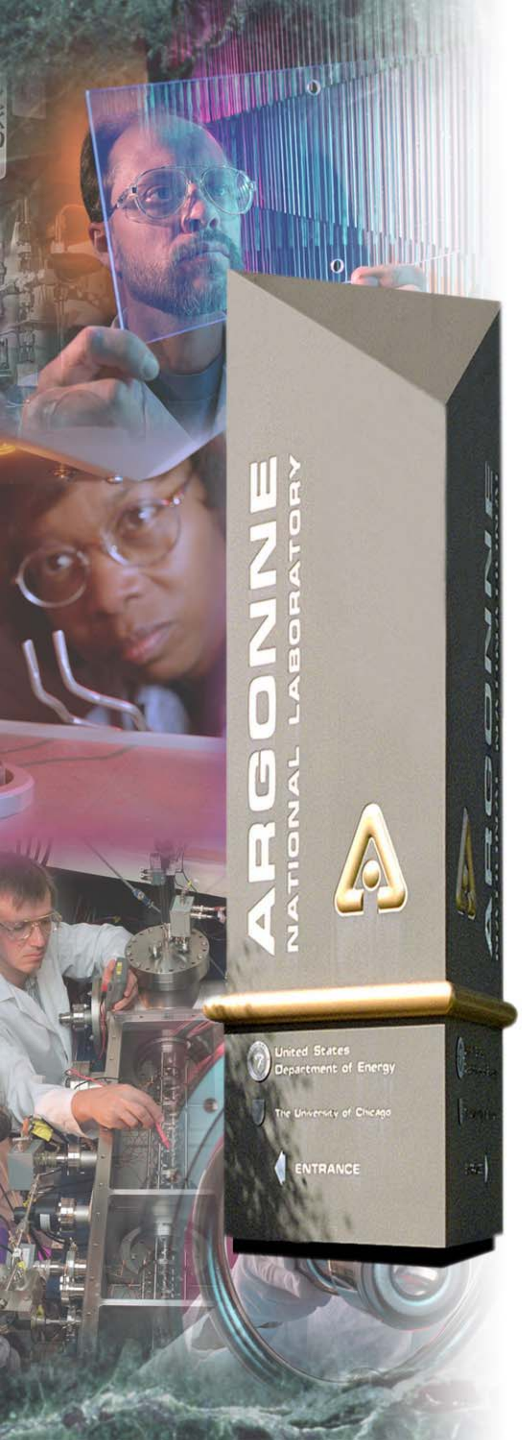

Plasma/Liquid-Metal Interactions During Tokamak Operation

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Outline of Talk

- Motivation and application of liquid-metals as PFCs in magnetic fusion devices (namely tokamaks)
- Normal vs Off-normal tokamak operation
- Sputtering of liquid-metals as a function of temperature
- Atomistic modeling of particle/liquid-metal interactions
- Erosion mechanisms during Edge Localized Modes (ELMs): Implications to the use of liquid-metals
- Erosion during off-normal events: disruptions & VDEs
- Summary and Conclusions

Normal vs Off-Normal Operation in Tokamak Fusion Devices

- **Important distinction between both normal and off-normal operation on plasma-material interactions**
  - PHYSICS ARE QUITE DIFFERENT BETWEEN THESE EVENTS!
- **Normal Operation**
  - Physical sputtering, particle recycling (diffusion, desorption, surface recombination, radiation-induced processes)
  - Particle retention (hydrogen isotopes), helium pumping
  - Surface mixing (e.g. Be and C mixing in ITER)
  - Edge Localized Modes (ELMs)
- **Off-Normal Operation**
  - Disruptions
  - Vertical Displacement Events (VDEs)

Motivation for use of liquid-metals as PFCs

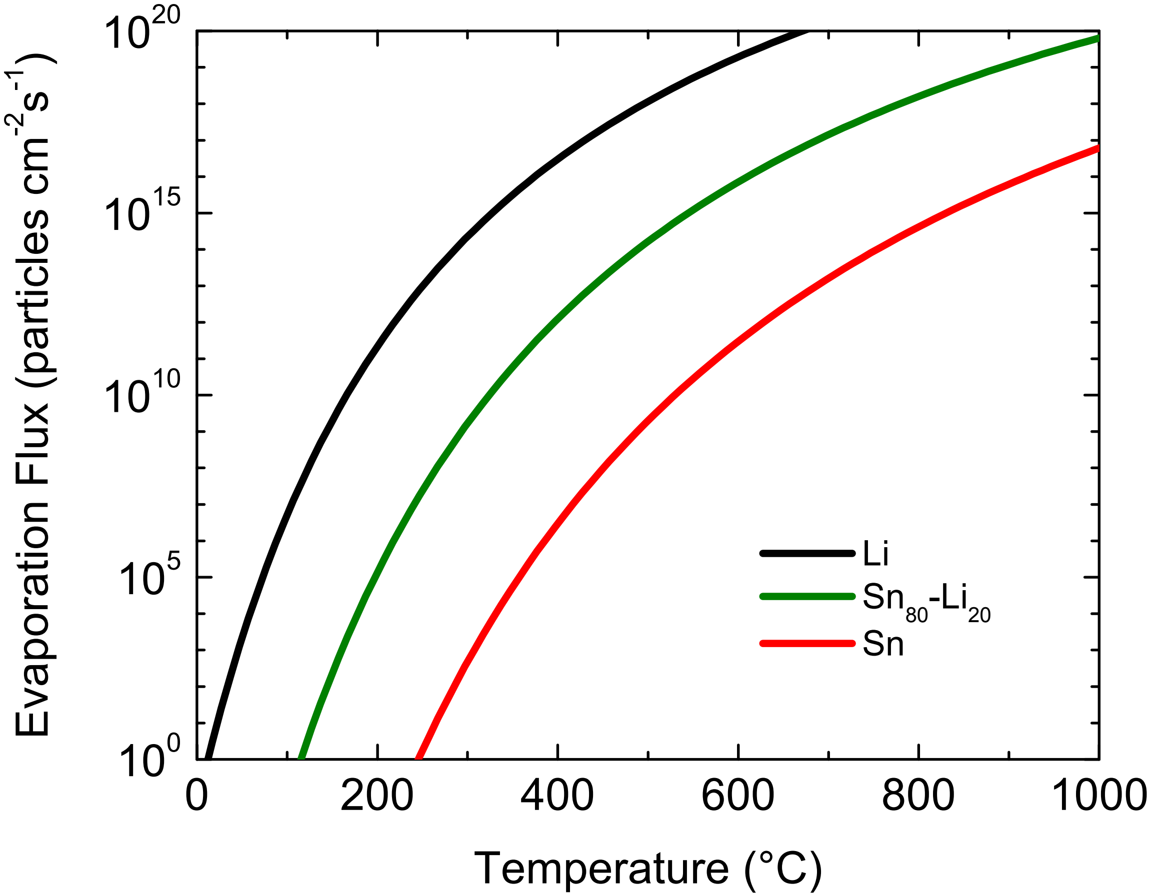
- Flowing liquid plasma-facing systems can rapidly remove heat
- Continuous recovery of damaged surfaces exposed to large heat fluxes due to off-normal events
  - **THIS IS ONE KEY ADVANTAGE OF FLOWING LIQUID PFCs**
- Specifically, lithium (for example) offers the advantage of low core plasma radiation and high ionization characteristics
- Enable new confinement regimes: low-recycling regimes (i.e. using Li)
- Some particular liquid PFCs can pump helium and hydrogen
- Some liquid PFCs could have solutions on tritium retention

Normal operation in tokamak fusion devices: important issues

- Normal operation of liquid-metals must consider the following plasma/surface interactions:
  - **Sputtering, Evaporation, Particle implantation/reflection, hydrogen species retention, tritium co-deposition**
- Implanted particles have additional issues:
  - **Pumping of helium and helium bubble generation**
  - **Hydrogen retention**
- ELMs will exist under H-mode confinement and its implications on liquid-metal erosion/contamination must be addressed
  - **splashing and macroscopic particle erosion**

Candidate liquid-metals and their vapor pressures

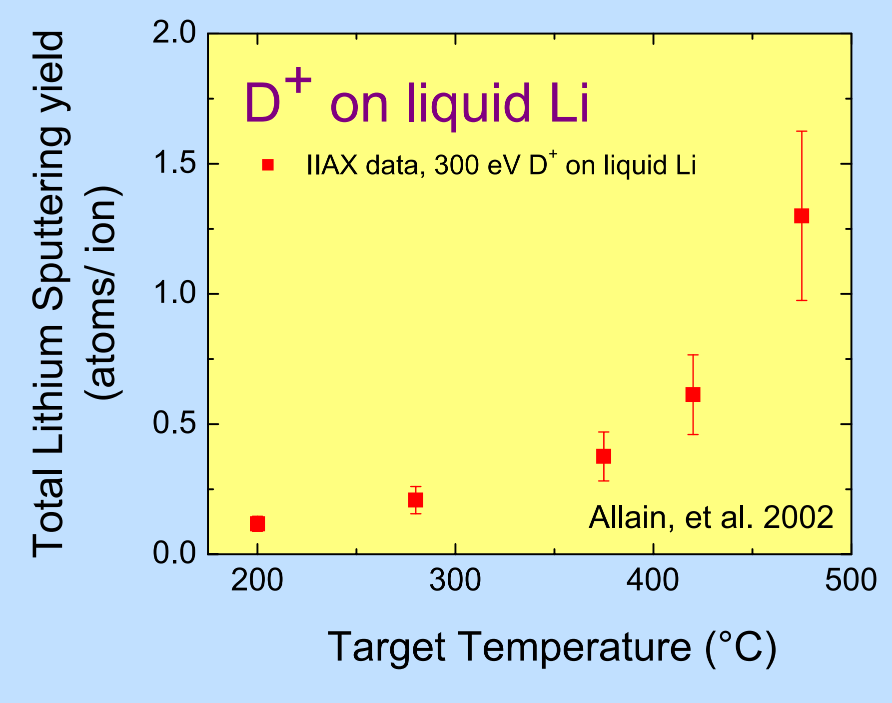
- Evaporation is equally as important as sputtering yield as both inject wall materials into plasma
- Sn has an evaporative flux many orders of magnitude lower than Li
- Vapor pressures along with other erosion mechanisms will limit the tokamak operational temperature window

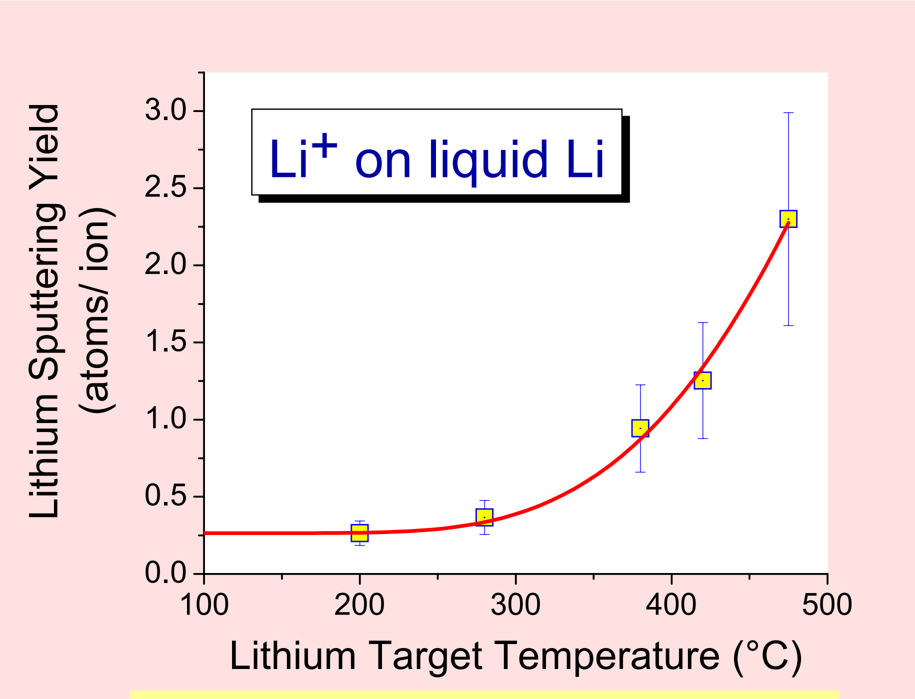


What we know about liquid-lithium sputtering

- No significant difference in sputtering from the solid to liquid state when temperature is near melting point
- Non-linear increase in *physical* sputtering from liquid-Li when temperature is about 50% higher than melting point (after accounting for evaporation)
- Two-thirds of lithium sputtered particles are in the charged state (consistent with well-known data on alkali metals)
- Implanted hydrogen leads to a ~ 40% decrease in *lithium* sputtering in the solid phase and near melting point
- High retention of hydrogen in liquid lithium (PISCES-B results)

Liquid Li temperature-dependent sputtering





J.P. Allain, et al., Fus. Eng. Des. 72, 1-3 (2004) 91-108.

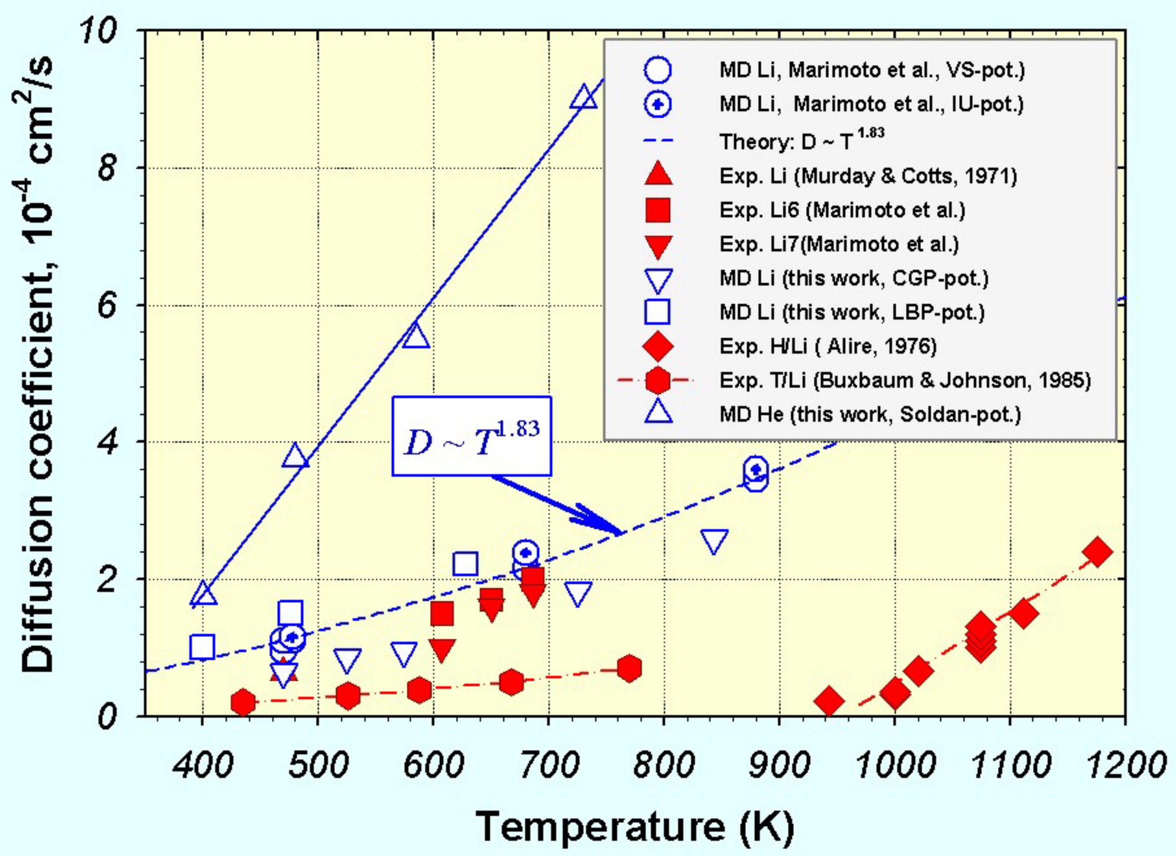
- **Enhanced erosion yields measured for: H$^+$, D$^+$, He$^+$ and Li$^+$ bombardment at low energies (0.1-1.0 keV) and 45-degree incidence**
- **Mechanism not well understood: possible bubble formation?**

Other issues: diffusion and particle retention

- In addition to *physical* sputtering other issues are important.
  - **For example: low-energy D, Li reflection from liquid lithium**
- MD work currently studies low-energy reflection and liquid Li sputtering as function of: temperature, incident particle energy
- Atomistic simulations (Z. Insepov) studies He diffusion in liquid Li and the effect of He bubble formation and stability in liquid Li

He diffusion in liquid Li

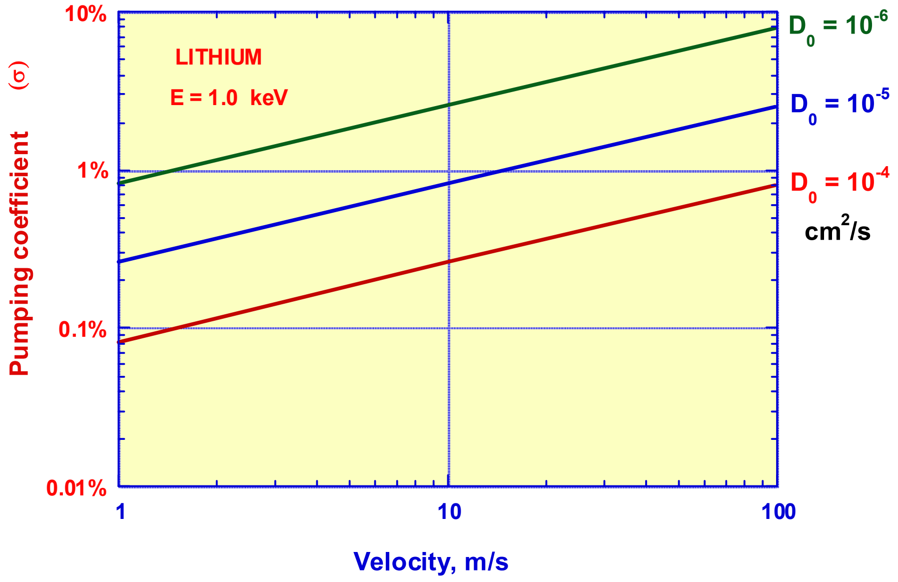
- For temperatures around 300 C, He diffusion in Li is about 5 x 10^{-4} cm^2/sec
- This could be lower due to He cavity formation in liquid Li
- Atomistic simulation is a helpful tool to guide understanding on how liquid Li may pump He particles



Helium pumping in liquid-metals

- Need He diffusion coefficient $< 10^{-4}$ cm^2/s for reasonable liquid velocities ≈ 10-20 m/s to pump He at the minimum required rate of a few%.
- Helium self-pumping can only be enhanced due to bubble formation and trapping. No significant enhancement is expected due to internal flows.
- Bubble formation near particle implantation region was proved experimentally to occur in liquids.
- Need to study synergistic effects of D, T, and He implantation in flowing liquids. In addition, more He diffusion data is needed
- However, bubble growth dynamics, bursting, and splashing before removal, if occurred, can lead to de-trapping of He

HEIGHTS Calculations of He Pumping Coefficient as a Function of Lithium Velocity

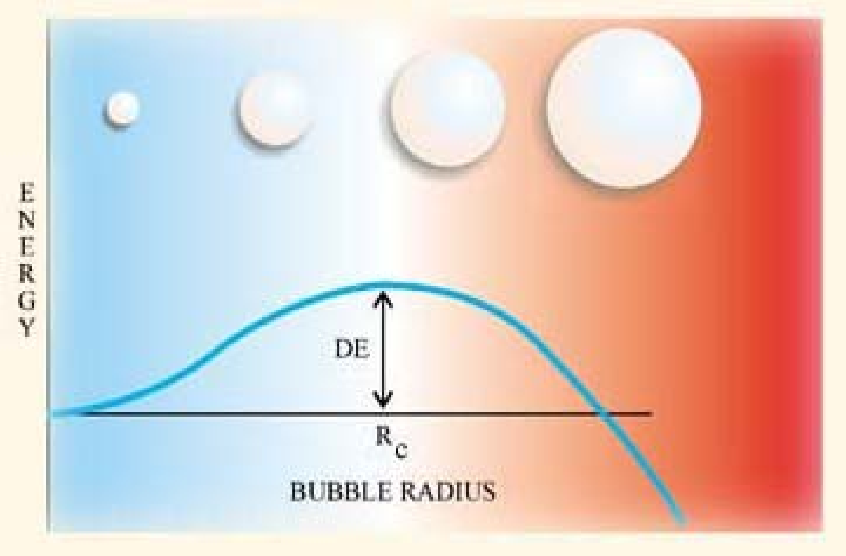


He bubbles in liquid Lithium

The mechanisms of bubble formation in liquid metals are not well understood. They are important for liquid surface erosion under irradiation with He ions.

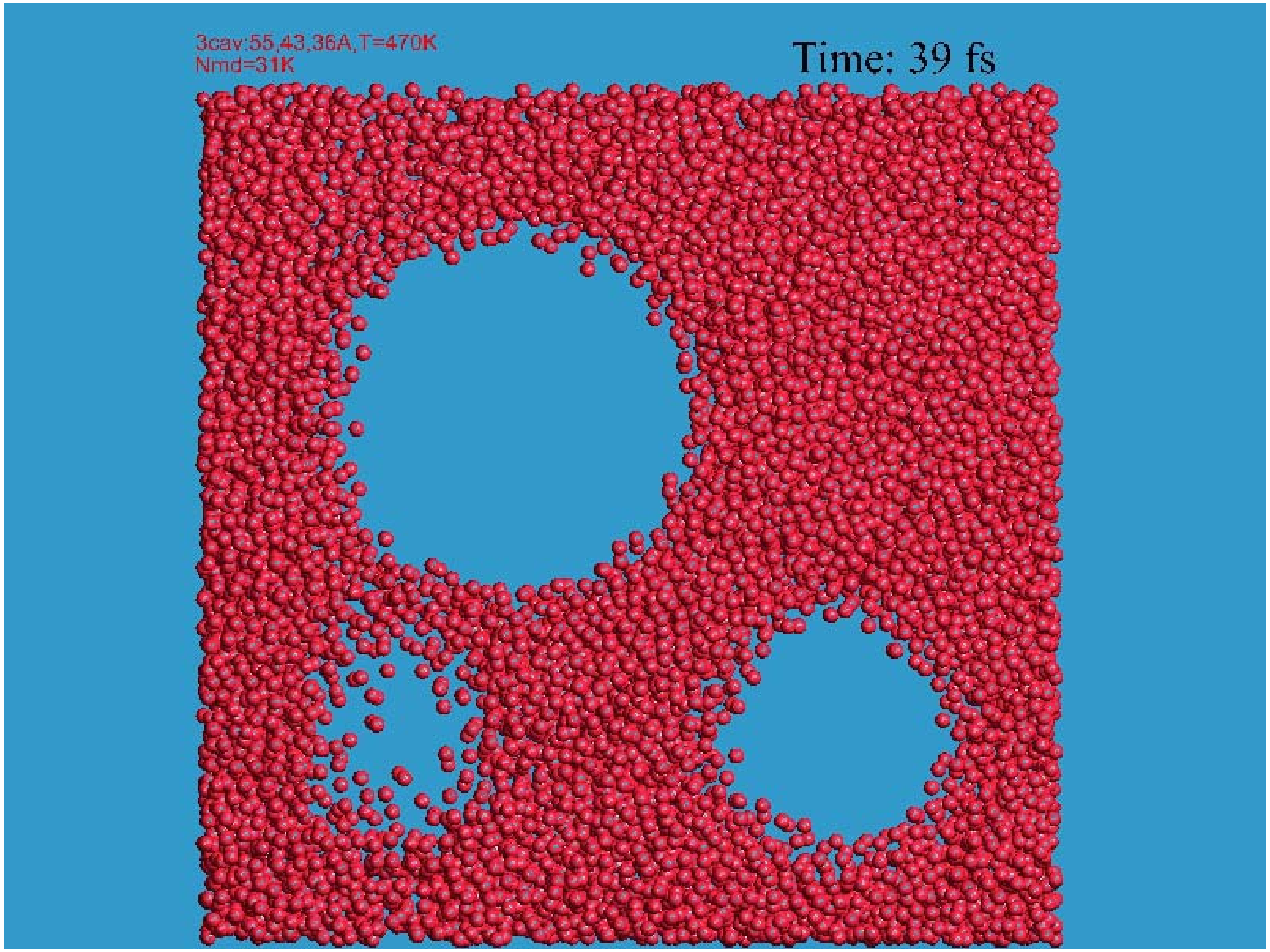
<u>D processes, with different physics:</u>

1. Local negative pressure – stretching of liquid
2. Local overheating – above the boiling point
3. Implantation of He from plasma



Thermodynamics shows that a critical Bubble radius should exist above which the bubble starts to grow

Cavities in Liquid Lithium

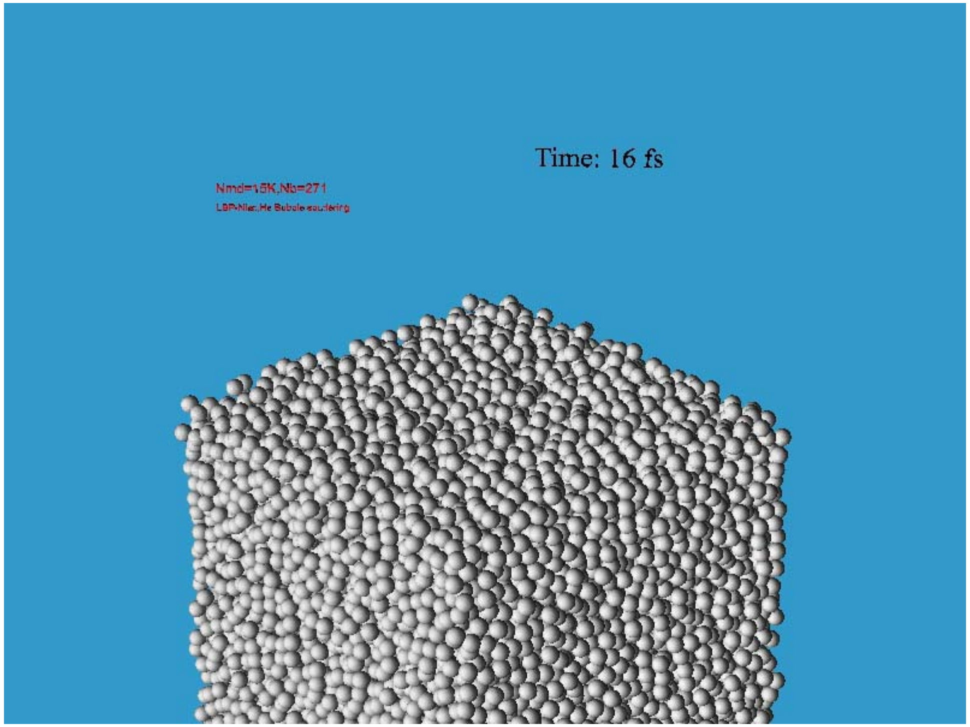


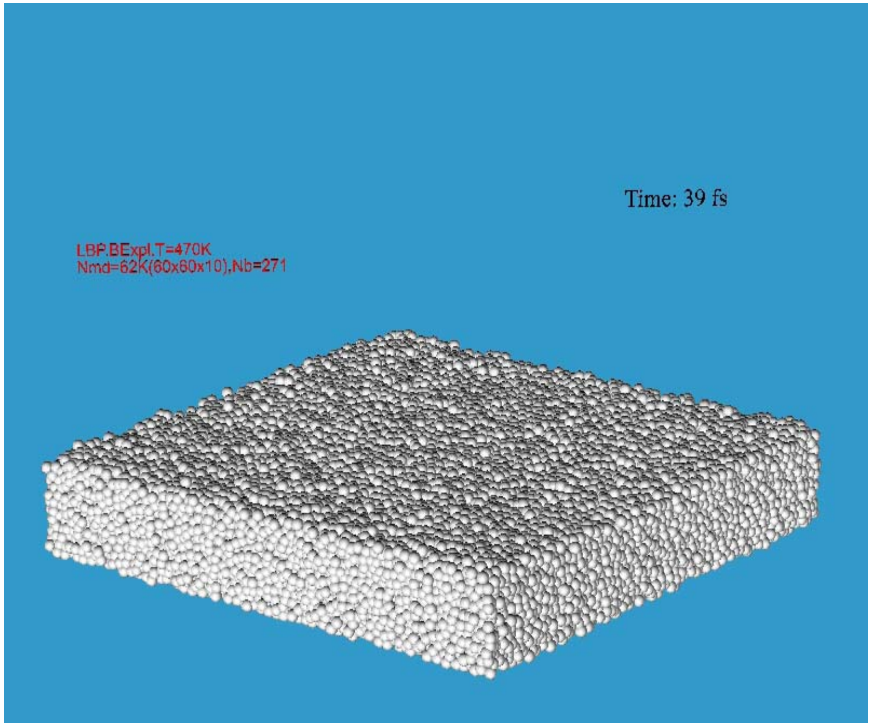
Our MD simulations show that the most important parameters for bubble formation or annihilation is the size and the local temperature.

We have simulated the effect of coalescence of two cavities in liq-Li.

Bubbles do exist in liquid Lithium!

MD simulation of liquid splashing





In this simulation, we study the parameters that control the stability in liquid Li surface containing He bubbles.

MD shows that the surface tension of the liquid, but not the binding energy of He-He interaction, results in largest sputtering during bubble explosion.

Erosion during H-mode and ELMs

- **Issues regarding PFC performance under ELM operation**
  - Limiting energy confinement
  - Density control and limiting impurity buildup
  - Surface erosion
- **What are some ELM characteristics?**
  - 1-10% of core plasma energy is released or deposited on divertor surfaces for about 0.1-1.0 msec at 10-100 Hz.
  - Incident power densities can increase from 5 $\mathrm{MW/m^2}$ to the order of 300-3000 $\mathrm{MW/m^2}$!
  - Differences in erosion between low power and high power energy deposition

Structure of ELMs

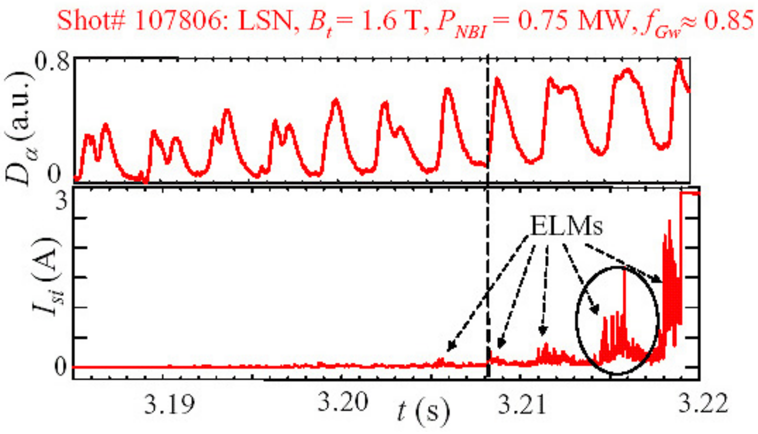
- ELMs, most of the times, are made up of high-frequency plasma blobs injected into the edge region and are not steady plasma ejection events.

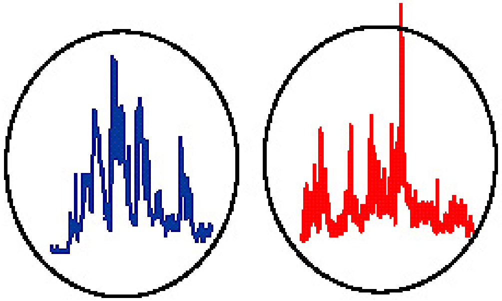
- Fine detailed D-alpha observations have shown that indeed each ELM event is actually a series of small plasma blobs that enter the edge-plasma region from the edge of the pedestal.

- However, in our analysis, because of the high sub-frequency of the blob ELM, it is assumed that these sub ELMs are continuous with total energy and pulse duration equal to the sum of the sub ELMs.

ELM Parameters

ELM Parameter	Value
Power Loading	~ 1-3 MJ/m^2
ELM Event Frequency	~ 1-10 Hz
Total ELM Duration	~ 0.1-1 ms
Blob Subfrequency	~ 10-100 kHz
Blob Pulse Width	~ 5-20 μsec
Plasma Temperature During ELM	1-2.5 keV
Plasma Density During ELM	~ 10^{19} m^{-3}
Magnetic Field Strength At Divertor	~ 1-5 T
Normal Edge-Region Plasma Temperature	~ 10-100 eV
Normal Edge-Region Plasma Density	~ 10^{18} m^{-3}





- To the probe ELMs appear as series of spikes rather than a discrete event as on D_α

Origin of ELMs

- ELM instability results from an overlap of many MHD modes producing a stochastic layer in the pedestal region. The pedestal energy/particles drains away until the ELM instability ends and the door between the pedestal and the SOL is closed.

- At least three types of ELMs have been observed, and is due to different instability:

Type I (“giant”) ELMs can cause the sudden loss of up to 10-15 % of the plasma stored energy. Type I has been associated with ideal ballooning mode unstable by the high edge pressure gradients in H-mode.

Type II (“grassy”) ELMs are observed in strongly shaped plasmas at high triangularity, when the magnetic shear is in the connecting region between the first and second regions of stability to ballooning modes.

Type III ELMs are observed near H-L transition and produce small energy dumps (1-3) % of the plasma stored energy.

ELM Particle & Energy Fluxes

- ELM causes a large increase in particle and heat flux in ξ times:

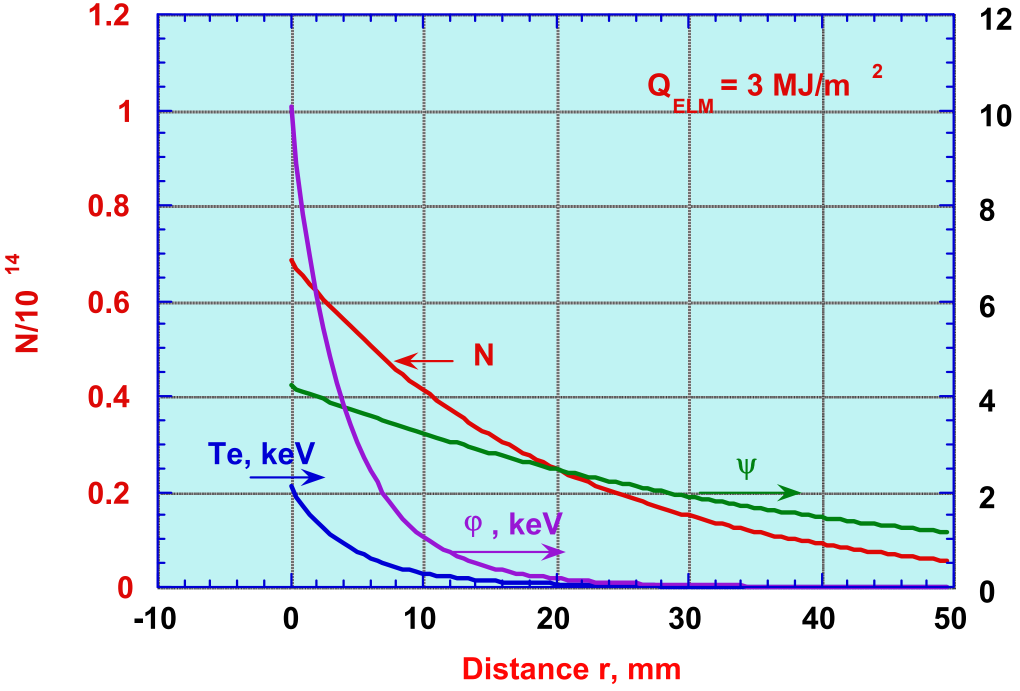
$$\xi = \eta \frac{\tau_E}{\tau_{ELM}} = 50 - 500$$

(for 1% to 10%)

- Can result in a significant increase of mass losses of divertor plate (sputtering, vaporization, brittle destruction and splashing).

- To define these losses and contamination of core plasma, two problems must be solved: dynamics of particles in SOL and interaction of particle and heat fluxes from SOL with divertor plate.

Spatial Distributions during ELMs



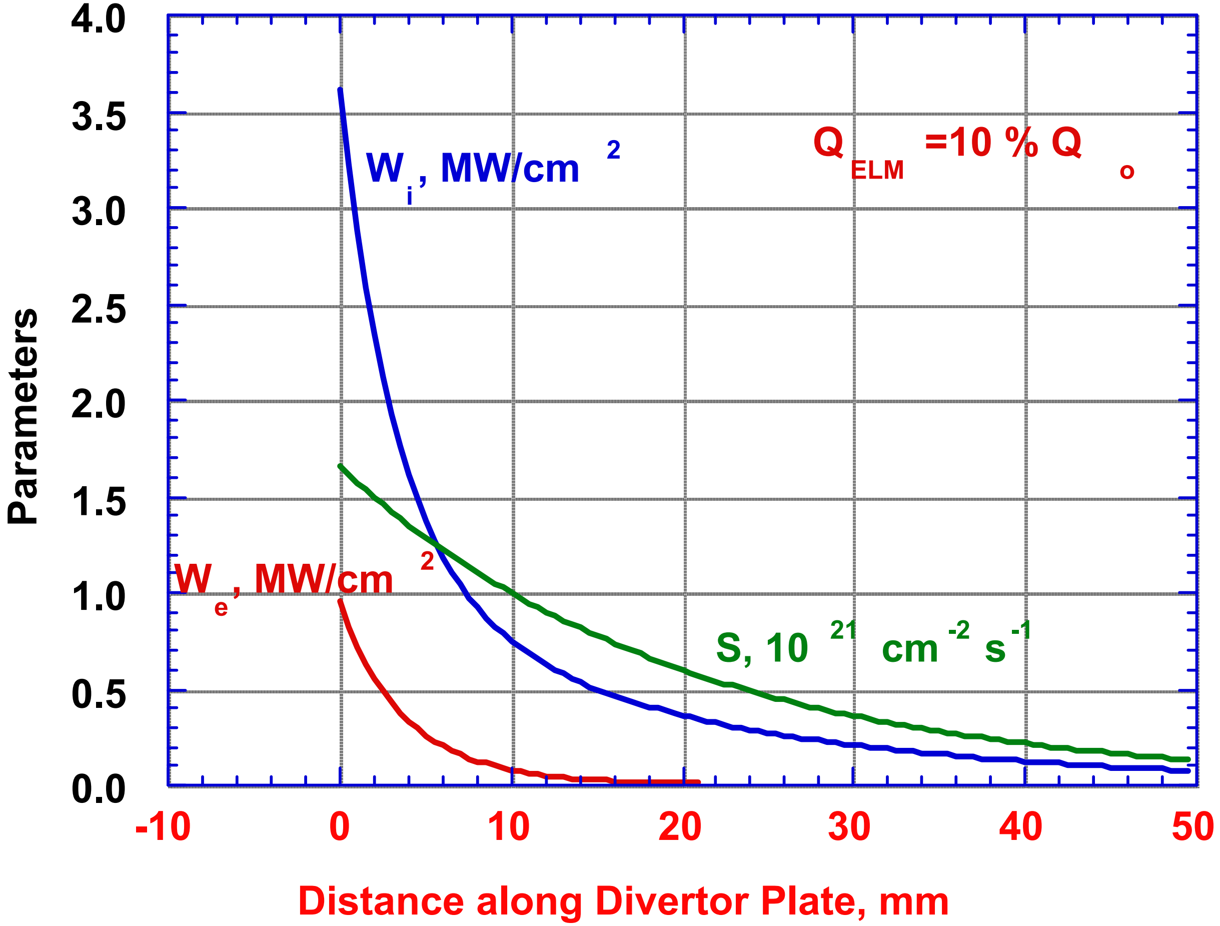
$$\frac{\partial n}{\partial t} = \frac{\partial S_\perp}{\partial r} - \frac{S_{||}}{L_{||}} = 0,\ S_\perp = D_\perp \frac{\partial n}{\partial r},\ S_{||} = nV_{i0}\ ,$$

$$\frac{3}{2} kn \frac{\partial T_i}{\partial t} = \frac{\partial W_{i\perp}}{\partial r} - \frac{W_{i\,||}}{L_{||}} + Q_{ei} = 0,\ W_{i\perp} = \chi_\perp \frac{\partial T_i}{\partial r},$$

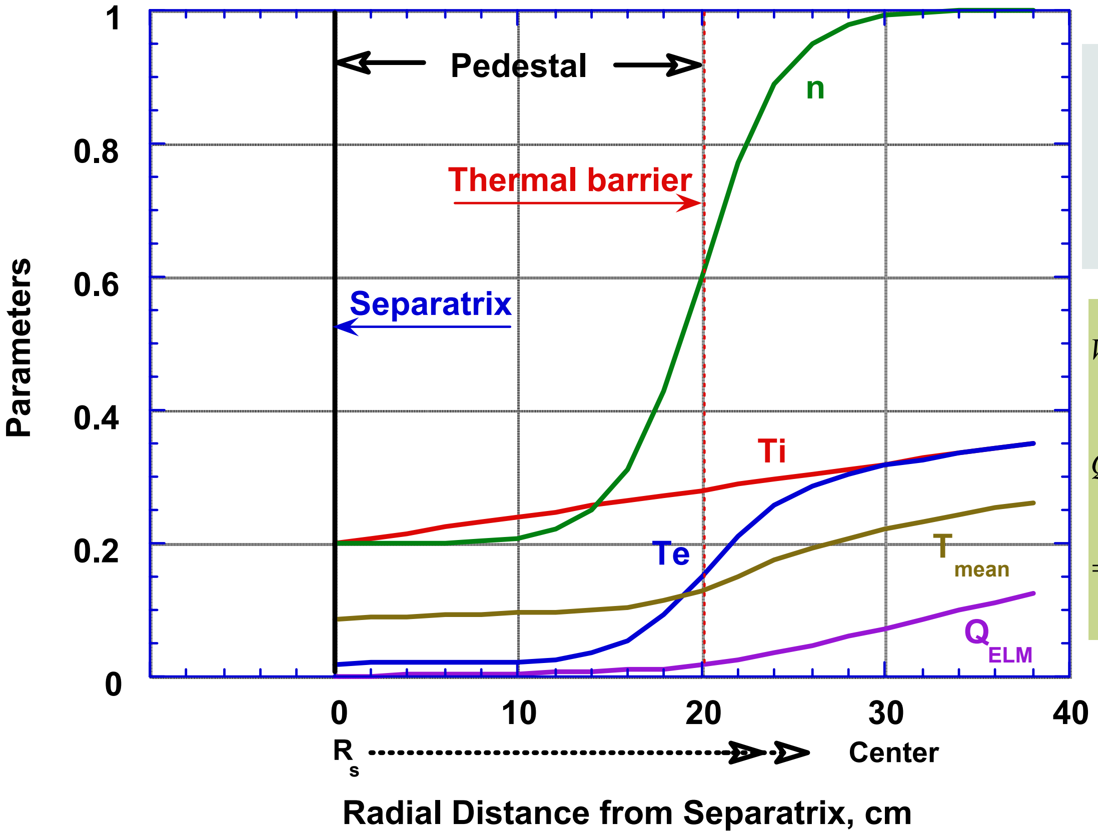
$$S_\perp(r = 0) = D_\perp \frac{\partial n}{\partial r} = \frac{1}{2\pi R}\frac{1}{2\pi a}\frac{N_{ELM}}{\tau_{ELM}}$$

$$W_{i\perp}(r = 0) = W_{e\perp} = \frac{3}{2} k\, T_{mean}\ S_\perp$$

Spatial distribution of particle and heat fluxes during ELMs



Predicted spatial-dependent ELM relative parameters



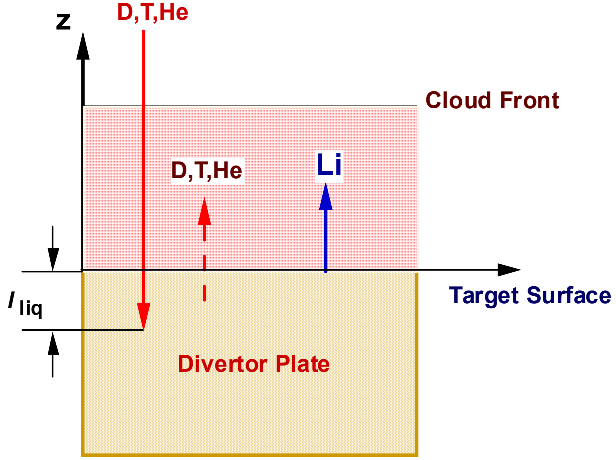
One can find the number of particles (DT ions), N_{ELM}, corresponding to an energy Q_{ELM} that escape to SOL during an ELM:

$$V_{ELM} = 2\pi R_0 \cdot \pi (R_s^2 - R_{ELM}^2), N_{ELM} = \int_{R_{ELM}}^{R_s} n_i(r) 2\pi R \cdot 2\pi r \cdot dr,$$

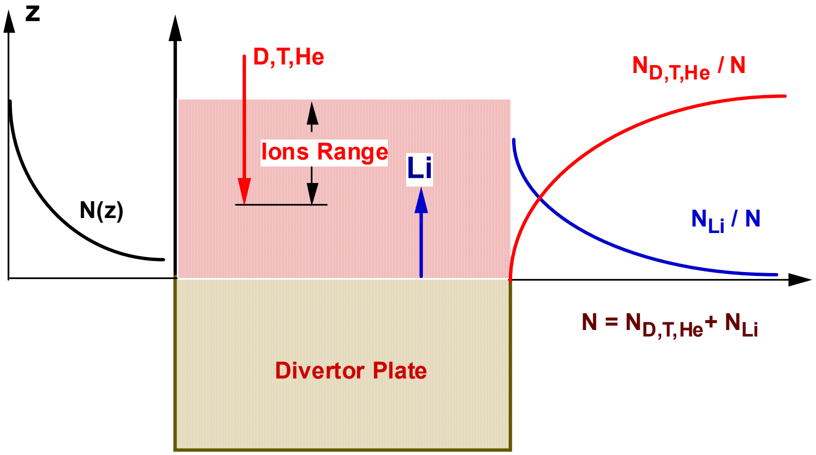
$$Q_{ELM} = \int_{R_{ELM}}^{R_s} \frac{3}{2} k \left(T_i + Z_{eff} T_e\right) n_i(r) 2\pi R \cdot 2\pi r \cdot dr =$$

$$= \frac{3}{2} k T_{mean} \left(1 + Z_{eff}\right) \cdot N_{ELM}, T_{mean} = \frac{2 Q_{ELM}}{3k \left(1 + Z_{eff}\right) N_{ELM}}$$

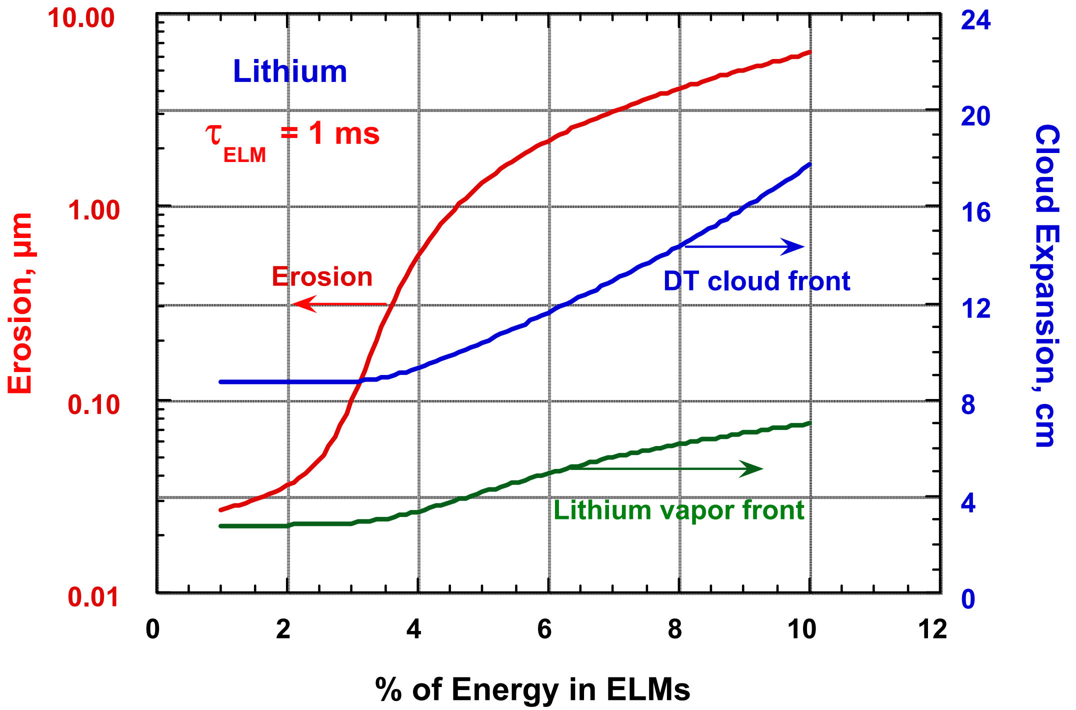
Lithium surfaces under ELMs



Initial Stage of Cloud Formation



Mixing Stage

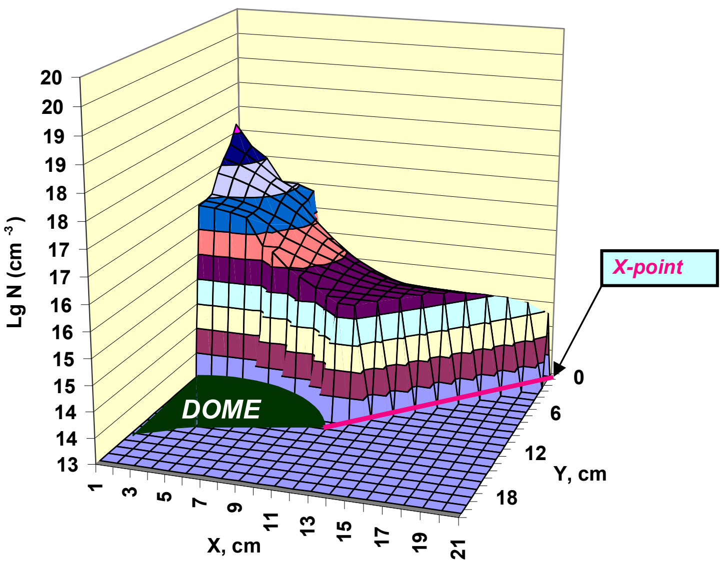


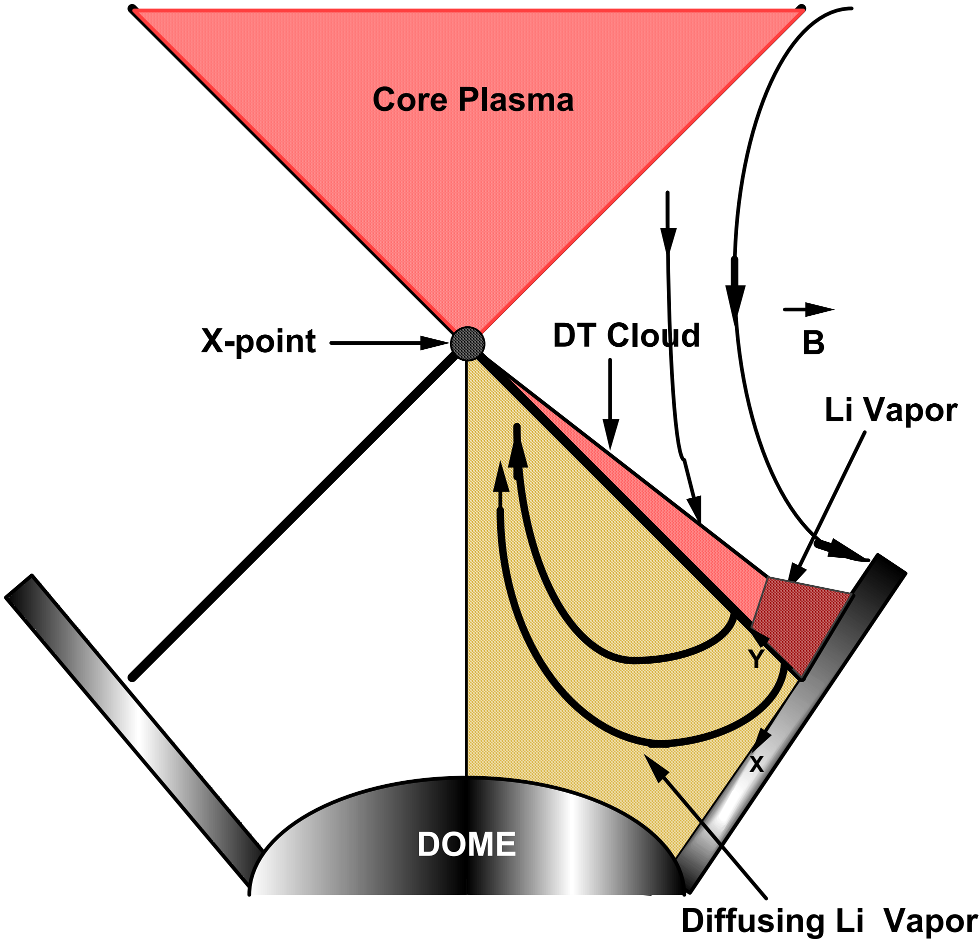
- notes

Lithium vapor transport in private flux region

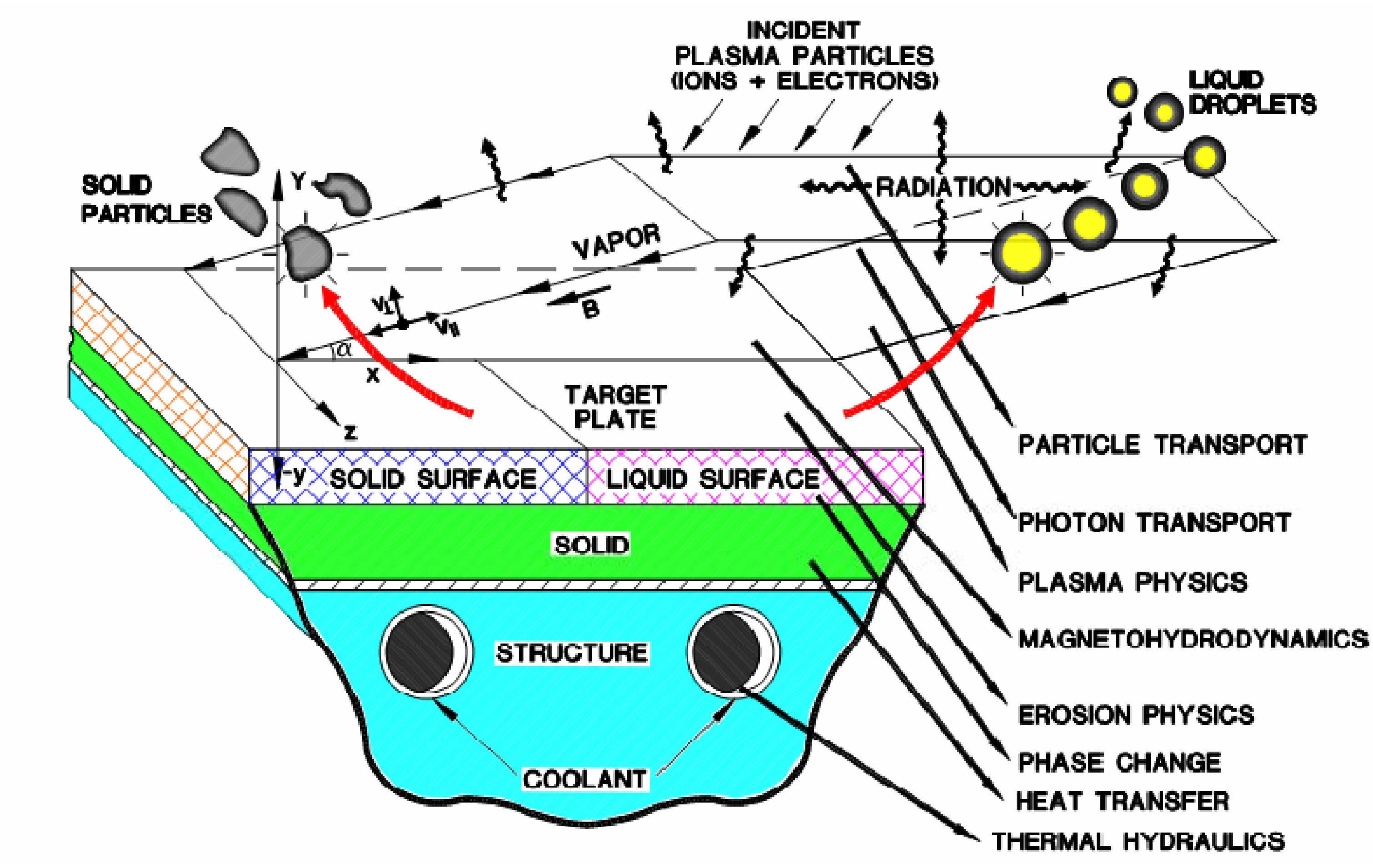
- **Impurities (Li Vapor) Can Reach Core Plasma From Lower Space Due to Diffusion Across Separatrix**

Li vapor, Density at t=100 μs



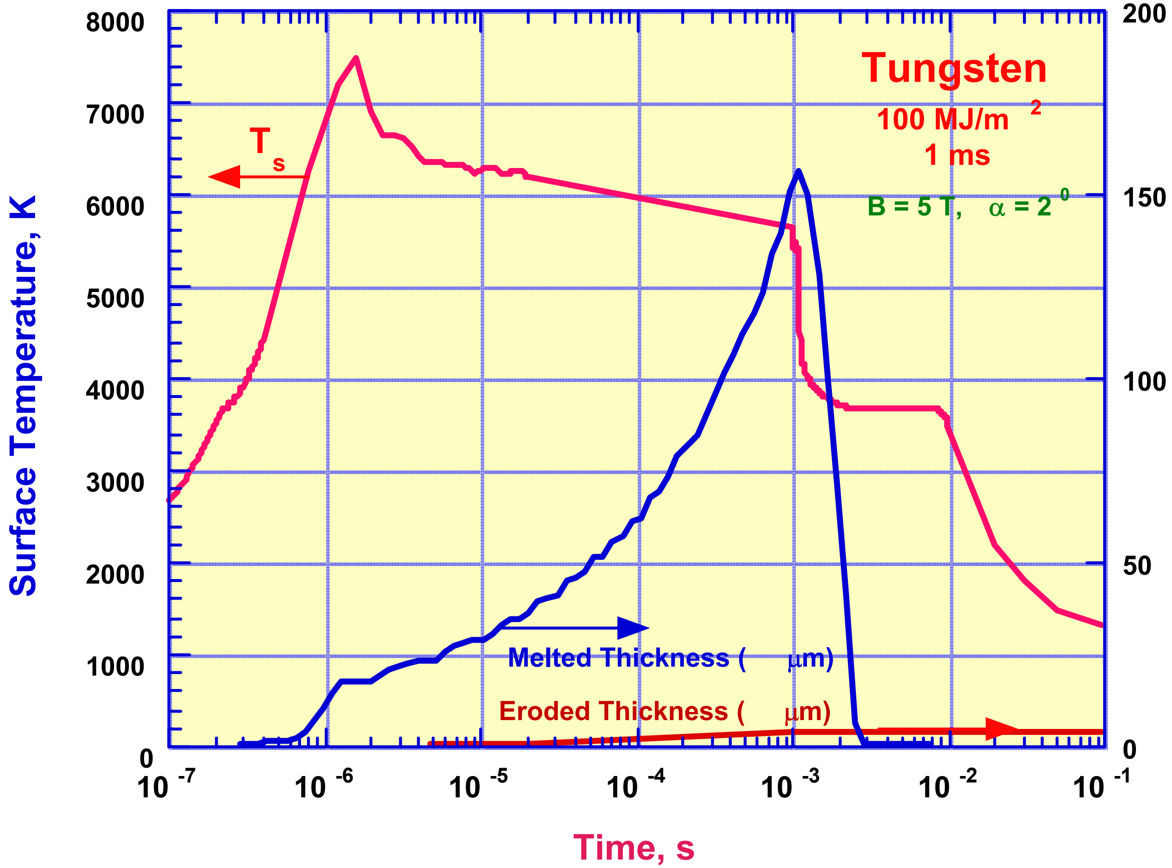


Models Integration of Various Beam-Target Interaction Physics in HEIGHTS

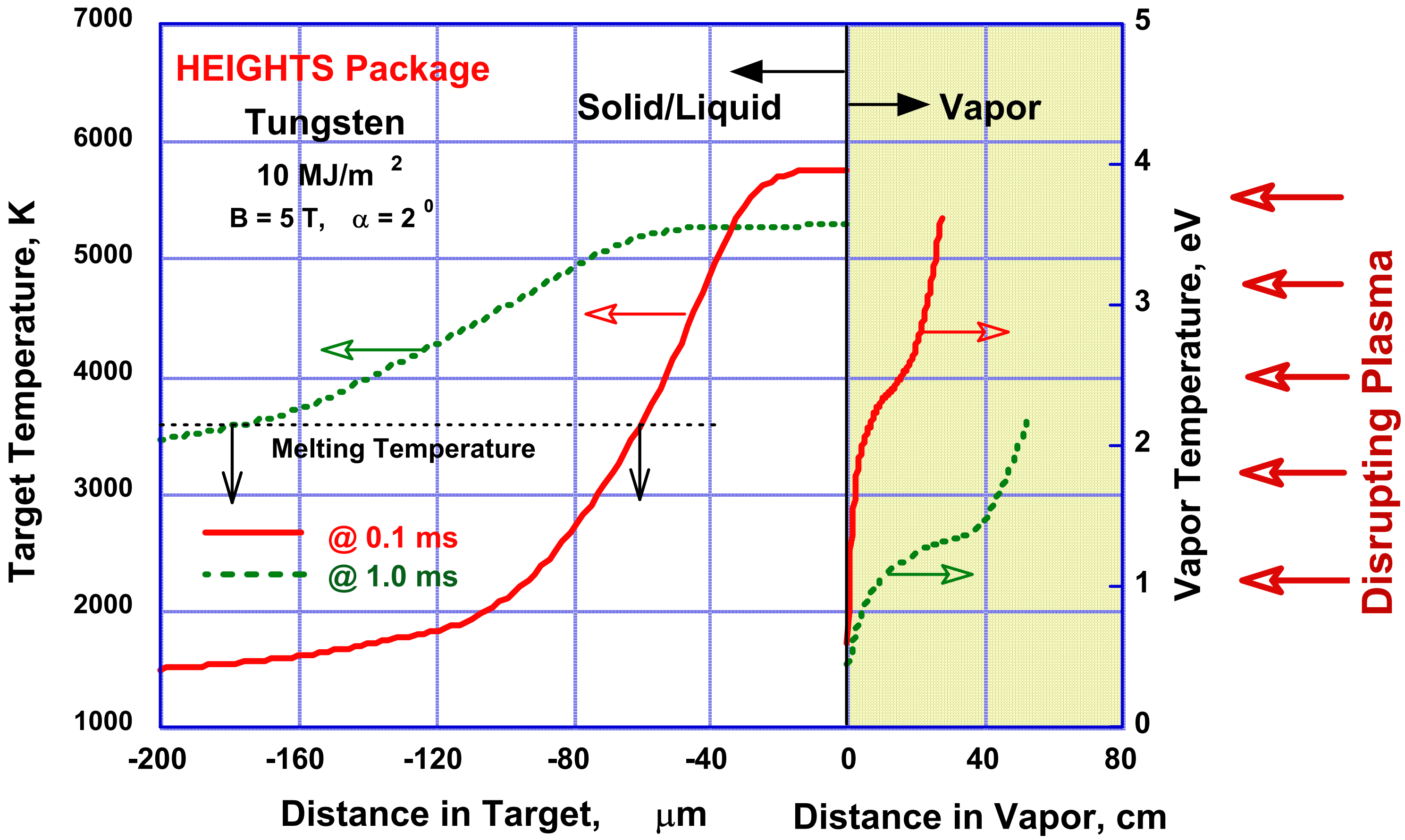


PFC response during disruptions

- **Sharp initial rise in temperature is due to the direct energy deposition of incident plasma particles at the material's surface**



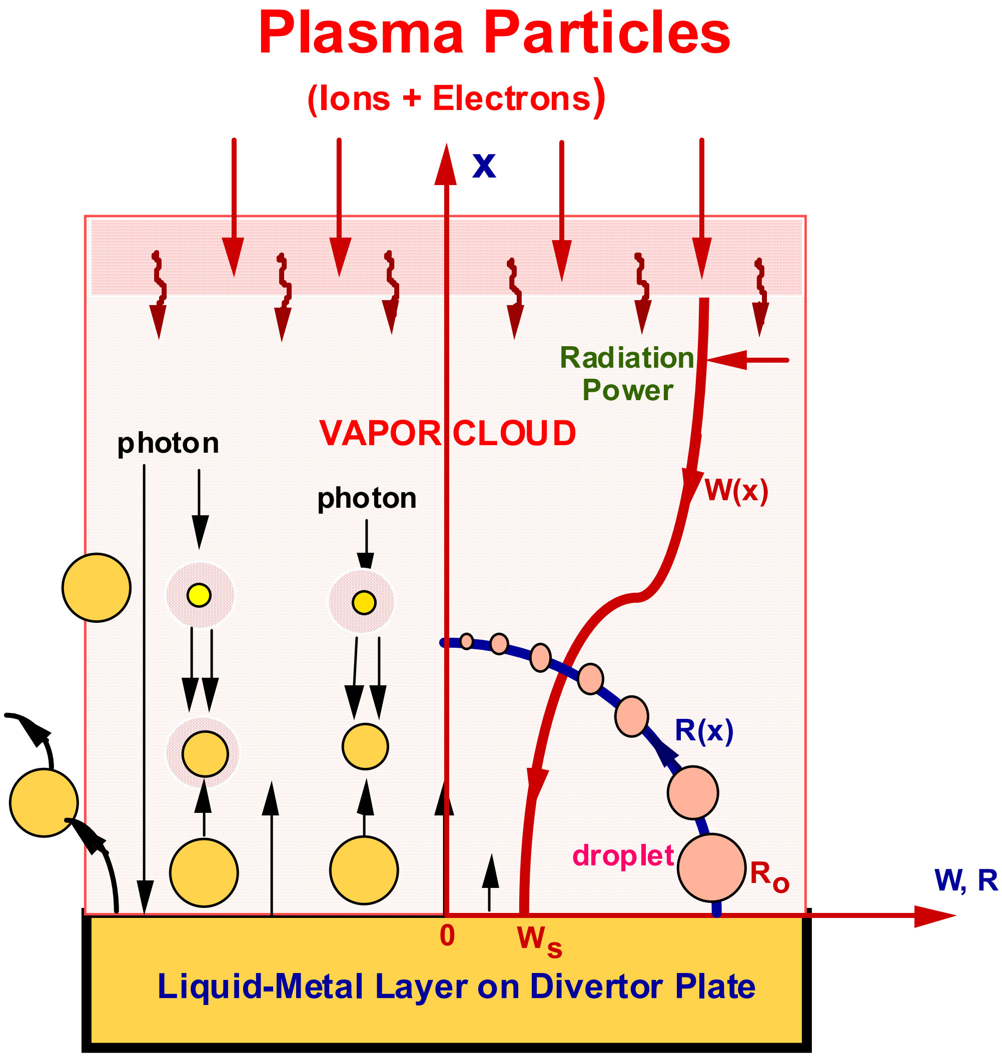
Erosion from disruptive plasmas



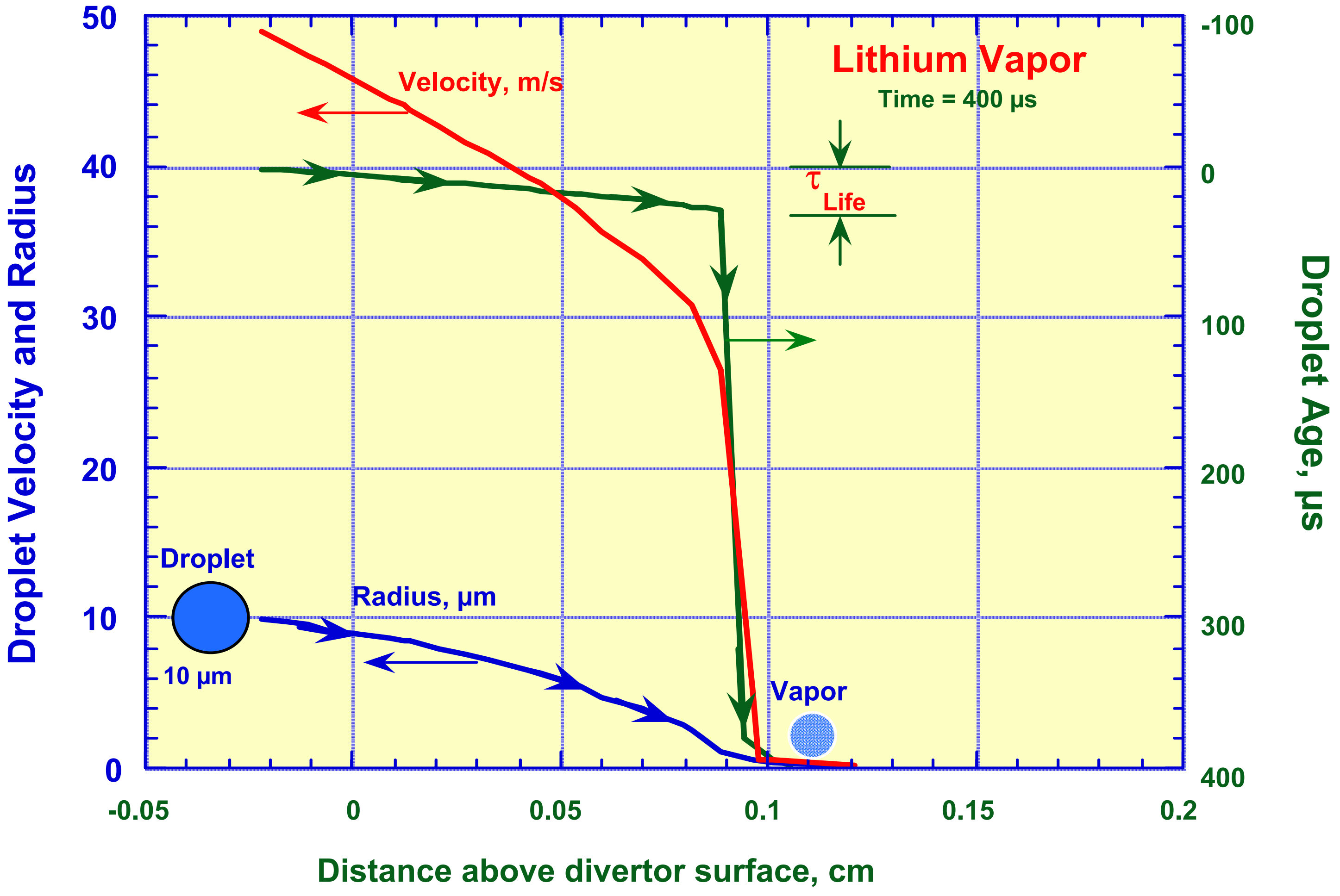
- At the shorter duration time, both the liquid-solid and vapor temperatures are higher than during longer disruption times!

Vapor shielding mechanisms

- **During the early stages of an intense power deposition on a target material (i.e. divertor, limiter), a vapor cloud from target debris is formed above the bombarded surface.**
- **This shielding vapor layer could be either beneficial or detrimental depending on application.**
- **Macroscopic particles (MP) emitted into the vapor cloud will significantly alter the hydrodynamic evolution of the vapor plasma.**

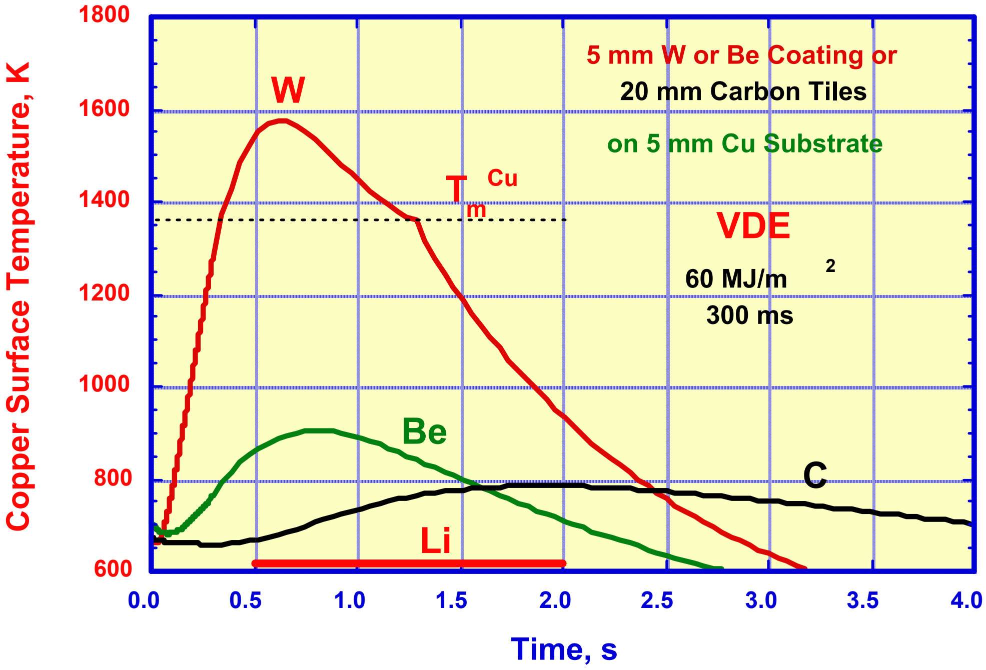


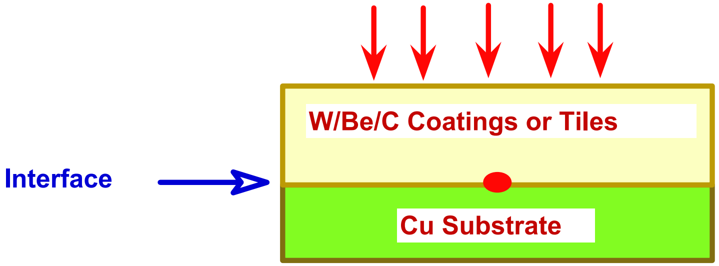
Evolution and lifetime of a lithium droplet (MP) moving in Li vapor



Structural material response under VDEs

- Surface temperature of the copper-structure during a VDE calculated for various PFC coatings
- Energy released to the surface ~ 60 MJ/m^2 in 300 ms
- Note that with a W coating, the copper surface interface melts!
- Most energy lost to low-Z vapor cloud leaving little energy to conduct




W/Be/C Coatings or Tiles

Interface

Cu Substrate

Summary and Conclusions

- Net erosion damage to PFCs due to plasma instabilities (e.g. ELMs in normal operation; or disruptions in off-normal operation) should include surface vaporization loss, erosion damage to nearby components from intense vapor radiation, and macroscopic erosion
- Liquid-metals (specifically Li) show promise due to self-healing properties and particle pumping capabilities
- Temperature-dependent erosion data indicate that for liquid Li strict limits on operation regimes must be met
- Both in ELM operation and during disruptions/VDEs, a complex interaction of eroded debris and incident plasma must be modeled self-consistently to obtain reliable data on tokamak performance
- Large-scale devices that intend to operate as burning plasmas (e.g. ITER) must address serious issues on handling extremely large particle and heat fluxes under both normal and off-normal operation