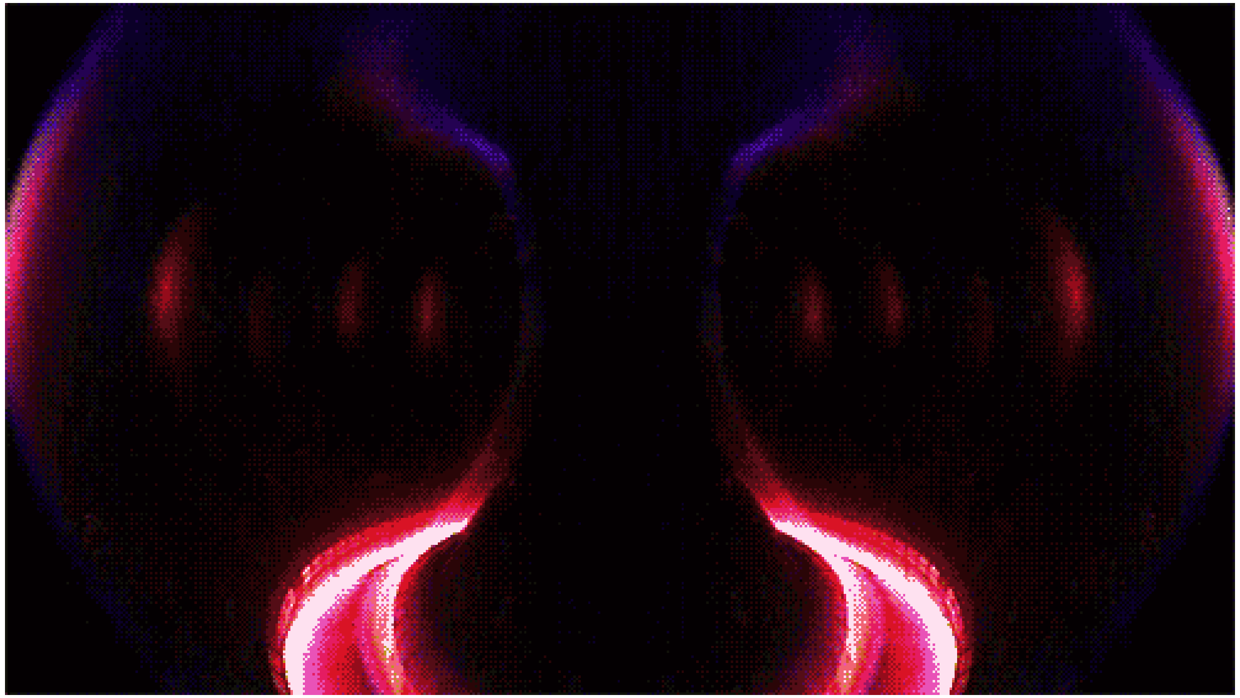


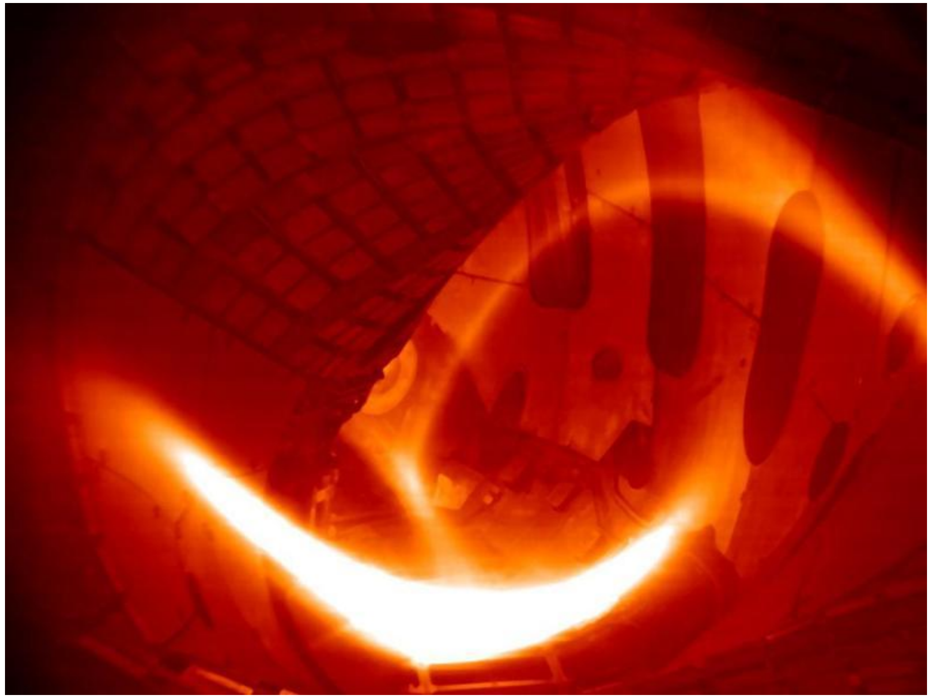
Plasma Material Interactions are Extremely Complex!





Do not forget about Stellarators!





- **Plasma Material Interactions will be an issue for any serious fusion reactor, magnetic, inertial or otherwise**

Overview:

- Materials Challenges – Beyond ITER
- Materials Needs
- Liquid Metals and their Properties
- Plasma Response to Low-Recycling Liquid Metals
- Flowing Liquid Metal PFC Technologies
- Fuel Loss and Retention
- Liquid Metal PFC Experiments
- Summary

Overview:

- Materials Challenges – Beyond ITER
- Materials Needs
- Liquid Metals and their Properties
- Plasma Response to Low-Recycling Liquid Metals
- Flowing Liquid Metal PFC Technologies
- Fuel Loss and Retention
- Liquid Metal PFC Experiments
- Summary

Materials Challenges – ITER and Beyond

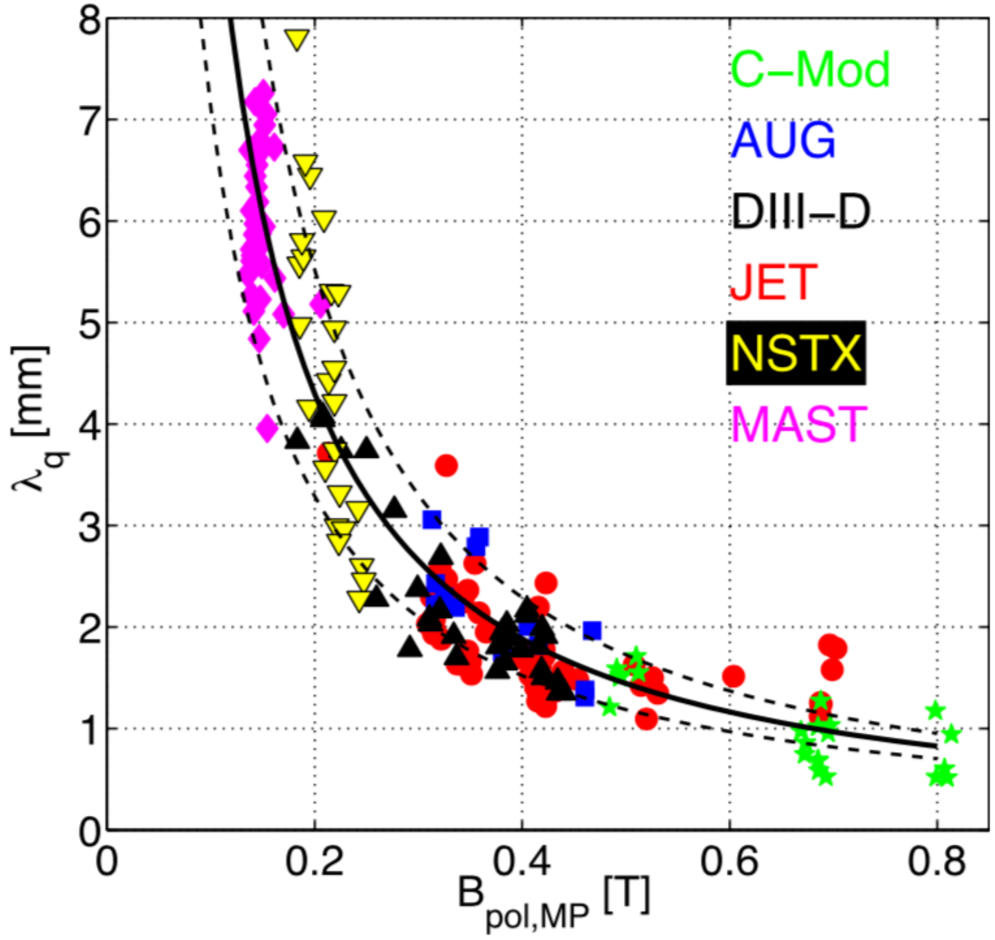
- Need to balance size (cost) with power flux (energy production)

Machine	R_0 (m)	a (m)	P_{fusion} (MW)	*Mean Power Flux (MW/m^2)	Normalized
ITER	6.2	2.0	500	1.47	1
FNSF	4.8	1.2	450	2.11	1.44
CFETR	5.7	1.6	200	0.68	0.46
K-DEMO	6.8	2.1	3000	7.27	4.95
E-DEMO	9.0	2.25	500	0.67	0.46

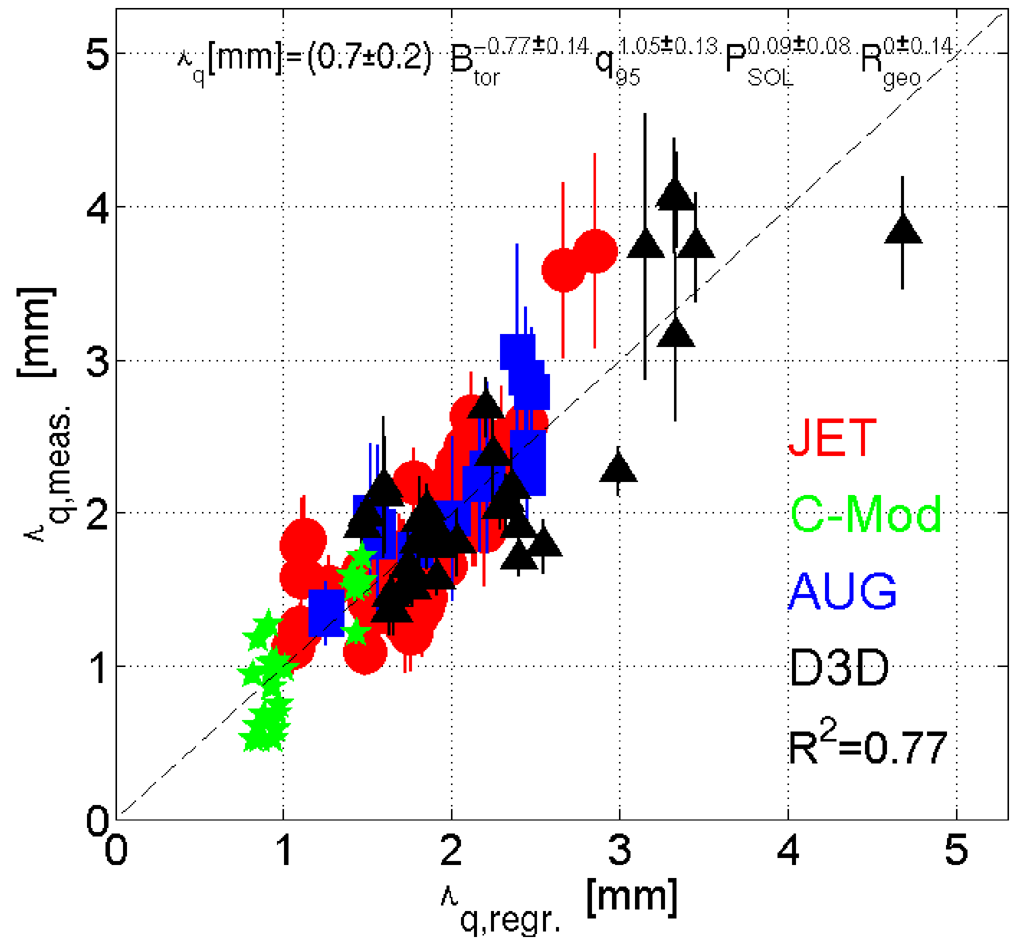
*Mean Power Flux calculated using $P_{fusion} / (R_0^2 - a^2)\pi^2$

- In general this is assumed that the maximum heat power flux, at the divertor, is limited to about 10 MW/m^2

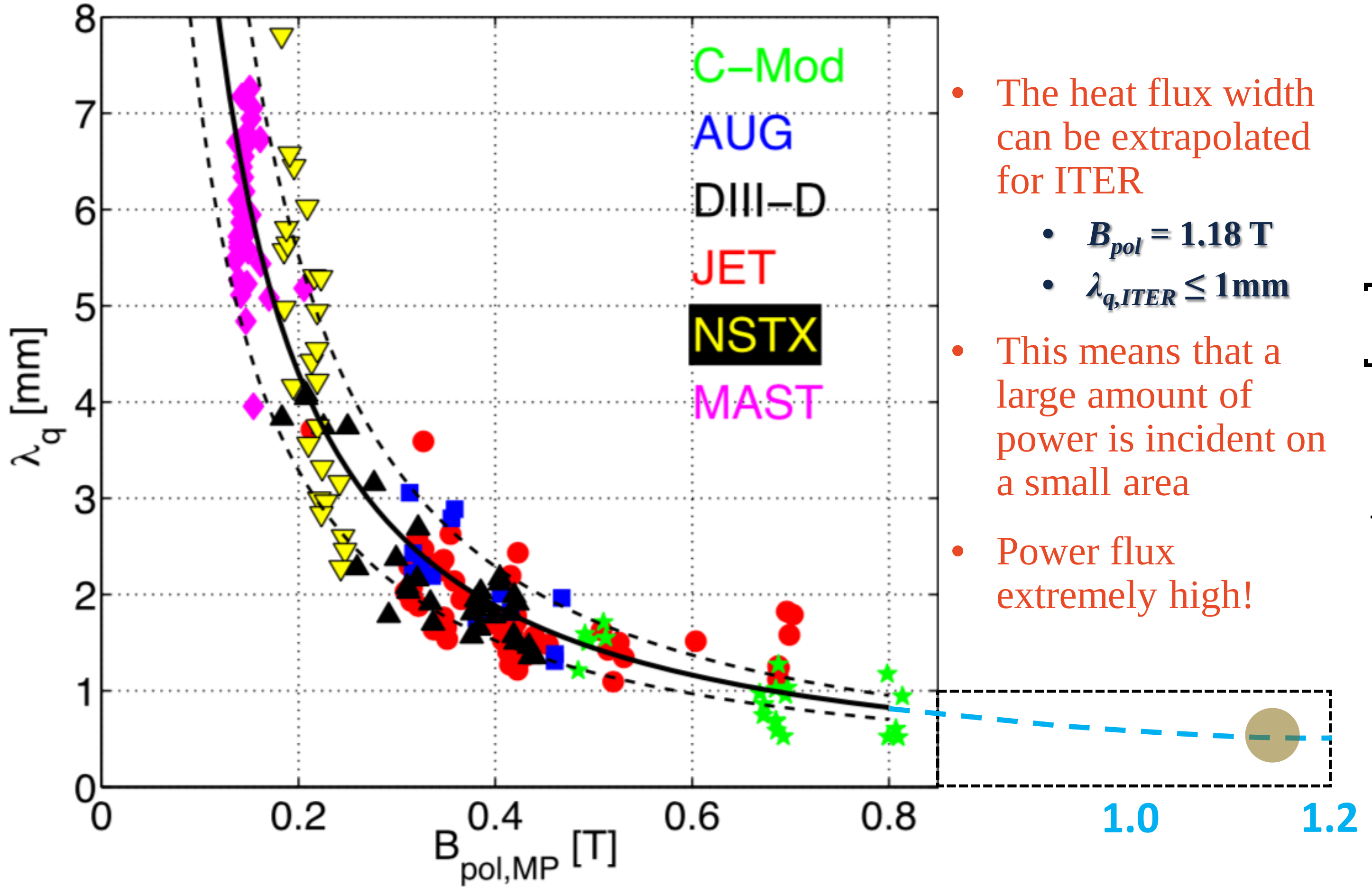
Width of the Heat Stripe Scales with Poloidal Field



$$\lambda_q(mm) = (0.63 \pm 0.08) \times B_{pol,MP}^{-1.19}$$

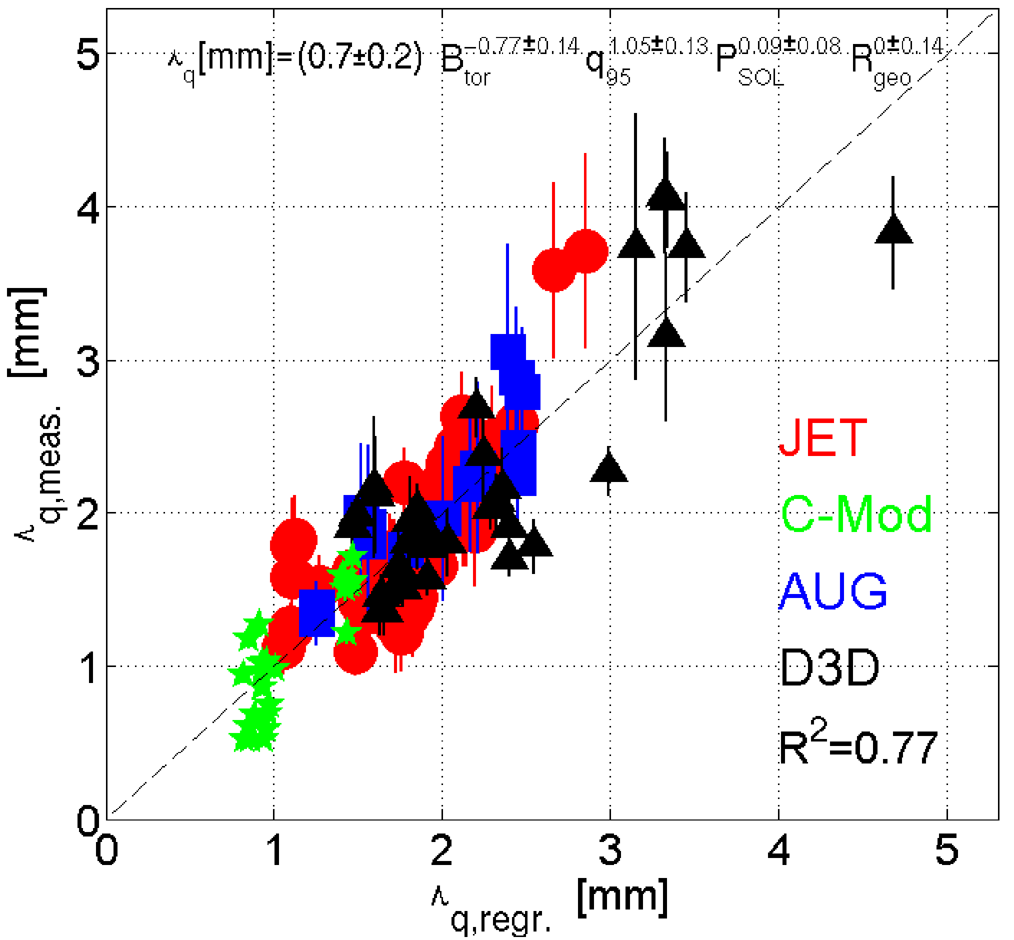


Width of the Heat Stripe Scales with Poloidal Field



$$\lambda_q(mm) = (0.63 \pm 0.08) \times B_{pol,MP}^{-1.19}$$

- The heat flux width can be extrapolated for ITER
  - B_{pol} = 1.18 T
  - $\lambda_{q,ITER} \leq$ 1mm
- This means that a large amount of power is incident on a small area
- Power flux extremely high!



Heuristic Model – The Quick and Dirty Version

- Goldston Model
- Magnetic drift are the cause of cross field transport
- The plasma is flowing along the magnetic field towards the divertor
  - $v = c_s/2$
- $L_{||}$ is proportional to λ_q

$$v_{\nabla B+R_C} = v_D = \frac{2T_e}{eB_T R}$$

$$\tau_{\parallel} = \frac{2L_{\parallel}}{\sqrt{\frac{T_e}{m_i}}}$$

$$\lambda_q = v_D \tau_{\parallel} = \frac{2T_e}{eB_T R}\frac{2L_{\parallel}\sqrt{m_i}}{\sqrt{T_e}}$$

$$= 4\frac{\sqrt{T_e m_i}}{eB_T}\frac{L_{\parallel}}{R}$$

$$= 4\rho_i \frac{L_{\parallel}}{R}$$

Heuristic Model – The Quick and Dirty Version

- Goldston Model
- Magnetic drift are the cause of cross field transport
- The plasma is flowing along the magnetic field towards the divertor
  - $v = c_s/2$
- $L_{||}$ is proportional to λ_q
- Where does the Poloidal field come into it?

$$\left.\begin{aligned} v_{\nabla B+R_C} &= v_D = \frac{2T_e}{eB_T R} \\ \tau_{\parallel} &= \frac{2L_{\parallel}}{\sqrt{\frac{T_e}{m_i}}} \end{aligned}\right\} \Rightarrow$$

$$\lambda_q = v_D \tau_{\parallel} = \frac{2T_e}{eB_T R}\frac{2L_{\parallel}\sqrt{m_i}}{\sqrt{T_e}}$$

$$= 4\frac{\sqrt{T_e m_i}}{eB_T}\frac{L_{\parallel}}{R}$$

$$= 4\rho_i \frac{L_{\parallel}}{R}$$

$$L_{\parallel} \approx a\frac{B_T}{B_P} \Rightarrow$$

$$\lambda_q = 4\frac{\sqrt{T_e m_i}}{e\cancel{B_T}}\frac{a\cancel{B_T}}{RB_P}$$

$$= \frac{4a}{R}\frac{\sqrt{T_e m_i}}{e\boldsymbol{B_P}}$$

Stellarators are not Dependent on B_p

- So can see that the main scaling for **tokamaks** is with the poloidal field.
- But lets not forget, what about Stellarators?
- The connection lengths can be so much longer!

$$L_{\parallel} = n2\pi R$$

- In a stellarator the poloidal field connection seems to be broken
- BUT! Not much data available for stellarators
- *E*-fields cause inward transport of high-Z impurities
- Need to avoid edge impurity sources.

$$\lambda_q = 4\frac{\sqrt{T_e m_i}}{eB_T}\frac{n2\pi\cancel{R}}{\cancel{R}}$$

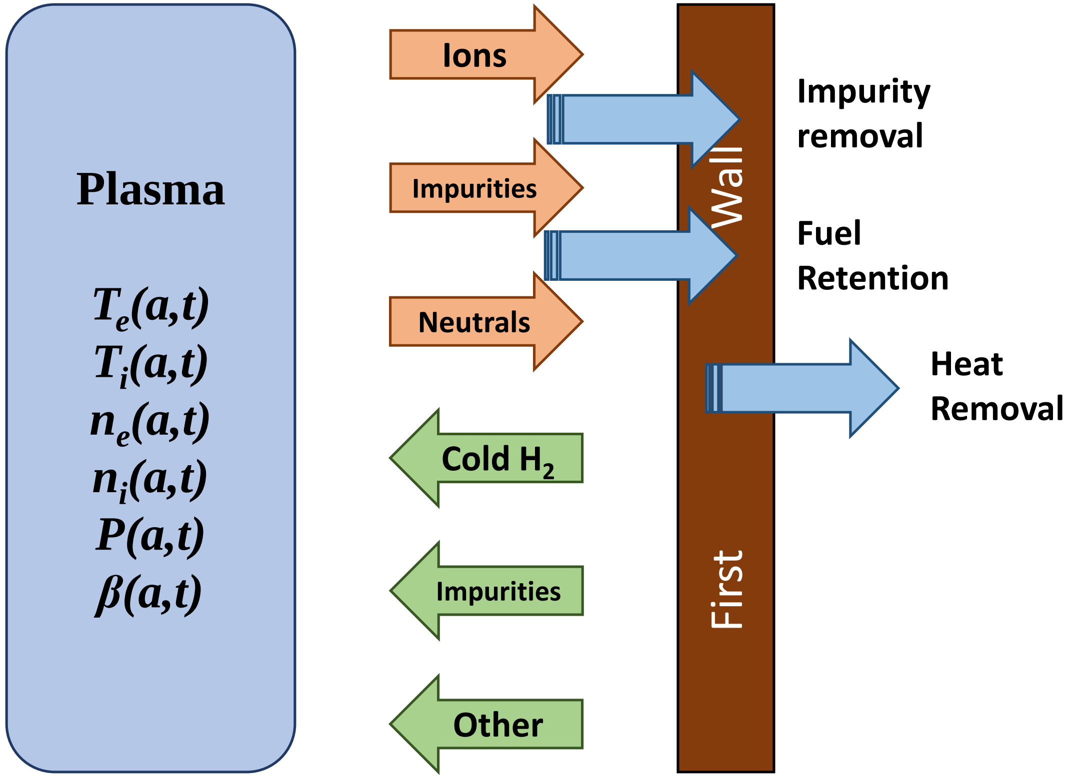
$$= 8\pi n\frac{\sqrt{T_e m_i}}{eB_T}$$

Overview:

- Materials Challenges – Beyond ITER
- Materials Needs
- Liquid Metals and their Properties
- Plasma Response to Low-Recycling Liquid Metals
- Flowing Liquid Metal PFC Technologies
- Fuel Loss and Retention
- Liquid Metal PFC Experiments
- Summary

Complex Behavior of Materials and Plasma - Solids

- Incident high energy ions and neutral will have a significant impact on the reactor surface
- Damage
  - Displacement of atoms within the lattice structure of the materials
  - Leads to embrittlement
- Surface structure formation
  - Fuzz
  - Blisters and bubbles
  - Fuel retention within the structure
- Recycling
  - Cold hydrogenic species
  - Impurity atoms
  - Secondary electron emission
  - other

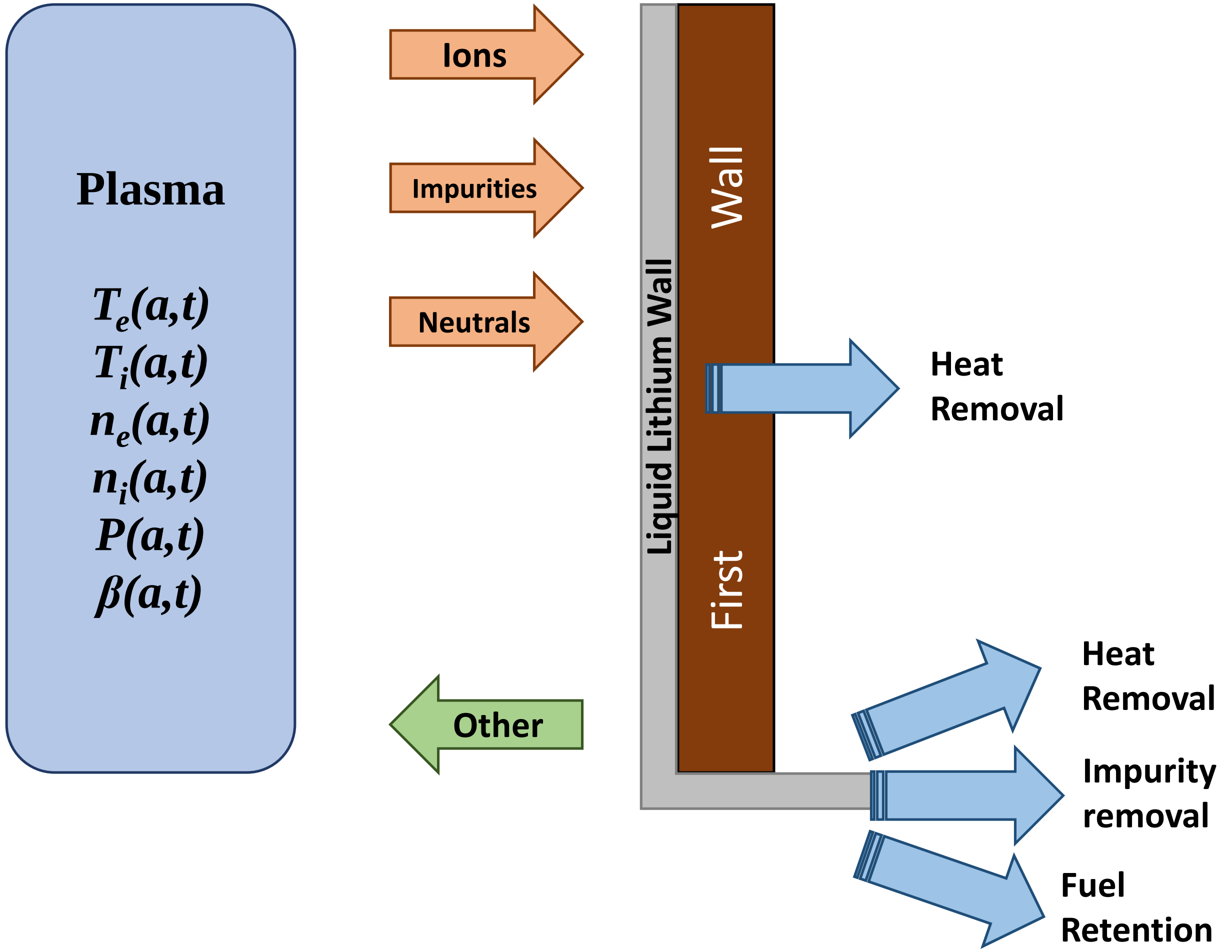


Materials Needs

Material	Disadvantage
Tungsten	High Z material
	Small thermal expansion compared to structure
	Embrittlement of surface through high energy neutron and ion bombardment
	Blister formation (D)
	Fuzz formation (He)
Molybdenum	Similar to tungsten
	Radiation damage and activation
Beryllium	High sputtering yield
	Low melting point
	Toxic
Graphite	Fuel retention
	Radiation damage

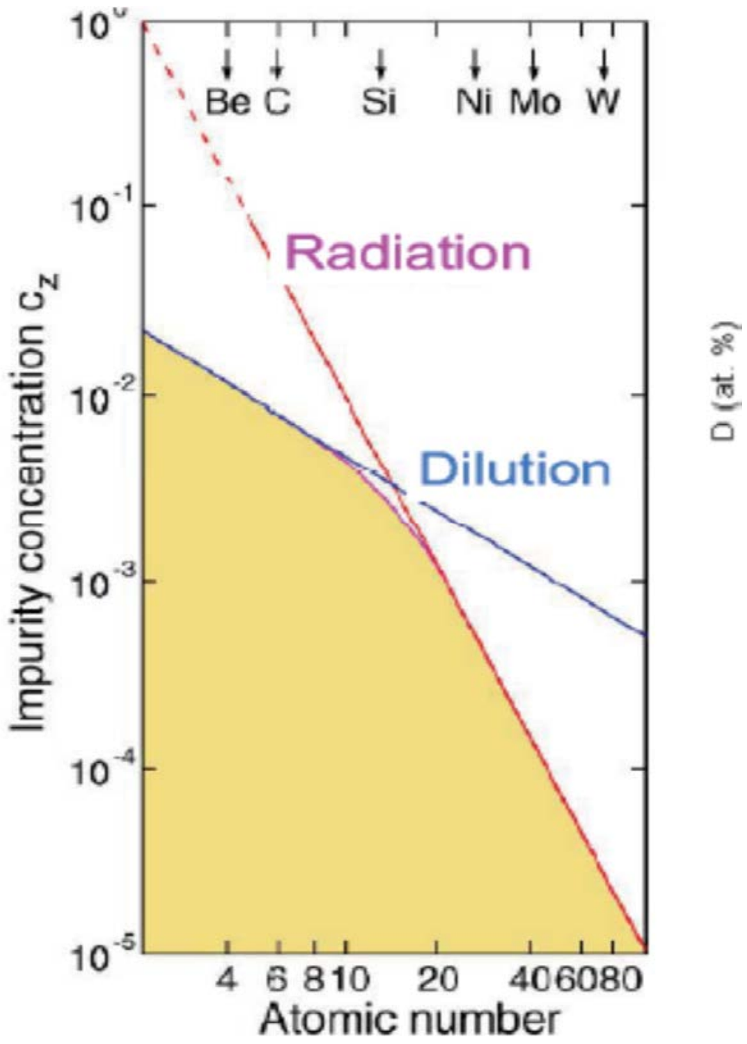
Complex Behavior of Materials and Plasma - Liquids

- As low-Z as possible:
  - Minimise power losses by reducing high-Z impurities entering the core.
- High affinity for ionised fuel species:
  - Mitigates instabilities and eliminates ELMs, Increases cross-sectional T_i while reducing particle wall flux.
- Constantly refreshing:
  - Removes impurities and products (if flows outside chamber) + minimises erosion
- Stable flow
  - Need to avoid any dry out or lack of wetting
  - Damage to the substructure
- Neutron tolerant

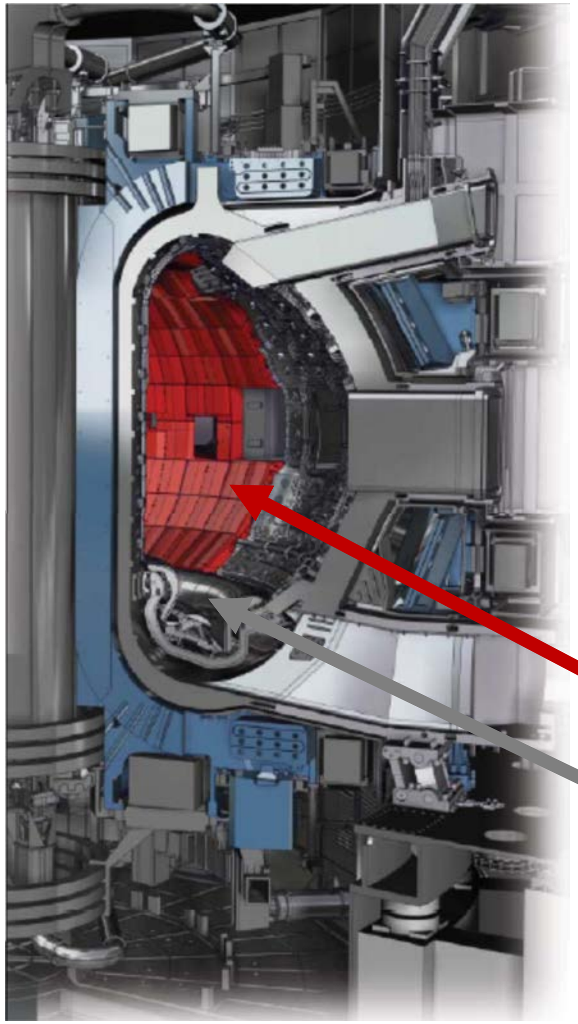


Minimization and Control of Impurities in the Plasma

- There is a maximum level of impurity allowed inside a fusion reactor
- Tolerances for High-z are much stricter than for low Z
- Anything the plasma touches will almost most definitely end up the fusion reactor and plasma
- So as low-Z as possible is desired



Maximum Level of Impurities Allowed Inside a Reactor

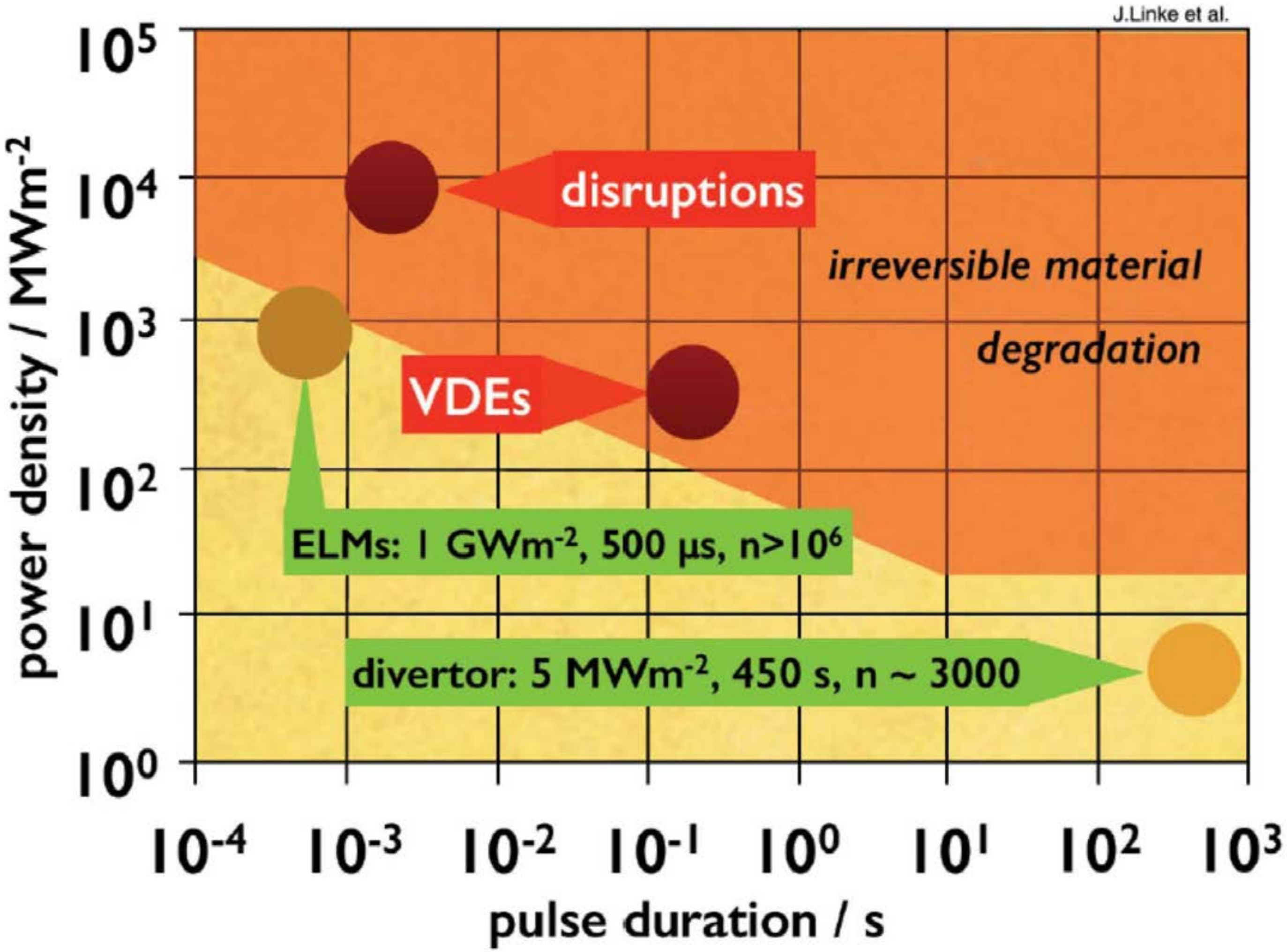


- Fuel Dilution
  - Power from the reactor is proportional to $n_D \times n_T$
  - Density of the electron is fixed:
    - e.g. 1 W atom fully stripped replaces 37 D and 37 T
  - Fusion power goes down from 50 × 50 = 2500 to 13 × 13 = 169
    - 1% impurity cuts the power by over 90%!
- Energy Loss from radiation
  - Bremsstrahlung radiation ∝ to Z^2
  - Takes a lot of energy to strip off all the electrons
  - Wasted energy
- First wall tiles are **Be**
- The divertor is **W**
  - Scale lengths are so large
  - Any eroded material should not make it back into the core

Heat Flux Limits - Tungsten

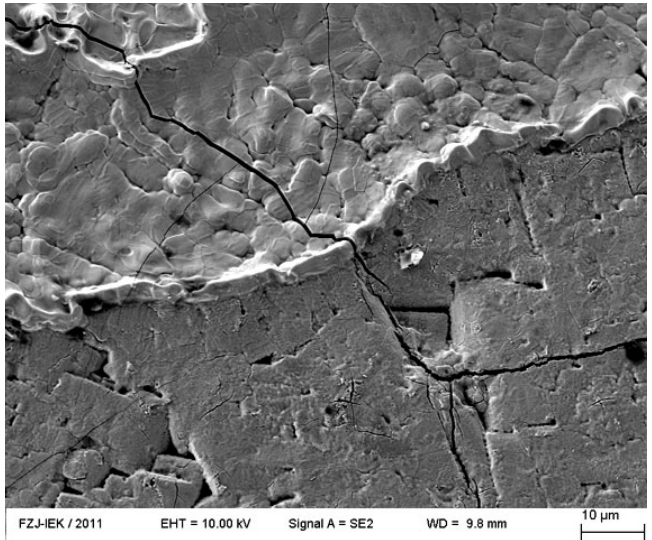
- Plasma stored energy $\propto R^5$
- Energy deposition area on plasma wetted surface $\propto R\lambda_q$
  - As seen earlier, λ_q, will potentially be very small in ITER and larger machines
  - Large uncertainties on wetted area at the transient time
  - Surface temperature rise due to transients:

$$\Delta T \propto \frac{E_{trans}}{A_{wet}t^{1/2}}$$



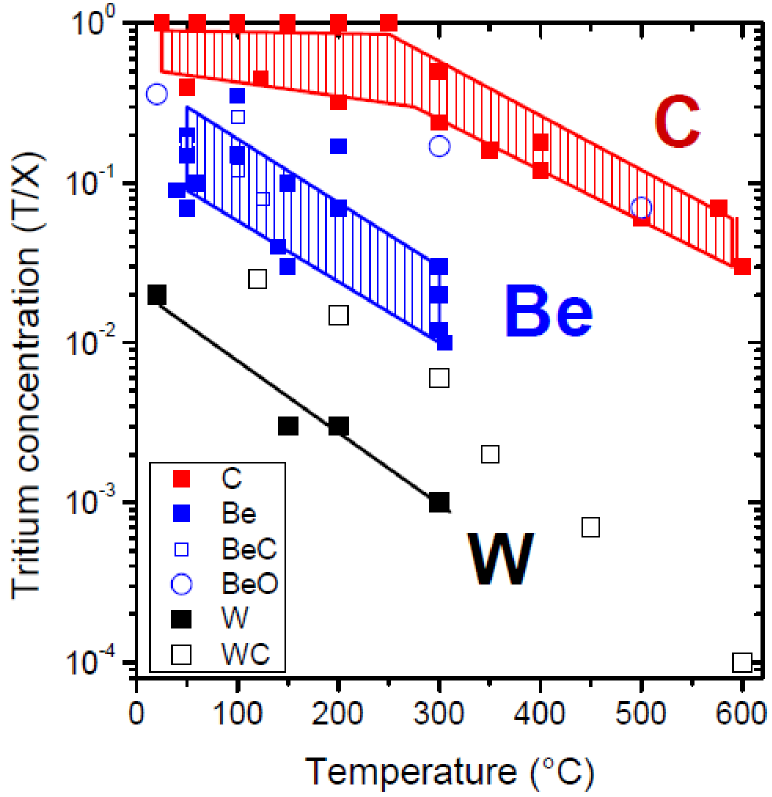
Heat Flux is One of the Most Critical Areas for Future Devices

- Need to manage:
  - Stationary heat fluxes at the limit of cooling technology
  - Near complete mitigation of transients
  - Low tritium retention
  - High throughput fuel cycle
  - Material migration and erosion rates on a scale never seen before
- Cracked, arced and melted tungsten
  - Like being in an arc-welder (heat flux 40 MW/m^2)
  - Surface of the Sun, 63 MW/m^2



Tritium (Fuel) Retention at the Surface and Boundaries

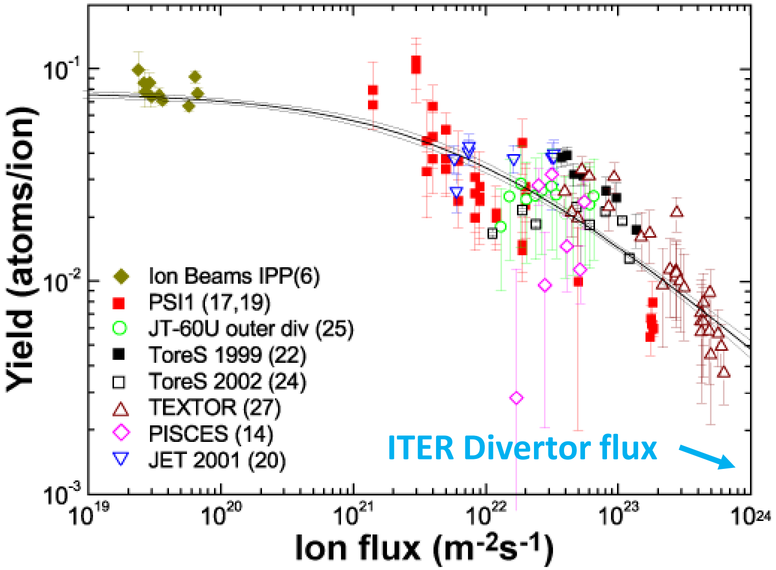
- A 400 s Q_{DT} = 10 ITER discharge will require ~100 g of tritium fueling
- Maximum in-vessel mobilisable T in ITER limited to 1kg
  - This is a safety issue
- In practice, administrative limit of ~700 g
  - 120 g in cryopumps
  - 180 g uncertainty
- Predicting the expected retention in ITER is fraught with uncertainty but progress is being made



- For C, complex interplay between erosion → hydrocarbons → dissociation / ionization → transport → re-deposition → migration to remote areas with high sticking coefficients and retention in co-deposits
  - Carbon traps D, T very efficiently
  - D/C ratio can be in the range ~0.4 → > 1
- For Be, co-deposition of T also possible - large potential source of Be from first wall
- For W, most of retention will be from implantation → not thought to constitute a large reservoir
- BUT effects of increased trapping due to neutron irradiation of metals – does not look like an issue from recent results

Cold and Neutral Atoms Coming off the Wall Surface will Interact with the Plasma

Chemical Sputtering

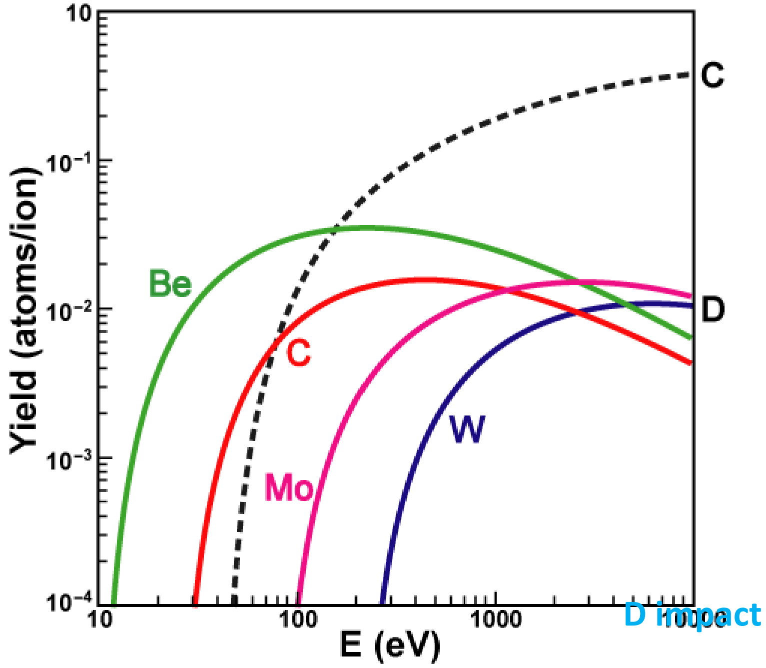


- Recycling rate

$$R = \frac{\Gamma_{wall \rightarrow plasma}}{\Gamma_{plasma \rightarrow wall}}$$

- Steep pressure gradients
  - Pedastal
- Surfaces will have different sputtering yields
- Higher Z have higher sputtering thresholds
  - Much higher yield for high-Z projectiles
  - Important if using seed gasses

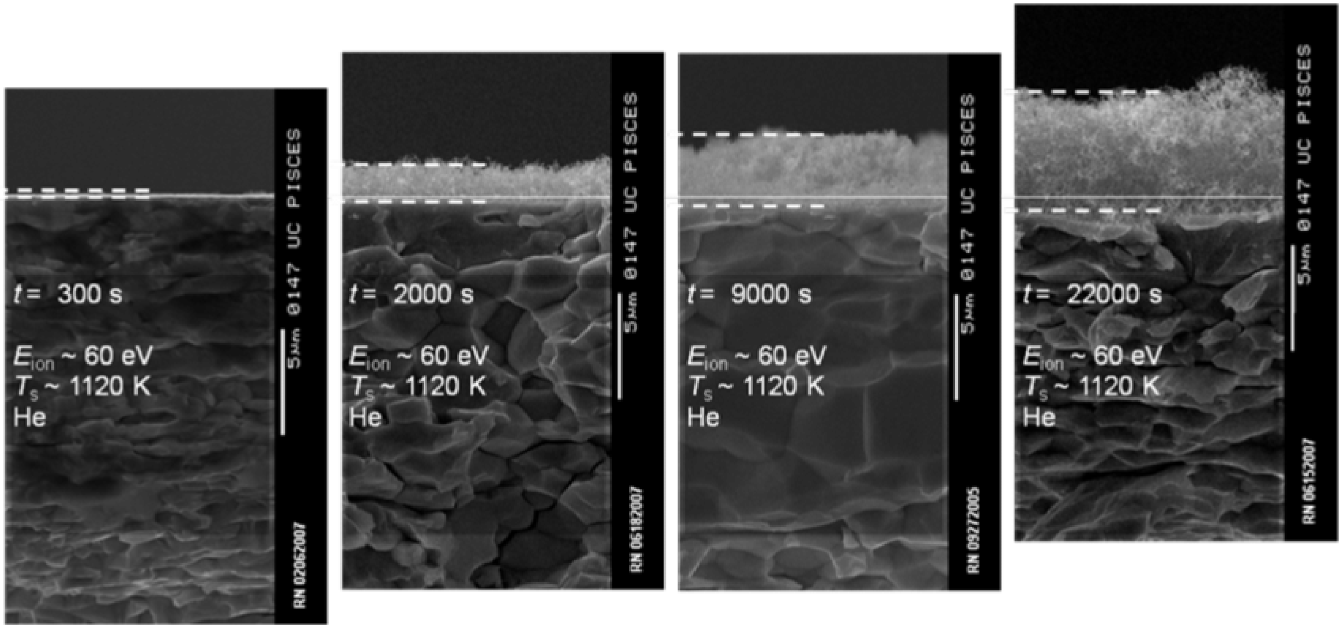
Physical Sputtering



M. J. Baldwin et al., J. Nucl. Mater 404 (2010) 165, J. Wesson, Tokamaks 4th ed. (2011)

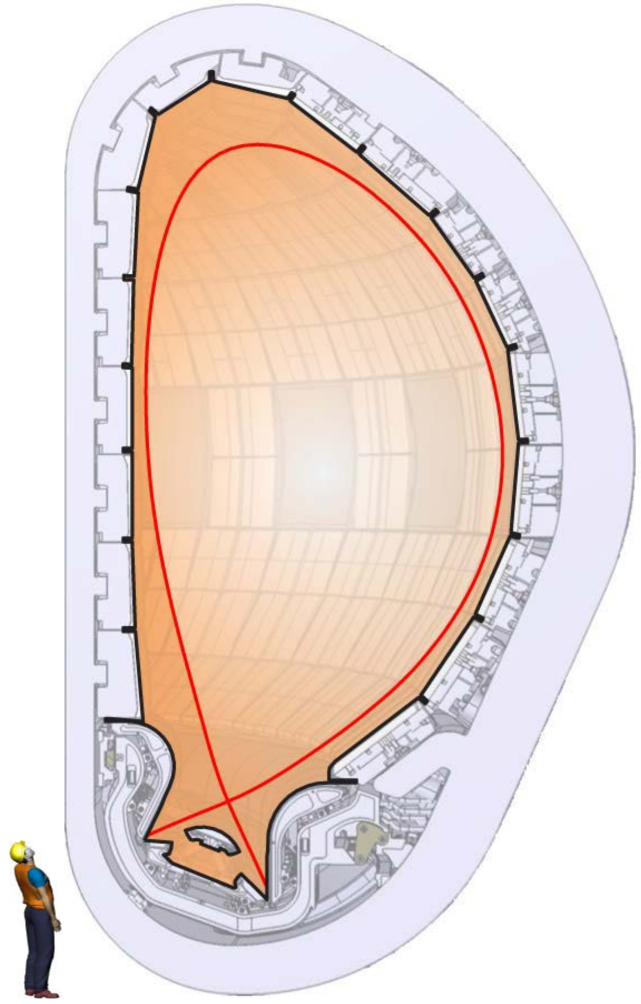
Surface modification can Lead to Dust and Safety Issues

- Hydrogenic species can form blisters and bubbles on a surface
- Tendril Growth/Fuzz with helium exposure
  - Seen not just on W but other metals as well
- Erosion of the fuzz leading to impurities, causing large losses in fusion power.



Surface modification can Lead to Dust and Safety Issues

- Expectation is that increase in duty cycle and erosion in ITER will lead to large scale-up in quantity of dust particles produced
- Like T-retention, dust is a safety issue
  - dust particles radioactive (tritium + activated metals)
  - potentially toxic (Be)
  - potentially responsible for a large fraction of in-VV mobilisable tritium
  - chemically reactive with steam or air
- Radiological or toxic hazard depends on how well dust is contained in accident scenarios and whether it is small enough to remain airborne and be respirable
  - size needs to be <~ 100 μm
  - depends on how dust is produced, e.g. crumbling of co-deposited layers or destruction (thermal overload) of tritiated layers during off-normal events
  - tritiated dust can levitate in electric fields as a result of self-charging due to emission of beta electrons



Overview:

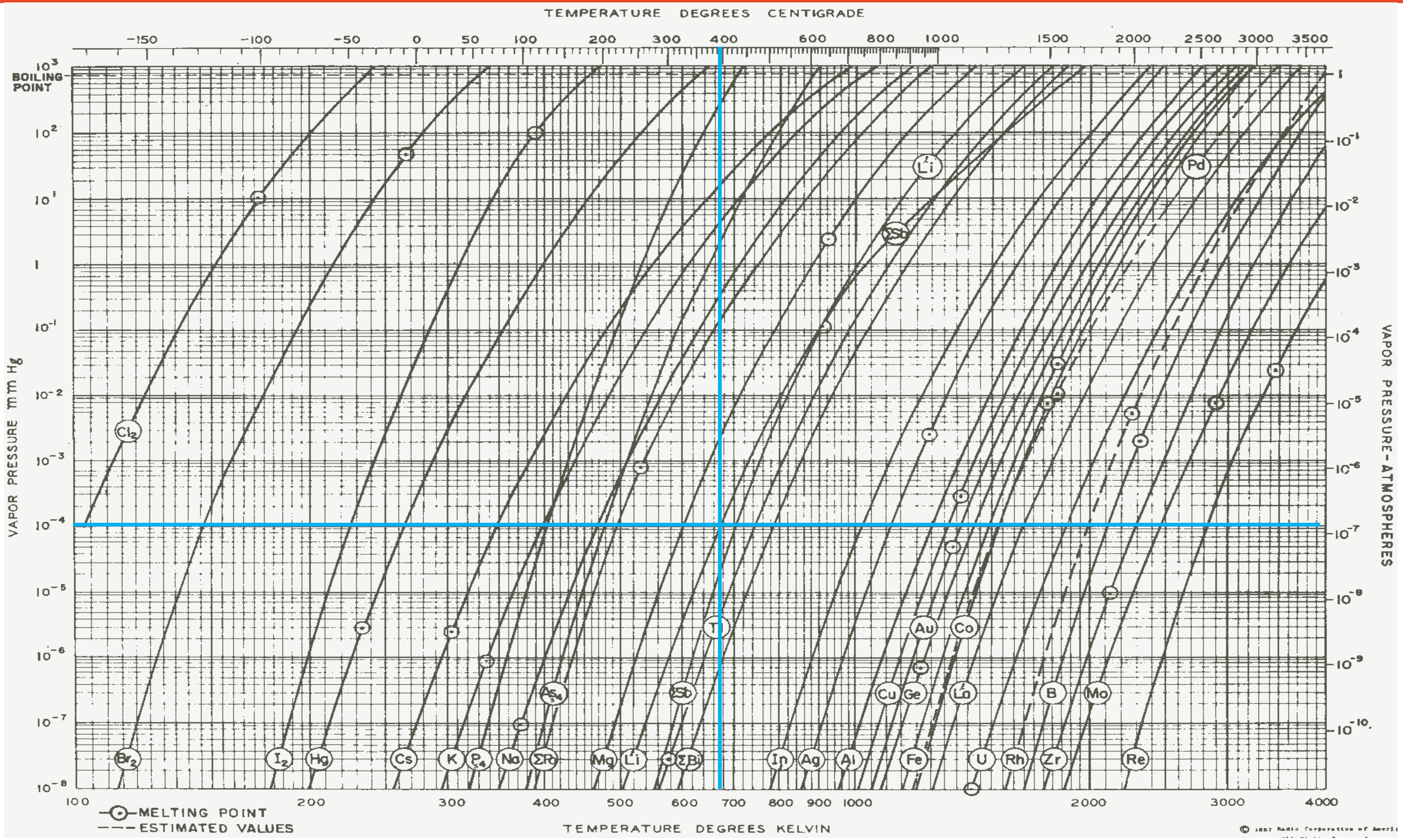
- Materials Challenges – Beyond ITER
- Materials Needs
- Liquid Metals and their Properties
- Plasma Response to Low-Recycling Liquid Metals
- Flowing Liquid Metal PFC Technologies
- Fuel Loss and Retention
- Liquid Metal PFC Experiments
- Summary

Why are Liquid Metals even Considered?

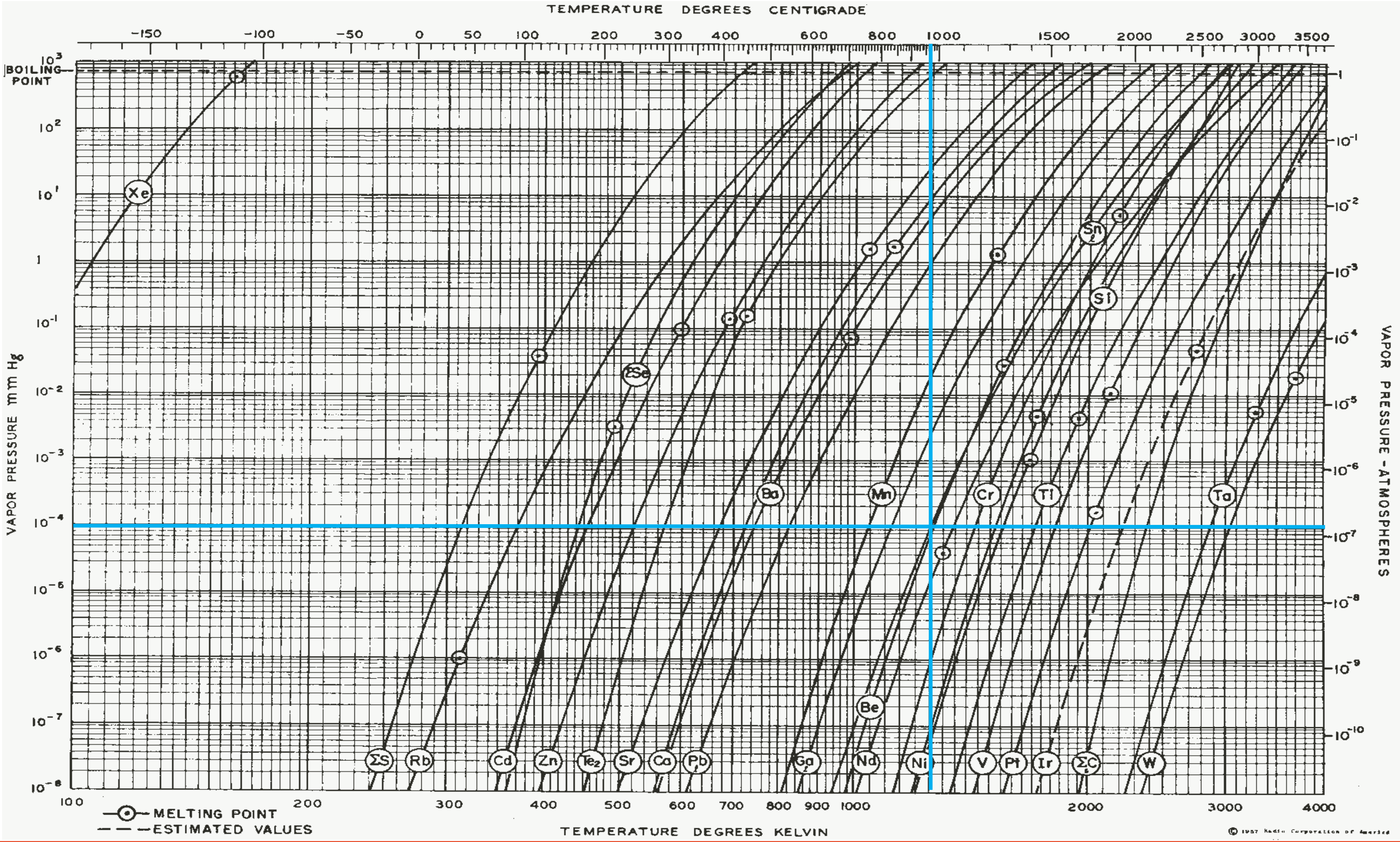
- ELM’s, VDE’s and other instabilities will eventually turn any surface into a liquid metal
- So why not start out with a liquid metal from the get go.
- Several options to look at:
  - Lithium
  - Tin
  - Gallium
  - Tin-Lithium

	Lithium	Tin	Gallium	Tin - Lithium
Z	3	50	31	~53
Mass	6.941	118.710	69.723	126.92
Melting Temp. [^{o}C]	180.54	231.93	29.76	344 - 488
Boiling temp. [^{o}C]	1330	2602	2400	?
Solid Density [kg m^{-3}]	534	7265	5910 (r.t)	6350
Liquid Density [kg m^{-3}]	512	6990	6095 (m.p)	?
Specific Heat [J kg^{-1}K^{-1}]	3570	227	368	?
Thermal Conductivity [W m^{-1}K^{-1}]	85	66.8	40.6	?
Electrical Resistivity [nΩ m]	92.8	115	270	?
Thermal Diffusivity [m^{2}s^{-1}]	4.45×10^{-5}	4.0×10^{-5}	2.0×10^{-5}	?
Dynamic Viscosity [Pa s]	5.69×10^{-4}	2.71×10^{-3}	$1.184\text{x}10^{-3}$	?
Surface Tension [N m^{-1}]	0.4	0.548	0.7239	?

Vapor Pressure curve for Lithium

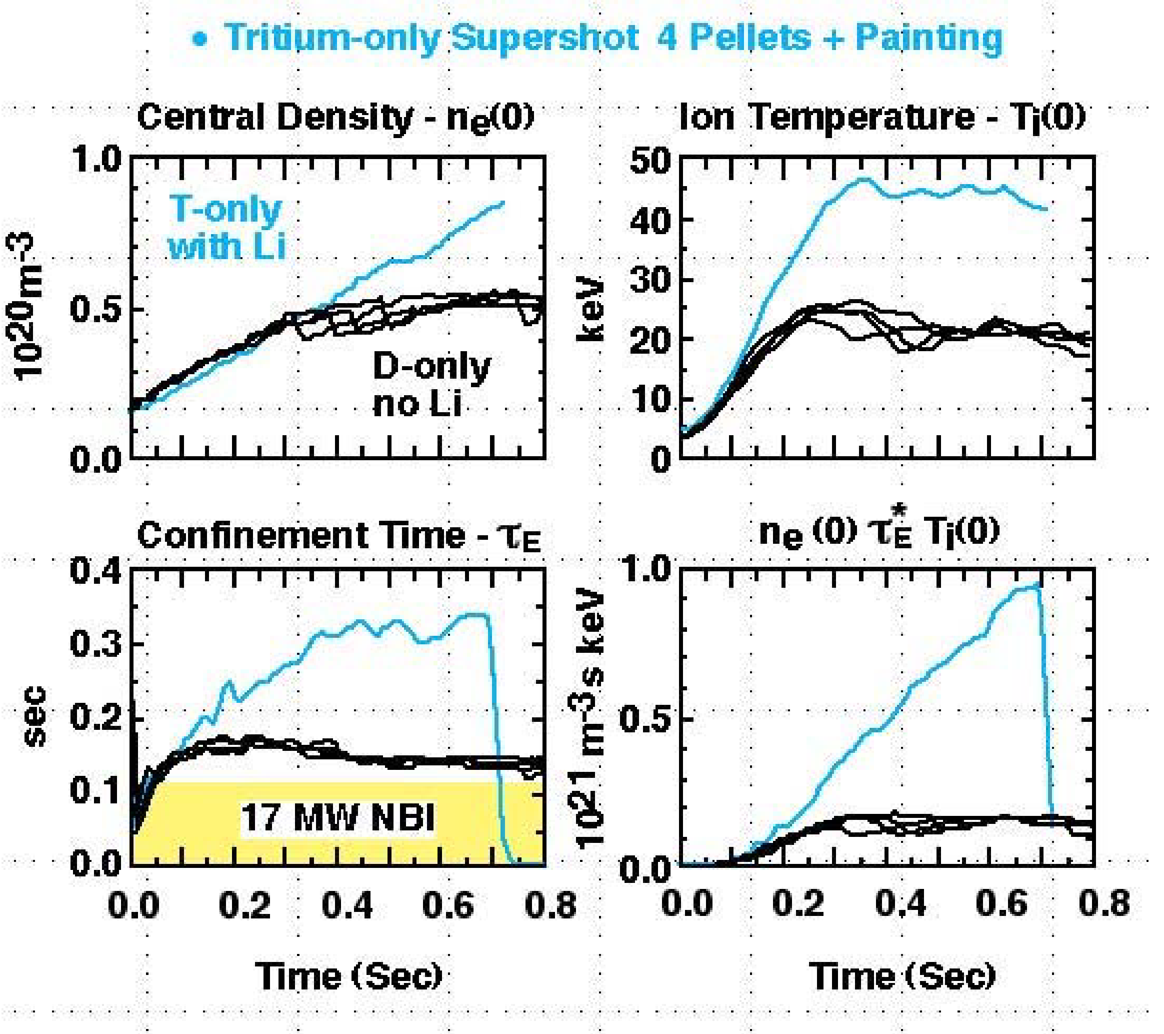


Vapor Pressure curve for Tin - Comparison



Liquid lithium has Become the more Studied Liquid Metal for Fusion

- First evidence for lithium were the TFTR super shots in 1994!
- Low Z
- Tends to stay in the edge
- Can be used for instability control
- Not to say that it has its own issues and challenges



Thermoelectric Properties of Lithium – Seebeck Effect

- Seebeck effect is what thermocouples are based on
  - Two dissimilar metals

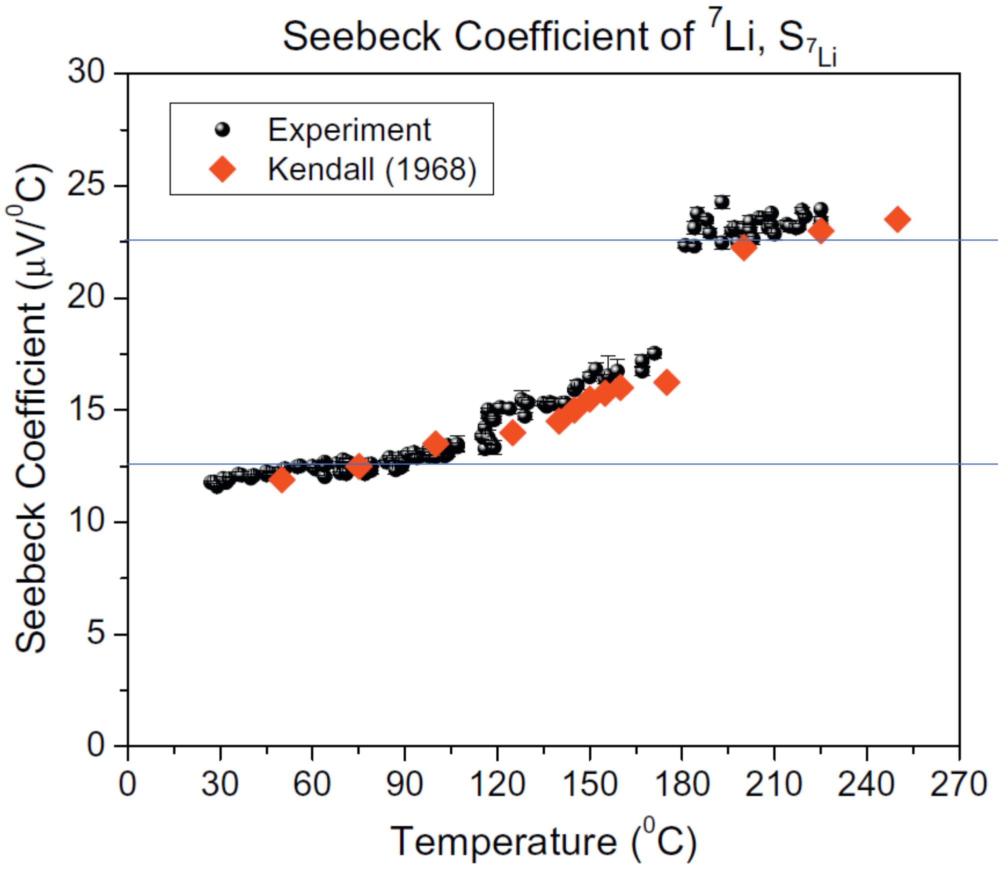
$$S = -\frac{\Delta V}{\Delta T}$$

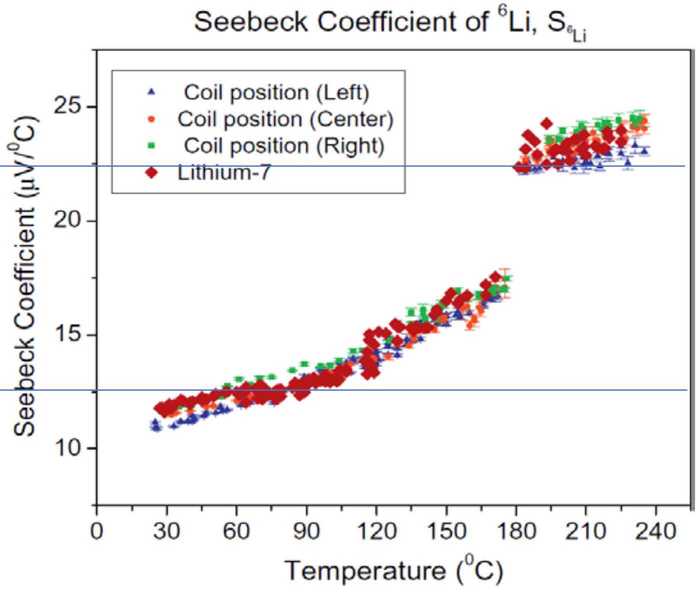
$$E = S\nabla T$$

- Lithium has one of the highest thermoelectric properties
  - Compared to stainless steel

$$S_{A-B} = S_A - S_B$$

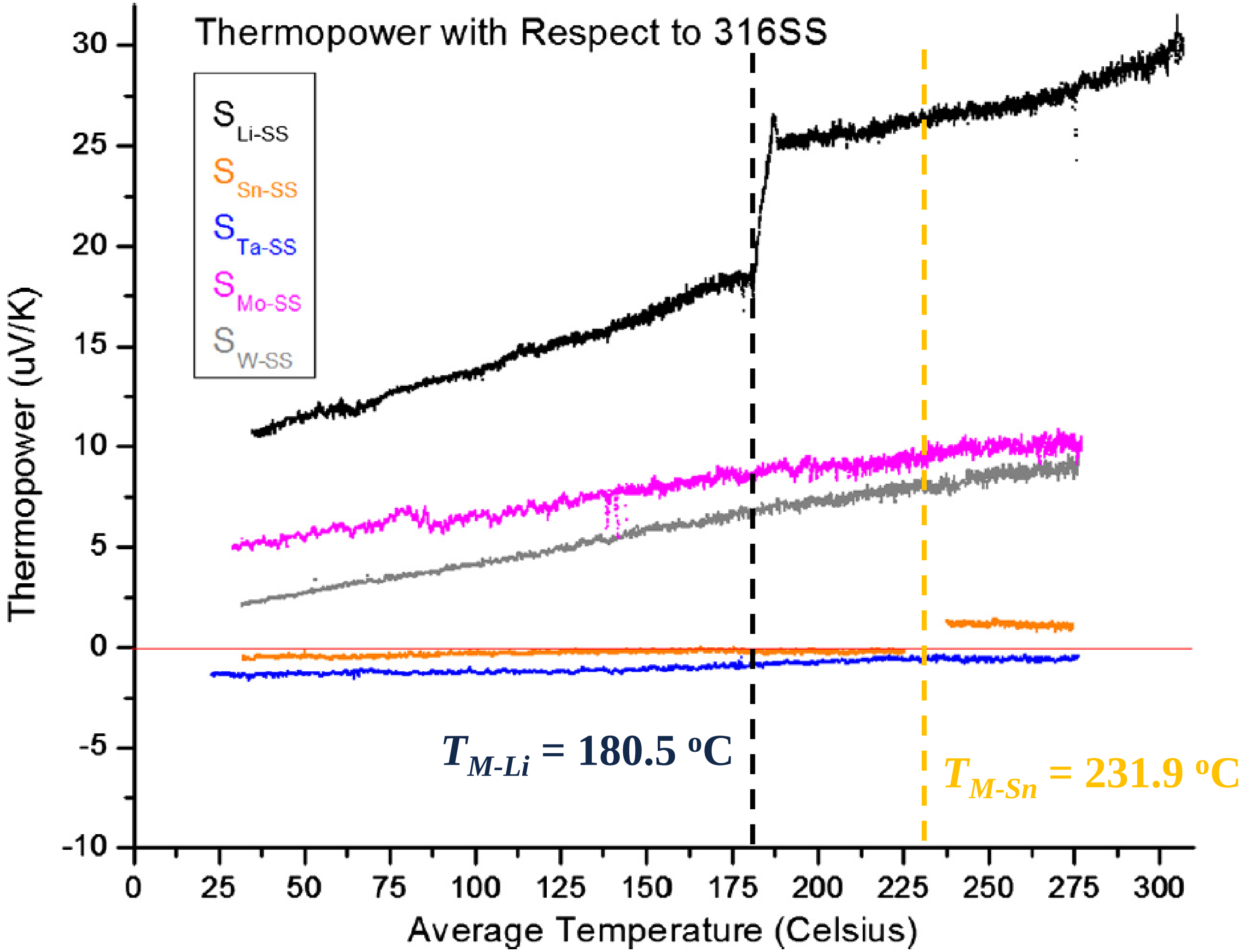
- Dependent on temperature





No difference between Li^6 or Li^7 in terms of the Seebeck coefficient.

Thermoelectric Properties of Lithium – Seebeck Effect

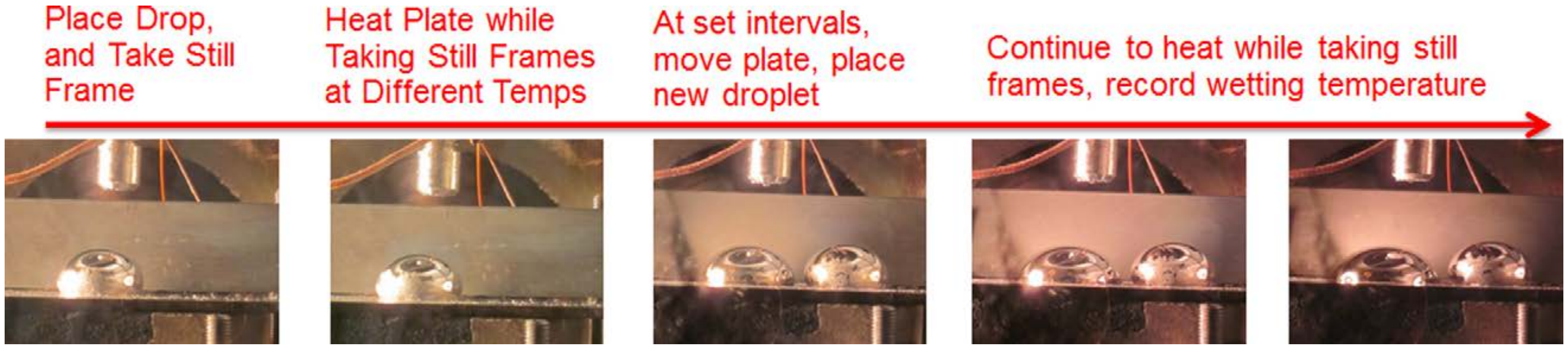


Liquid lithium is the most Popular and Common Liquid Metal

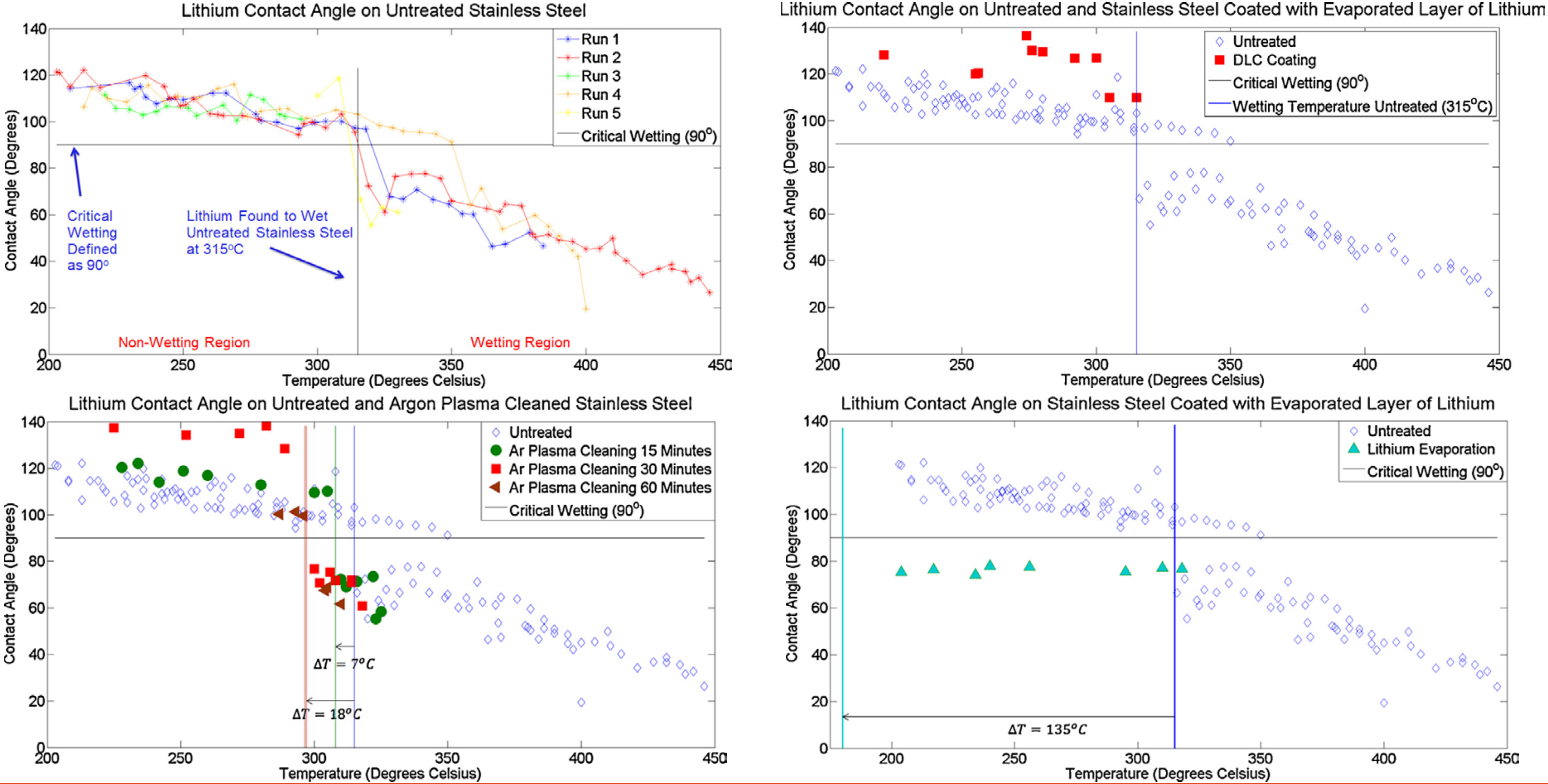
- Many of the concepts that use liquid lithium (and metals) require wetting of the surface.
  - Surface energy

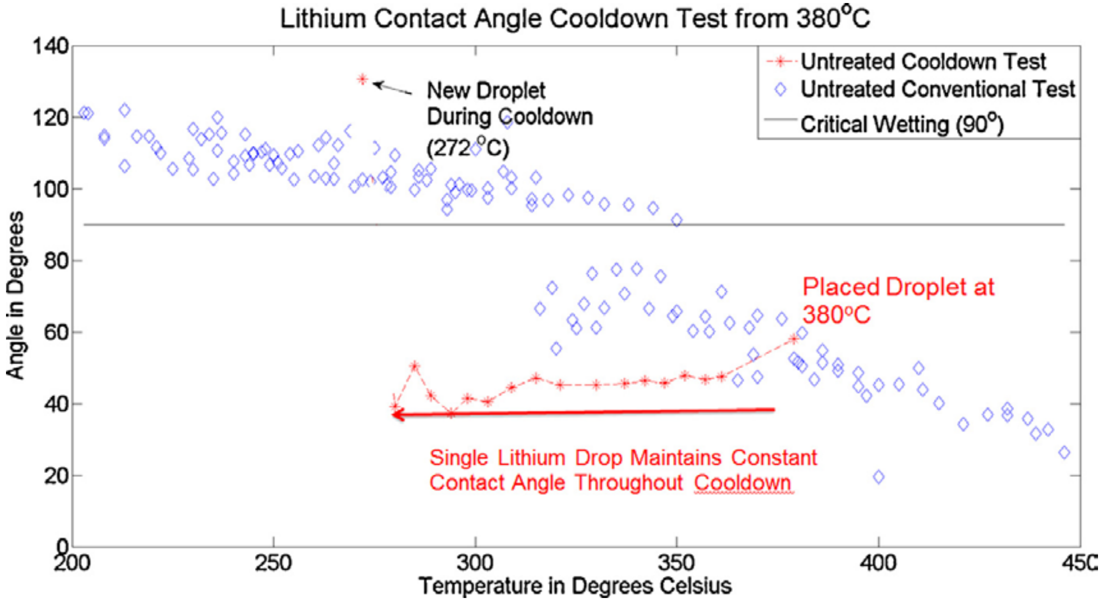
$$\gamma_{SV} = \gamma_{SL} + \gamma_{LV} \cos(\theta)$$

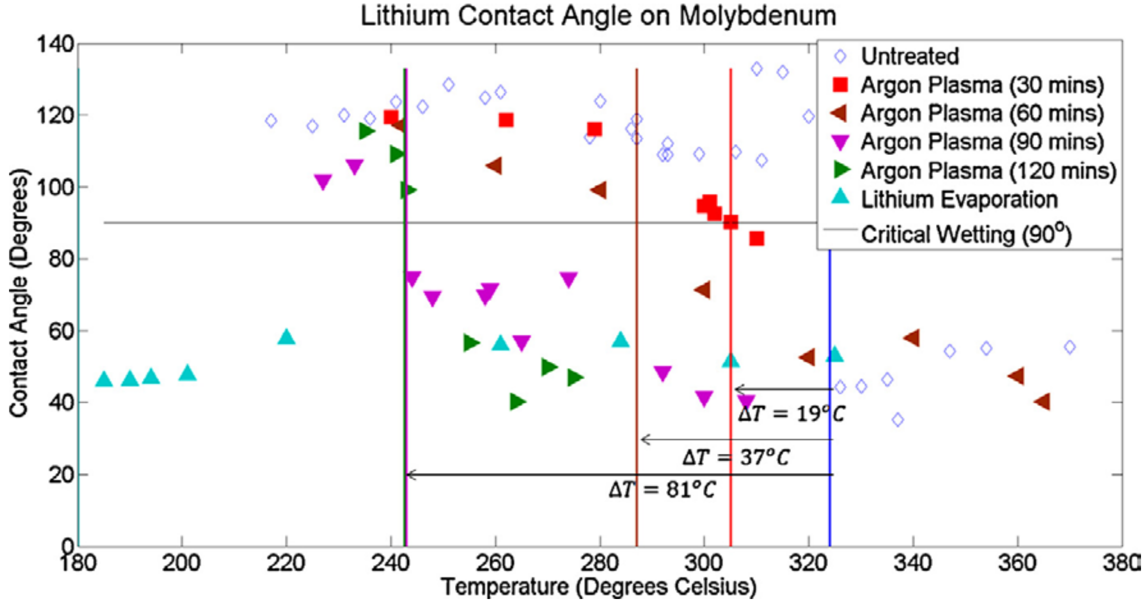
- Wetting is defined when the angle is less than 90°
- Will occur at a certain temperature
  - Can be changed with surface modification
    - Smoothing of the surface
    - Plasma treatment
    - Lithium evaporative coating
    - Surface treatment

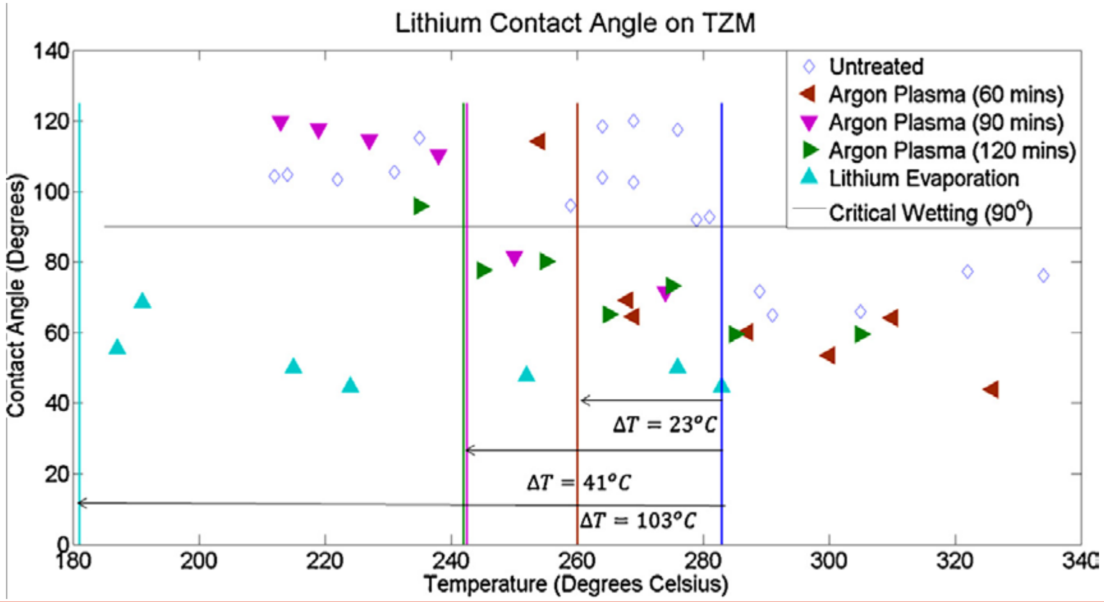


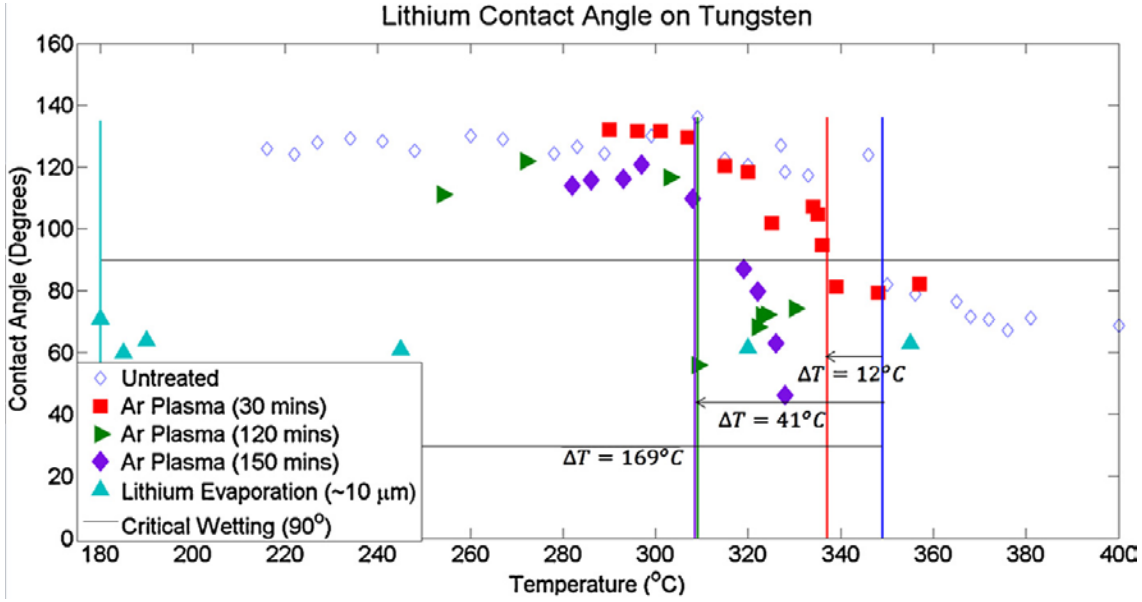
P. Fiflis et al., Fusion Eng. Design 89 (2014) 2827

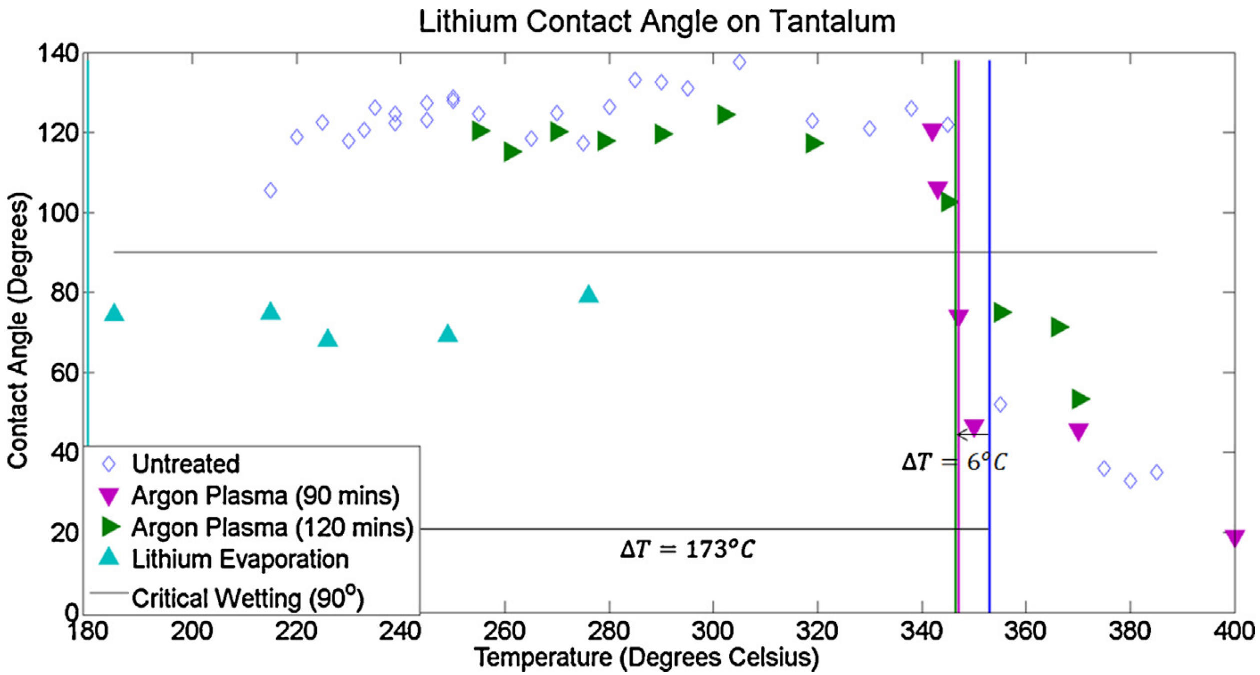



Lithium Contact Angle Cooldown Test from 380°C
Untreated Cooldown Test
Untreated Conventional Test
Critical Wetting (90°)
New Droplet During Cooldown (272°C)
Placed Droplet at 380°C
Single Lithium Drop Maintains Constant Contact Angle Throughout Cooldown
Angle in Degrees
Temperature in Degrees Celsius

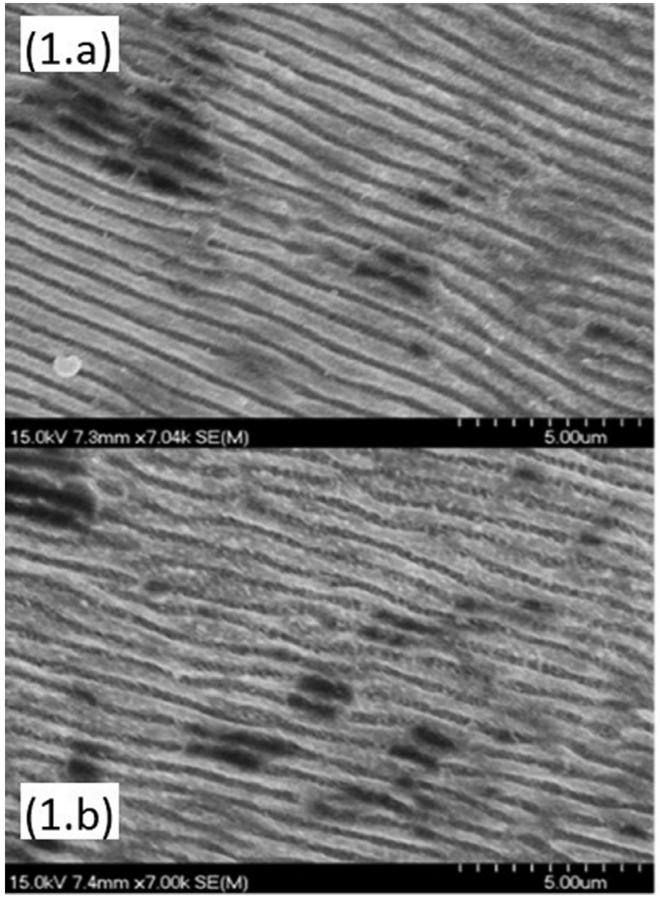

Lithium Contact Angle on Molybdenum
Untreated
Argon Plasma (30 mins)
Argon Plasma (60 mins)
Argon Plasma (90 mins)
Argon Plasma (120 mins)
Lithium Evaporation
Critical Wetting (90°)
ΔT = 19°C
ΔT = 37°C
ΔT = 81°C
Contact Angle (Degrees)
Temperature (Degrees Celsius)

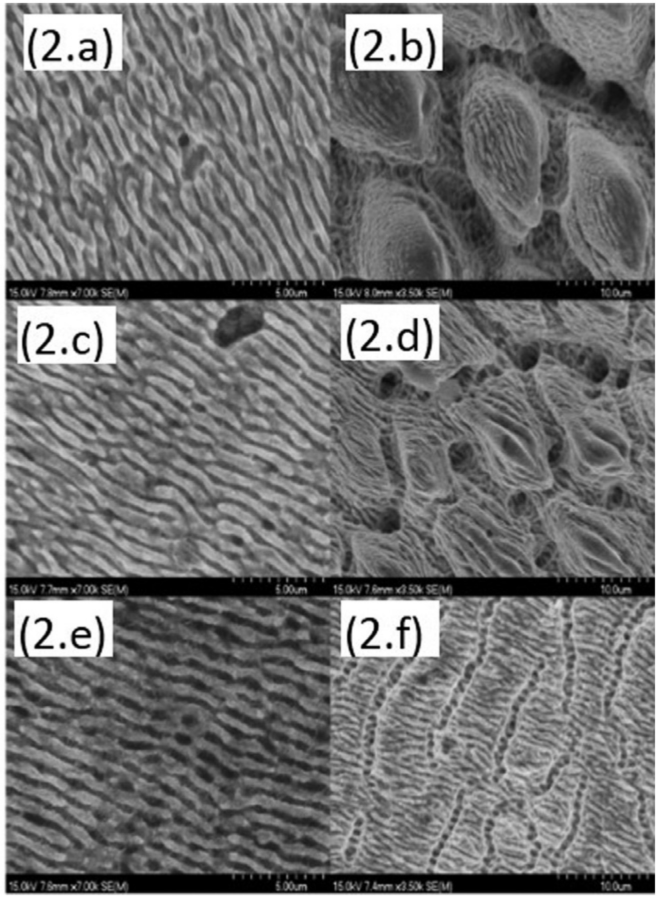

Lithium Contact Angle on TZM
Untreated
Argon Plasma (60 mins)
Argon Plasma (90 mins)
Argon Plasma (120 mins)
Lithium Evaporation
Critical Wetting (90°)
ΔT = 23°C
ΔT = 41°C
ΔT = 103°C
Contact Angle (Degrees)
Temperature (Degrees Celsius)

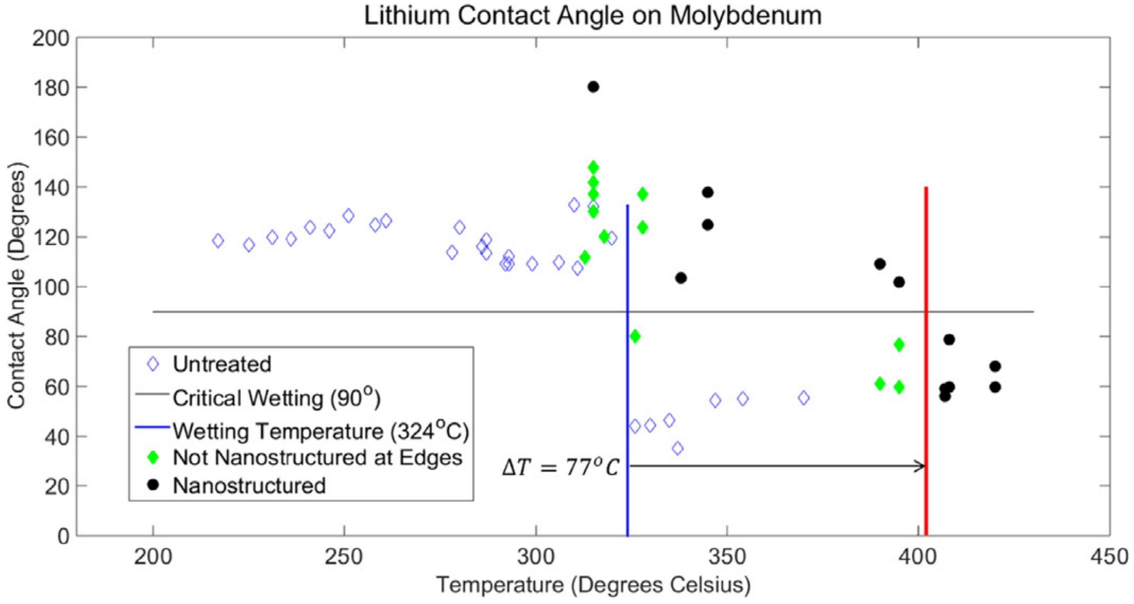

Lithium Contact Angle on Tungsten
Untreated
Ar Plasma (30 mins)
Ar Plasma (120 mins)
Ar Plasma (150 mins)
Lithium Evaporation (~10 μm)
Critical Wetting (90°)
ΔT = 12°C
ΔT = 41°C
ΔT = 169°C
Contact Angle (Degrees)
Temperature (°C)

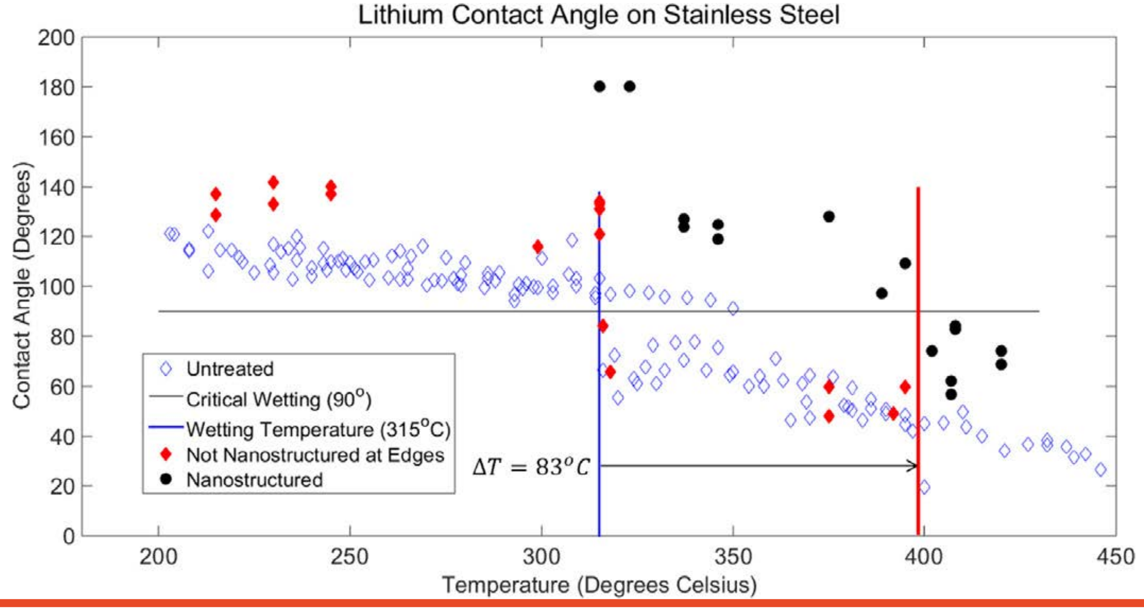


Wetting temperatures of lithium on various surfaces	Untreated [ºC]	Argon Plasma Cleaning [ºC]	Lithium Coating [ºC]
Stainless Steel	315	297	180
Molybdenum	324	243	180
Tantalum	353	347	180
TZM	284	243	180
Tungsten	349	337	180







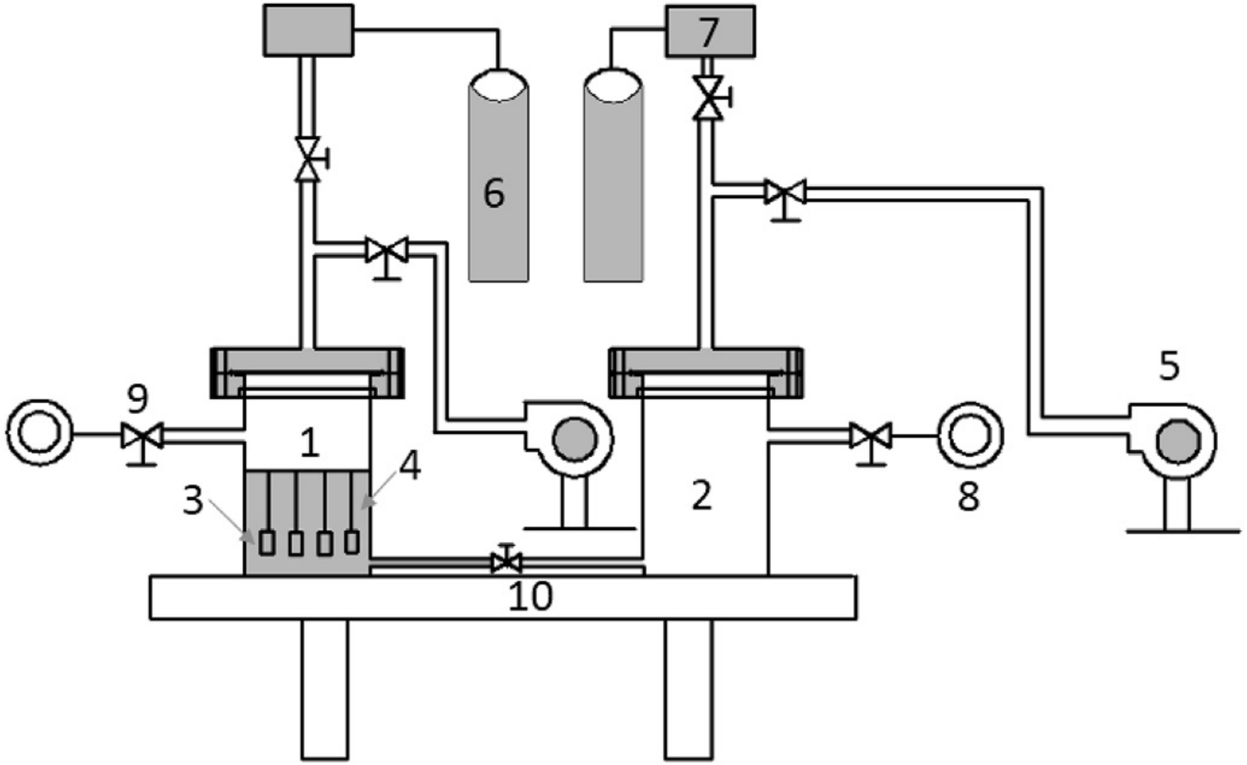


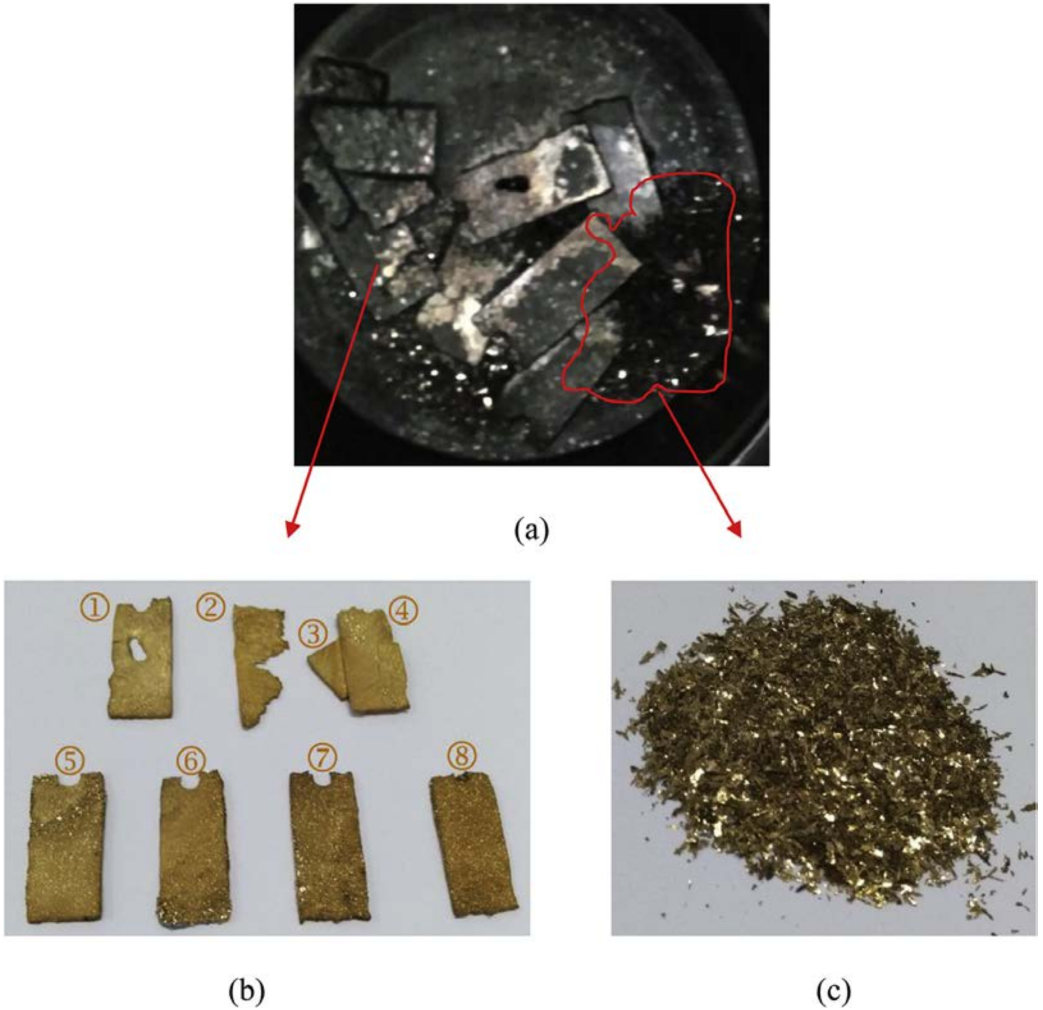
Scanning electron microscopy images of the molybdenum samples (1.a, 1.b) and the 316 stainless steel samples (2.a –2.f). The lithium contact angle studies were performed on the samples 1.a and 2.b. Molybdenum samples show a change in surface morphology under various laser power densities, while steel samples show changes based on the number of passes the laser made over a single radial position.

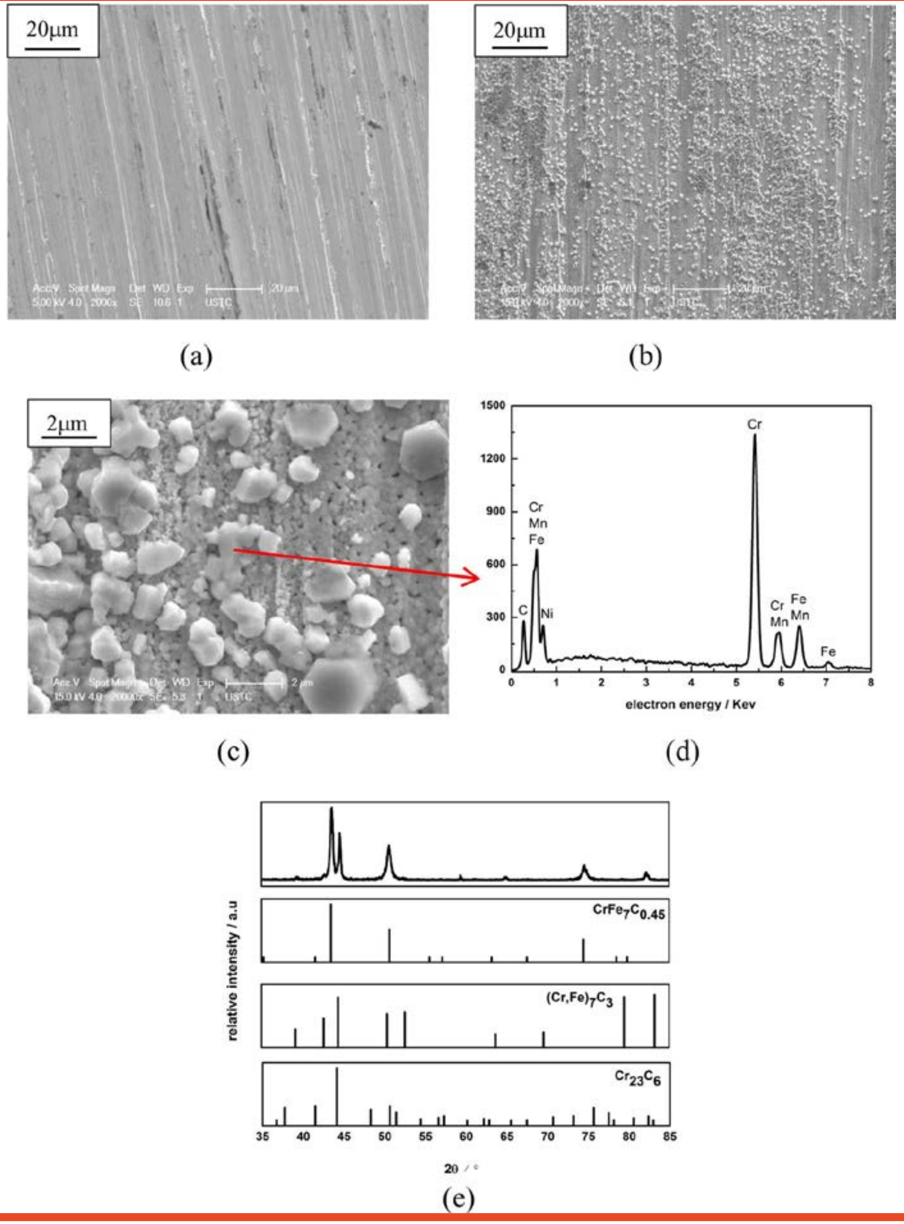
Solid Metals within the Reactor need to Survive Liquid Metal Exposure

- There are many different materials within a fusion reactor that will be exposed to hot, liquid metals
  - Copper
  - Aluminium
  - Stainless steel (304, 316)
  - Tungsten
  - Carbon
  - Molybdenum
- Lithium especially can be very corrosive to most metals
- Refactory metals and stainless steel are resistant to attack
  - Stainless steel (316)
  - Tungsten
  - Molybdenum
  - TZM
  - (tantalum, rhenium niobium)

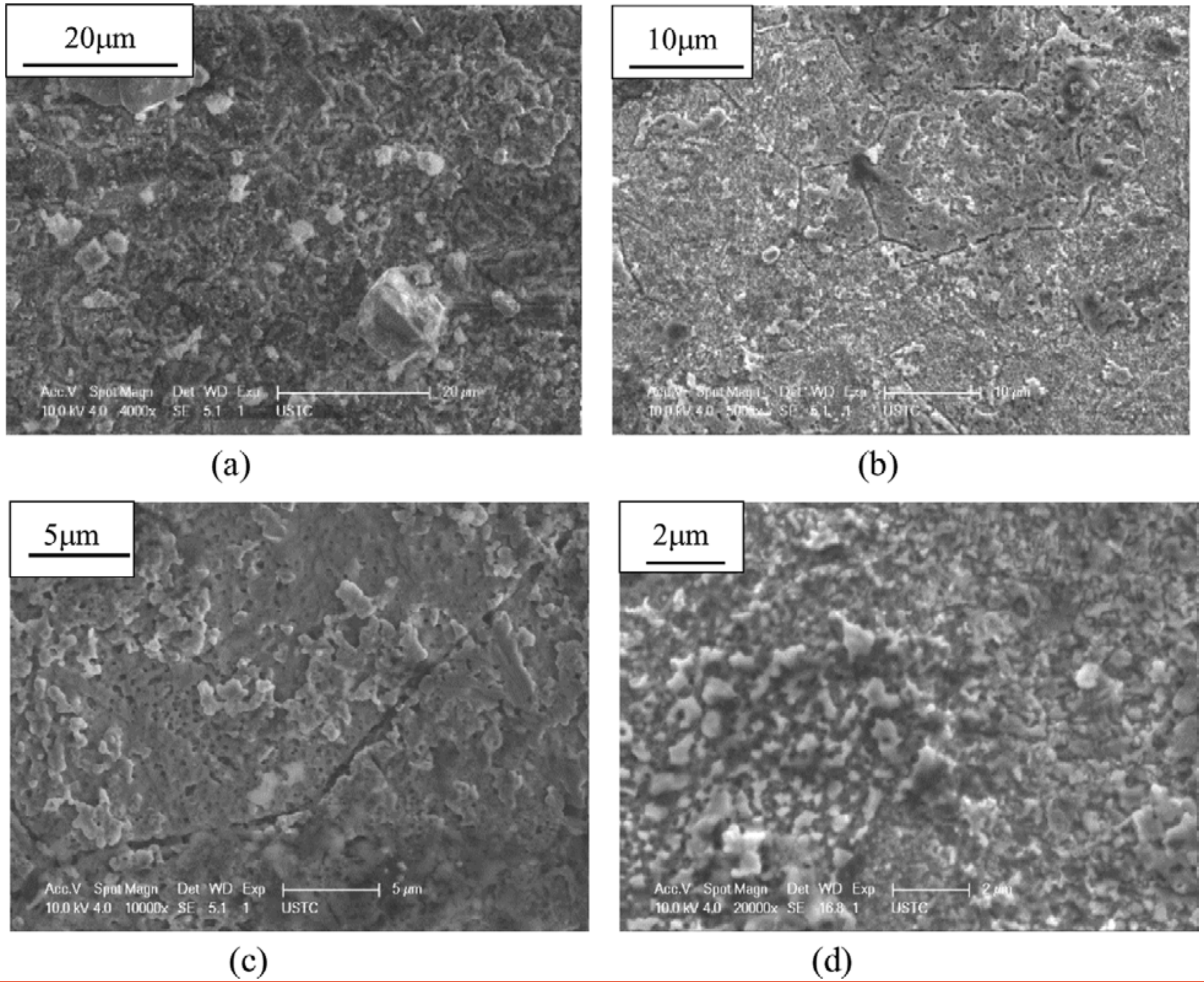
Copper Corrosion Exposure to Lithium – avoid at all costs

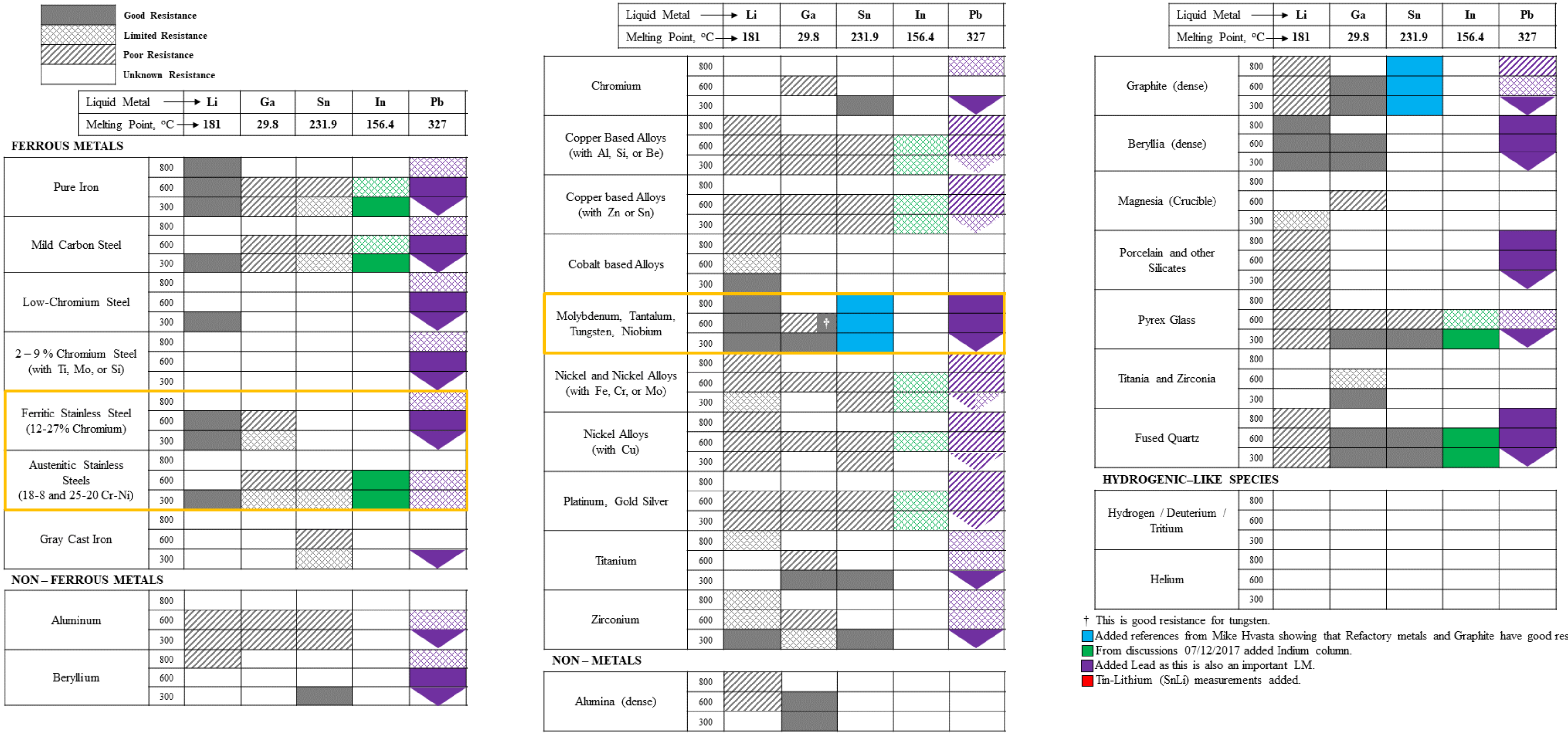






Stainless Steel has much Better Resistance, but not Perfect





† This is good resistance for tungsten.

- Added references from Mike Hvasta showing that Refactory metals and Graphite have good resistance.
- From discussions 07/12/2017 added Indium column.
- Added Lead as this is also an important LM.
- Tin-Lithium (SnLi) measurements added.

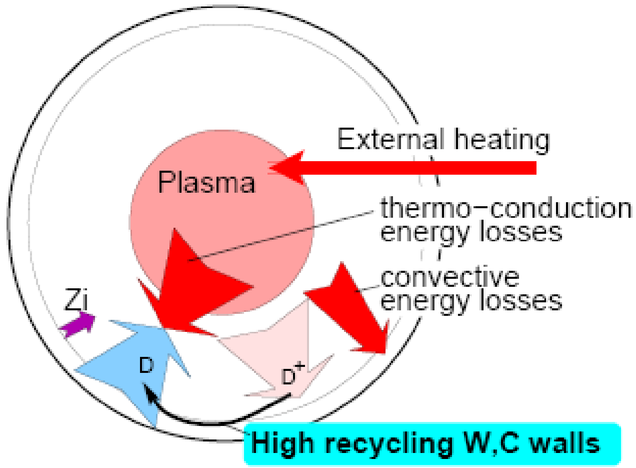
Name	Formula	Molar mass (g/mol)	Density (kg/m^3)	Melting Point (^{o}C)	Boiling Point (^{o}C)	Appearance	Reacts with Water	Other
Lithium	Li	6.938	534 (r.t) 512 (m.p)	180.5	1330	**Silver white**	Yes	Reacts with most metals except refactories
Lithium Nitrate	LiNO3	68.964	2380	255	600	**White to light yellow solid**	Soluble in water	Irritant and corrosive to skin
Lithium Amide	$LiNH_2$	22.96	1178	375	430	**White solid**	Reacts	Yes
Lithium Hydroxide	LiOH	23.95 (anhydrous) 41.96 (monohydrate)	1460 (anhydrous) 1510 (monohydrate)	462	924	**White solid odorless**	Hydroscopic	Yes. Irritant to skin, toxic.
Lithium Carbide	Li_2C_2	37.9034	1300	550	? (refactory)	**White solid**	Reacts	Hard, refactory, resistant to wear
Lithium Bromide	LiBr	86.854	3464	552	1265	**White solid**	soluble	Psychoactive and somewhat corrosive
Lithium Hydride	LiH	7.95	780	688.7	900 – 1000	**Colorless to gray solid**	yes	
Lithium Carbonate	Li_2CO_3	73.89	2110	723	1310	**Odorless white powder**	Soluble	Used in medicine
Lithium Nitride	Li_3N	34.83	1270	813	?	**Red, purple solid**	Yes	Corrosive to everything
Lithium Oxide	Li_2O	29.88	2013	1438	2600	**White solid**	Corrosive, reacts violently to form LiOH	

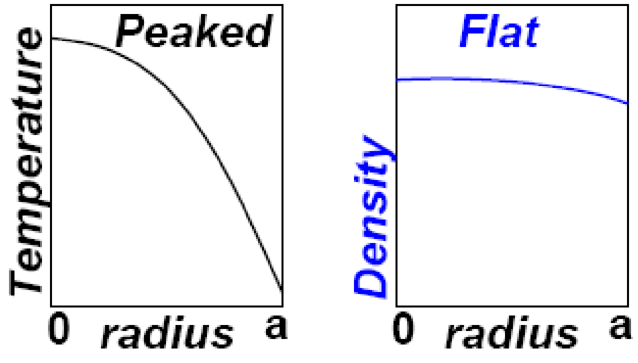
Overview:

- Materials Challenges – Beyond ITER
- Materials Needs
- Liquid Metals and their Properties
- Plasma Response to Low-Recycling Liquid Metals
- Flowing Liquid Metal PFC Technologies
- Fuel Loss and Retention
- Liquid Metal PFC Experiments
- Summary

What Low recycling does for fusion – Lithium Wall Fusion (LiW)

- No cold hydrogen returns from the wall – Plasma stays hot
- Standard case





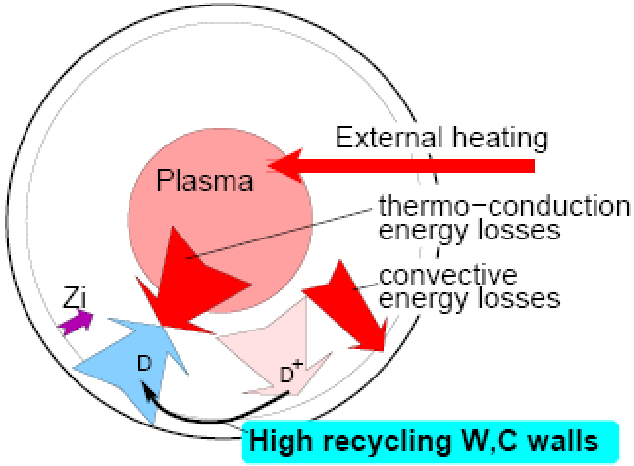
Plasma Physics and alpha heating get ion and electron temperature gradient turbulent transport for stability

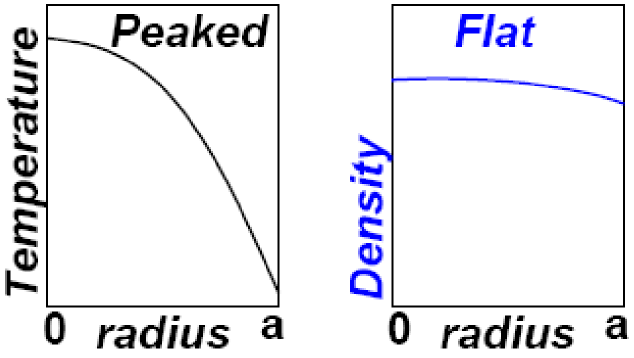
Bad core and edge stability (sawteeth, ELMs etc…)

Most of the plasma volume does not produce fusion

What Low recycling does for fusion – Lithium Wall Fusion (LiW)

- No cold hydrogen returns from the wall – Plasma stays hot
- Standard case



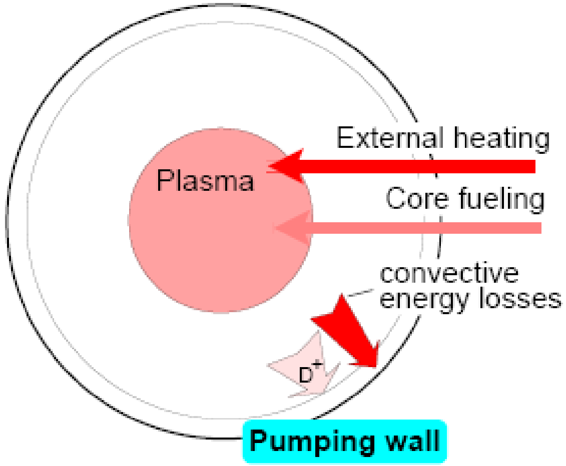


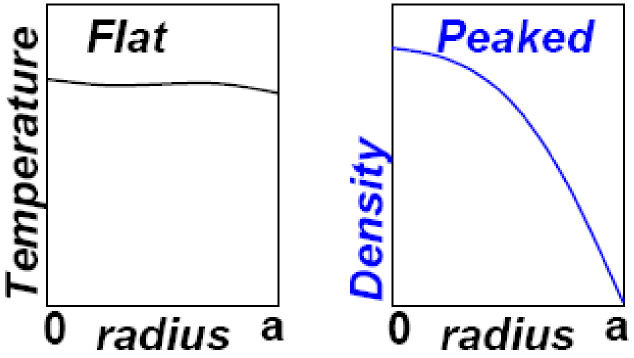
Plasma Physics and alpha heating get ion and electron temperature gradient turbulent transport for stability

Bad core and edge stability (sawteeth, ELMs etc…)

Most of the plasma volume does not produce fusion

- Lithium case:
  - The radius needed is only 1/3
  - Volume, and the cost of fusion power reduced
  - Factor ~ 27!



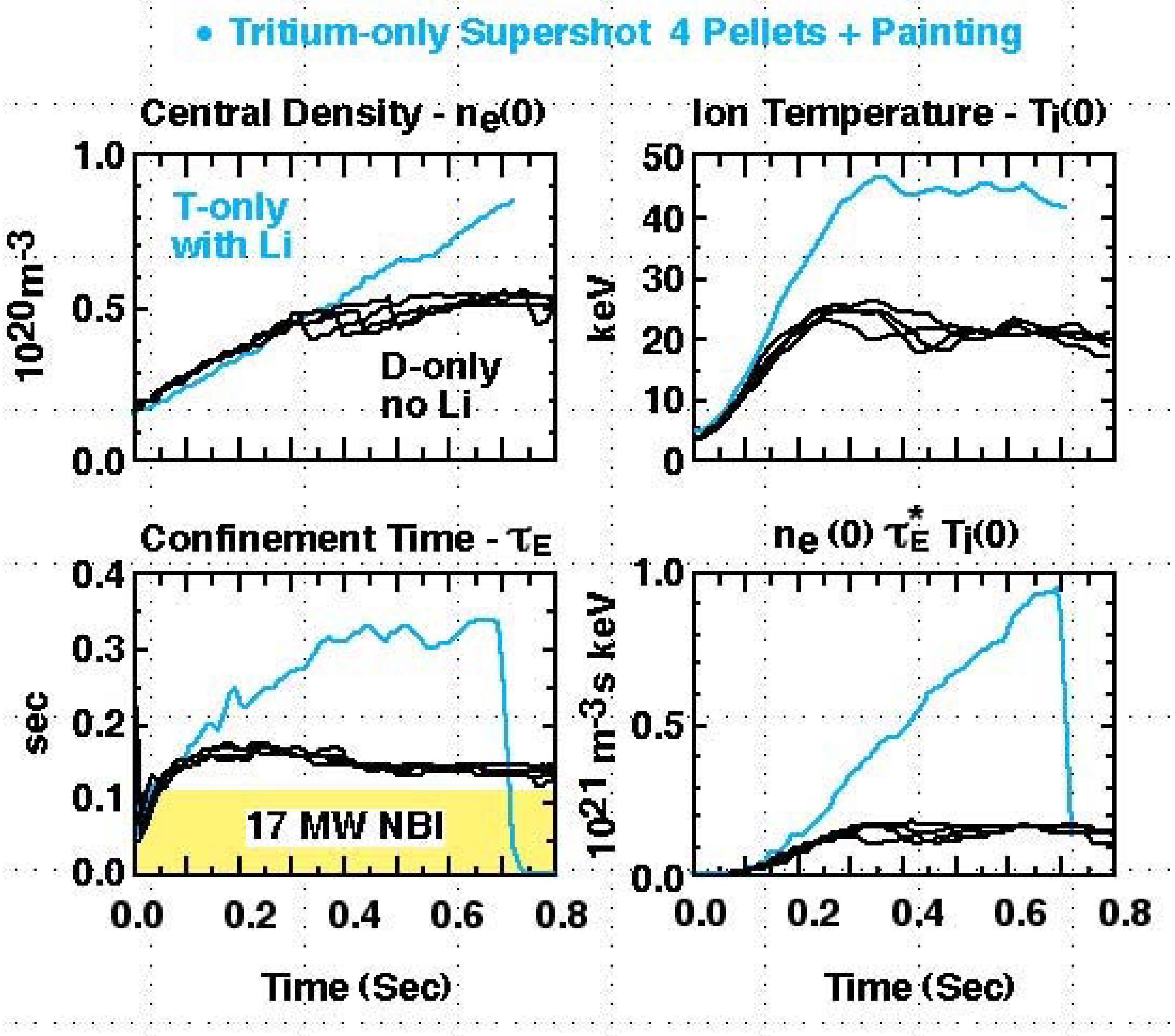


Nothing from the physics expected or accepted

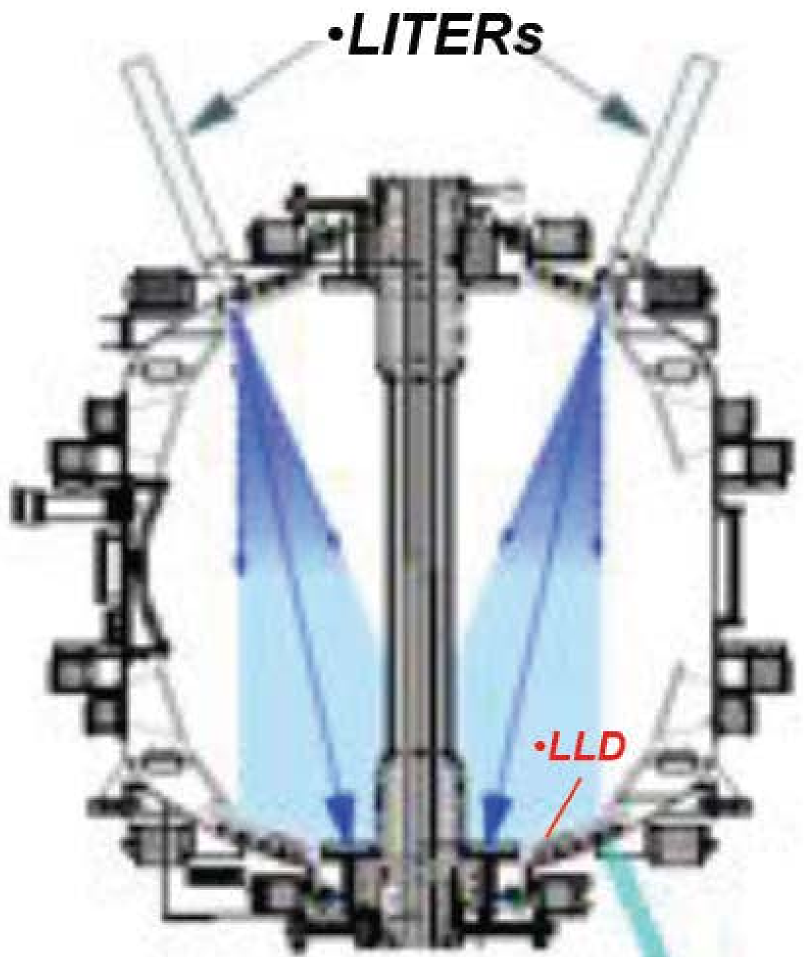
Stability is excellent, no instabilities, external control

The whole plasma volume produces fusion

First Lithium Evidence – TFTR Supershot 1994

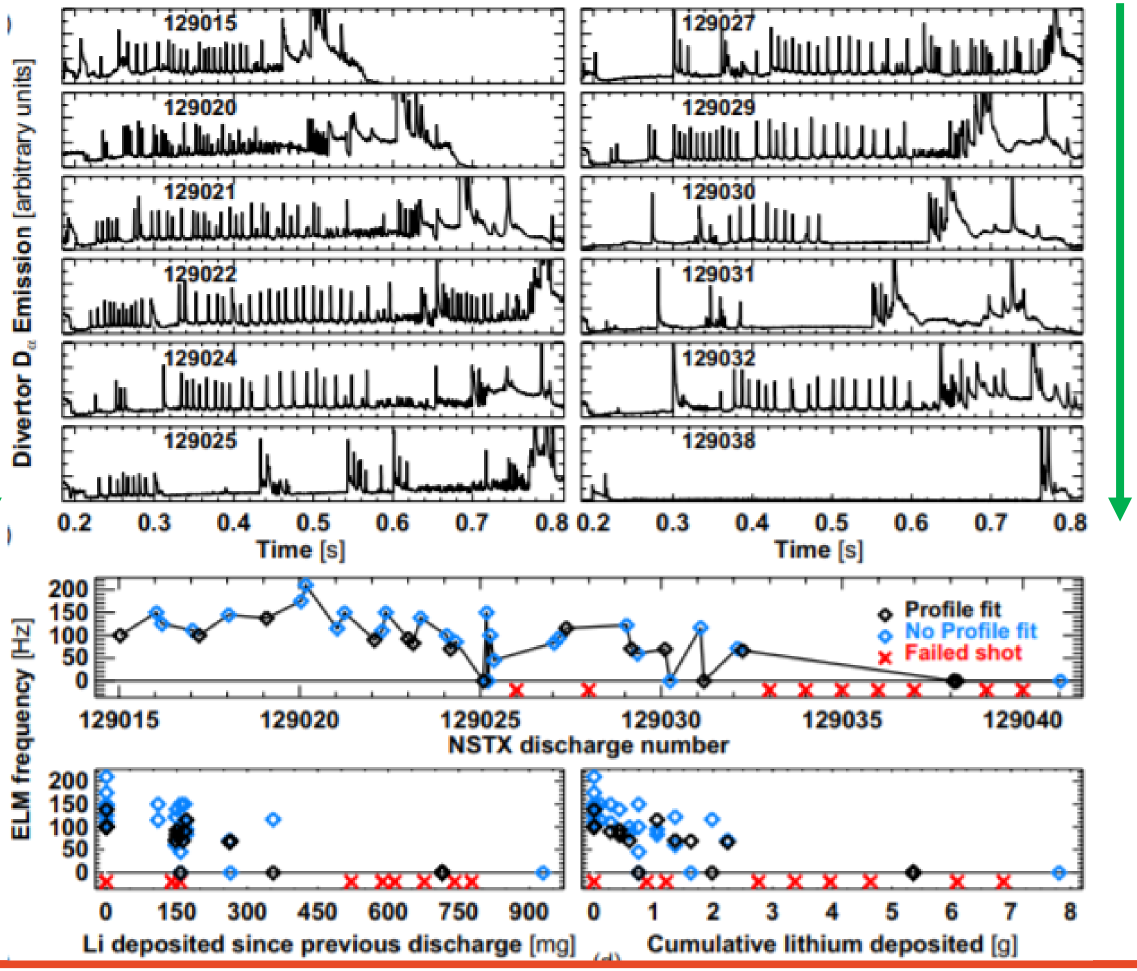


Lithium evaporation in NSTX to coat walls and Liquid Lithium Divertor

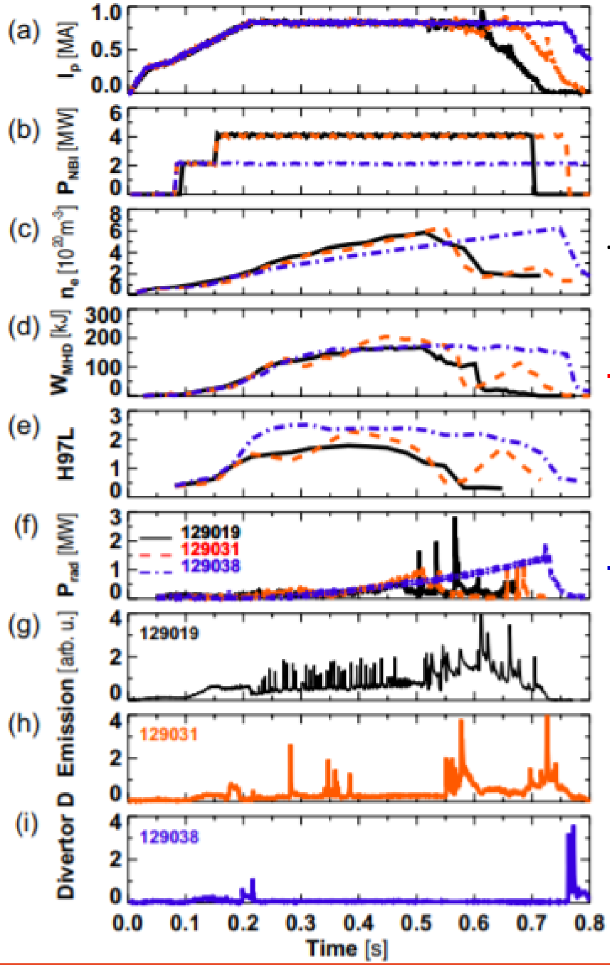


- Lithium evaporators (LITER) aimed toward the LLD.
- Lithium beam covers large area and plasma migration
- Exposure to air converts the lithium to other compounds.

Lithium coatings reduce the D recycling, reduces H-mode power threshold, broadens T_e profile, reduces electron thermal diffusivity, improves confinement and ELM Suppression



Increasing Lithium Up to 600 mg

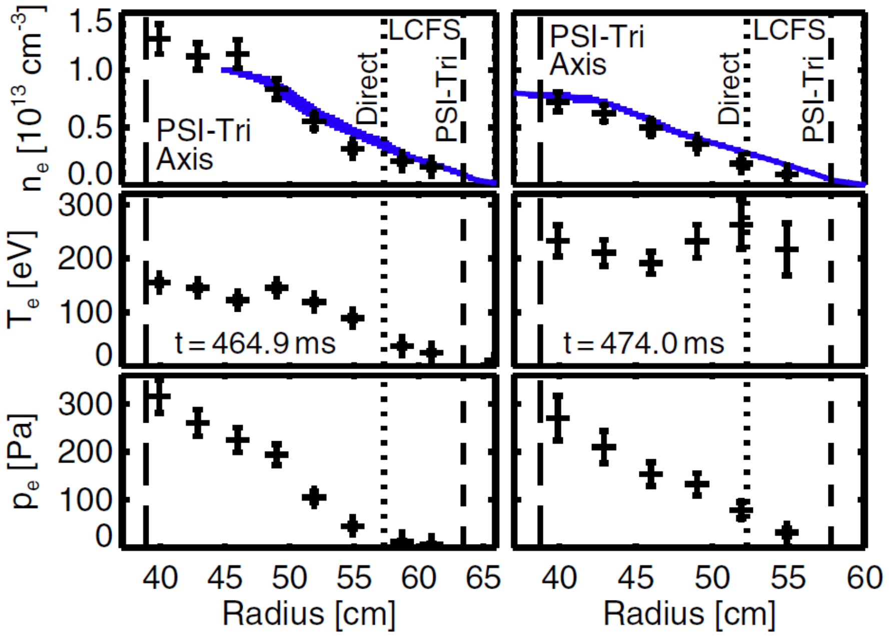


– No Li

– Medium Li coating

– Thick Li coating

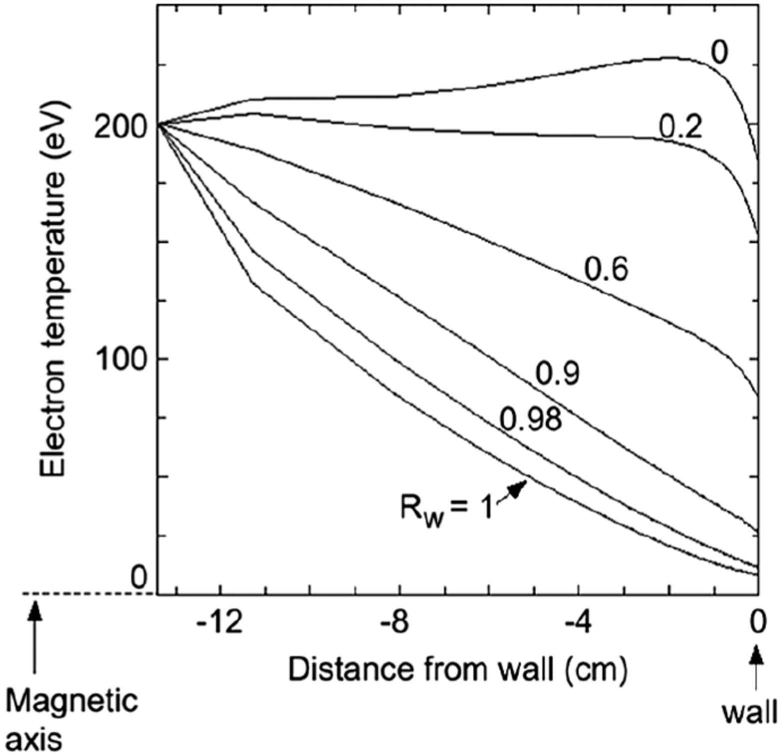
Flat Temperature Profiles Observed on LTX



Thomson scattering n_e, T_e, and P_e profiles during the peak of the gas puff (left) and after fueling ceased (right). The magnetic axes and last closed flux surfaces (LCFS) from PSI-Tri magnetic reconstructions are shown as vertical dashed lines, while the LCFS from direct magnetic measurements are shown as vertical dotted lines. **Reflectometer ne profiles** are overlaid on the TS profiles.

- For a couple decades, now, the prevailing understanding of low recycling regime is that the temperature profiles should flatten out
  - Should be flat all the way out to the wall
- Never comprehensively observed until recently in LTX
- 60% of the hydrogen retained in the liquid metal walls
  - About a R = 0.4
- Density profiles slightly lower but also smooth out as expected.

T_e profiles from UEDGE simulations as function of wall recycling coefficient R_w (ratio of incoming wall neutrals to outgoing plasma ions). Core T_e and n_e were held fixed at 200 eV and 5×10^{19} m^{-3}.



Consequences of lithium

- Advanatges
  - Increased confinement time
    - Seen across the world
  - Higher temperatures and flattening of profiles
  - ELM suppression
  - Density con troll possible
  - Lower Z_{eff} (initially)
- Disadvantages
  - Fuel retention
  - Helium pumping
  - Power handling (?)
  - Potential impurity accumulation increases radiated power and Z_{eff}

Overview:

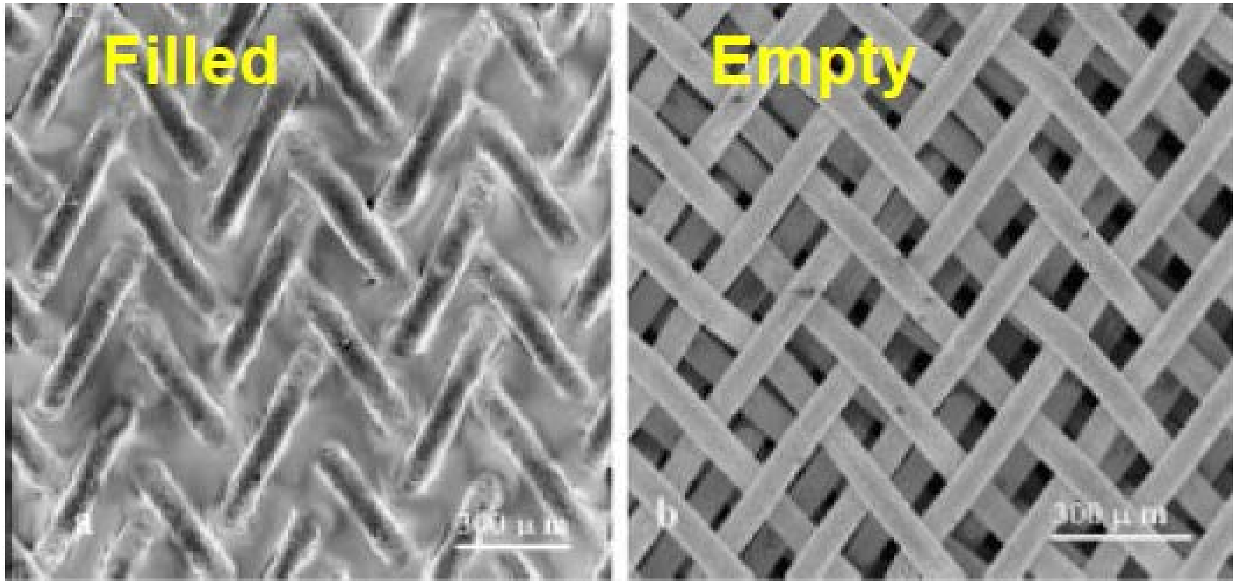
- Materials Challenges – Beyond ITER
- Materials Needs
- Liquid Metals and their Properties
- Plasma Response to Low-Recycling Liquid Metals
- Flowing Liquid Metal PFC Technologies
- Fuel Loss and Retention
- Liquid Metal PFC Experiments
- Summary

So How can Flowing Li be Utilized? Low Recycling, Heat Flux Handling?

- Lithium melts at 180 ^{o}C and evaporates at 400 ^{o}C
  - So, will have to ultimately be a flowing liquid system
- A liquid metal is a conductor and subject to MHD effects
- All fusion devices have large currents and magnetic fields
  - Can this be utilized in some way?
  - Careful planning is needed
- Low density, half of water, but a high surface tension, 4 times that of water. Difficult to deal with
- Highly corrosive with some materials
  - Careful engineering needed
  - Fortunately SS, W, Mo are compatible with Li.

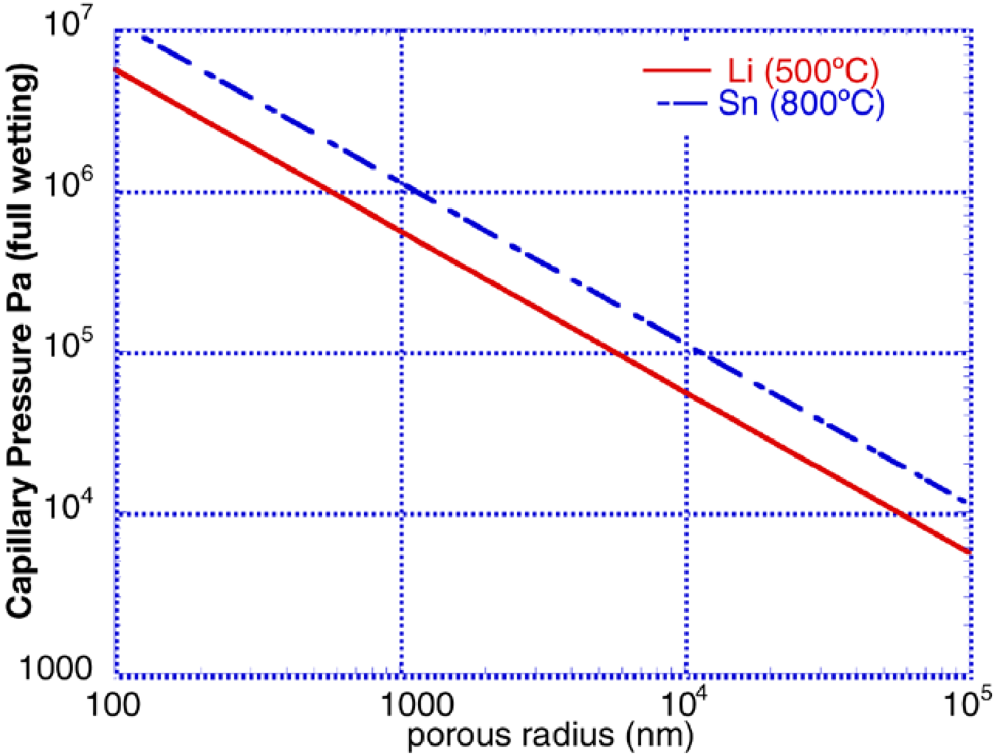
CPS (Capillary Porous System) Concept

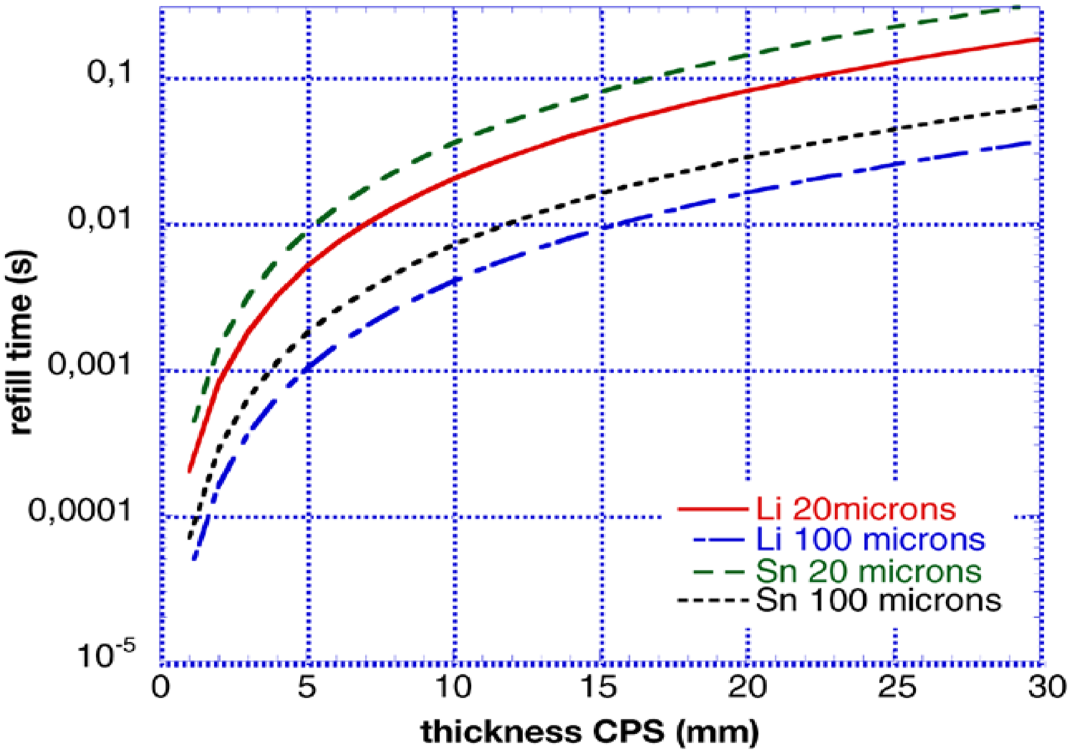
- LM can be confined in a porous metallic mesh due to surface tension forces (capillarity)
- The CPS structure would basically act as a sponge for the Liquid Metal
- Solution to avoid MHD induced instabilities (splashing, dropping…) in the liquid
- Firstly developed by Russian teams in molybdenum mesh



CPS Essential Requirements

- Porous size must be in the range of microns for suitable capillarity and refilling of liquid surface (protection of substrate) after LM evaporation





CPS Essential Requirements

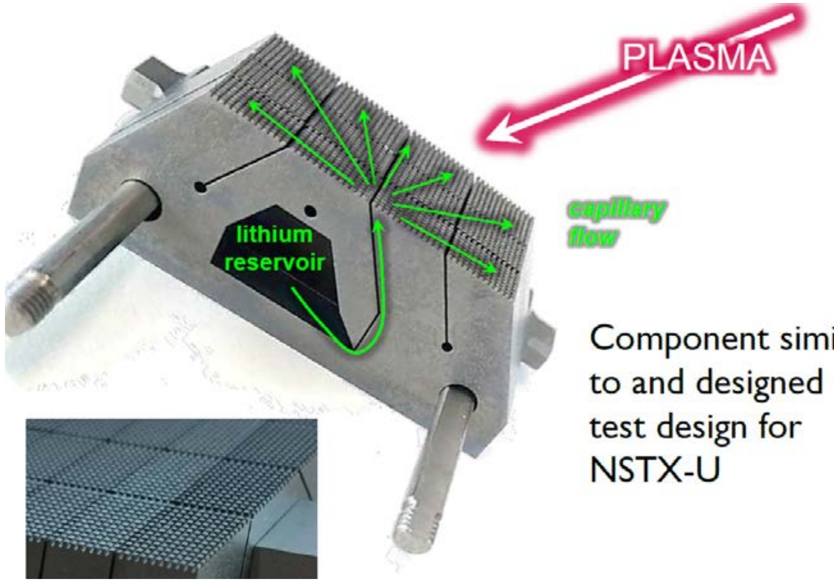
- Wetting characteristics of the LM on the mesh to guarantee the capillarity effect
  - It is strongly dependent on substrate temperature, and impurity presence on mesh surface (mainly oxides).
  - Especially important in the case of Tin (normally requires wetting temperatures beyond 1000°C)
  - Good previous chemical etching on porous mesh is generally required
- Compatibility of mesh material and LM is a concern. LM are generally quite corrosive.
  - In practice these constrains reduce the number of suitable LM to: Lithium, Tin and Lithium-Tin alloy
  - Lithium present problems with copper but SS, Mo and W are in principle compatible. Tin is extremely corrosive with SS but compatible with Mo and W

CPS Experimental Development

- Widely tested both in fusion devices and at laboratory scale
- Li has been the most studied material (limiters in TJ-II stellarator, FTU and T11 Tokamaks…)
- Sn (FTU limiter) and LiSn (CPS fingers in TJ-II stellarator) has been also tested
- Most promising results have obtained with Li
  - Promising confinement improvement and reactor relevant power exhaust capabilities
  - Excessive evaporation and tritium related retention suppose an issue
- Tin presents a wider temperature operational window. Hydrogenic retention much lower than Li
  - wetting and material compatibility constrains
  - plasma contamination (high Z Sn impurities)
- SnLi (eutectic) could combine the benefit of both materials
  - problems of stability (preferential evaporation/sputtering)
  - material compatibility and wetting issues

CPS Future Development

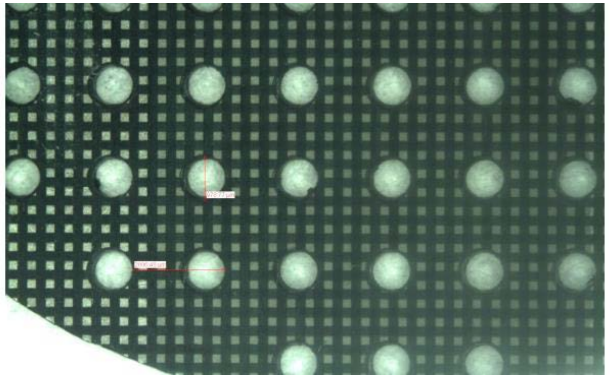
- Liquid Metal Divertor (LMD) task within the EUROfusion consortium
- Development of a LM divertor concept alternative to traditional solid W ITER based design for DEMO
  - Engineering and design activities based on W monoblock solution (ITER) but including CPS and LM structures
  - Rational election of suitable LM and CPS structure solution
  - Investigation of several ideas and concepts are currently underway
  - Simplest solution is to add a surface texturized layer or mesh on the of the W monoblock



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

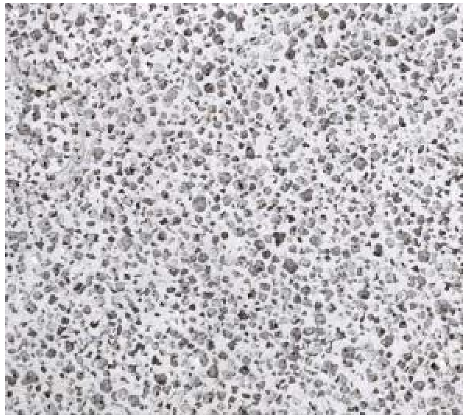
CPS Future Development

- Innovative ideas are emerging. Use of 3D printed, laser and sputtering texturized CPS structures



Laser texturized CPS structures

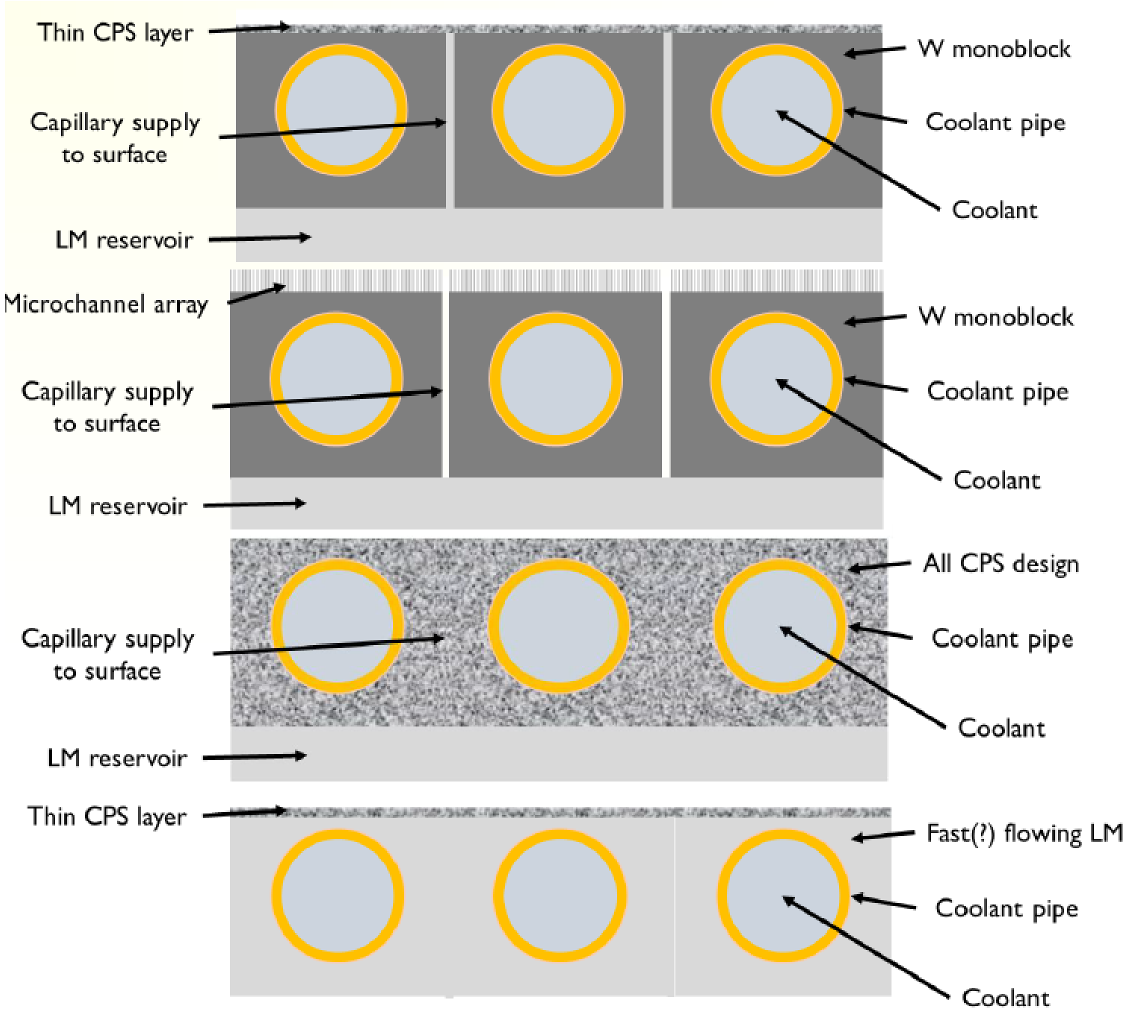
3D printed monoblock prototype



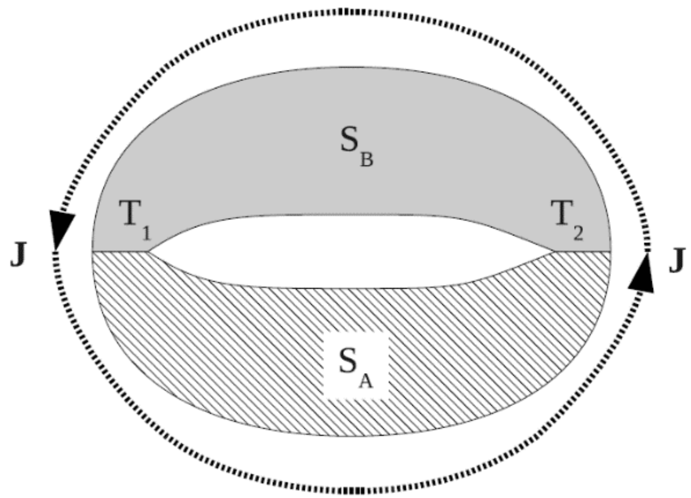
3D printed foam porous structures

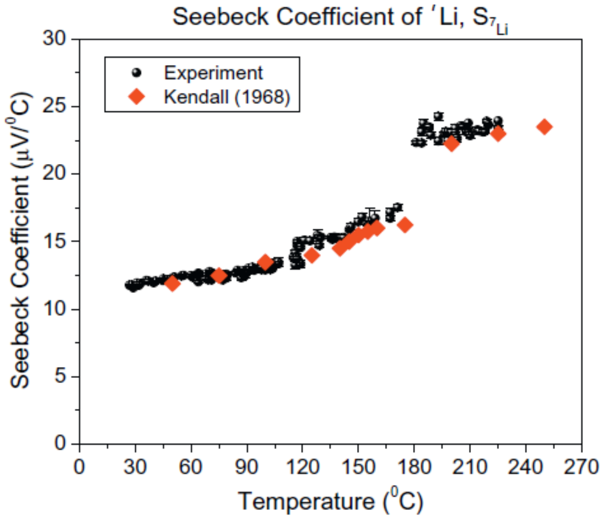
CPS Future Development

- Engineering integration into the W based design to DEMO (Monoblock)
- Several alternatives varying in technologic complexity
- Possible overlapping with flowing liquid PFC schemes
- Critical issues in cooling structures:
  - mechanical stress of cooling pipe materials
  - choice of coolant and heat sinks materials
- CuCrZr most promising for heat sinks
  - intermediate layer (W, Mo)to avoid contact with LM
  - T_{limit}=350°C (mechanical stress failures)

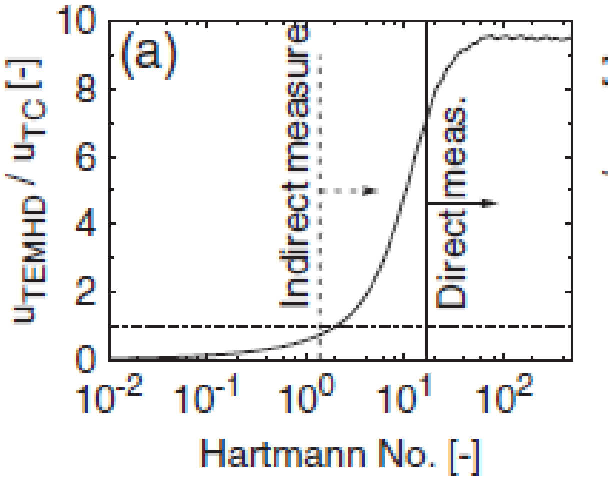


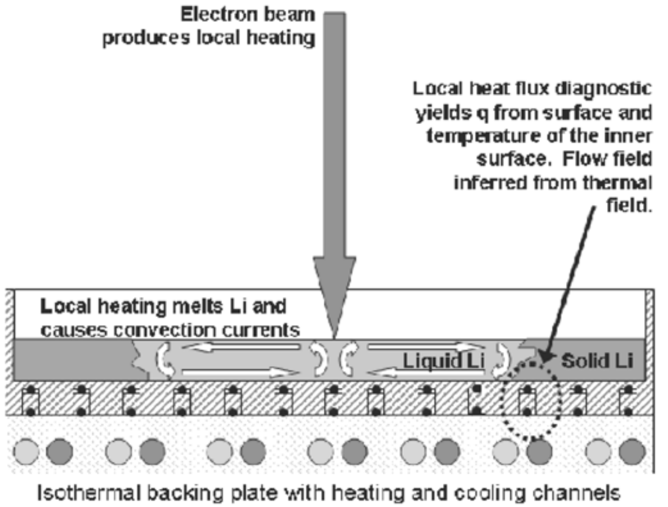
Thermoelectric Mixing of Lithium with an Electron Beam seen on CDX-U





- Thermoelectric effect
  - Causes thermocouple junction voltage
  - Electric field generated by temperature gradient
  - Proportional to Seebeck coefficient ($E=S*\partial T/\partial x$)
  - Requires different material (or TE power) to provide
  - current return path and to
  - generate current
  - Lithium has a high Seebeck coefficient and is beneficial to fusion plasma. (low recycling, improved confinement, flat temperature profile and so on)



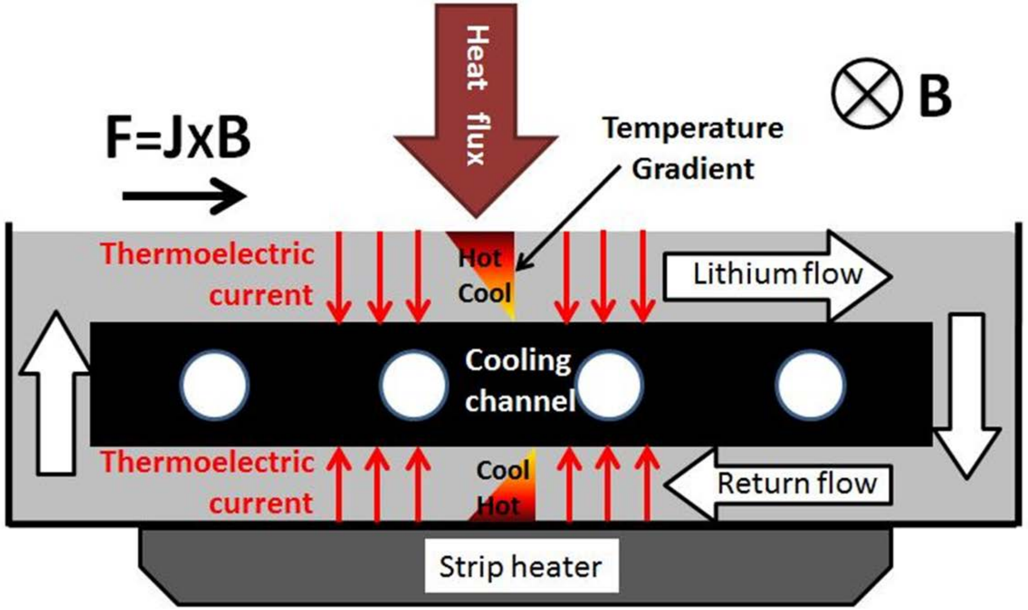


Thermo-electric Magneto-hydro-dynamics (TEMHD) – what can be done with this?

Use What the Plasma Gives You!!!

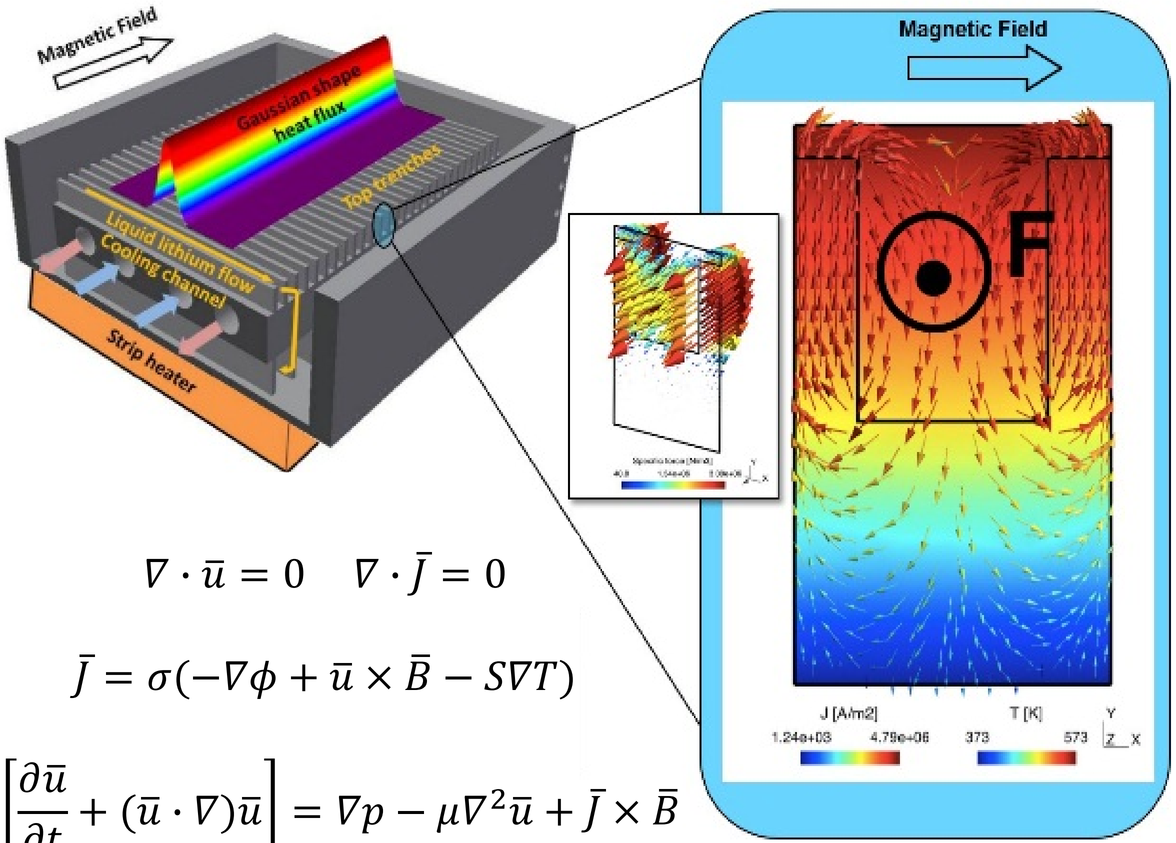
Lithium Metal Infused Trenches (LiMIT)

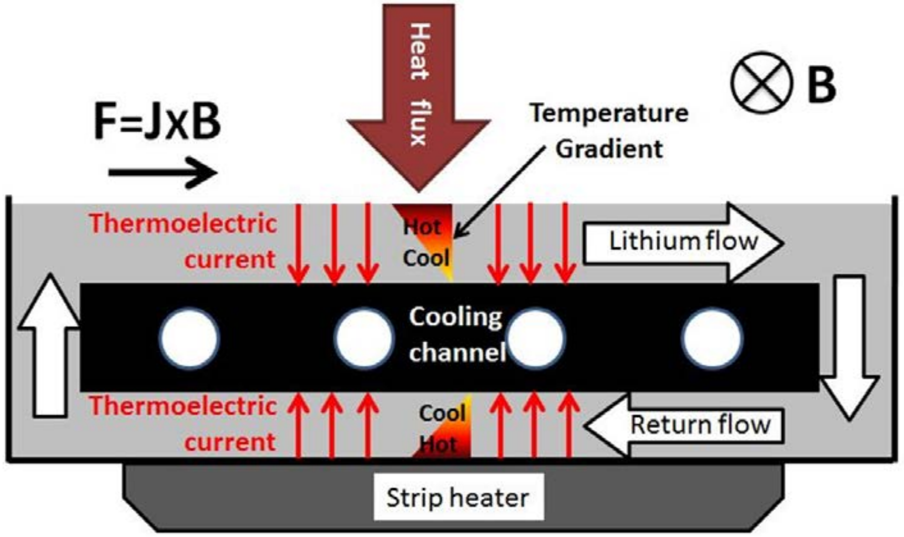
- Concept for heat removal using TEMHD:
  - The Li flows in the slots of the metal plate powered by the vertical temperature gradient.
  - This vertical temperature gradient generates **vertical current**, which when "crossed" by the **toroidal magnetic field**, will create a **radial force on the Li driving it along the slot**.
  - This flow will transfer the heat from the strike point to other portions of the divertor plate.
  - The bulk of the metal plate could be actively cooled for a long-pulsed device or passively. Under the plate the Li flows back naturally.



Liquid Metal Infused Trenches (LiMIT)

- Seebeck Effect creates thermoelectric current at junction between liquid lithium and solid trenches when a thermal gradient is present
- A transverse magnetic field is applied, which generates a ***J***×***B*** force, propelling the liquid through the trenches





$$\nabla \cdot \bar{u} = 0 \quad \nabla \cdot \bar{J} = 0$$

Electric current

$$\bar{J} = \sigma(-\nabla\phi + \bar{u} \times \bar{B} - S\nabla T)$$

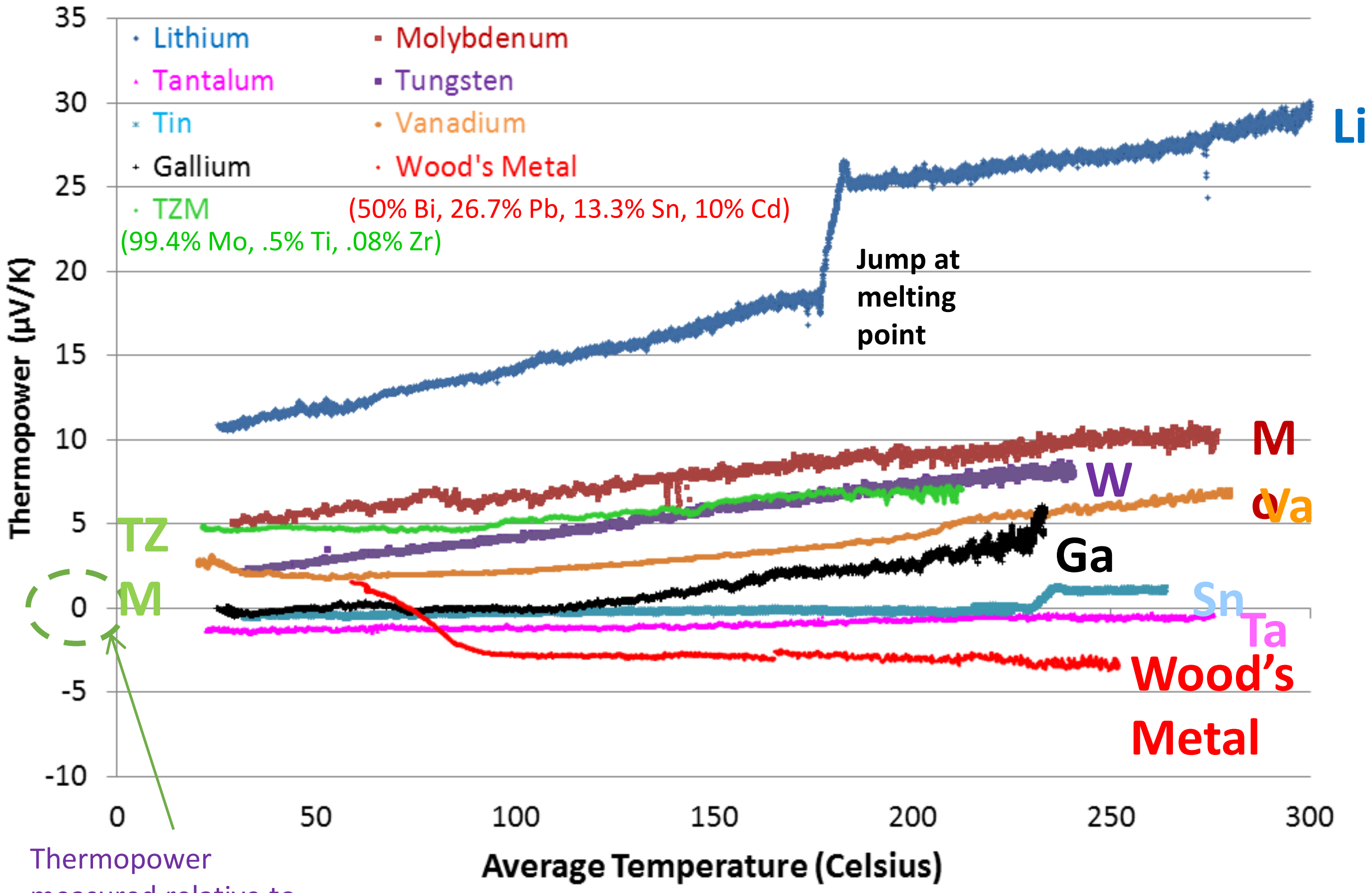
Laminar flow

$$\rho\left[\frac{\partial \bar{u}}{\partial t} + (\bar{u} \cdot \nabla)\bar{u}\right] = \nabla p - \mu\nabla^2\bar{u} + \bar{J} \times \bar{B}$$

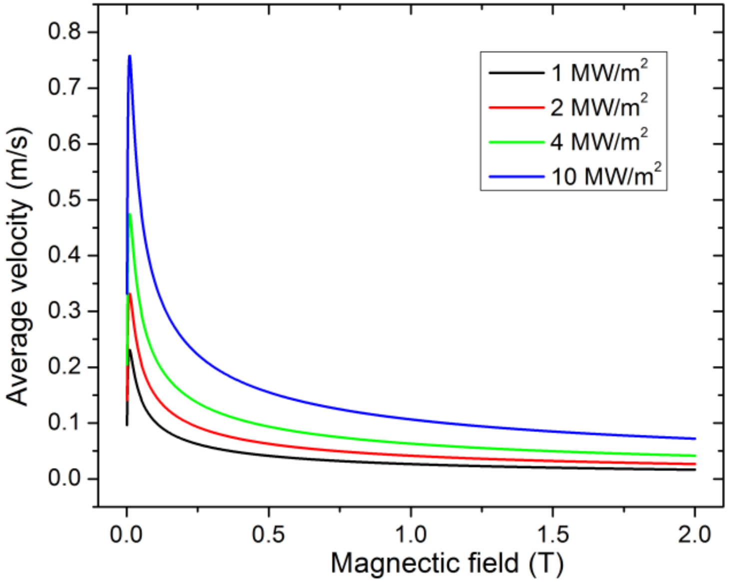
Heat transfer

$$\rho C_P\left(\frac{\partial T}{\partial t} + \bar{u} \cdot \nabla T\right) = \nabla \cdot (k\nabla T)$$

Flowing Lithium in the LiMIT Trenches

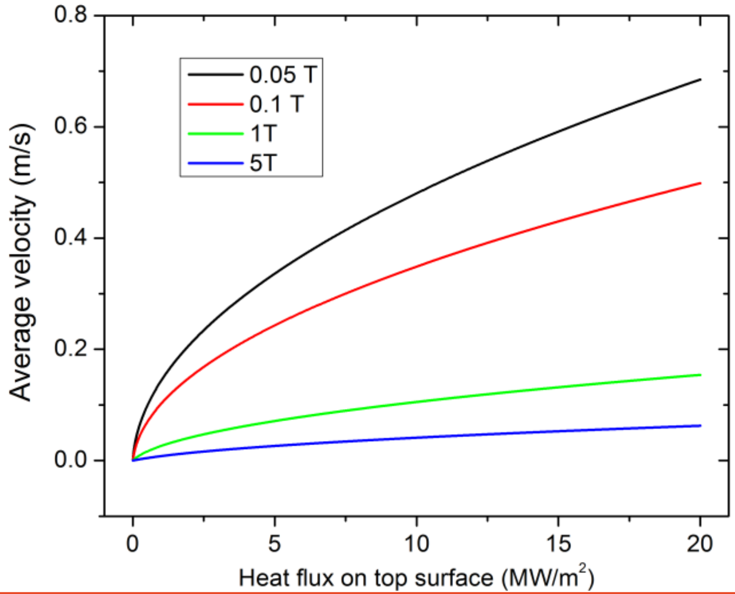


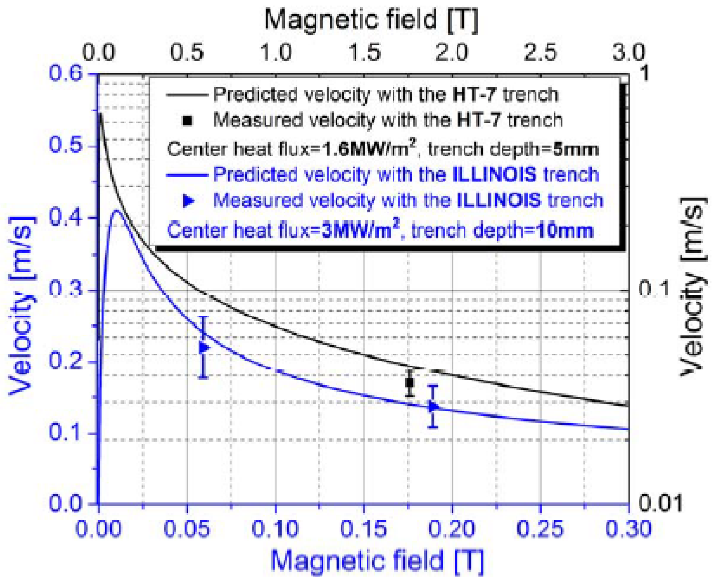
Thermopower measured relative to **stainless steel**

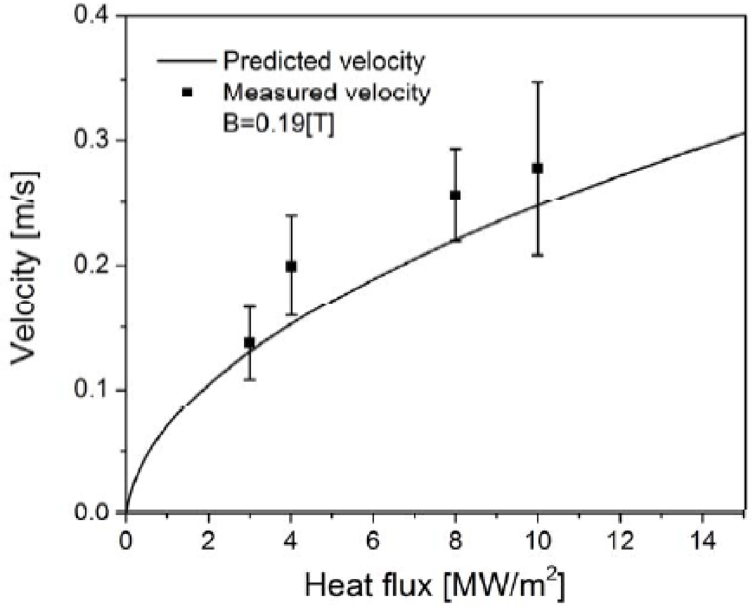


Flow Velocity Results

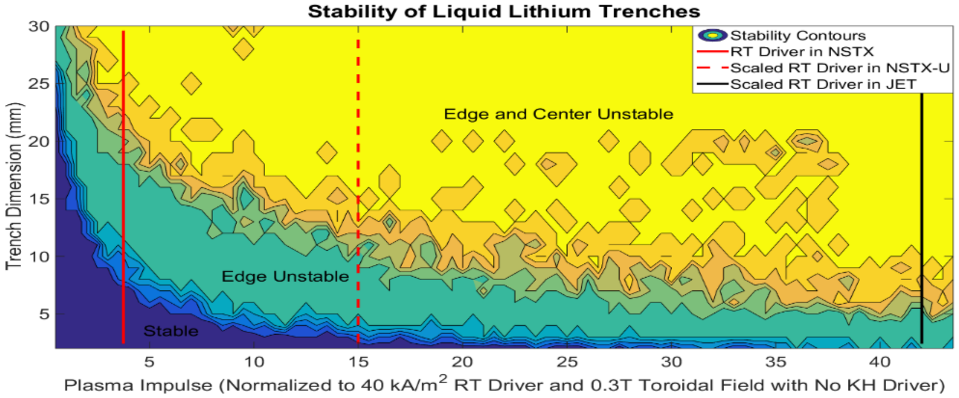
- The first plot shows the velocity at *B* = 0.059 T and *B* = 0.19T for the same heat flux of 3MW/m^2
- The velocity at high field is smaller (0.13 m/s) than the velocity at lower magnetic field (0.22 m/s)
- The second plot shows velocities at higher heat fluxes
- The measured velocity is compared with the 1D model.
- The model also predicts
  - V = 0.053 m/s at B = 1.0 T
  - V = 0.035 m/s at B = 2.0 T
- Which means that lithium can flow across half of the trench length within 1 second even in a magnetic field as strong as fusion reactor magnetic fields.

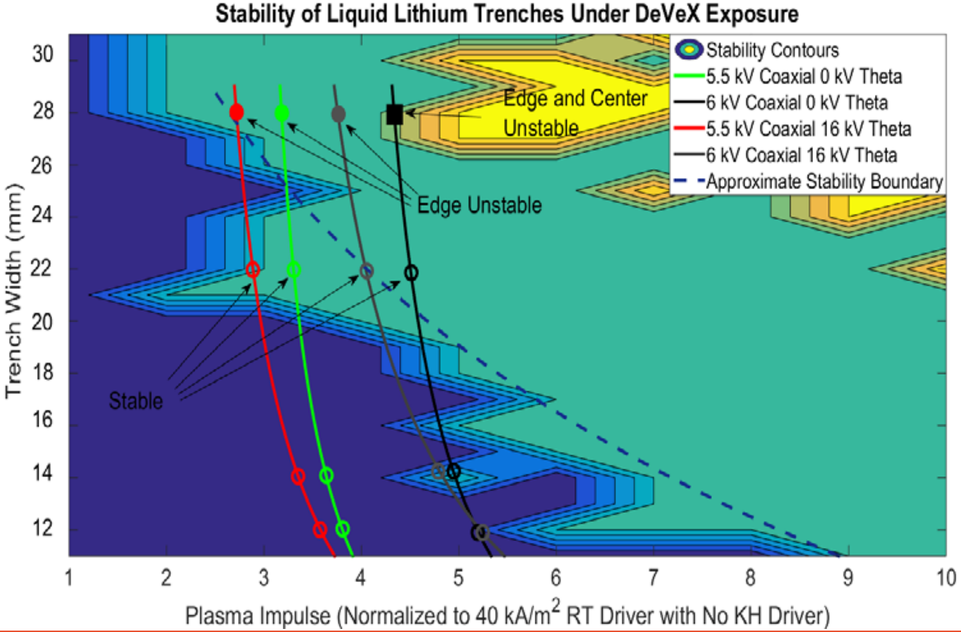






Can Design to Eliminate Droplet Emission

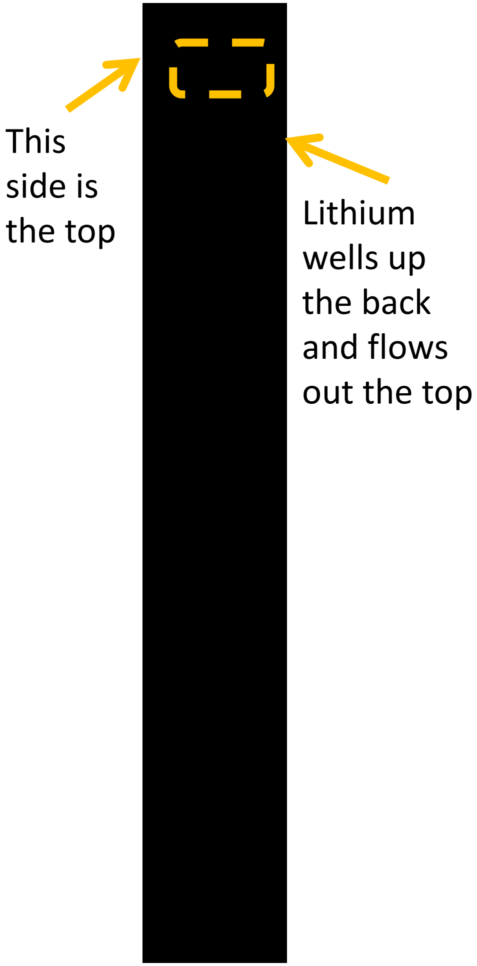


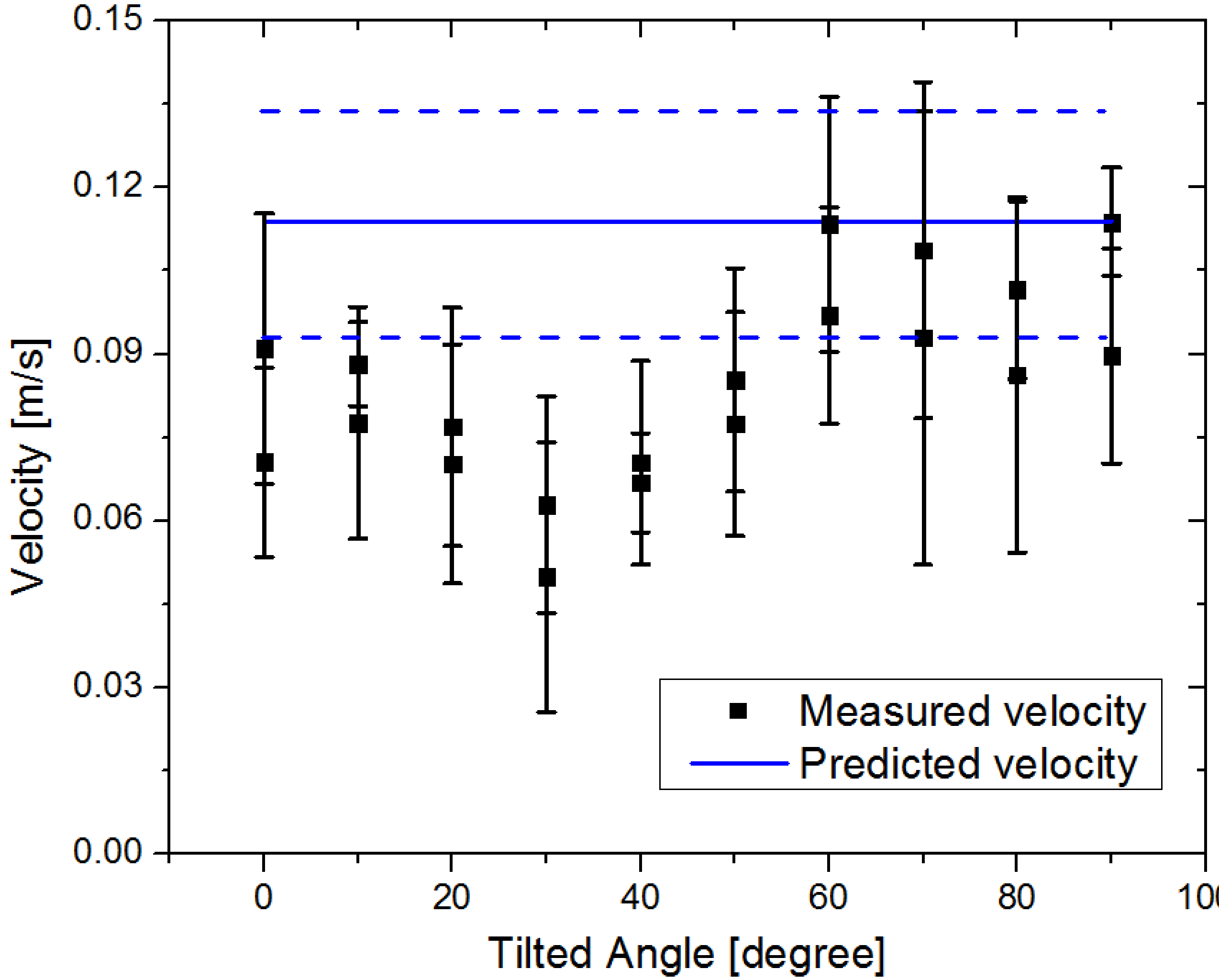


- Experiments determined which size trenches were unstable to being hit by ELMS and why droplets are sometimes expelled

180 degree chamber rotation, TEMHD flow at different angles

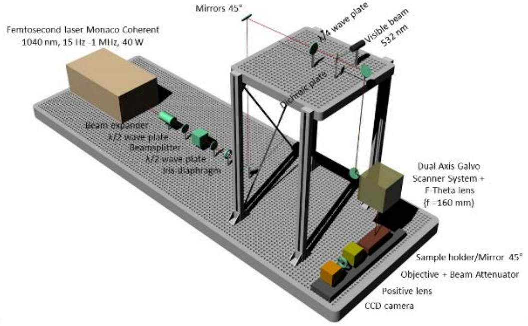
- Sustained flow demonstrated at arbitrary angle from horizontal (0 to 180 degrees)

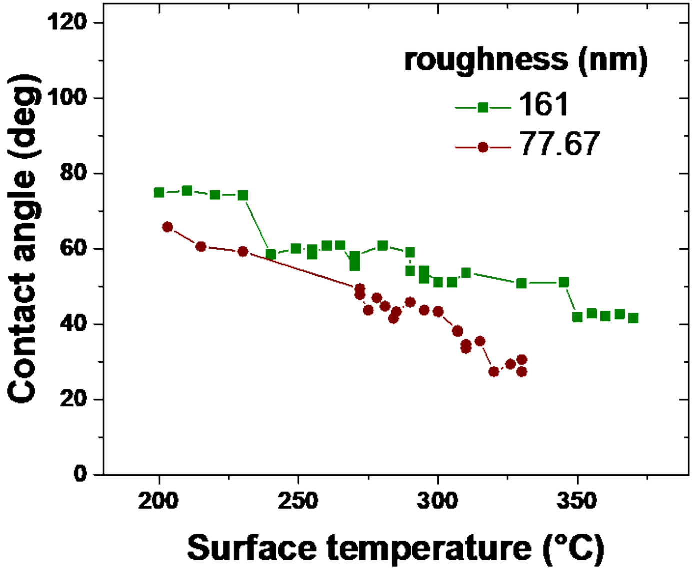




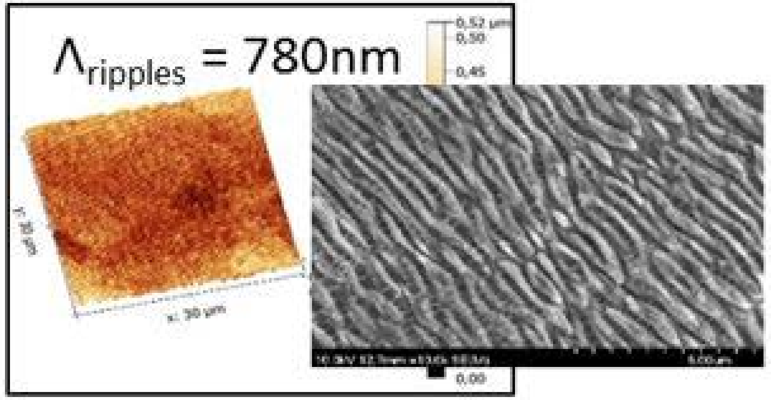
Texturing of surfaces can aid or prevent wetting

- Using a femtosecond laser creates a nano-texture which prevents wetting.
- Mirror-polishing the surface makes wetting much easier.

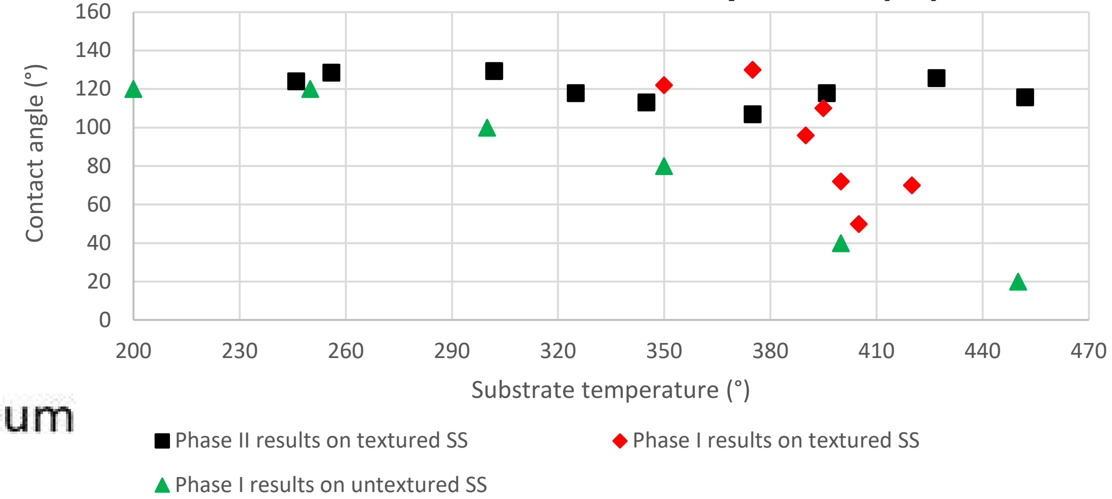




Coherent Femtosecond Laser

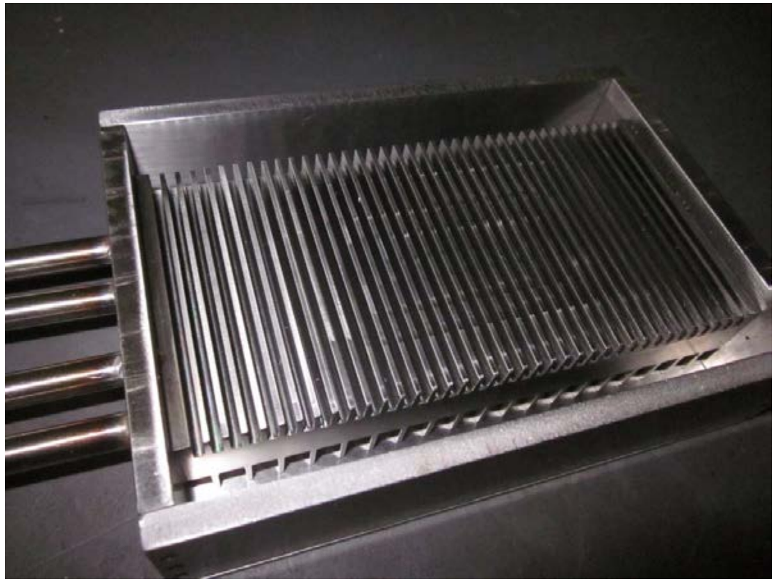


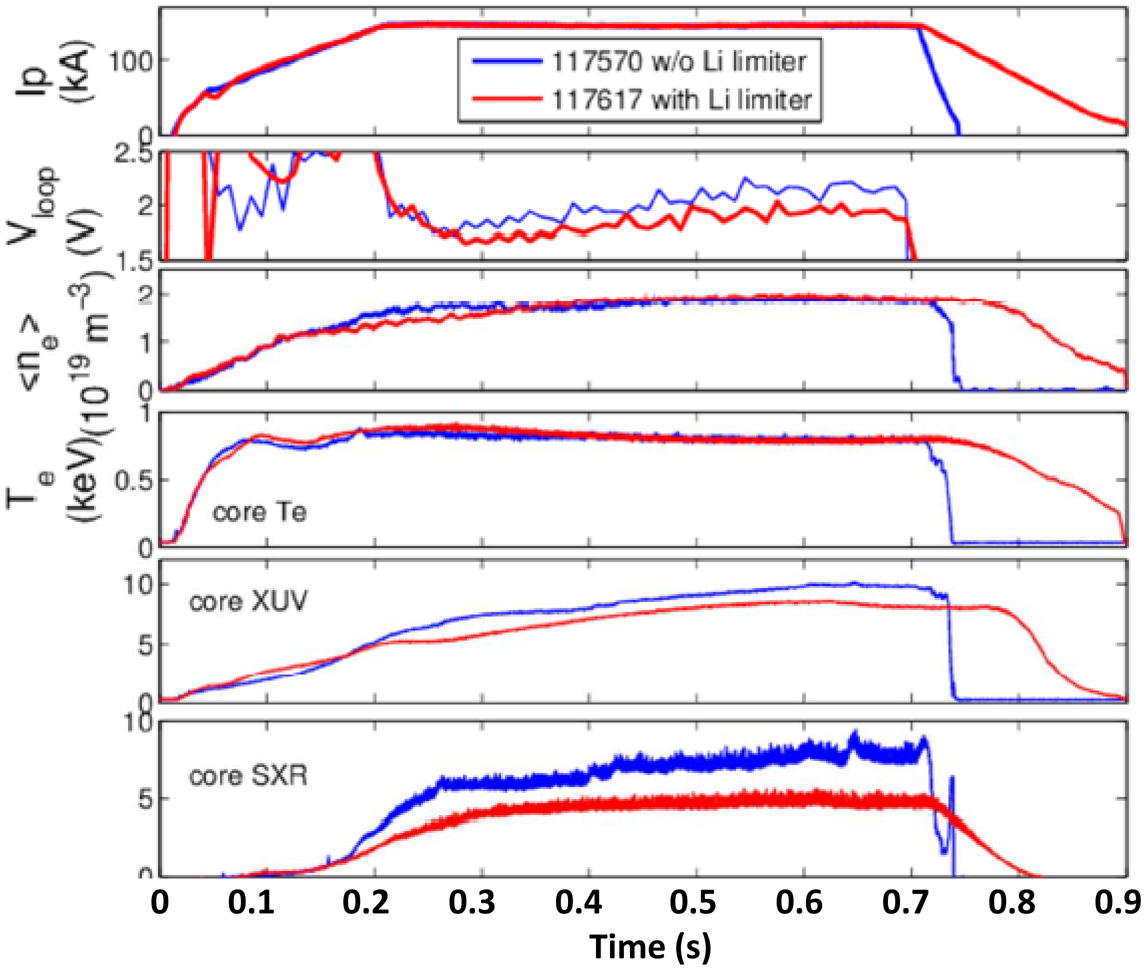
F=0.38J.cm^{-2} and N=200, Δ_x=Δ_y=50um



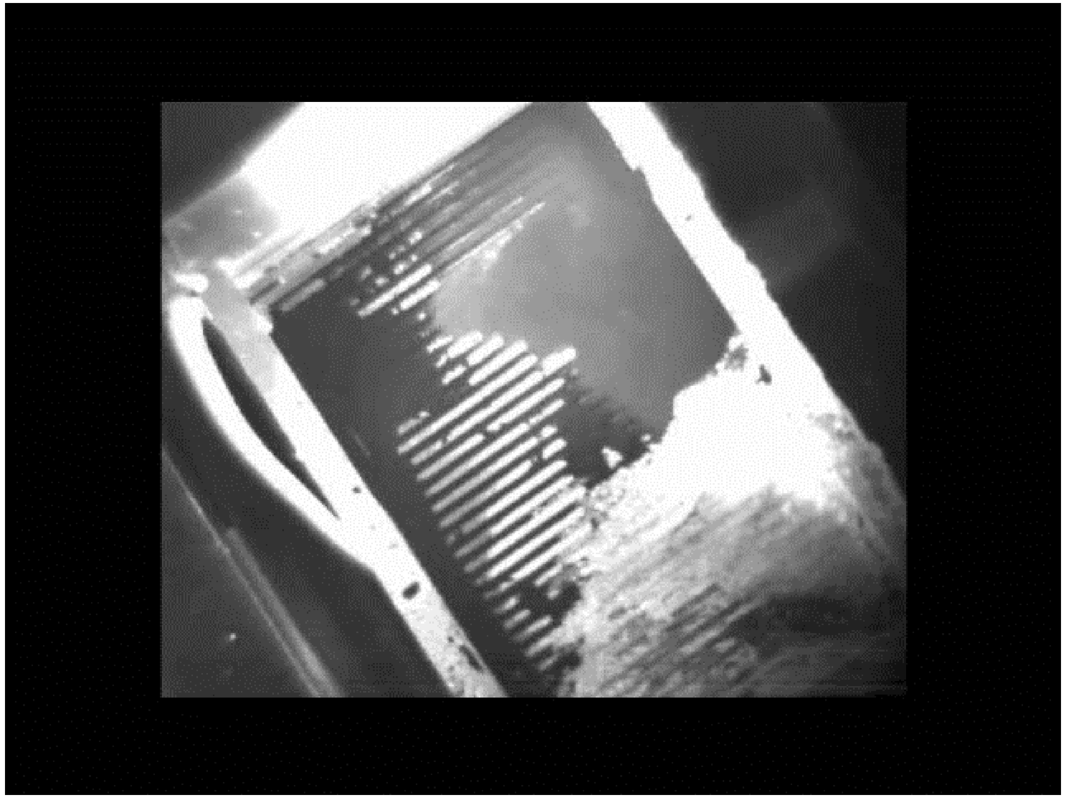
HT-7, First Shots with a LiMIT Limiter - Comparison

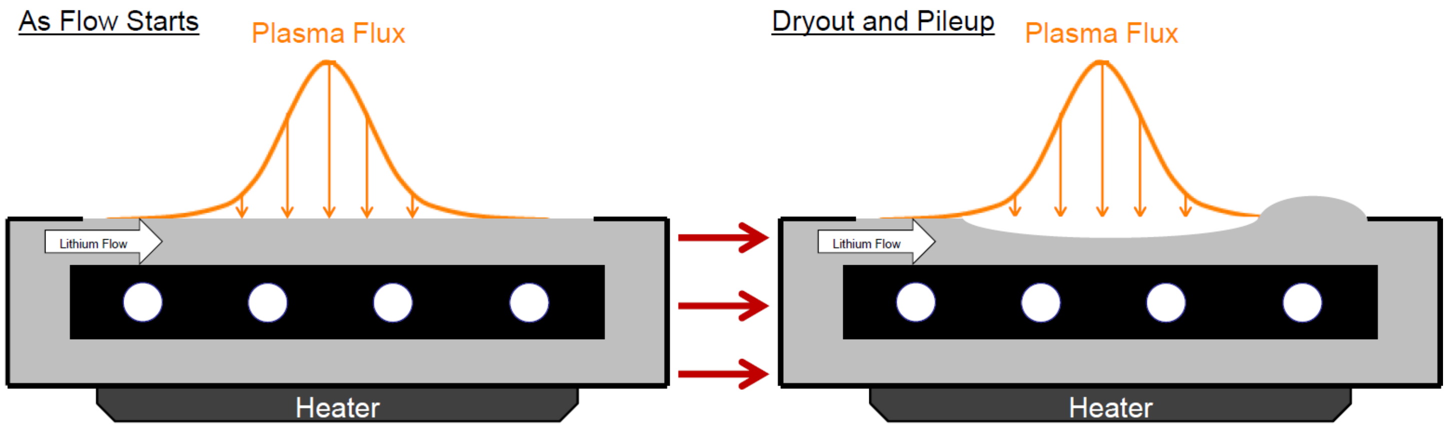
- n_e and T_e profiles are similar.
  - **The confinement increase ~10% with UIUC LiMIT limiter** due to the decrease in radiation
- This result is for LiMIT positioned 2 cm outside the last closed flux surface.
  - **Greater improvement expected** as it is moved closer !





Dry out will be an issue that needs to be solved

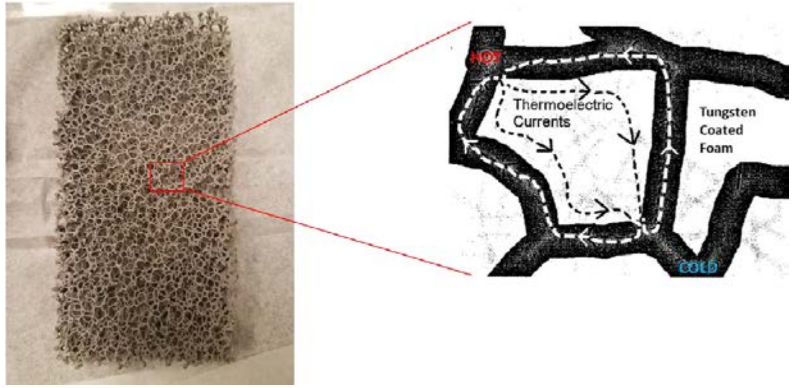


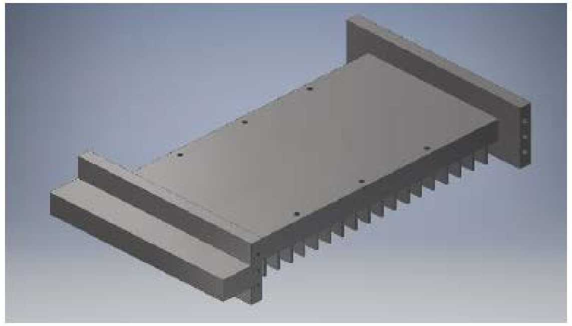


- As plasma flux impinges on the surface of the lithium, the lithium is locally accelerated where the plasma flux is greatest, leading to depression of the lithium surface and pileup of lithium downstream
- This causes the top of the trenches to become exposed which could lead to overheating of the LiMIT module

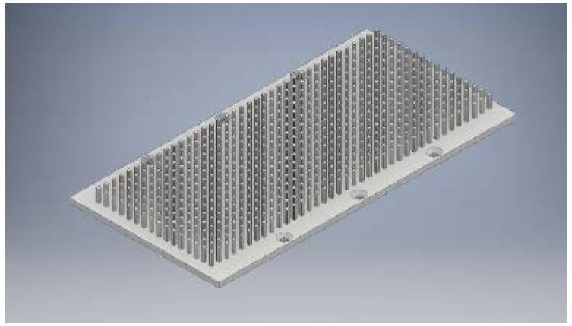
Could LiMIT be used in DEMO? Yes(?)

- The key is to keep a fresh surface of lithium facing the plasma. The speed of the lithium is not important – as long as it is not zero – this is the solution to the technology problem. Then the low-recycling is preserved and can be used to enable more economical plasma regimes which have higher confinement, more stability and higher power density.
- Flowing lithium suggests a new approach for the T recovery.
- The surface temperature can be limited to below 400 ^{o}C on the divertor face if the thickness of lithium layer is thin and the heat removal below it is large. Consider a thin film of lithium propelled by TEMHD using shallow LIMIT trenches.
- Eutectics containing lithium could also be driven using this effect, broadening the allowable temperature range.
- The use of lithium as a high-heat-flux PFC should not be ruled out.

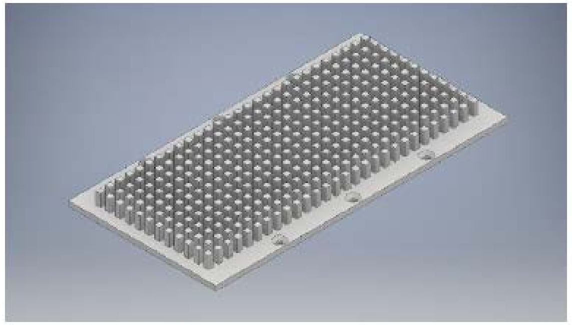




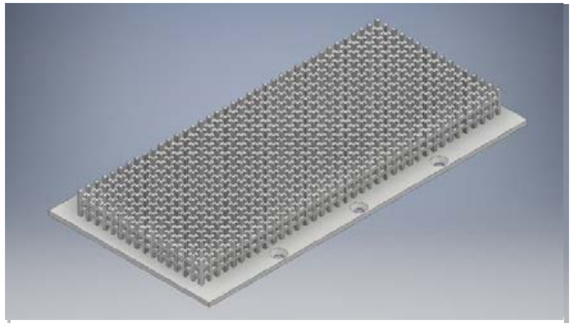
Base Module



1x1mm Posts – 2mm Separation



2x2mm Posts – 2mm Separation



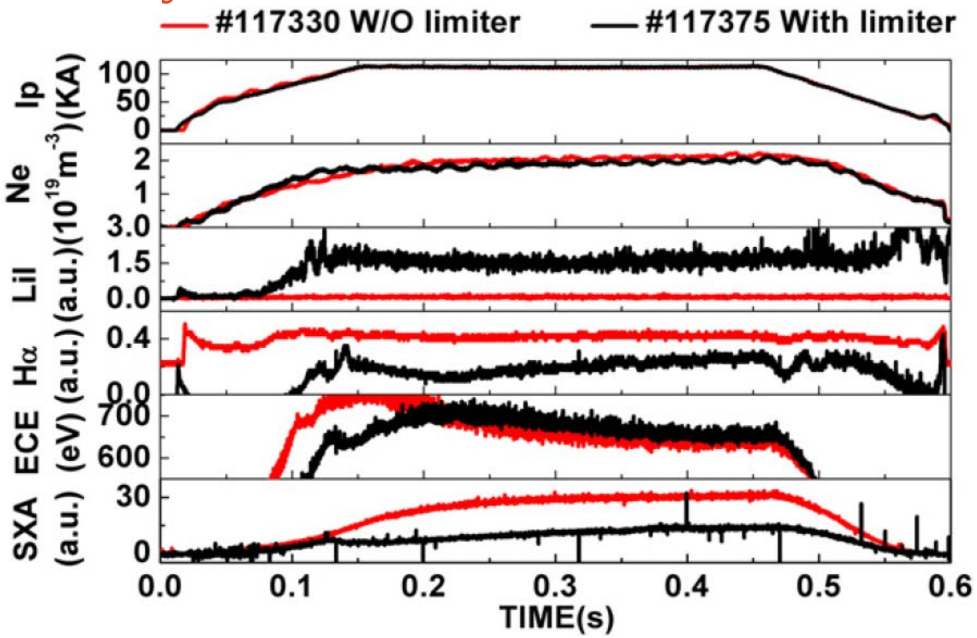
1mm wires – 2 mm Openings

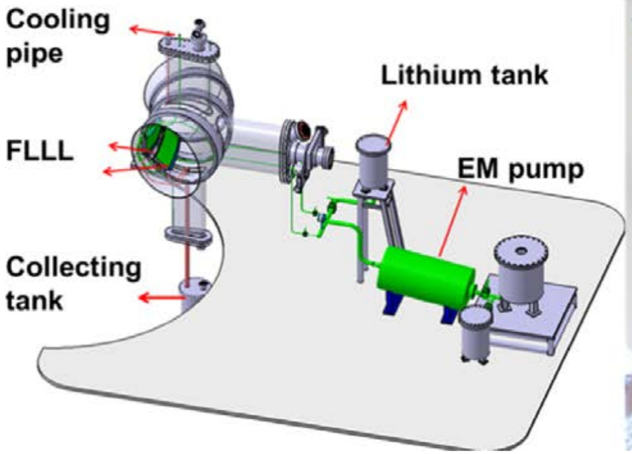
Dual trench structures produce "posts" for mitigating dryout – cross talk

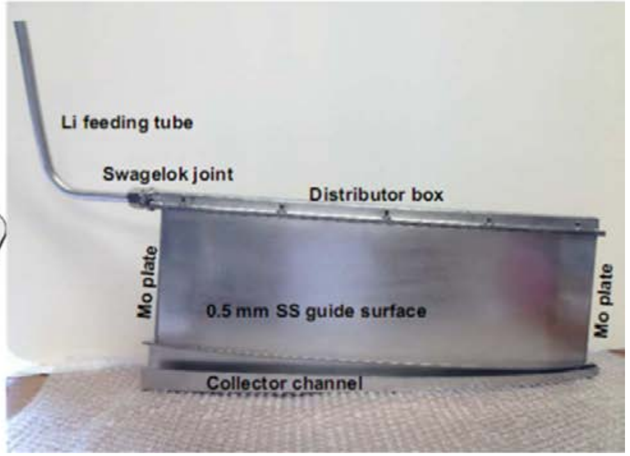
J. Ren et al., Phys. Scr. T159 (2014) 014033

Flowing Liquid Lithium (FLiLi) Limiter

- FLiLi is a gravity based flowing lithium system
- Lithium flows down a flat plate. A distribution and collection reservoir keep the lithium circulating
  - MHD pump used for circulation
- First experiments were performed on HT-7 on its last run day
  -

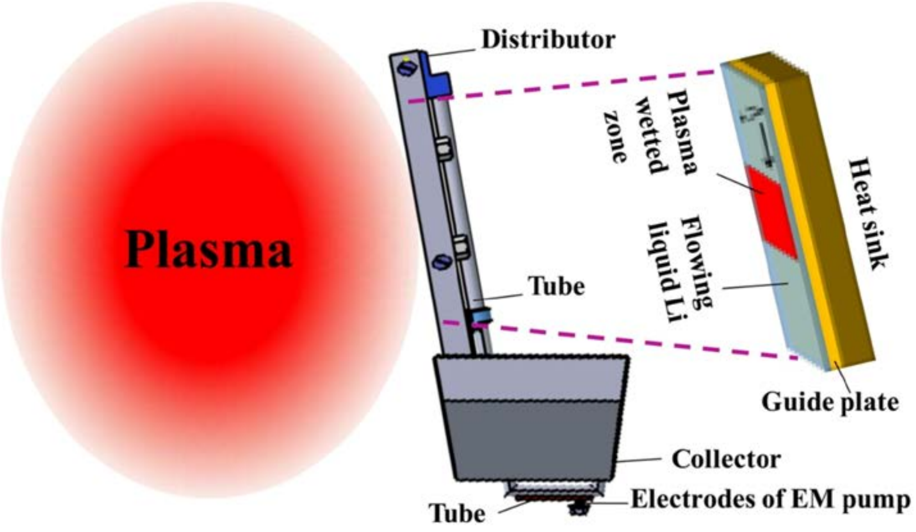




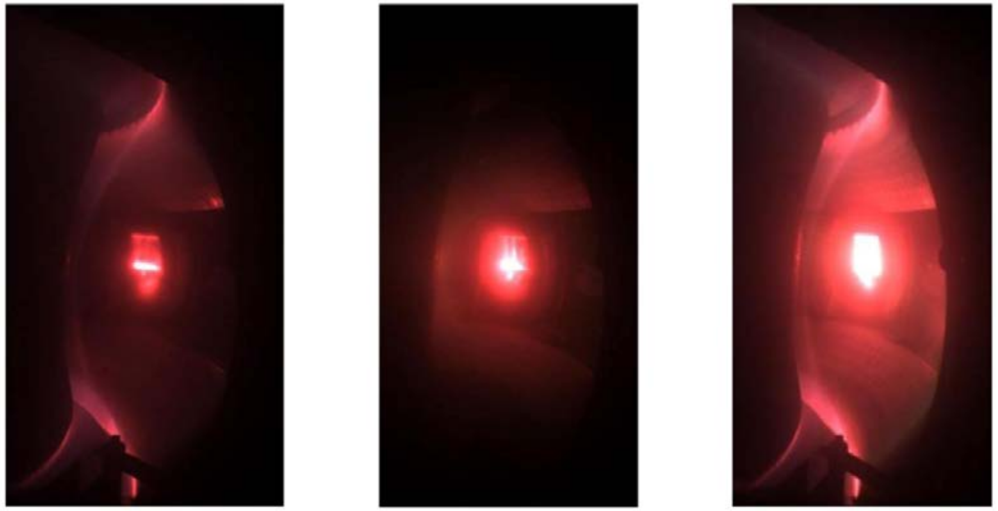


FLiLi is now being used on EAST routinely - In its Third Generation of development

- With HT-7 now shutdown, EAST has taken on the Lithium research.
  - The FLiLi plates are now coming up to their third generation
    - Gen 1 – 1 mm SS explosively bonded to copper
    - Gen 2 – 2 mm SS explosively bonded to copper
    - Gen 3 – Molybdenum
  - Future generations
    - Tungsten
    - LiMIT, Mo, W and additive engineering

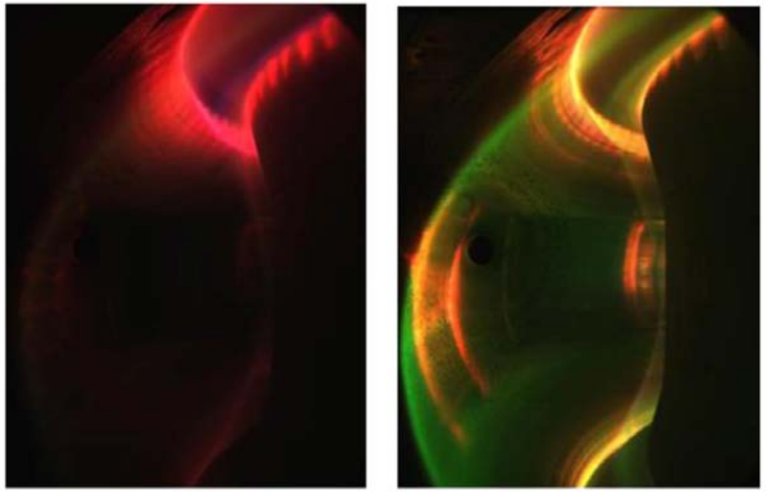


Liquid Metal PFC Experiments - EAST



(a) (b) (c)

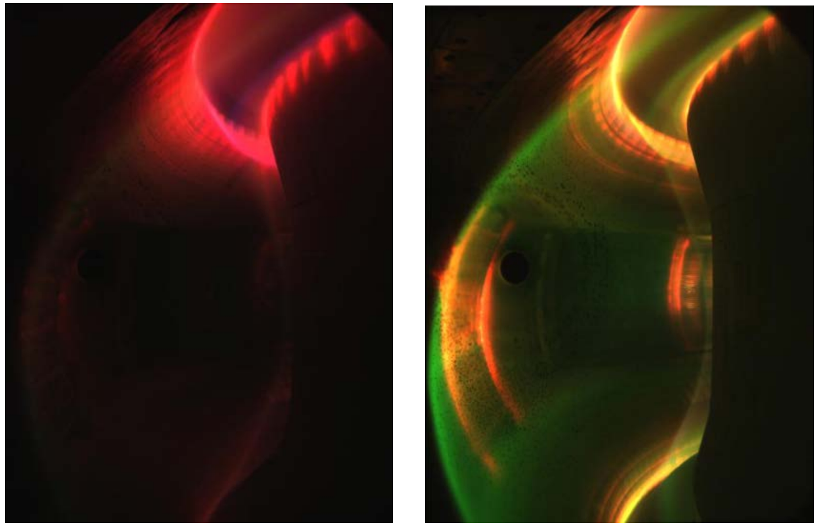
- Li Flow on the surface of SS guide plate:
  a) without DC current, at the ramp up phase of plasma at 0.2 s;
  b) with 20 A DC current, at the ramp up phase of plasmas at 0.2 s;
  c) with 20 A DC current, at the flat-top phase at 2.75 s.
- Li ionized and transported at edge in plasma during the 2016 experiment of the 2nd flowing liquid Li limiter.



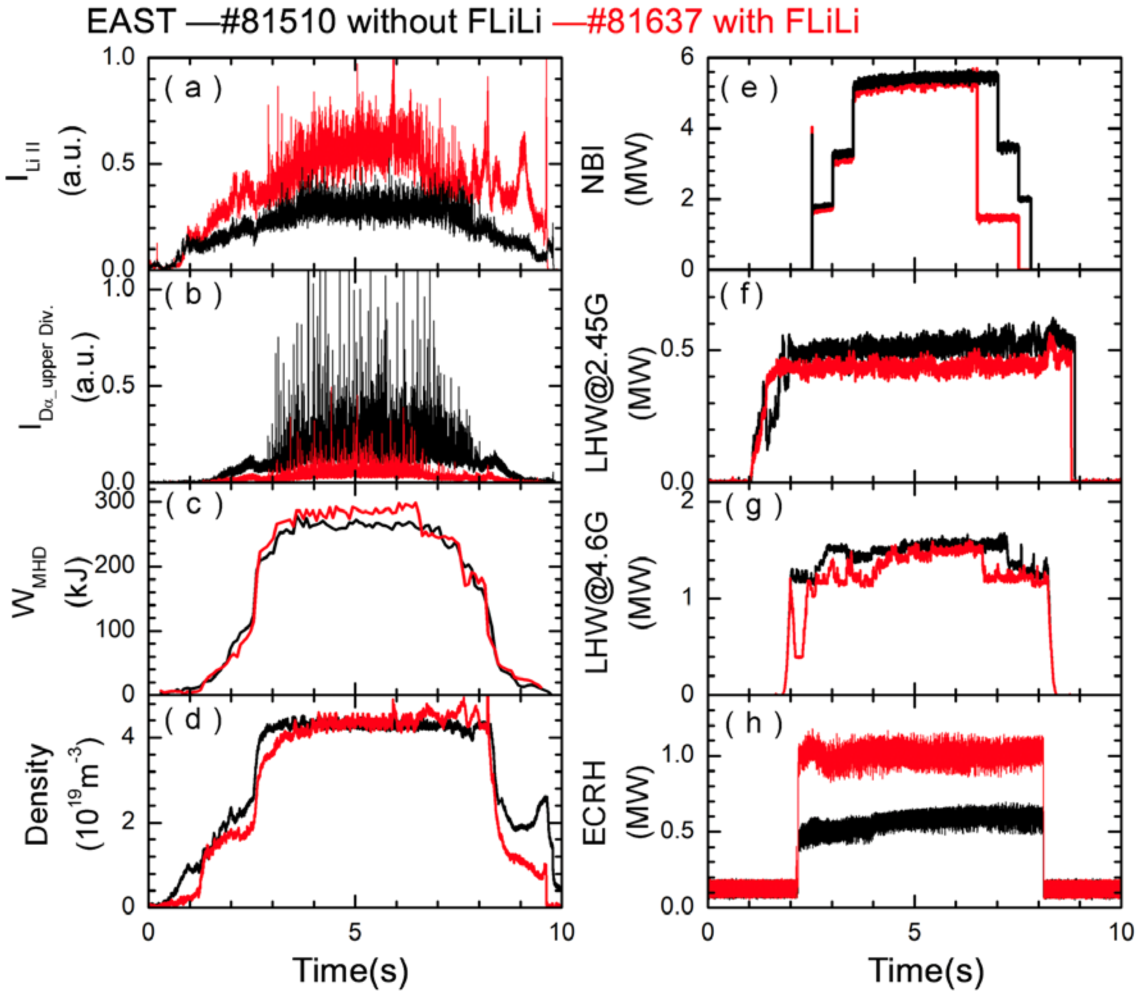
Without FLiLi With FLiLi

Operation of flowing liquid lithium limiter in EAST shows improvement in plasma performance

- Experiment in Aug. 2018 exposed FLiLi limiter to EAST plasmas with P_{aux} = 8.3 MW
  - Initial results show ELMs being suppressed and about a 15 - 20% increase in stored plasma energy
  - Detailed analysis still in progress

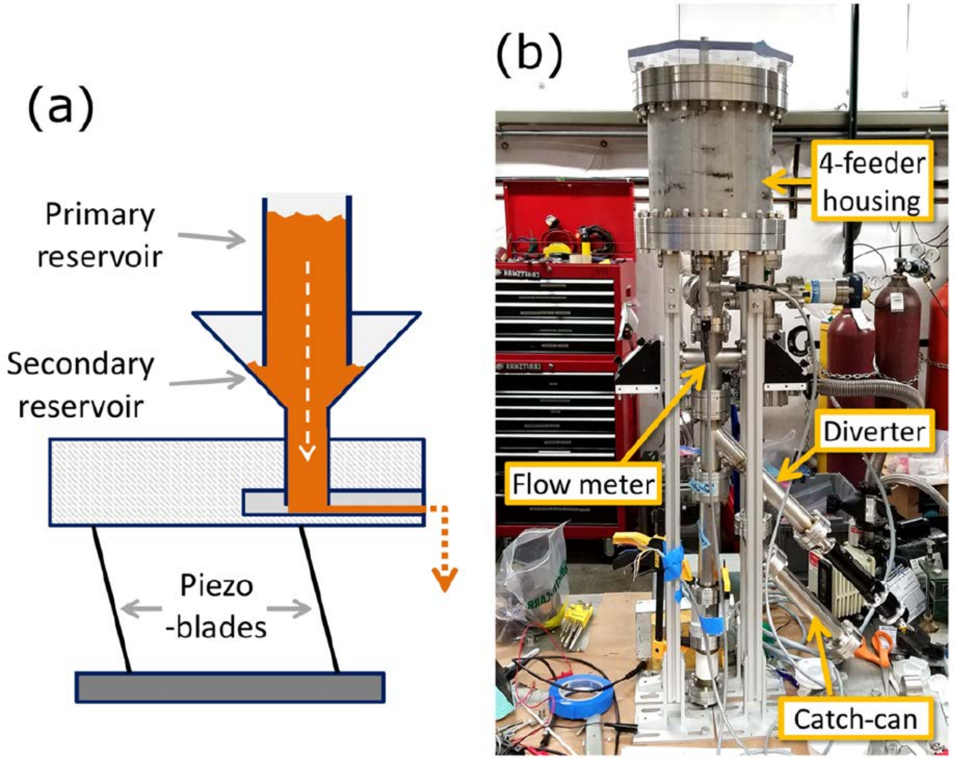


Without FLiLi With FLiLi

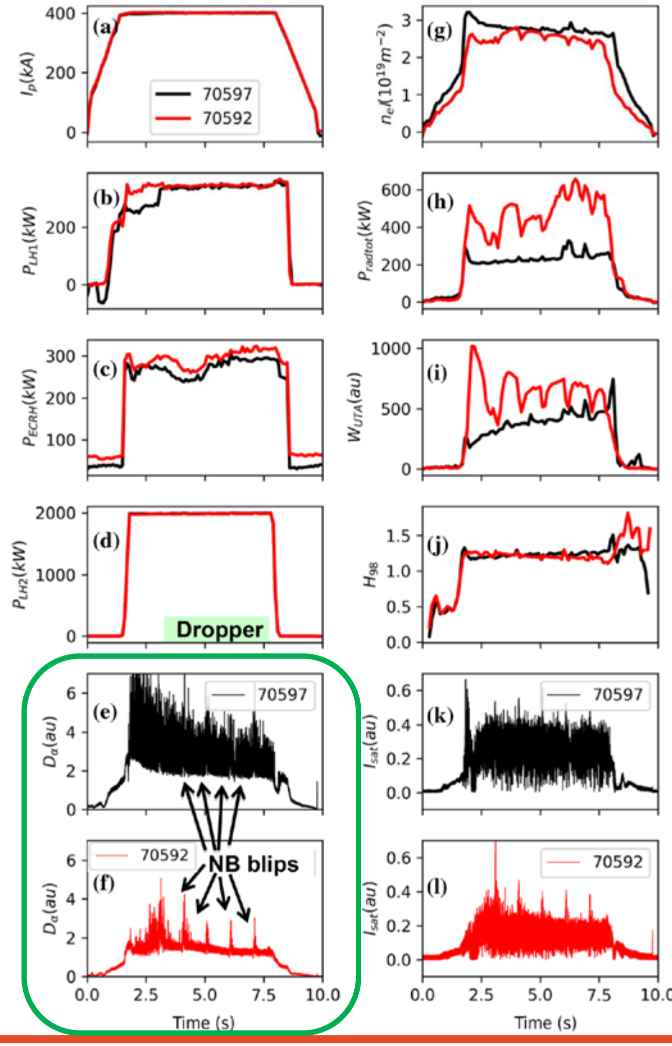


Alternate Concepts – Powder Dropper

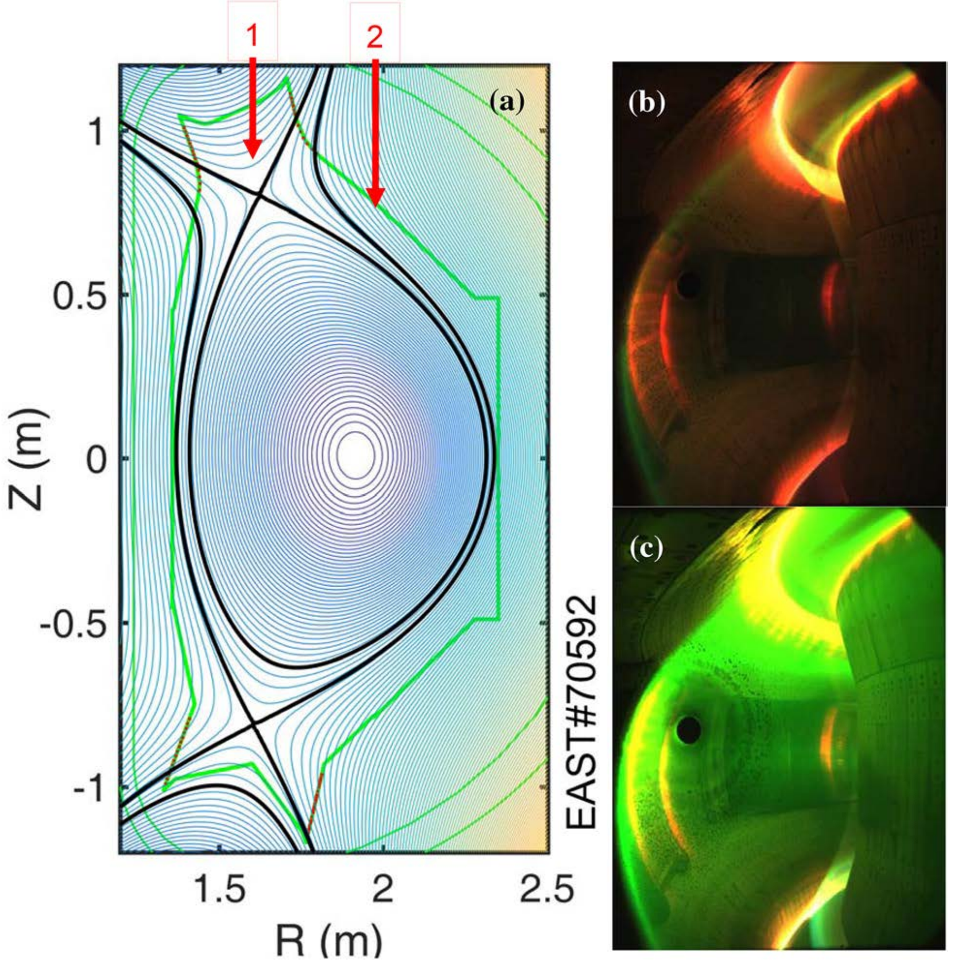
- Dropper can be used to "shake" lithium powder into the plasma.
- Dust is ablated as it interacts with plasma and lithium is distributed throughout the machine
- A way to coat the walls
  - Also a direct way to interact with the edge plasma
  - Impurity removal and instability suppression

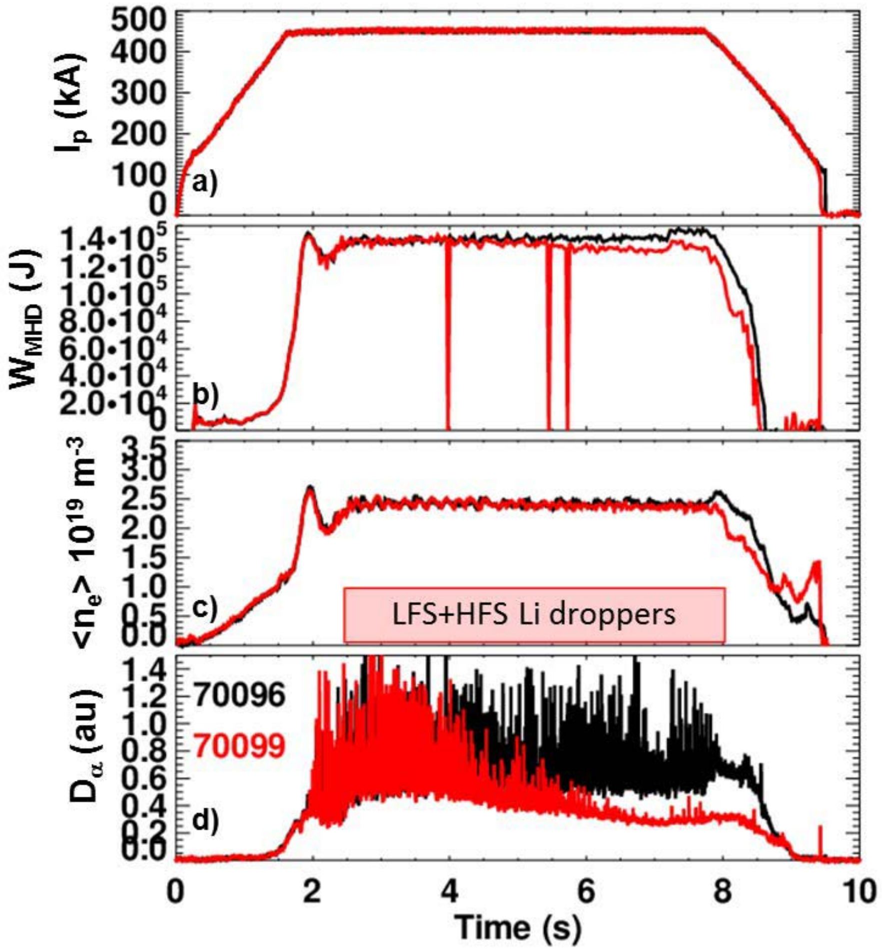


(a) Schematic longitudinal cross section of a powder feeder illustrating the flow of powder from the primary reservoir to the secondary and trough. (b) Impurity powder dropper assembly on the test-bench, for vacuum testing before installation.



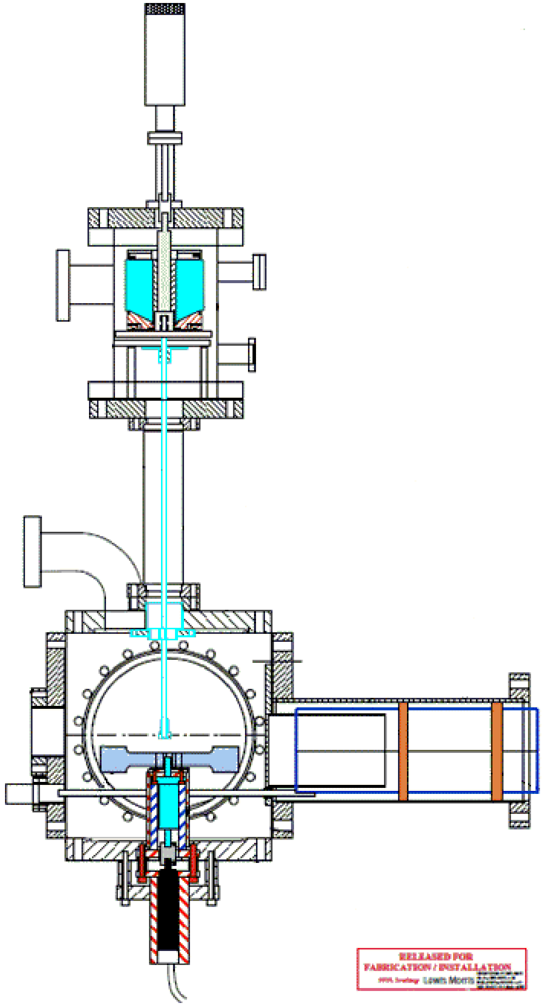
Recycling can be controlled with powder injection

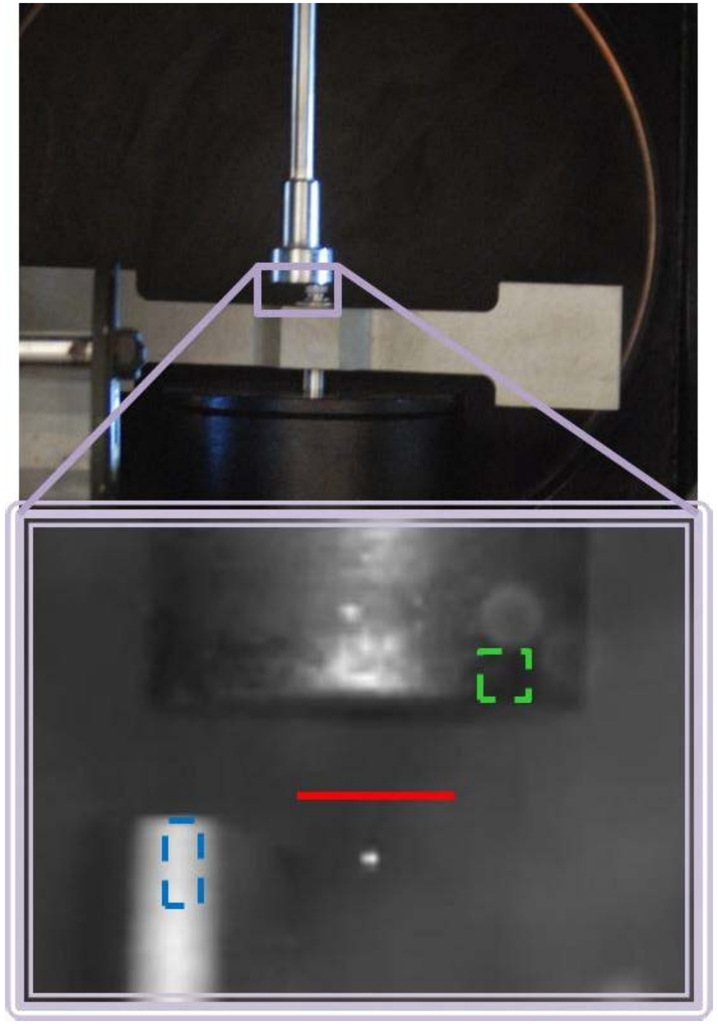




Alternate Concepts – Granule Injector

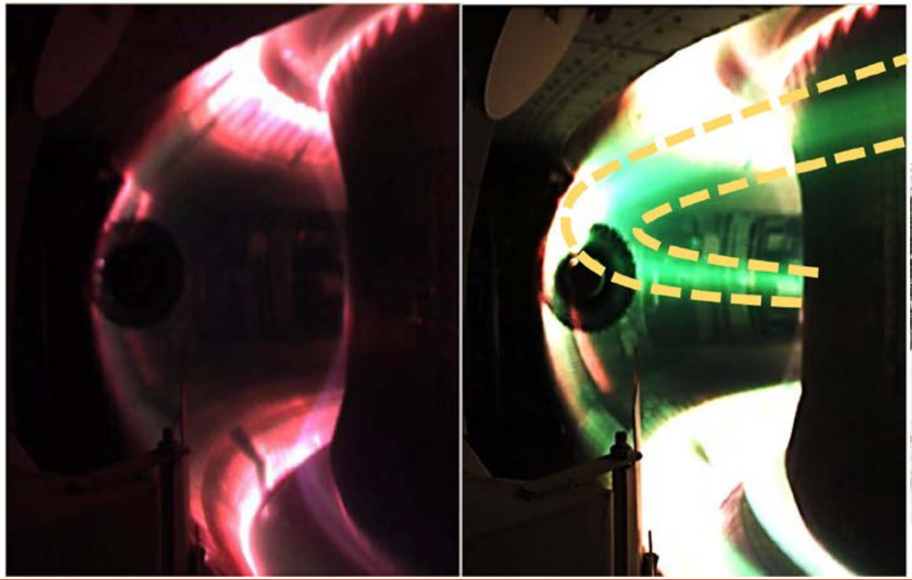
- Next step up from the powder is to inject granules.
- 0.1 – 2 mm in diameter
  - Can select 4 different sizes
  - A piezo-plate vibrated at desired frequency to drop granules
- Rotating impeller is used to “slap” the granules into the plasma
  - Frequency is matched to the frequency of dropping granules
- Near 100% strike rate
  - The occasional “baseball” flyball
- ELM pacing

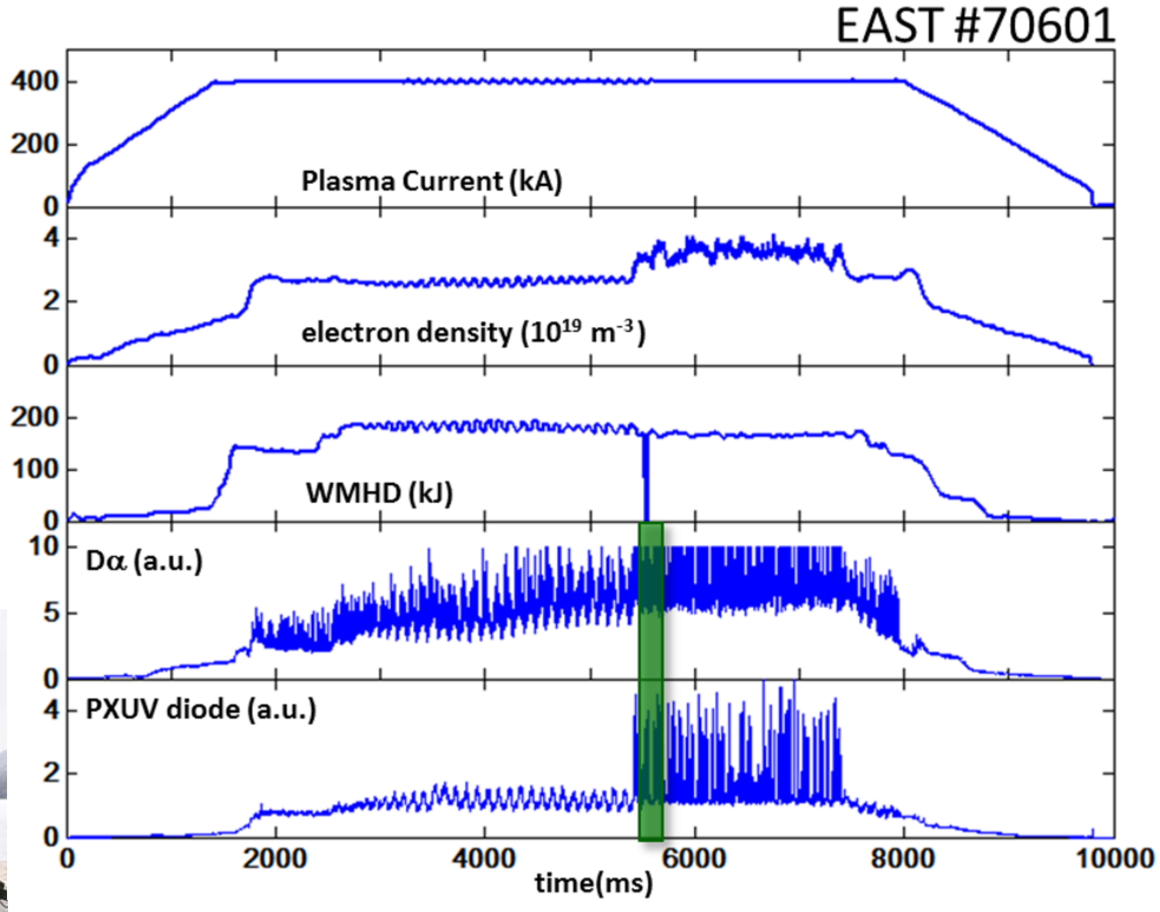




Granule injector – Control of the Size and Frequency of ELMs

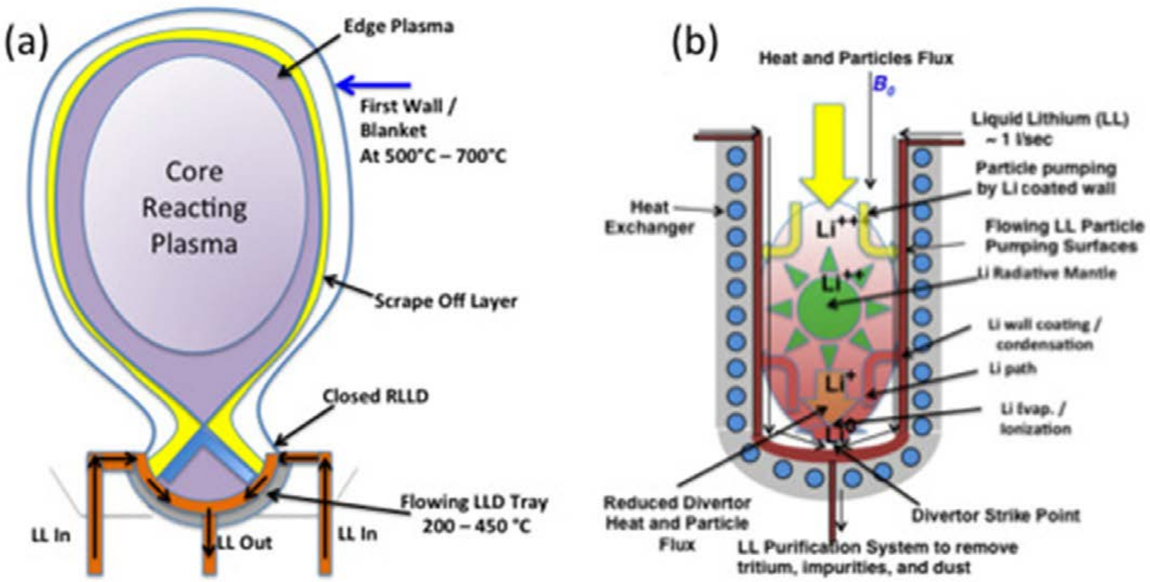
- Can control the size and frequency of ELMs
- Flush out impurities from the core through small ELMs
  - Fast and small
  - Rather than slow and big
- Think of avalanche prevention with a cannon!





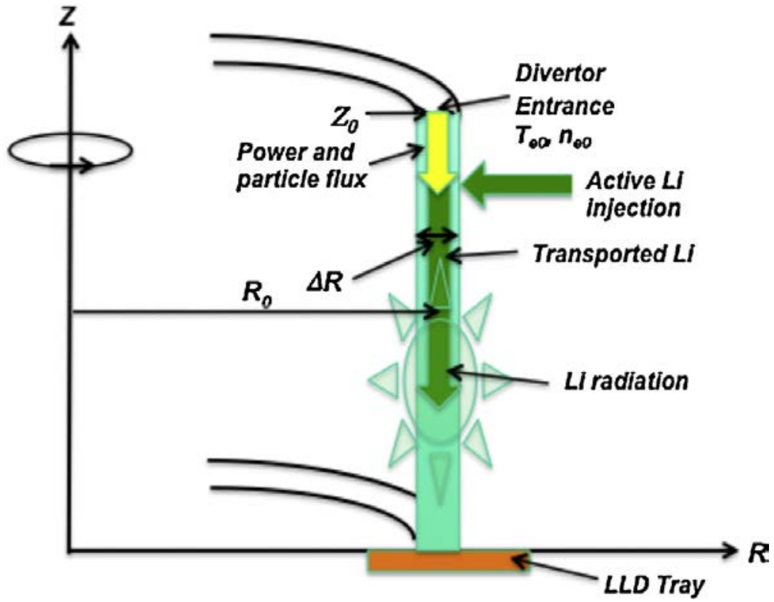
Liquid Lithium Divertor (LLD) Concepts

Radiative Liquid Lithium Divertor



Possible RLLD configuration in a fusion power plant. (*a*) RLLD is envisioned to be placed at the bottom of the reactor chamber to capture LL, dust, and other solid impurities. (*b*) A simplified schematic of RLLD chamber. The LL flows down along the side wall to provide pumping and the thicker LL layer at the bottom provide a radiative Li source for heat flux reduction and divertor substrate protection.

Active Radiative Liquid Lithium Divertor



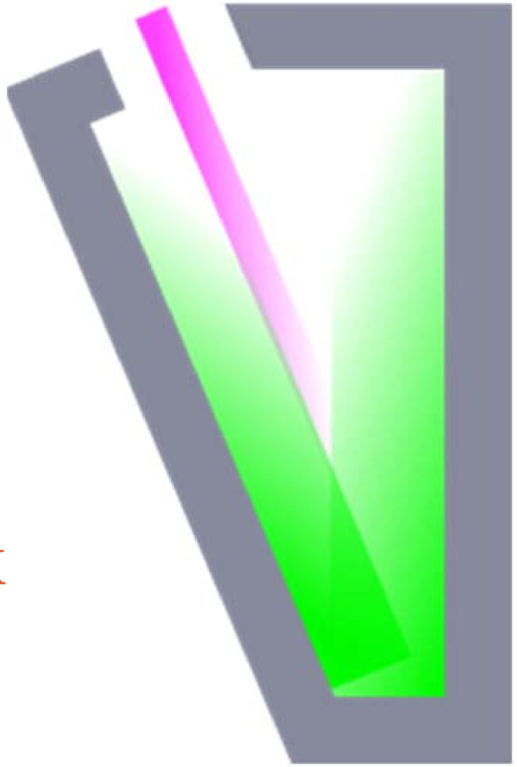
Active version of the RLLD (ARLLD) where LL is injected in the upstream region of divertor.

Find that the ARLLD has similar effectiveness in reducing the divertor heat flux as the RLLD

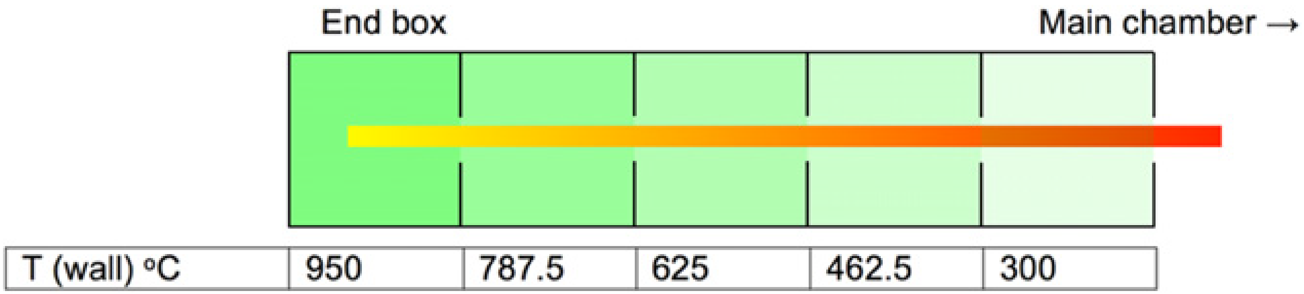
Alternate Concepts – Lithium Vapor Box

- Fusion power plants likely to require near complete detachment of the divertor plasma from the divertor target plates
  - Acceptable heat flux at the target
    - avoid prompt damage
  - Also acceptable plasma temperature at the target surface
    - minimize long-term erosion.
- Impurity puffing experiments show that detached operation:
  - Leads to x-point MARFEs
    - MARFE (Multifaceted Asymmetric Radiation From the Edge)
  - impure plasmas
  - degradation in confinement
- One possible way that to get around this is the lithium vapor box
  - Local evaporation
  - Strong differential pumping through condensation to localize low-Z gas-phase material that absorbs the plasma heat flux
  - So achieve detachment while avoiding previous difficulties.

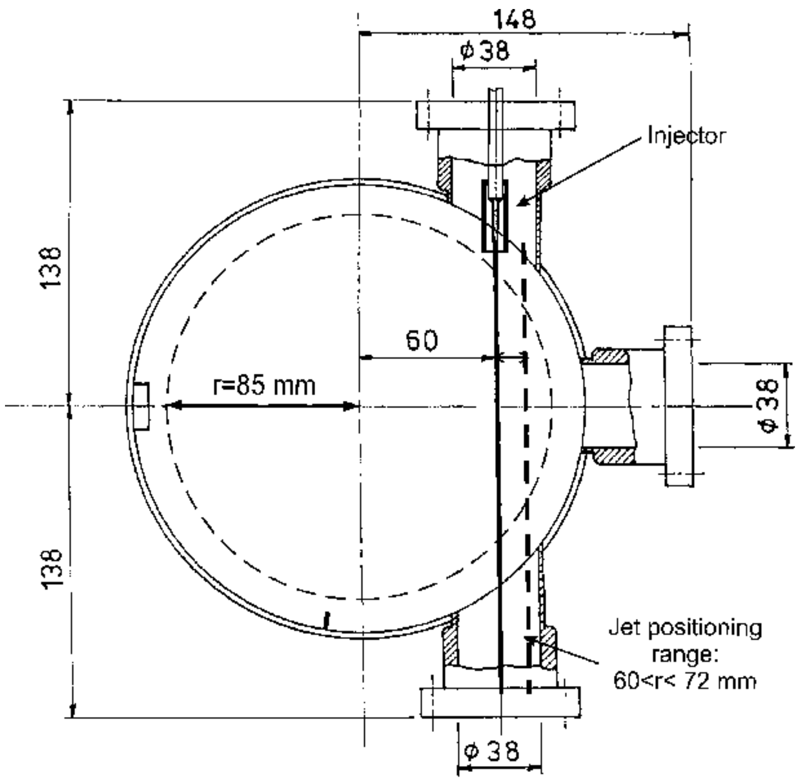
Original Vapor Box divertor



Differentially pumped Vapor Box divertor



Alternate Concepts - JET Limiter



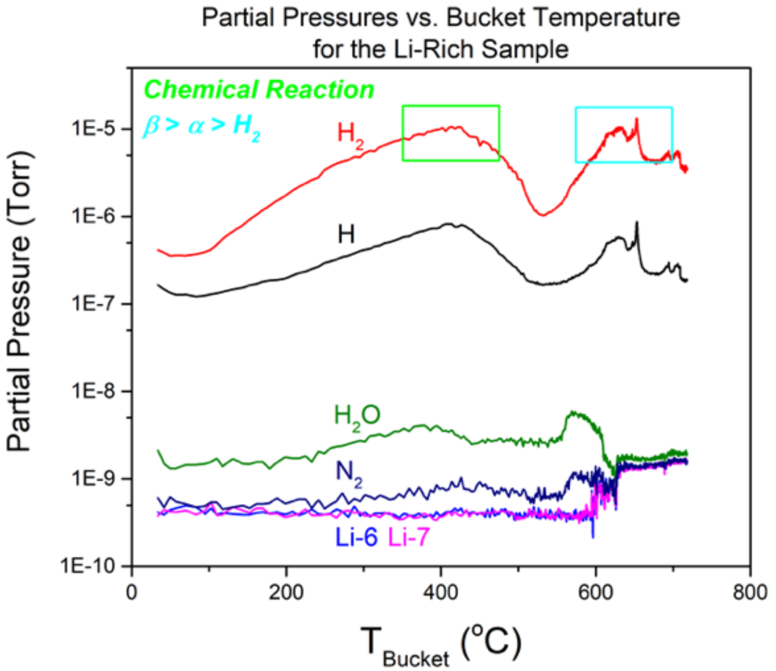
- ISTTOK device installed a gallium JET limiter
- Interaction od the gallium limiter with plasma
- Stable jet
  - No noticeable effect from magnetic field
  - No degradation of plasma seen
  - No contamination
  - Droplets observed
- Plasma parameters
  - $R_0 = 0.46$ m
  - $a = 0.085$ m
  - $T_e = 150$ eV
  - $n_e = 5\times10^{18}$ m^{-3}
- Eventually to have a liquid jet wall

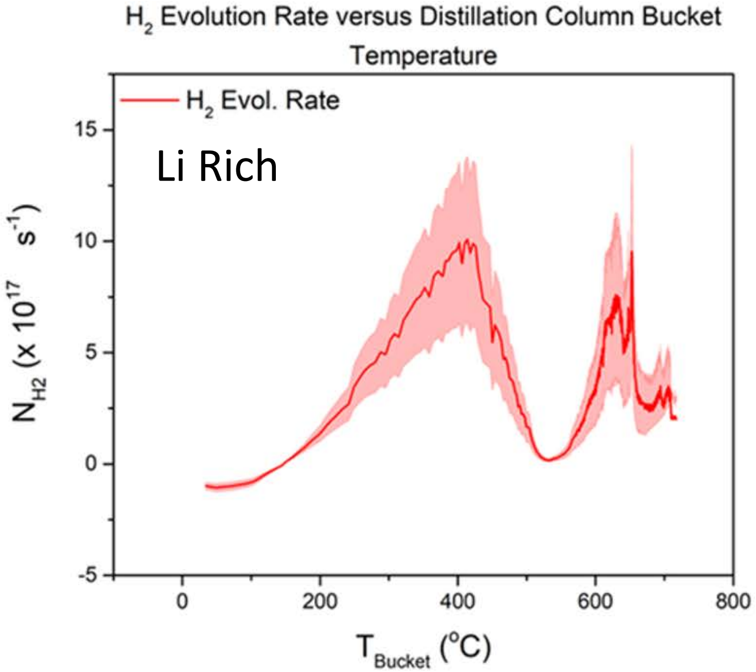
Overview:

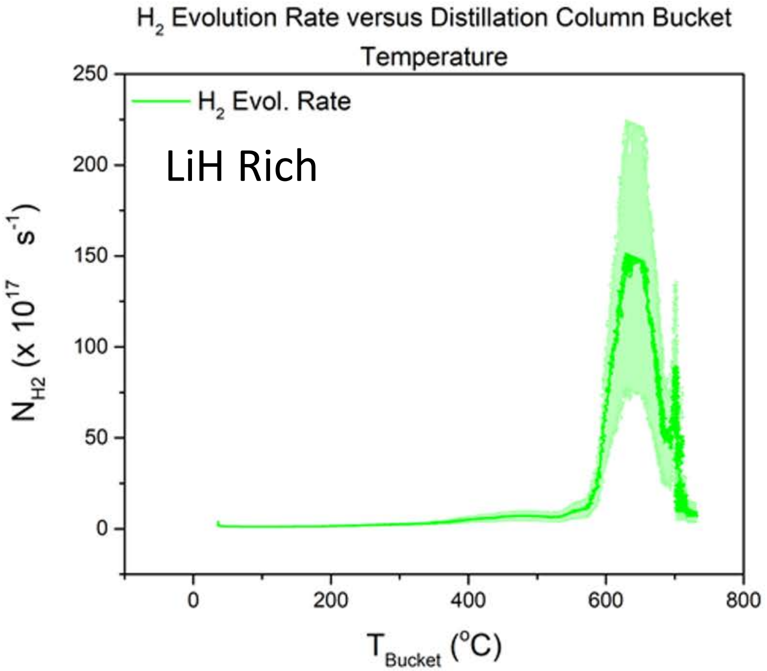
- Materials Challenges – Beyond ITER
- Materials Needs
- Liquid Metals and their Properties
- Plasma Response to Low-Recycling Liquid Metals
- Flowing Liquid Metal PFC Technologies
- Fuel Loss and Retention
- Liquid Metal PFC Experiments
- Summary

High H:Li Ratio Needed to Produce Relevant Evolution Rates

- Hydrogenic species (H, D, T) will be dissolved in Li or react to form LiH, LiD or LiT
  - Fuel losses
  - Need to be replaced or reused
- H_2 evolution occurs near melting temperature of 690 ^oC
- LiH rich melt needed to elevate the H_2 evolution to relevant values

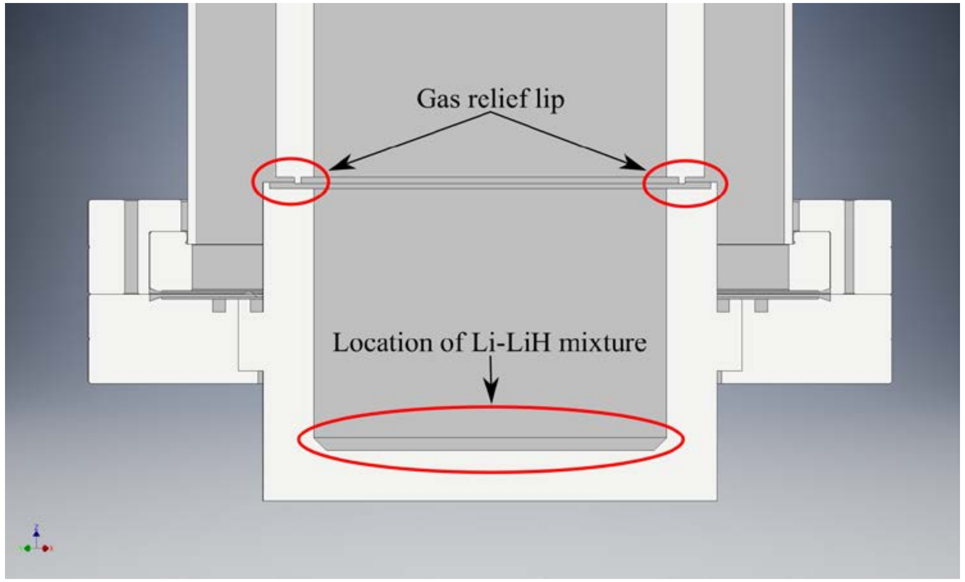




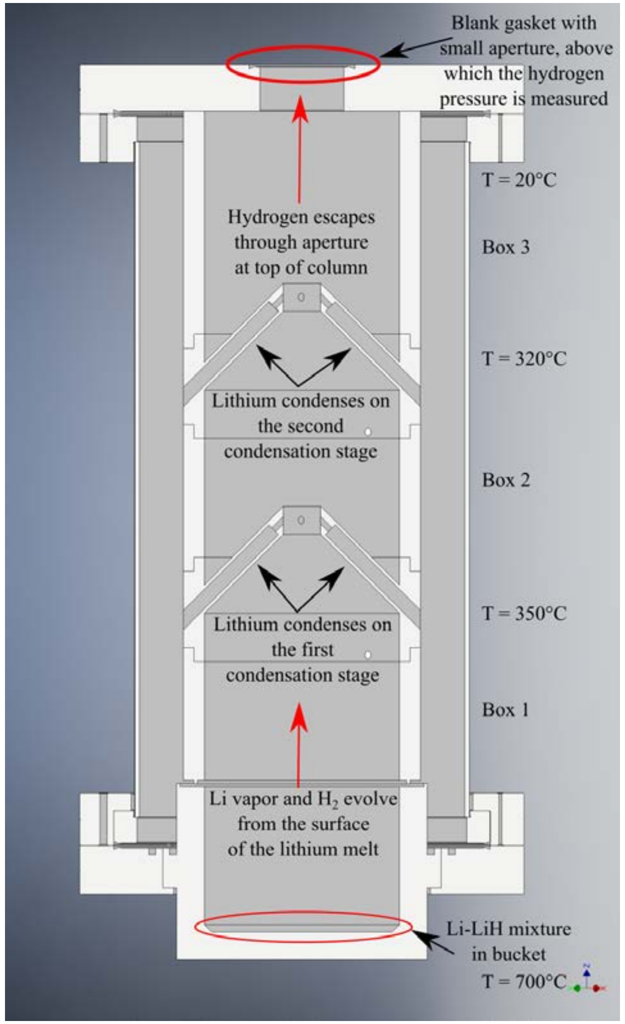


Distillation Column Designed for Hydrogen Isotope Removal from Lithium Melts

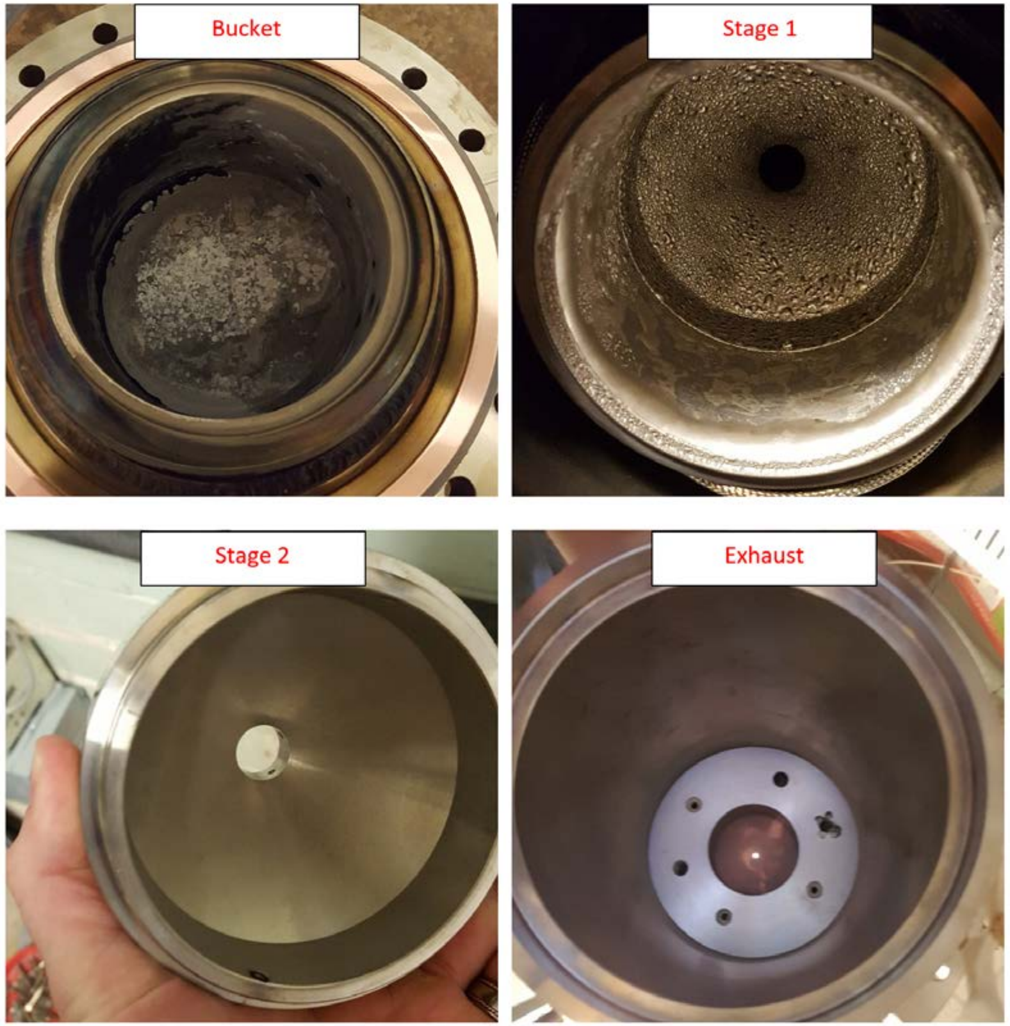
- High hydrogen isotope retention in lithium plasma-facing components
- Lithium and hydrogen separation with distillation column
- Condense lithium on stages
- Allow gas to escape out the top of the column



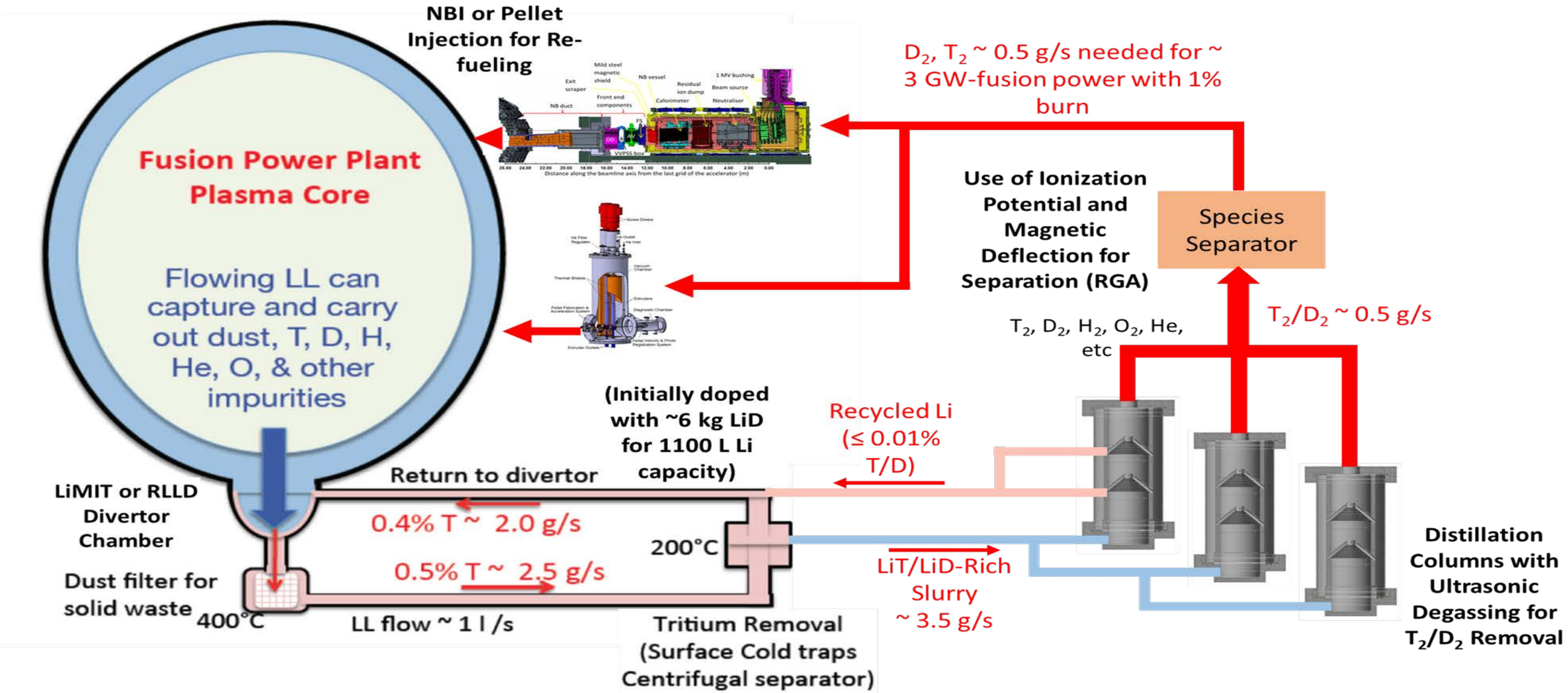
- RGA used to determine evolution rates
- Will need to be Part of an overall back end solution



Proof-of-Concept Test

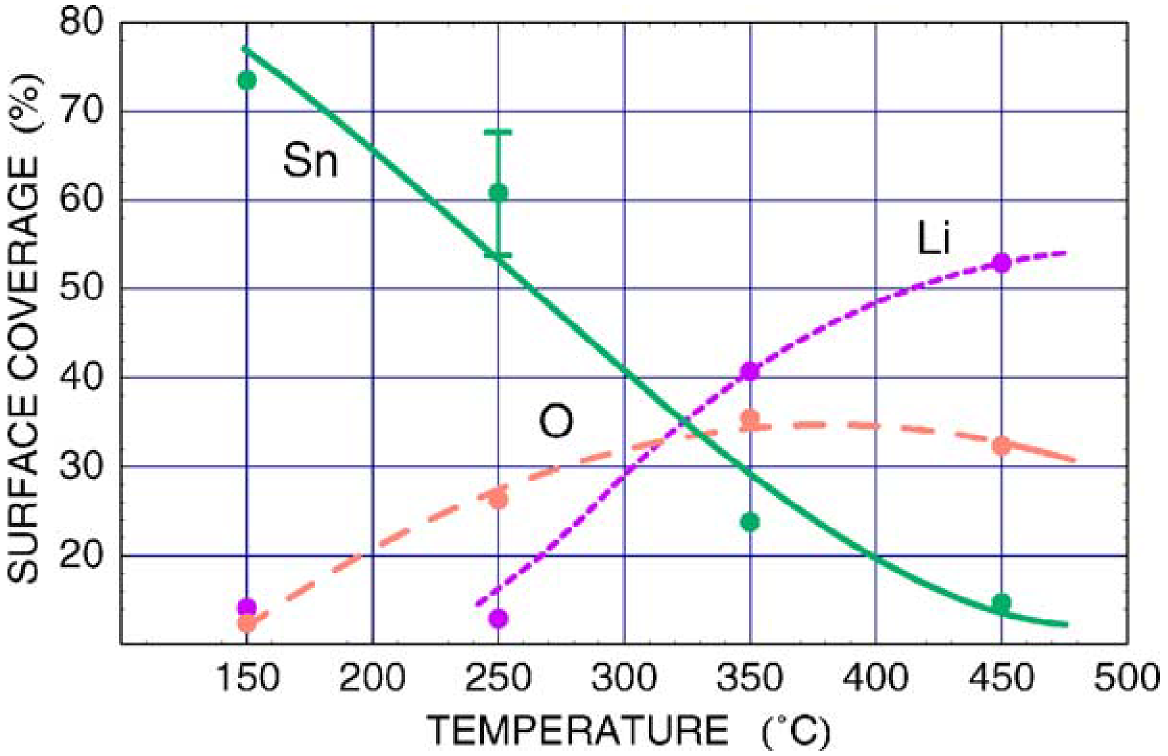


Envisioned Loop Diagram



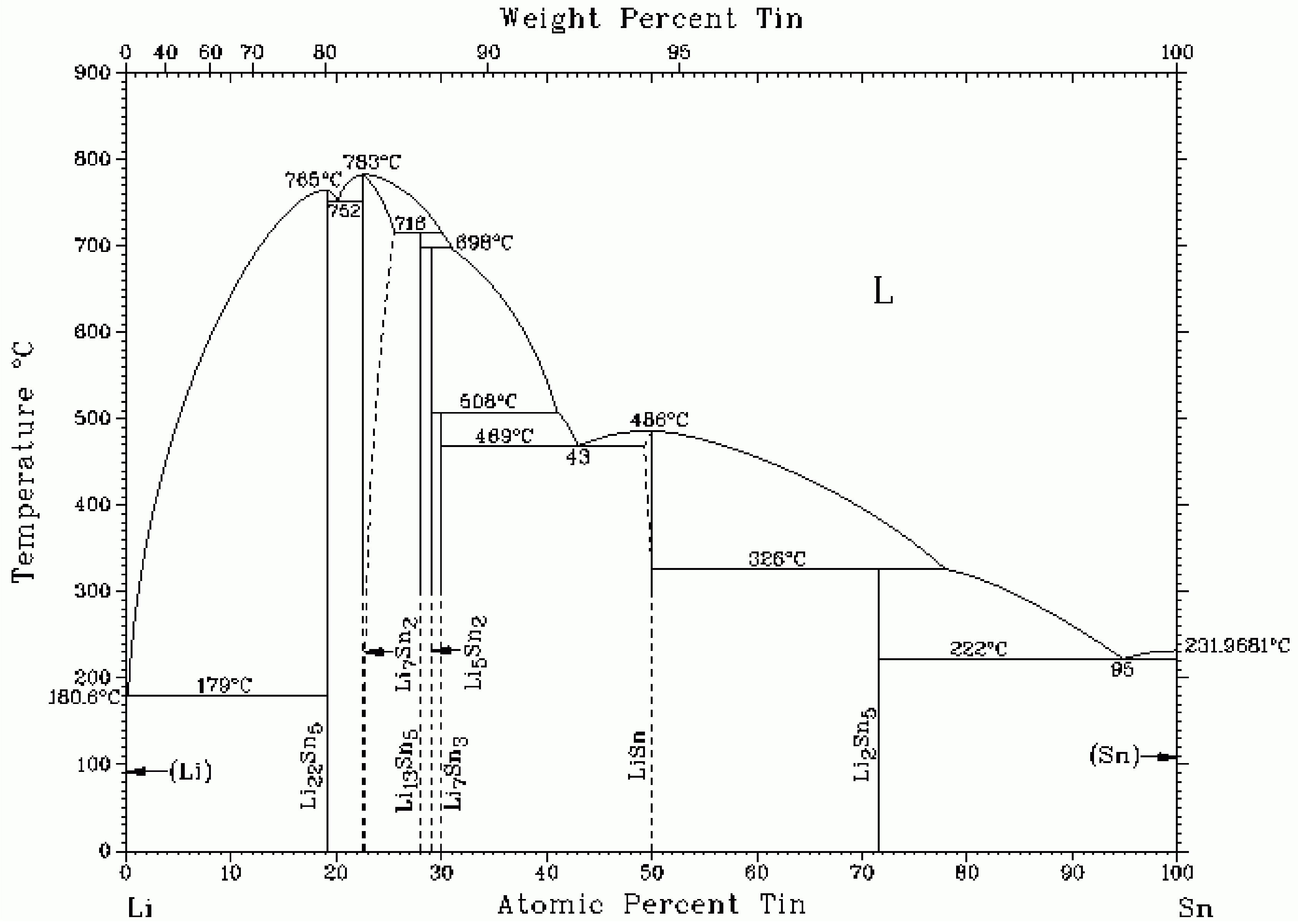
Sn-Li is Gaining Popularity as a Potential Liquid Metal PFC

- 80:20 ratio of Sn:Li is typical
  - Melting point stll in the 200 ^oC range
  - Though not a true Eutectic, liquid alloy.
- Can we get all the good benefits of lithium and tin without the negative?
  - Lithium – low recycling
  - Tin – high temperature before evaporation
- Segregation of the lithium to the surface suggests this
  - Species that lower the surface tension of a material tend to segregate to its surface
- Reduced erosion
- Fuel retention comparable to lithium

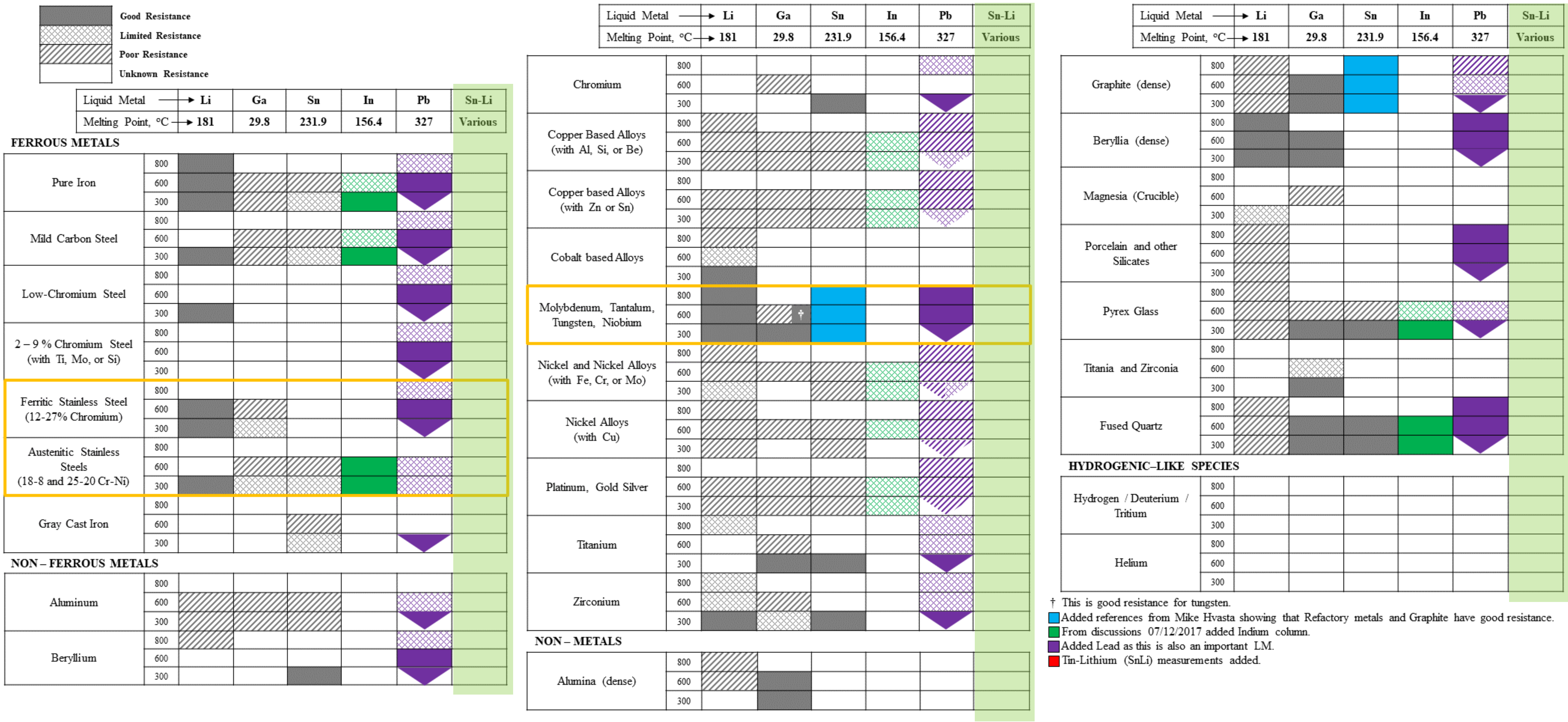


- **THIS IS A NEW FIELD AND MUCH WORK IS TO BE DONE STILL!!!**

J. P. Allain et al., J. Nucl. Mater. 290-293 (2001) 33



R. N. Lyon et al., Liquid Metals Handbook 2nd ed. (1954)



† This is good resistance for tungsten.

- Added references from Mike Hvasta showing that Refactory metals and Graphite have good resistance.
- From discussions 07/12/2017 added Indium column.
- Added Lead as this is also an important LM.
- Tin-Lithium (SnLi) measurements added.

Overview:

- Materials Challenges – Beyond ITER
- Materials Needs
- Liquid Metals and their Properties
- Plasma Response to Low-Recycling Liquid Metals
- Flowing Liquid Metal PFC Technologies
- Fuel Loss and Retention
- Liquid Metal PFC Experiments
- Summary

Liquid Metal Devices – Past, Present and Future

PAST

- **TFTR**
  - **USA**
  - Laser ablation
  - Supershots
- **NSTX**
  - **USA**
  - LITER
  - Liquid lithium divertor (LLD)
  - Granule injectors
- **CDX–U**
  - **USA**
  - Liquid lithium limiter (LLL)
- **T-10**
  - **Russia**
  - Jets and curtains
  - Capillary pore system (CPS)
- **LTX**
  - **USA**
  - Evaporative coatings
  - Flowing lithium pool/wall
- **HT-7**
  - **China**
  - Limiter systems (FLiLi and LiMIT)

Liquid Metal Devices – Past, Present and Future

PAST

- TFTR
  - USA
  - Laser ablation
  - Supershots
- NSTX
  - USA
  - LITER
  - Liquid lithium divertor (LLD)
  - Granule injectors
- CDX–U
  - USA
  - Liquid lithium limiter (LLL)
- T-10
  - Russia
  - Jets and curtains
  - Capillary pore system (CPS)
- LTX
  - USA
  - Evaporative coatings
  - Flowing lithium pool/wall
- HT-7
  - China
  - Limiter systems (FLiLi and LiMIT)

PRESENT

- EAST
  - China
  - Granule injector (GI)
  - Pellet injector (slapper)
  - Limiter systems (FLiLi and LiMIT)
- NSTX–U
  - USA
  - Evaporators (LITER)
  - Granule injectors (GI)
  - Pellet injector (slapper)
- LTX–U
  - USA
  - Same as LTX, upgraded plasma heating
- ISSTOK
  - Portugal
  - Gallium jet curtain
- T–11M
  - Russia
  - Capillary pore system (CPS)
- FTU
  - Italy
  - Capillary Pore System (CPS)
  - Evaporative coatings
- D–IIID
  - USA
  - Granule injector
  - DiMES
- TJ–II
  - Spain
  - Capillary pore system (CPS)
  - Evaporative coatings
  - Tin – lithium (Sn-Li)

Liquid Metal Devices – Past, Present and Future

PAST

- TFTR
  - **USA**
  - Laser ablation
  - Supershots
- NSTX
  - **USA**
  - LITER
  - Liquid lithium divertor (LLD)
  - Granule injectors
- CDX–U
  - **USA**
  - Liquid lithium limiter (LLL)
- T-10
  - **Russia**
  - Jets and curtains
  - Capillary pore system (CPS)
- LTX
  - **USA**
  - Evaporative coatings
  - Flowing lithium pool/wall
- HT-7
  - **China**
  - Limiter systems (FLiLi and LiMIT)

PRESENT

- EAST
  - **China**
  - Granule injector (GI)
  - Pellet injector (slapper)
  - Limiter systems (FLiLi and LiMIT)
- NSTX–U
  - **USA**
  - Evaporators (LITER)
  - Granule injectors (GI)
  - Pellet injector (slapper)
- LTX–U
  - **USA**
  - Same as LTX, upgraded plasma heating
- ISSTOK
  - **Portugal**
  - Gallium jet curtain
- T–11M
  - **Russia**
  - Capillary pore system (CPS)
- FTU
  - **Italy**
  - Capillary Pore System (CPS)
  - Evaporative coatings
- D–IIID
  - **USA**
  - Granule injector
  - DiMES
- TJ–II
  - **Spain**
  - Capillary pore system (CPS)
  - Evaporative coatings
  - Tin – lithium (Sn-Li)

FUTURE

- HIDRA
  - **USA**
  - Flowing limiter systems (FLiLi and LiMIT)
  - Flowing lithium loop (LiHD)
  - Flowing liquid metal divertor test section (FLMDTS)
  - Materials analysis teststand (HIDRA-MAT)
- KTM
  - **Kazakhstan**
  - Divertor

FUTURE

- COMPASS
  - **Czech Republic**
  - Divertor module/tile
  - Capillary pore system (CPS)
- TAE
  - **USA**
  - Liquid lithium walls
- SPARC
  - **USA**
  - Integrated wall/divertor/blanket
- General Fusion
  - **Canada**
  - Spinning liquid metal compression
- Tokamak Energy
  - **England / UK**
  - Divertor

Liquid Metal Devices – Past, Present and Future

PAST

- TFTR
  - USA
  - Laser ablation
  - Supershots
- NSTX
  - USA
  - LITER
  - Liquid lithium divertor (LLD)
  - Granule injectors
- CDX–U
  - USA
  - Liquid lithium limiter (LLL)
- T-10
  - Russia
  - Jets and curtains
  - Capillary pore system (CPS)
- LTX
  - USA
  - Evaporative coatings
  - Flowing lithium pool/wall
- HT-7
  - China
  - Limiter systems (FLiLi and LiMIT)

PRESENT

- EAST
  - China
  - Granule injector (GI)
  - Pellet injector (slapper)
  - Limiter systems (FLiLi and LiMIT)
- NSTX–U
  - USA
  - Evaporators (LITER)
  - Granule injectors (GI)
  - Pellet injector (slapper)
- LTX–U
  - USA
  - Same as LTX, upgraded plasma heating
- ISSTOK
  - Portugal
  - Gallium jet curtain
- T–11M
  - Russia
  - Capillary pore system (CPS)
- FTU
  - Italy
  - Capillary Pore System (CPS)
  - Evaporative coatings
- D–IIID
  - USA
  - Granule injector
  - DiMES
- TJ–II
  - Spain
  - Capillary pore system (CPS)
  - Evaporative coatings
  - Tin – lithium (Sn-Li)

FUTURE

- HIDRA
  - USA
  - Flowing limiter systems (FLiLi and LiMIT)
  - Flowing lithium loop (LiHD)
  - Flowing liquid metal divertor test section (FLMDTS)
  - Materials analysis teststand (HIDRA-MAT)
- KTM
  - Kazakhstan
  - Divertor

FUTURE

- COMPASS
  - Czech Republic
  - Divertor module/tile
  - Capillary pore system (CPS)
- TAE
  - USA
  - Liquid lithium walls
- SPARC
  - USA
  - Integrated wall/divertor/blanket
- General Fusion
  - Canada
  - Spinning liquid metal compression
- Tokamak Energy
  - England / UK
  - Divertor

- CFETR (?)
  - China
  - Wall / limiters / divertor (?)
- FNSF (?)
  - USA
  - Wall / limiters / divertor (?)
- DEMO (?)
  - Country ?
  - Wall / limiters / divertor (?)

Overview:

- Materials Challenges – Beyond ITER
- Materials Needs
- Liquid Metals and their Properties
- Plasma Response to Low-Recycling Liquid Metals
- Flowing Liquid Metal PFC Technologies
- Fuel Loss and Retention
- Liquid Metal PFC Experiments
- Summary

Summary

- Future fusion power station material needs are going to be greater than what we have now
    - Can be up to 1 GW/m^2 for transients
    - Need materials that will handle the heat fluxes
    - Or solutions to negate the heat fluxes
- Solid materials will be exposed to conditions that will turn any solid metal into a liquid metal
    - So why not start out with a liquid metal
- Beyond ITER, demonstration (commercial) power stations may also be stellarators, not just a tokamak
    - Stellarators are catching up
    - But there are many concepts on the table now… need to look at all of them
- These material need not only handle the heat flux:
    - Provide a low sputtering yield and impurity ejection into the plasma
    - Low recycling
    - Low-Z
    - Fuel retention (how to handle this)
    - Material compatability
- Liquid metals (Lithium) can provide the solution!
    - Liquid does not damage – self healing system
    - Lithium provides protection to underlying surface
    - Low recycling
    - Therma, thermo-electric, wetting properties are all important aspects to consider in a LM

Summary

- Positive response by plasma
  - Temperature profiles flatten out, density smooths out as well, no server pressure gradients – pedestal
  - Low recycling – background D_α goes down
  - Stored plasma power goes up
  - ELM control and mitigation
- There are many technologies already being developed or starting to be developed
  - Limiters – Capillary pore system (CPS), Flowing liquid lithium limiter (FLiLi) – Lithium/Metal infused trenches (LiMIT)
  - Liquid lithium divertors (RLLD, ARLLD)
  - Powder and granule injectors
  - JETS
- The back end, fuel loss and retention
  - Need to recover fuel that is absorbed or reacted
  - Distillation column
  - Sn-Li eutectic/alloy
- Future devices
  - Room for the smaller devices still.
  - Do much of the R&D for LM
- Question is, are future fusion devices willing to take the leap and use full scale liquid lithium/metal systems.

6th International Symposium on Liquid Metal Applications for Fusion (ISLA2019)

University of Illinois, Urbana-Champaign, Illinois USA

September 30th – 3rd October 2019

ISLA2019 continues the series of symposia on liquid metal applications for fusion. Liquid lithium as well as other liquid metals will also be included in the program

The program will cover theoretical and experimental data obtained in fusion and laboratory devices, as well as technological and safety aspects of liquid metals

International Organizing Committee

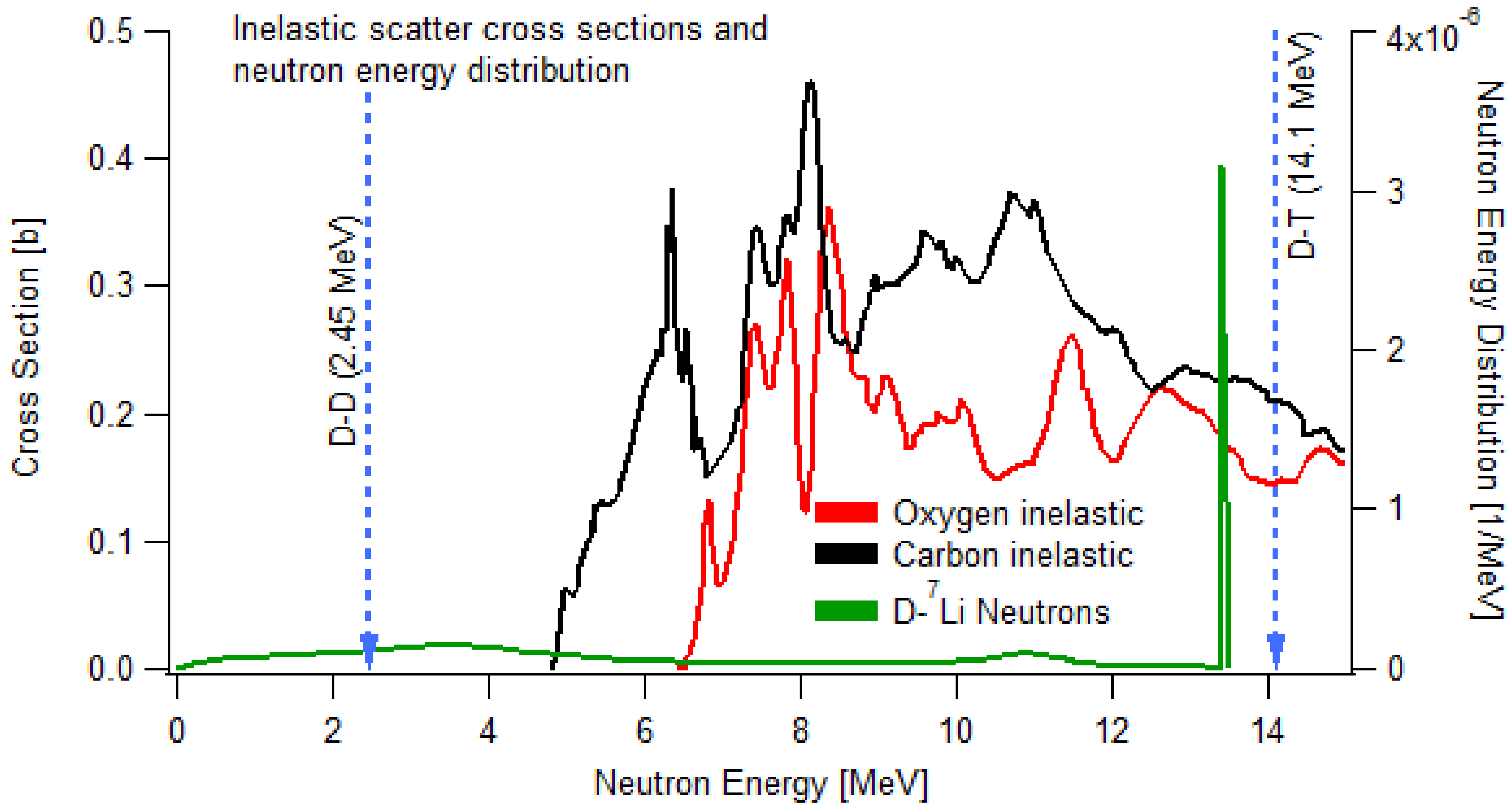
Dr. S. Mirnov	***Chairman***	**(Russia)**
Dr. A. Romannikov		**(Russia)**
Dr. M. Ono		**(USA)**
Dr. G. Mazzitelli		**(Italy)**
Dr. F. L. Tabarés		**(Spain)**
Dr. Y. Hirooka		**(Japan)**

Local Organizing Committee

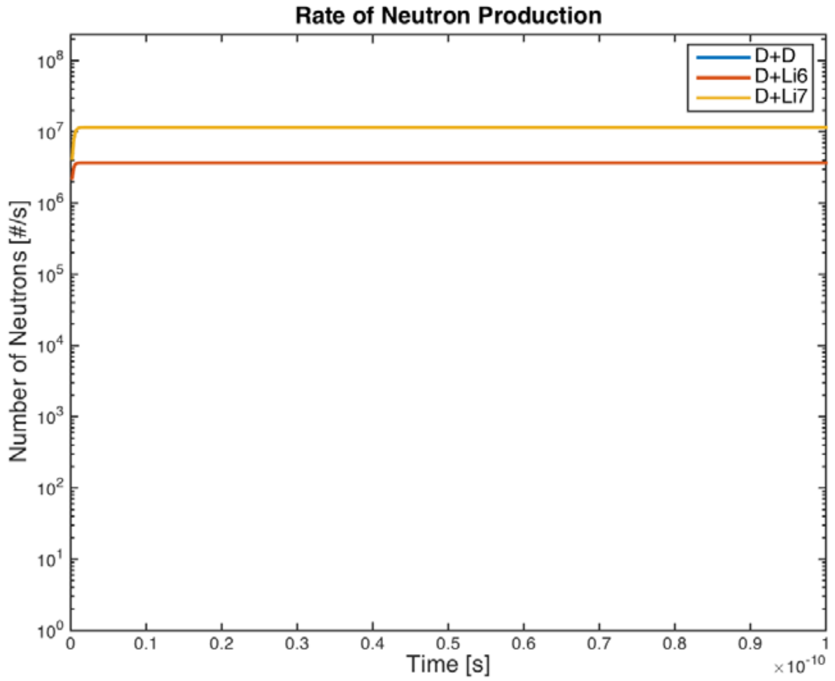
Chair	**Dr. D. N. Ruzic**	**(UIUC)**
Secretary	**Dr. D. Andruczyk**	**(UIUC)**
Social Events	**Dr. D. Andruczyk**	**(UIUC)**
Local ANS	**J. Mettler**	**(UIUC)**

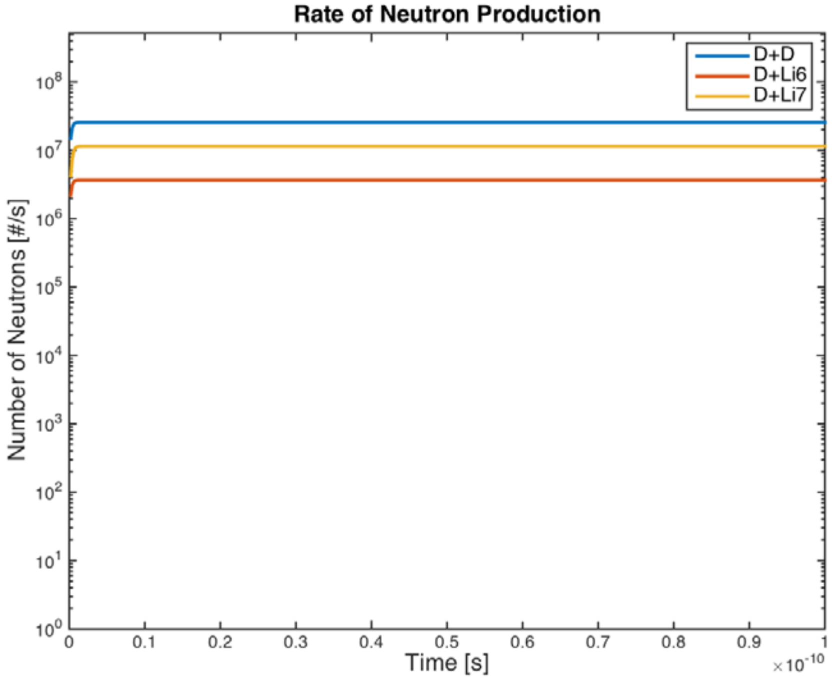
BACK UP SLIDES

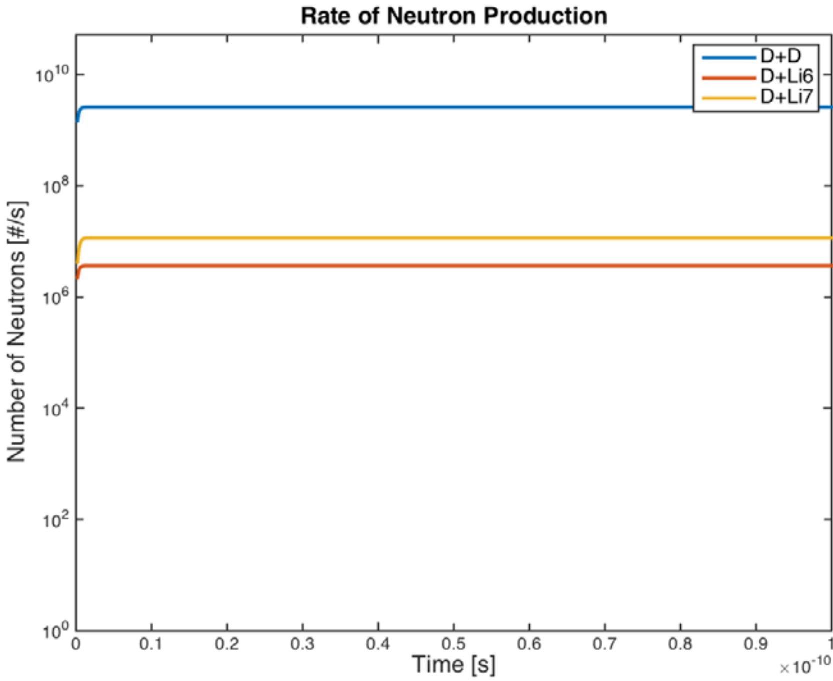
Liquid lithium for neutron generation



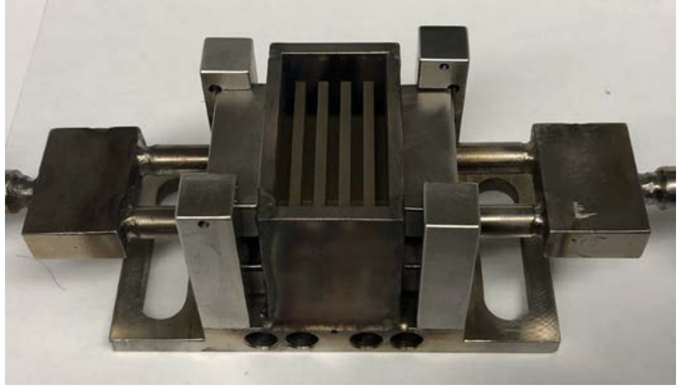
Liquid lithium for neutron generation

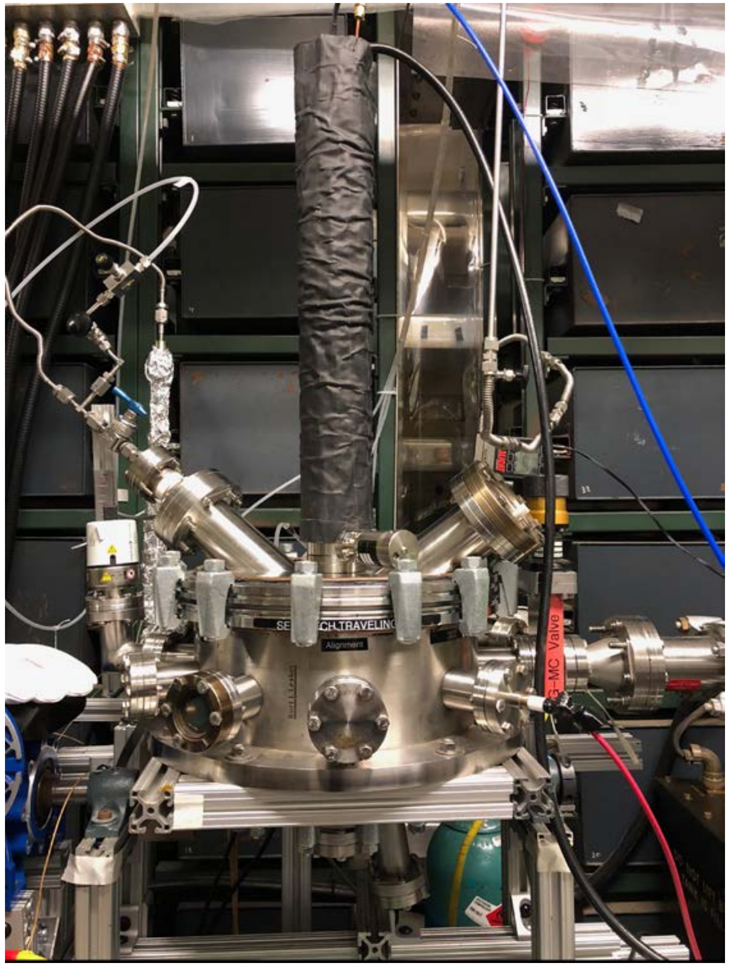


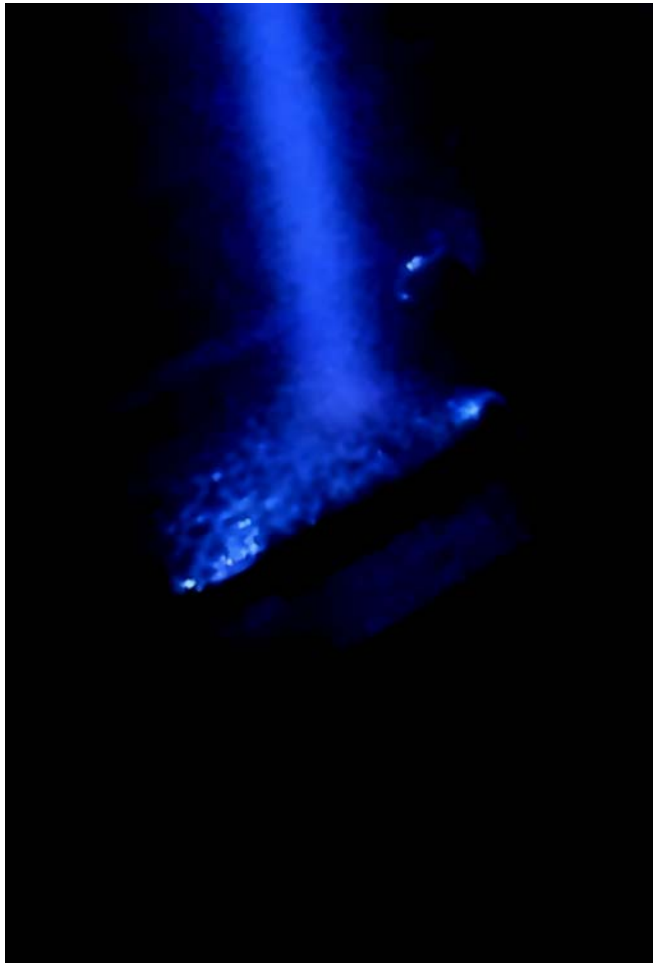




Liquid lithium for neutron generation







He Pumping and Retention by Liquid Lithium