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# Response of Plasma Facing Components to Various Transient Events in Tokamak Devices: Serious Concerns for ITER!

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Presented at 1st International Symposium on "Edge Plasma and Surface Component Interactions in Steady State Magnetic Fusion Devices"

NIFS, Toki, Gifu, Japan

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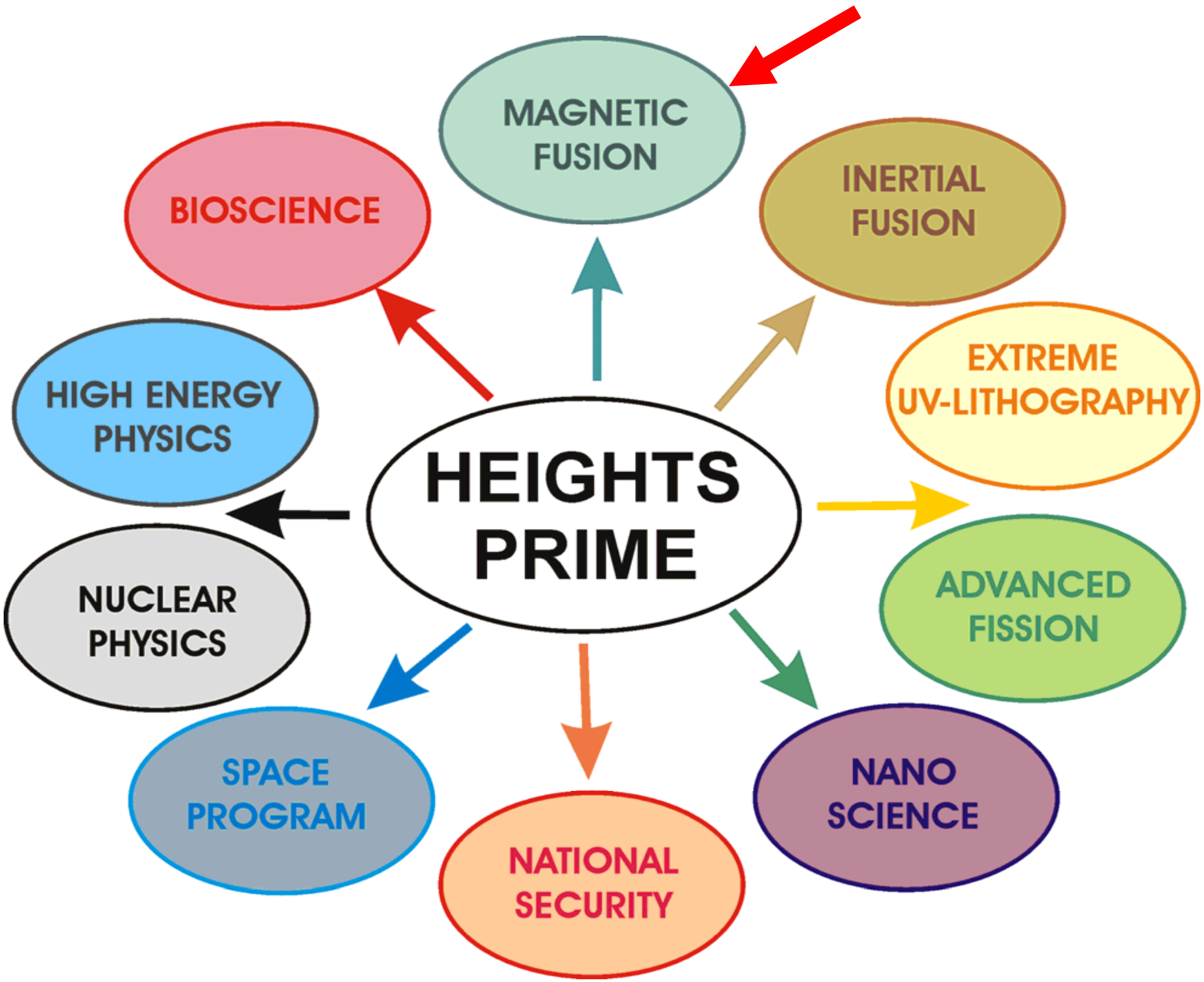
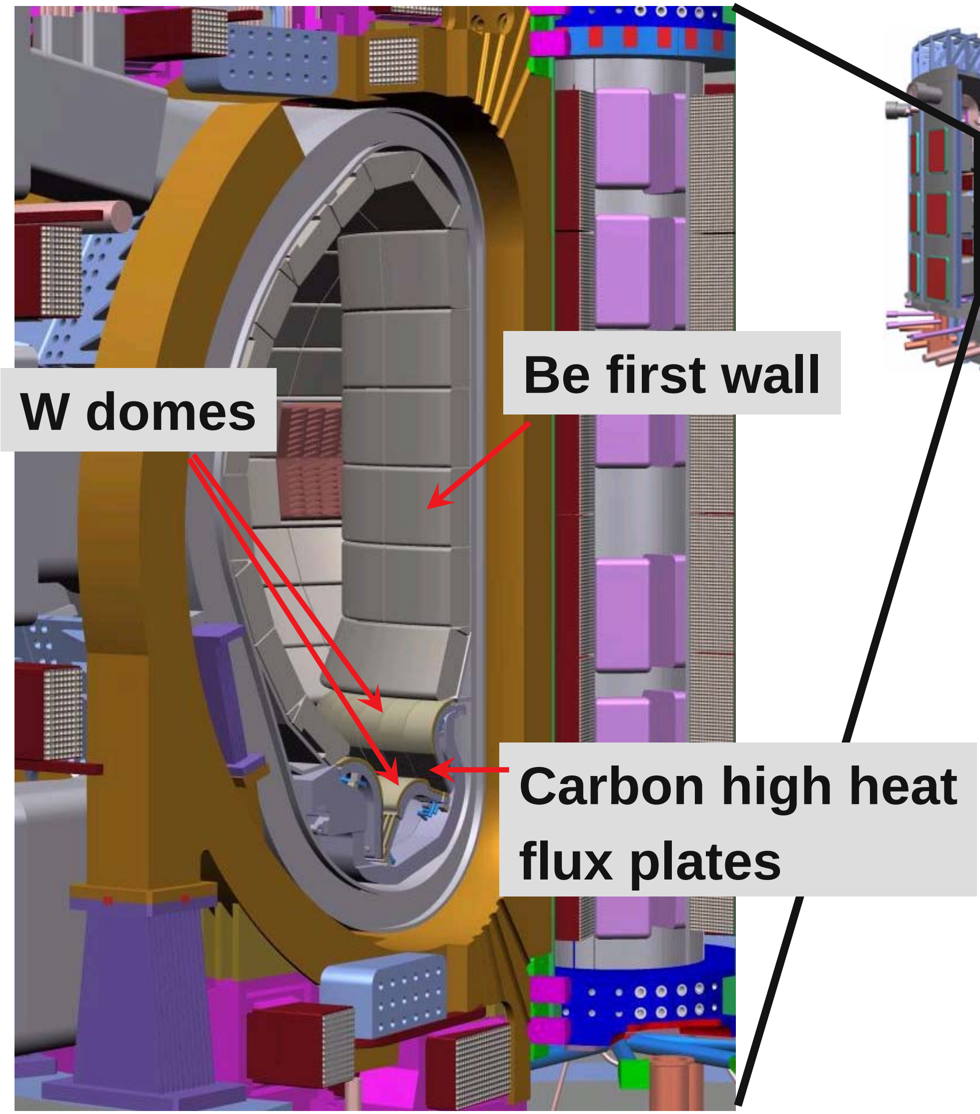
# Outline

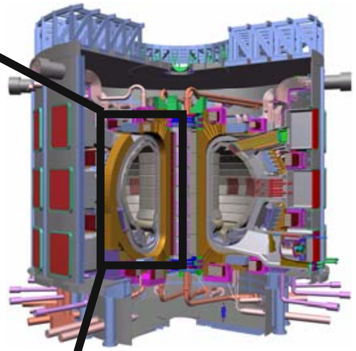
- Various Modeling Activities at Argonne
- Magnetic Fusion Applications
- Various Plasma Transient Events
- Disruption Modeling & Simulation
- Edge-Localized Modes (ELMs)
- Vertical Displacement Events (VDEs)
- PRIME Facilities & Simulated Experiments
- Summary & Conclusions

# Magnetic Fusion Activities



# Magnetic Fusion (ITER) work at Argonne



- **Plasma-Material Inter.**
  - Material response under plasma instabilities
  - Tritium behavior in walls
  - MHD effects

- **Surface effects**
  - Mixed-material models predictions
  - Eroded material migration from wall to divertor

- **PRIME Experiments**
  - Mixed-materials testing in *IMPACT* (benchmark surface codes) and multiple-beam experiments
  - High-heat flux materials testing (benchmark HEIGHTS)
  - Liquid metal behavior

# ITER Abnormal Events

- **Transient events in Tokamaks and their effects on plasma facing and structural components are probably the most serious issue hindering the successful production of fusion energy**

- **Transient events include:**

  **- Plasma disruptions**

  **- Edge localized modes (ELMs)**

  **- Vertical displacement events (VDEs)**

- **HEIGHTS (High Energy Interaction with General Heterogeneous Target Systems) was developed to study various beams (laser, ions, electrons, plasma) with target materials and resulting damage in an integrated and self-consistent package.**

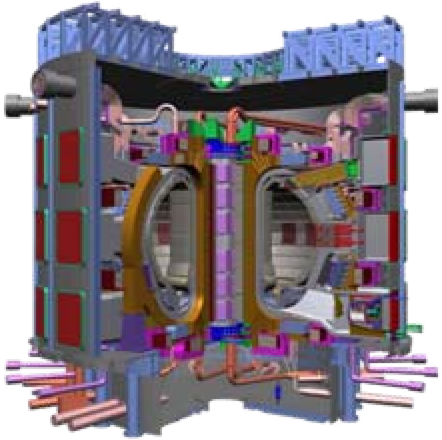
# *Response of PFC during Transient Events*

- **Performance under Disruption**
  - **Plasma is terminated**
  - **Low frequency events**

- **Performance under ELM operation**
  - **Normal operation**
  - **Various types of ELMs**

- **Performance under VDE**
  - **Low frequency events**
  - **Could have severe effects on structural materials!**

# Characteristics of Transients

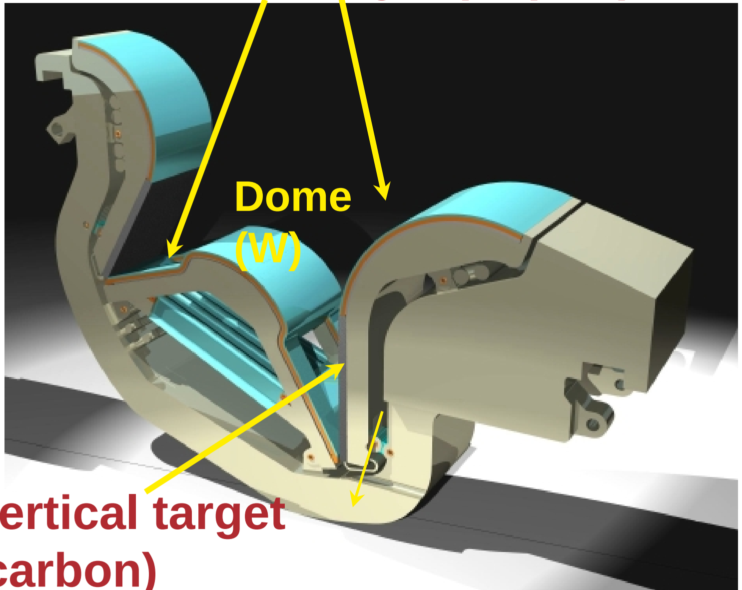


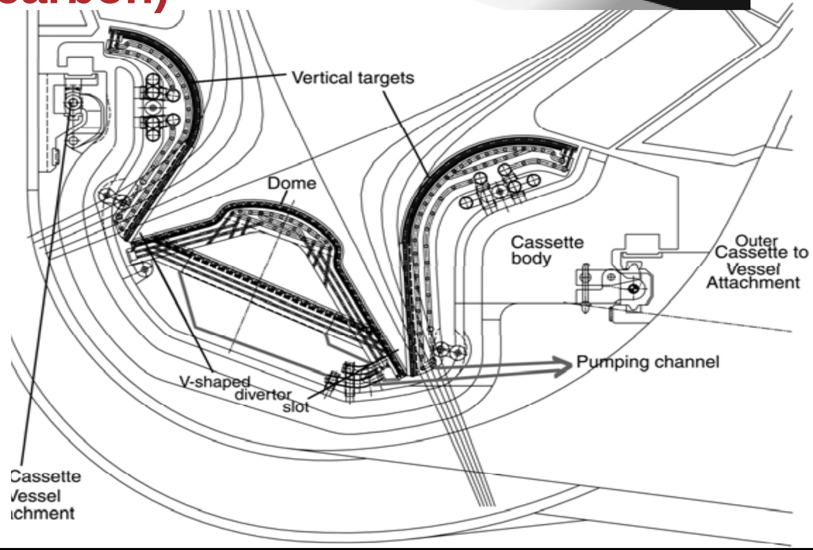
## I. Disruptions

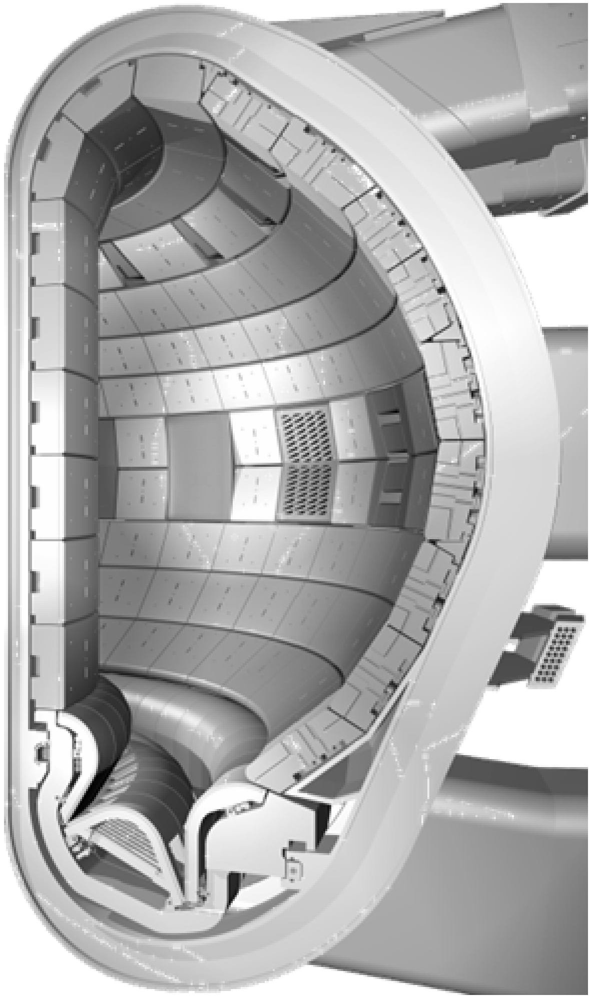
- Disruption is a complete loss of plasma confinement
- Up to 100 $MJ/m^2$ is deposited on divertor materials
- Deposition time is from 1 -10 ms.
- Complicated physics:
  - Vapor cloud shielding
  - Vapor instabilities
  - Damage to nearby PFC
- Disruptions in Tokamaks can be simulated in powerful plasma gun devices.

| Event | Repetition | Duration [ms] | Energy dump $[MJ/m^2]$ | Power flux $[GW/m^2]$ |
|---|---|---|---|---|
| Disruption | Low | 1-10 | $10\text{-}10^2$ | $10^2$ |
| A giant ELM | >1 Hz | 0.1-0.5 | 1-3 | 1-10 |
| VDE | Low | $10^2\text{-}10^4$ | 20-60 | 0.01-0.1 |

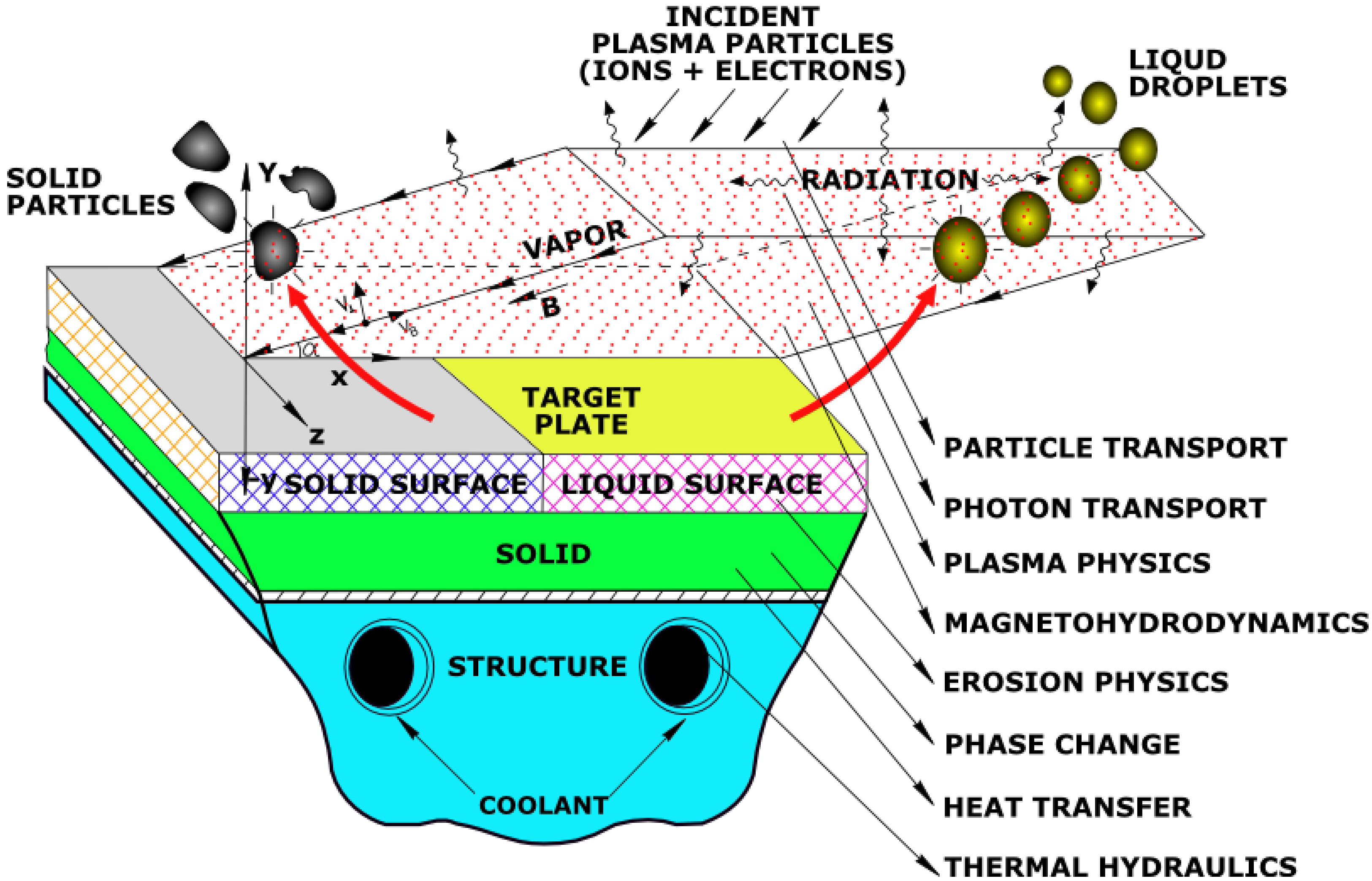
# ITER Divertor Design



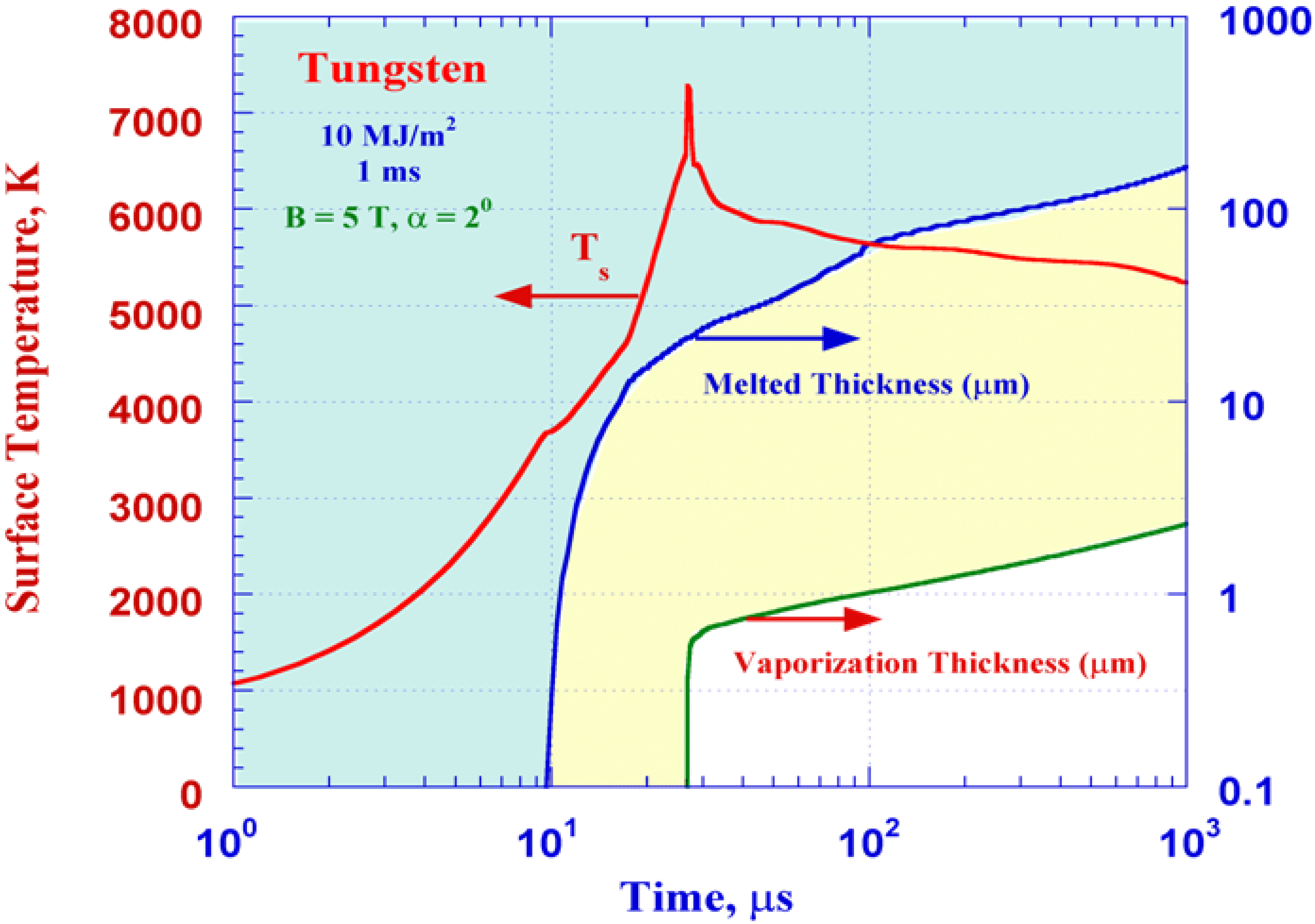
# Models Involved in Predicting High-Intensity Plasma/Surface Interactions



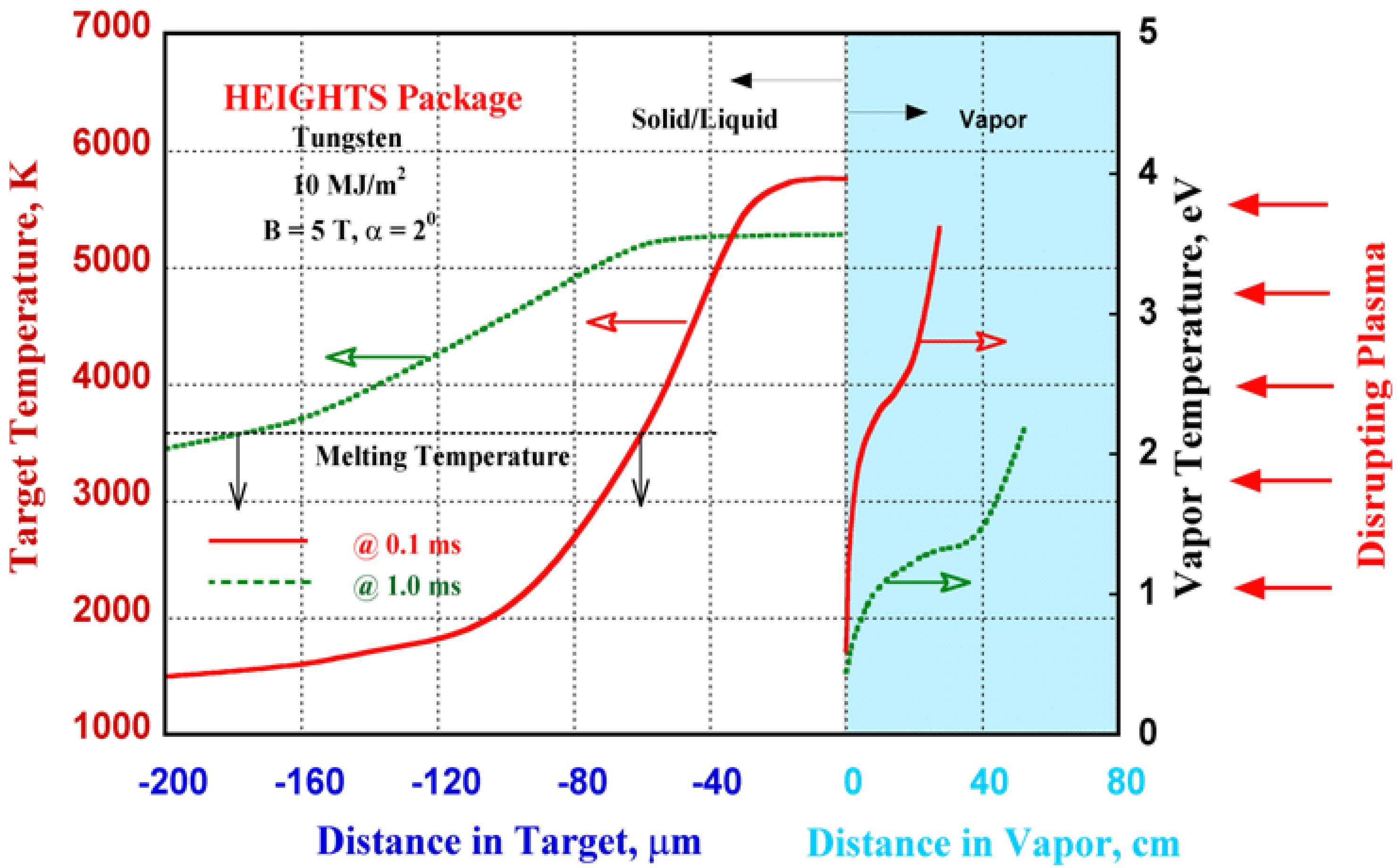
# HEIGHTS Modules & Physics (2-3D Capabilities)

- **Heat Transfer and Thermal Evolution**
- **Thermal-Hydraulic Analysis**
- **Physics of Beam/Plasma/Target Interactions**
- **Ion Implantation and Transport**
- **Particle Diffusion and Permeation**
- **Surface Modification**
- **Magnetohydrodynamics (MHD) Analysis**
- **Atomic and Plasma Physics**
- **Photon Radiation and Transport**
- **Liquid-Metal Splashing and Fragmentation**
- **Shock Wave Physics**
- **Material Erosion, Destruction, and Lifetime Prediction**

# HEIGHTS Analysis of Tungsten Target Thermal Evolution during Intense Energy Deposition



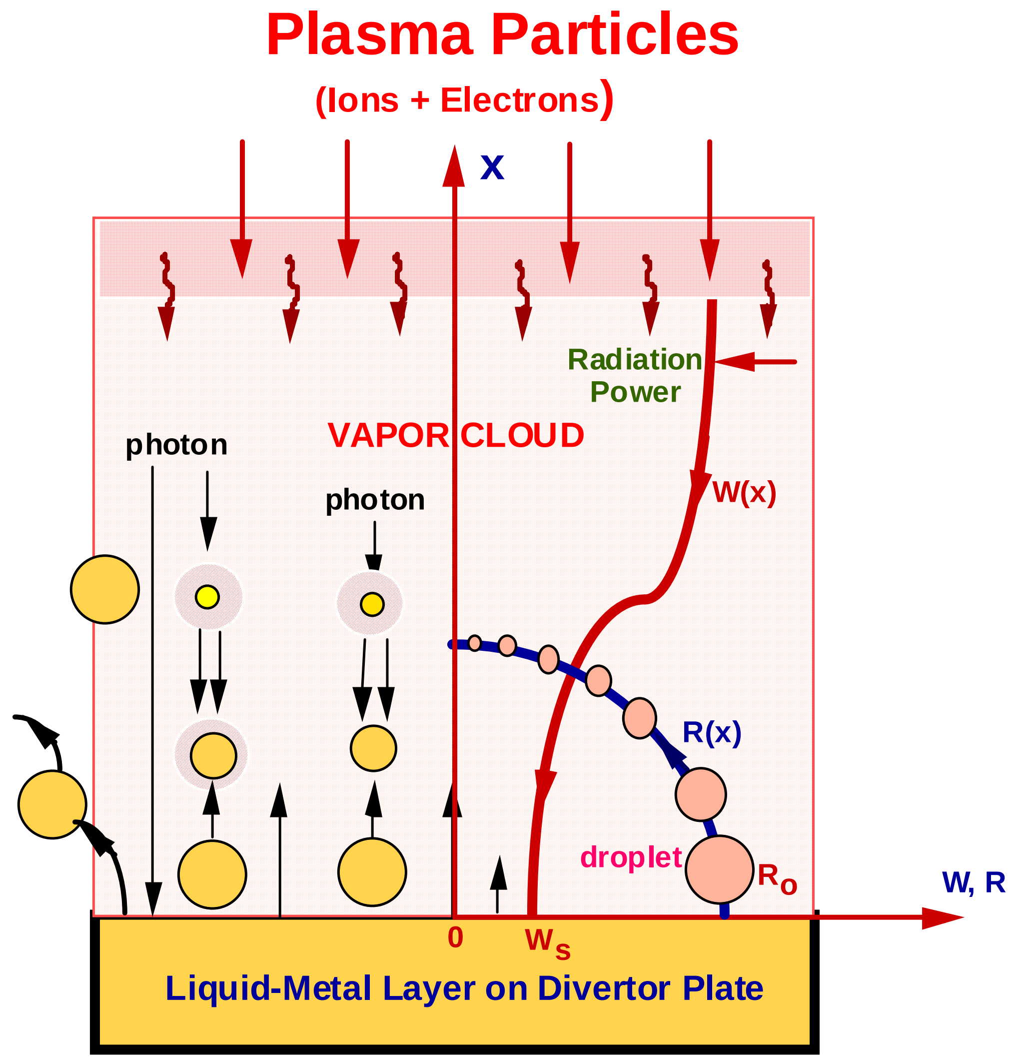
# Spatial Evolution of Tungsten Solid-Liquid-Vapor Cloud Temperatures at Two Disruption Times



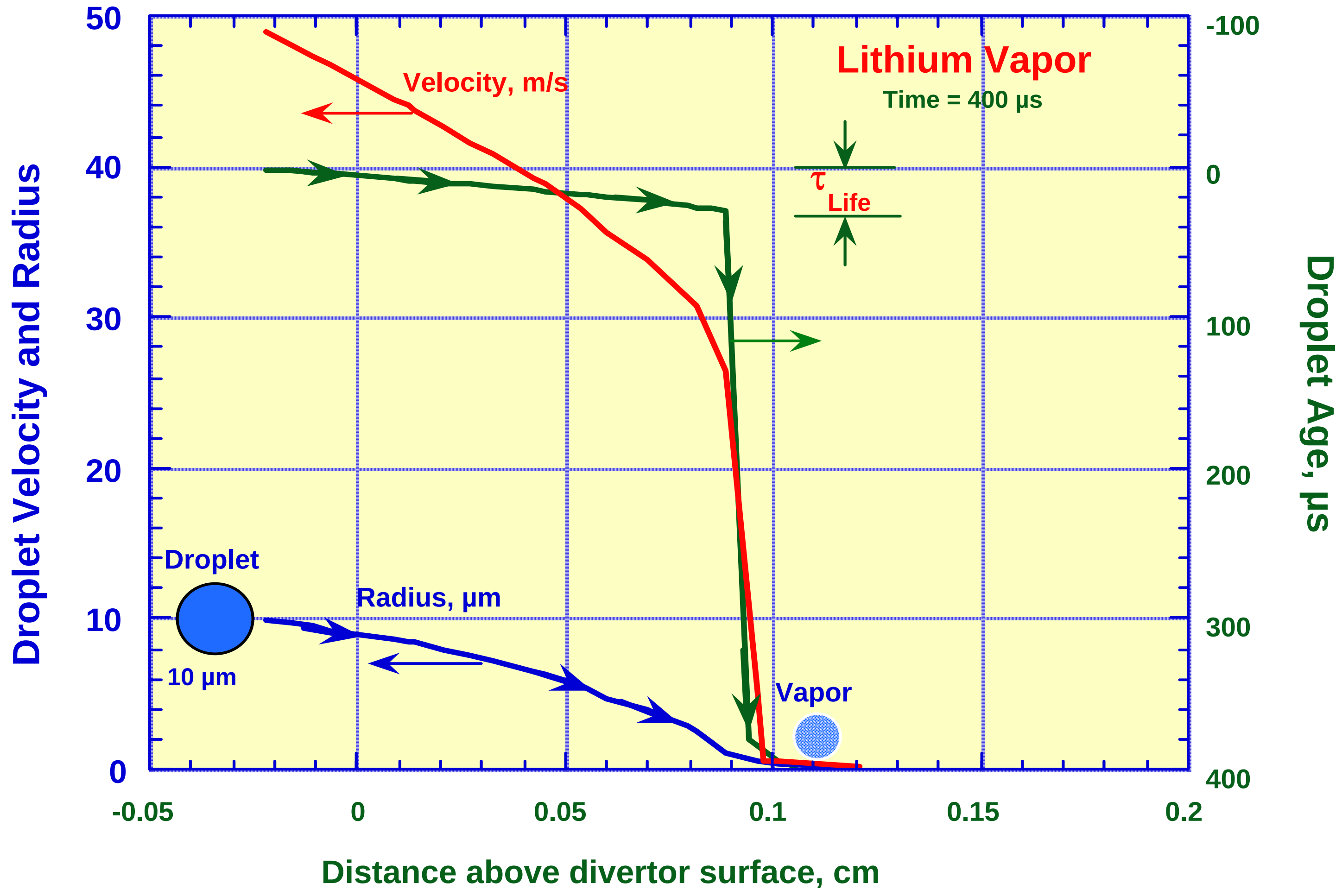
# Vapor/droplet Shielding Mechanisms

- 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.

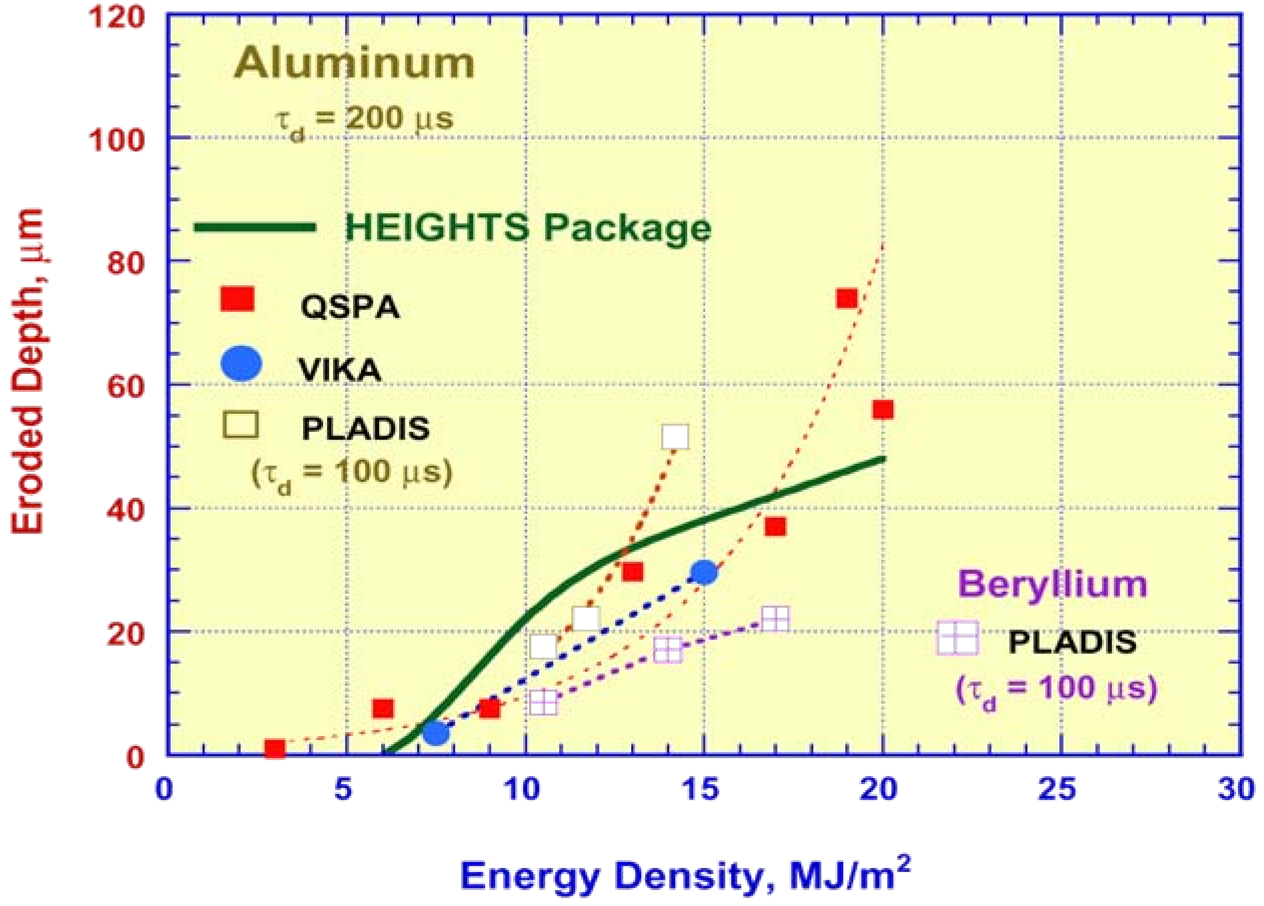
- Macroscopic particles emitted into the vapor cloud will significantly alter the hydrodynamic evolution of the vapor plasma.



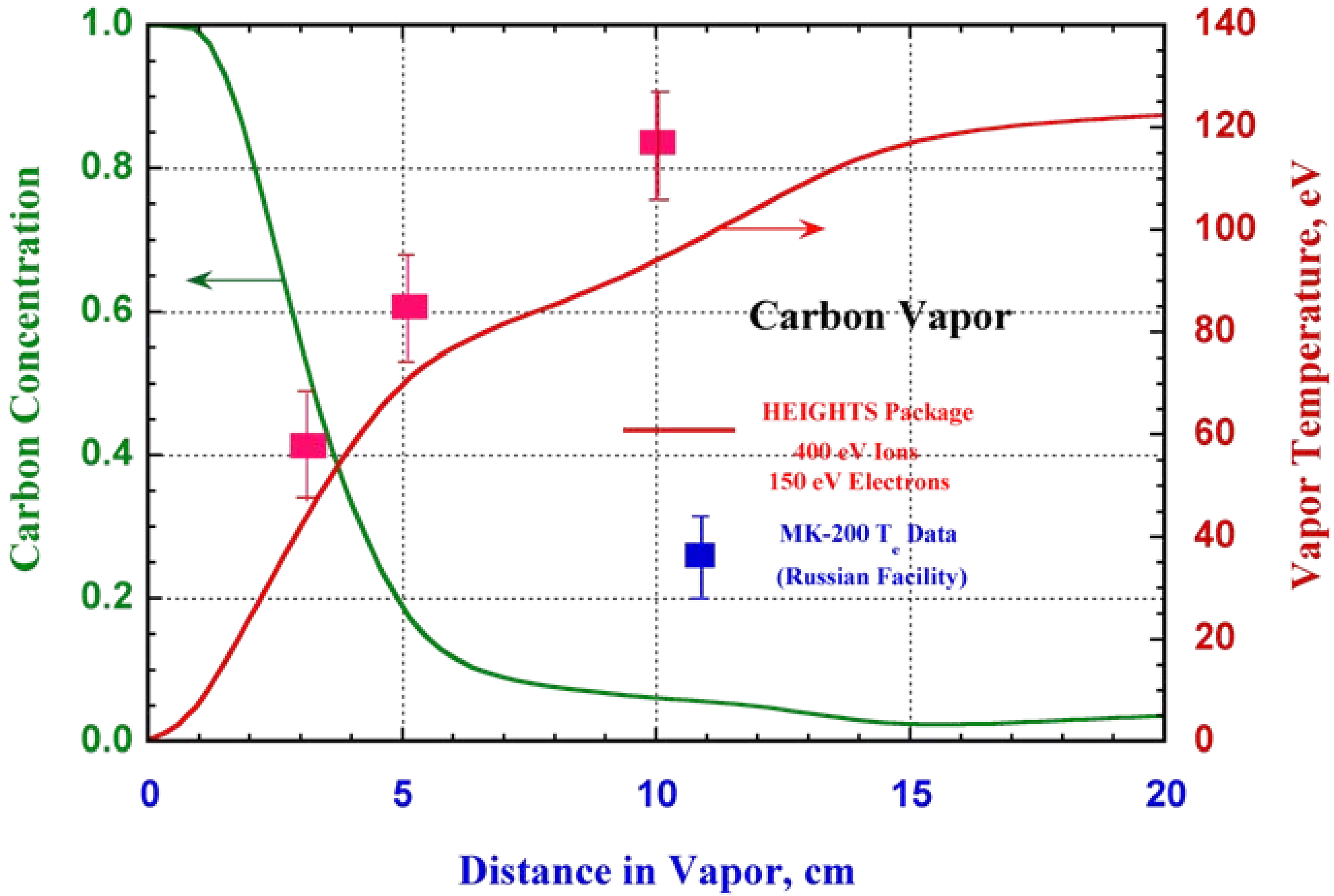
# Evolution and lifetime of a macroscopic droplet moving in vapor cloud



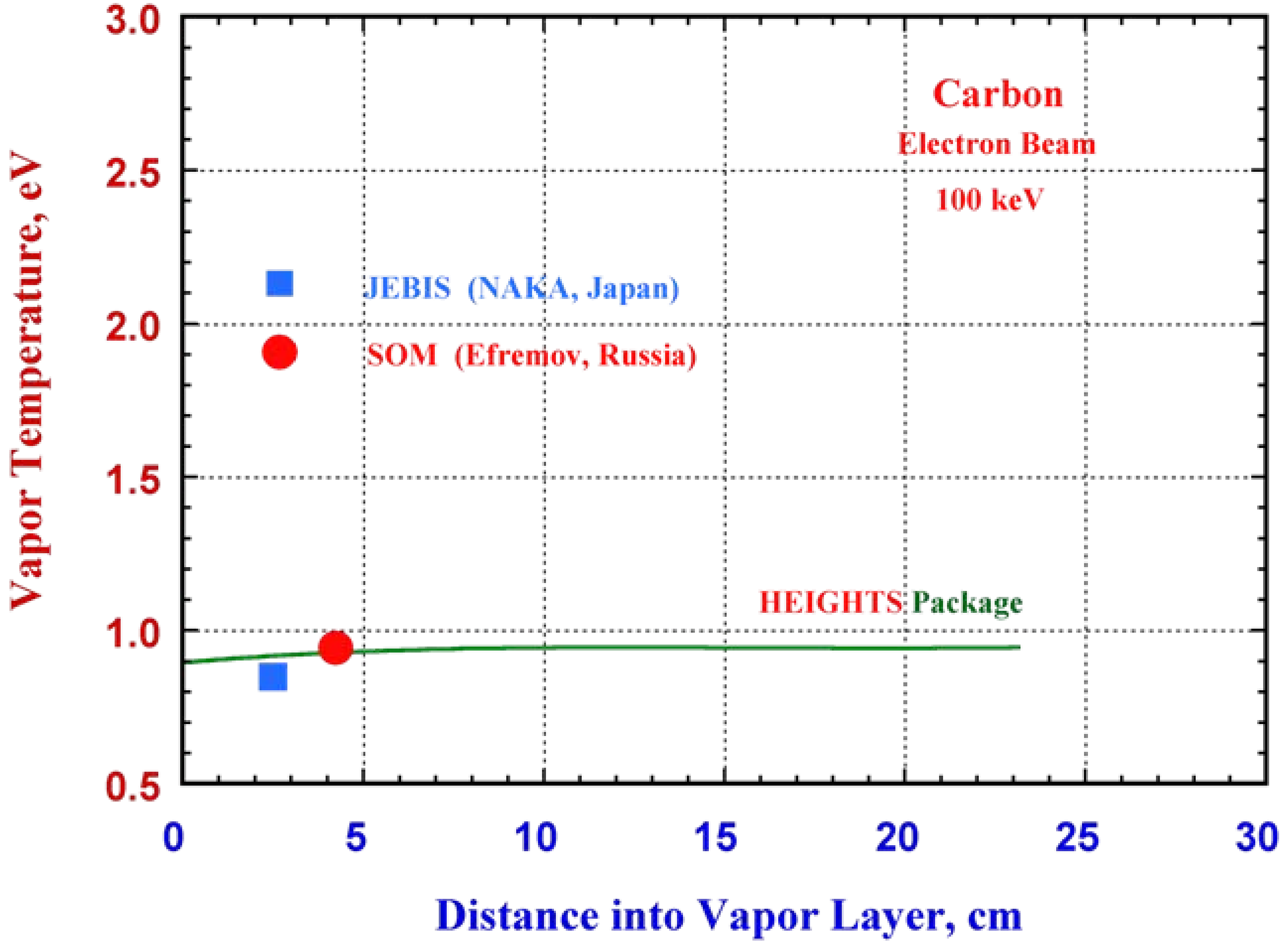
# HEIGHTS Analysis of Aluminum Erosion Data from Plasma-Gun Energy Deposition



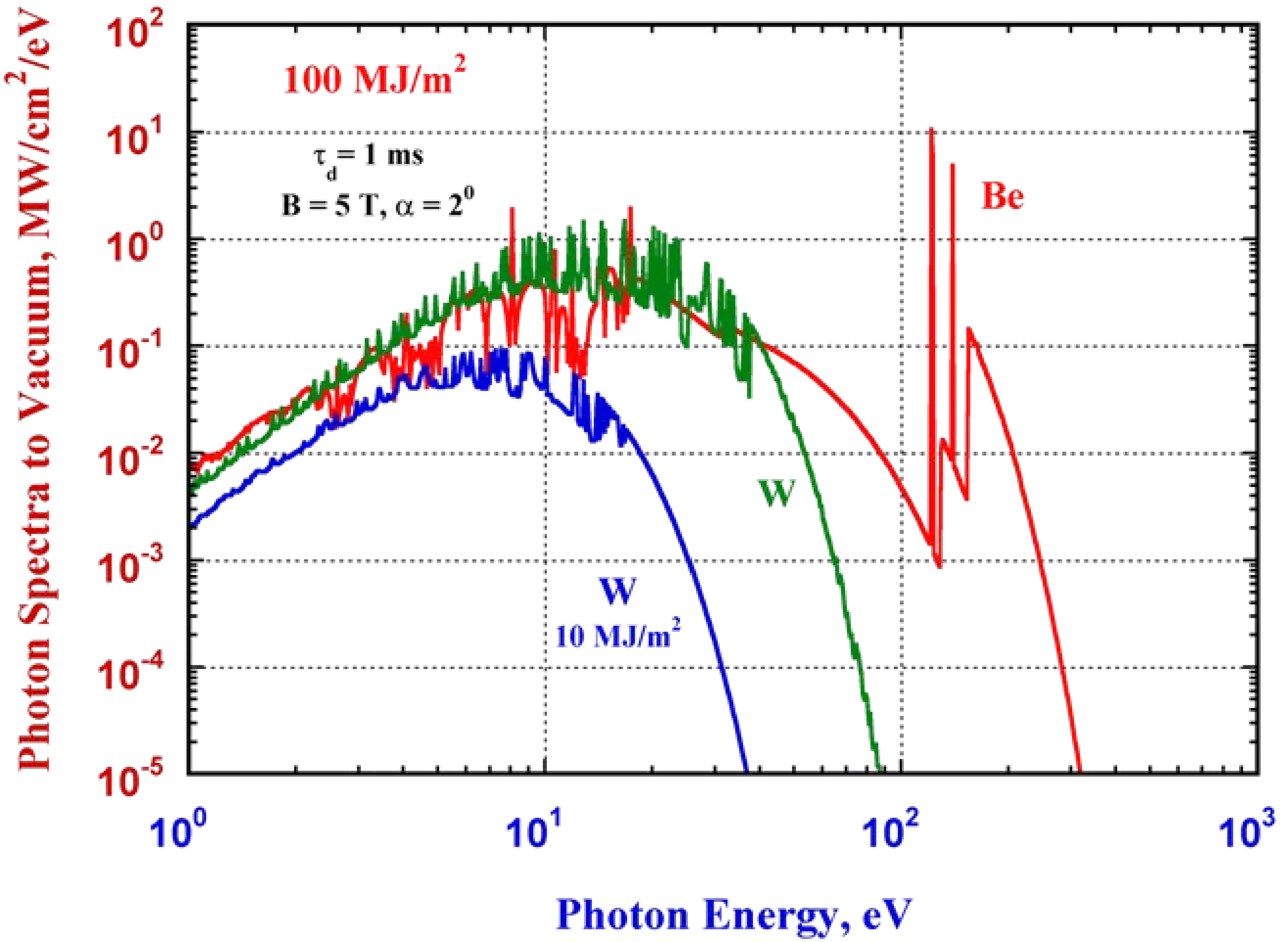
# HEIGHTS Comparison of Plasma Gun Experimental Data of Carbon Target



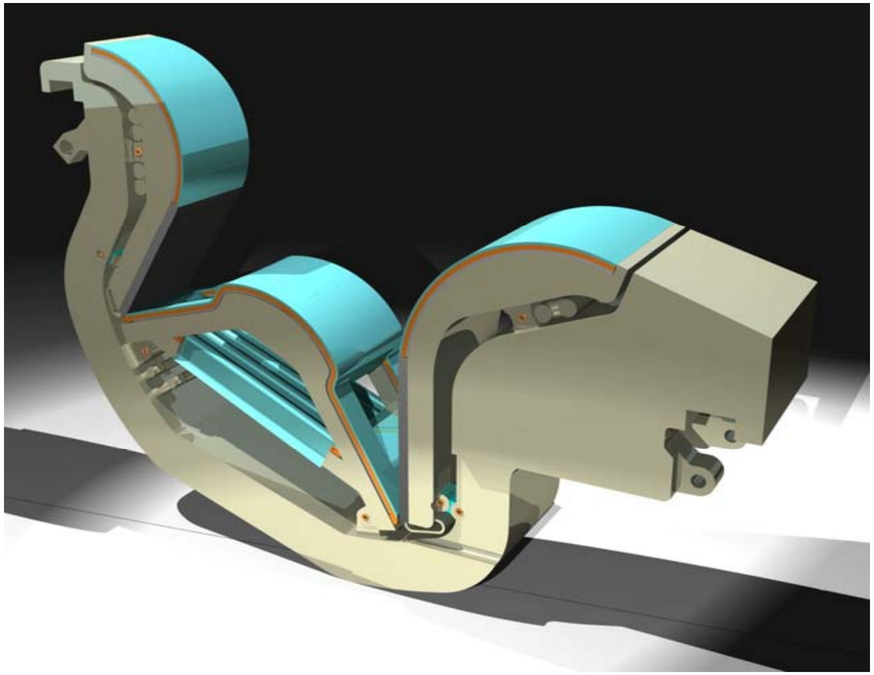
# Comparison of HEIGHTS with Experimental Data Using Electron Beams on Carbon Target

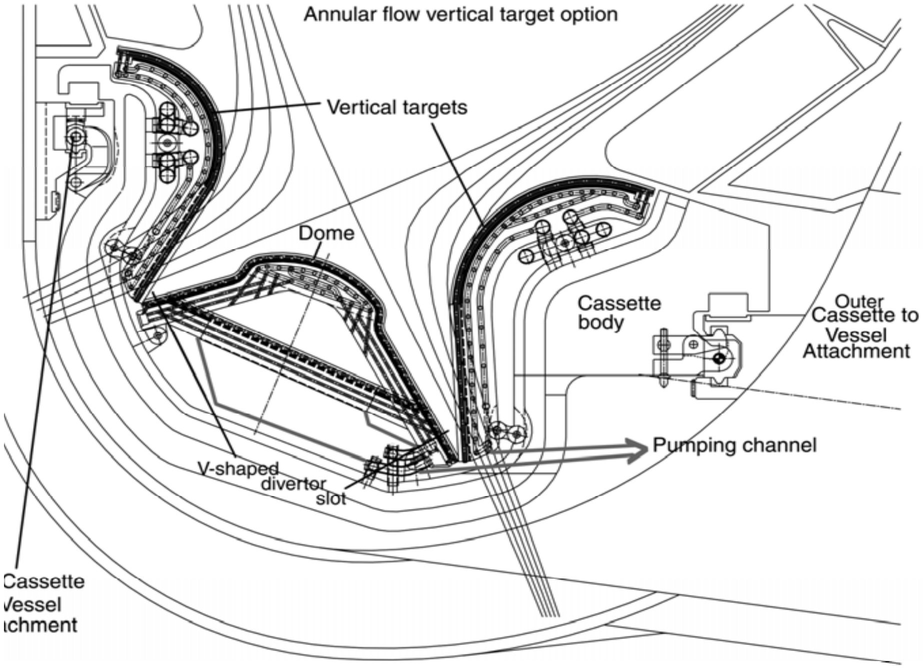


# HEIGHTS Analysis of Emitted Photon Radiation Spectra of Beryllium and Tungsten Vapor

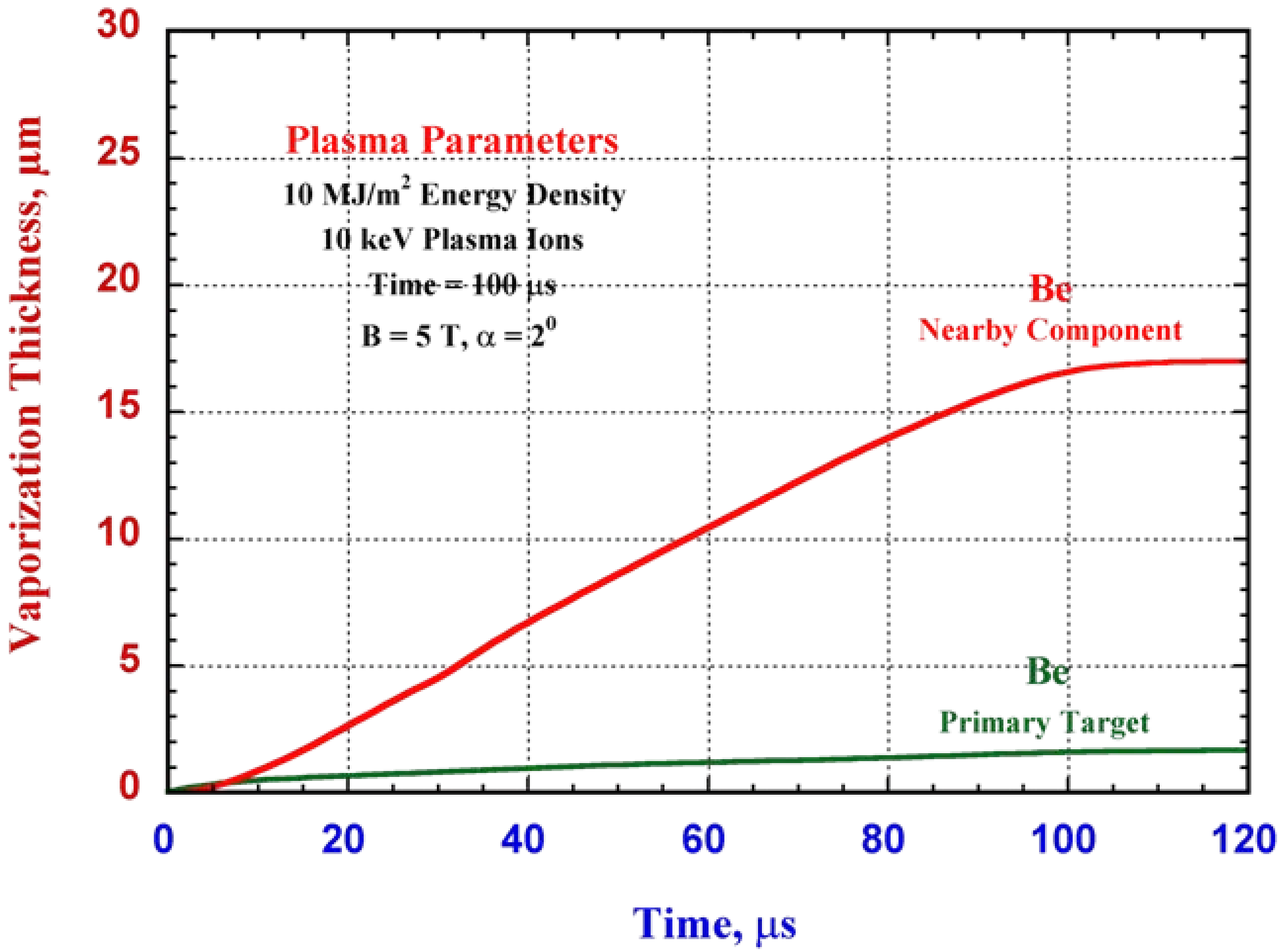


# Divertor Cassette Design and High Radiation Flux to Nearby Components

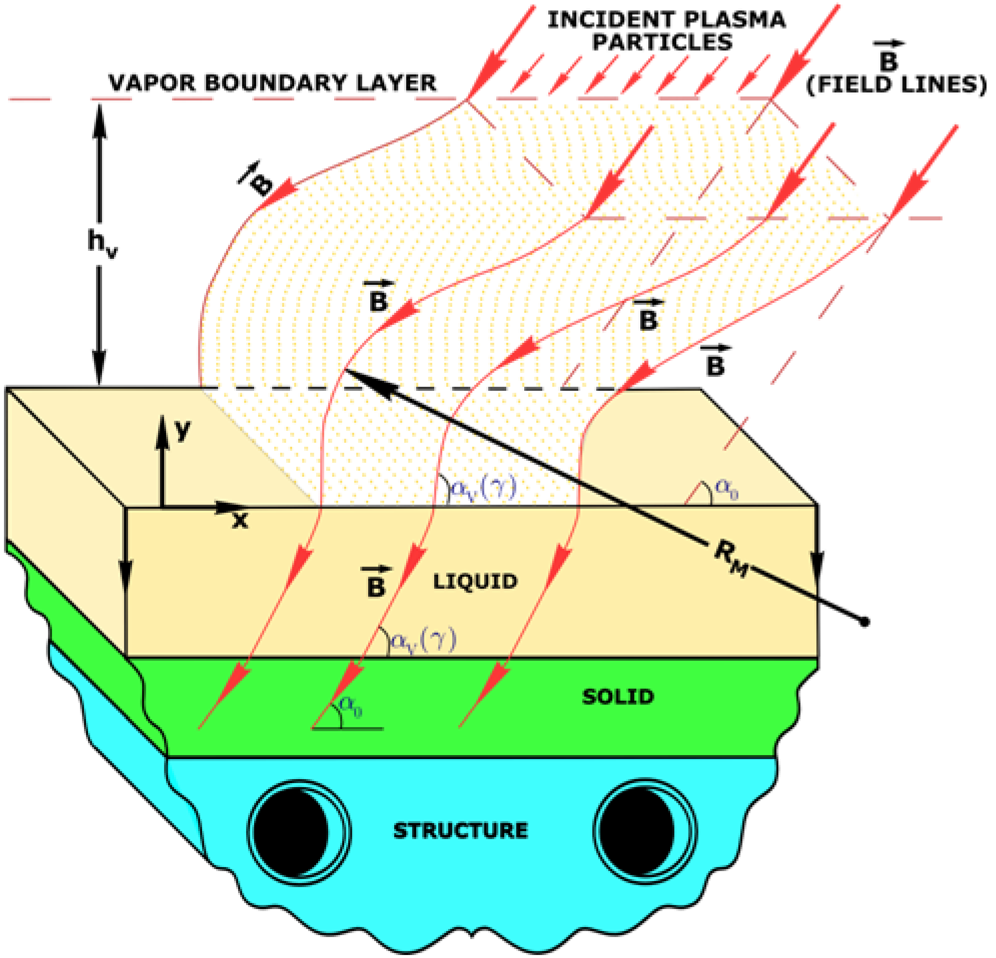




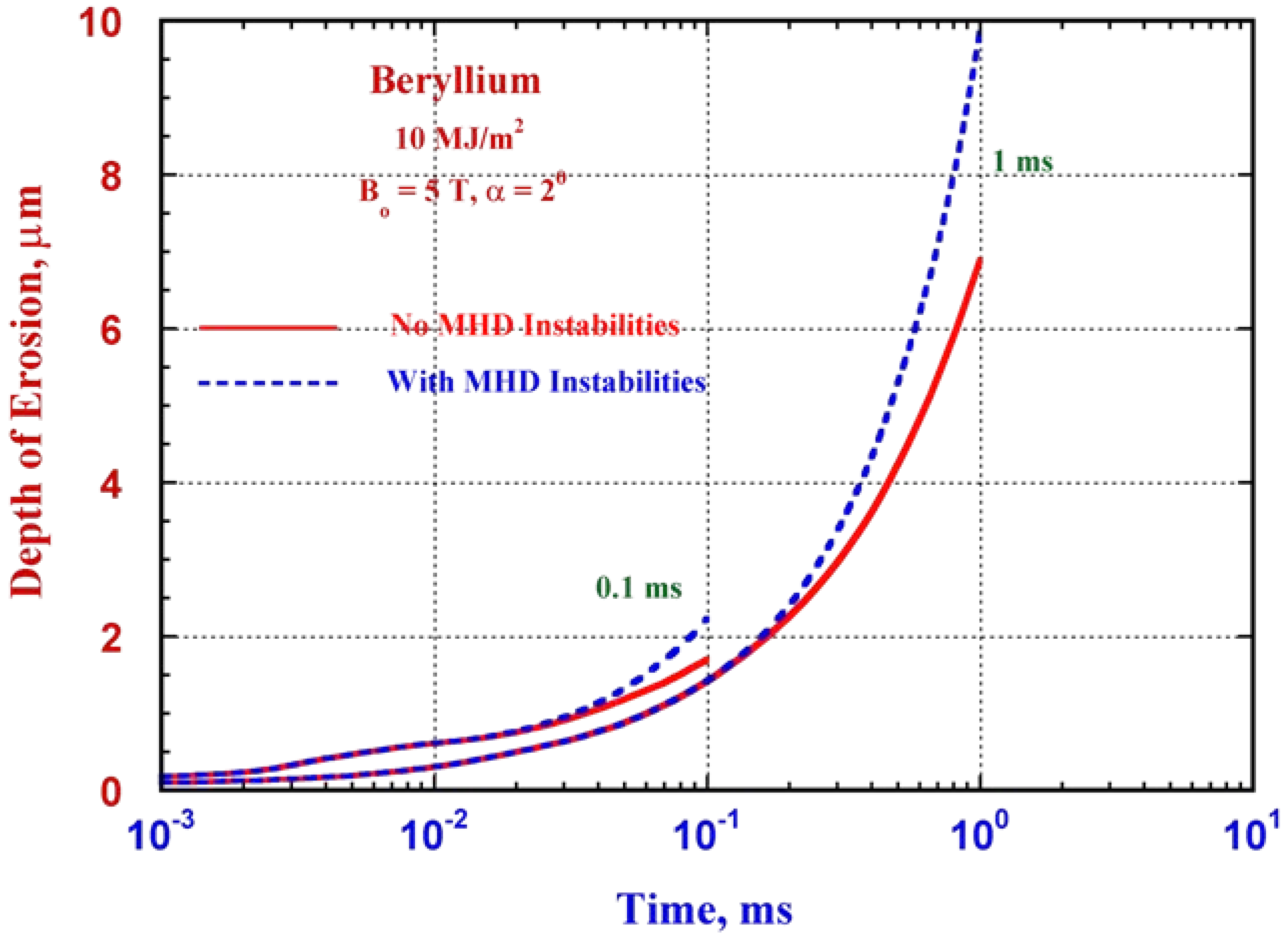
# HEIGHTS Erosion Analysis of Beryllium Primary and Secondary Targets during Disruption



# Debris Cloud Instability under Inclined Magnetic Fields



# HEIGHTS Analysis of the Effect of Vapor MHD Instabilities on Erosion Thickness



# Characteristics of ELM Transients

## II. Edge-Localized Modes

- Much more frequent and must be tolerated (1-10 Hz)
- Lower energy density about 1-3 $MJ/m^2$ (up to 10% $Q_o$)
- Deposition time is less than 1 ms.
- Complicated physics:
  - Lower density vapor cloud
  - Higher cloud temperature and velocity
  - Mixing effects of vapor and plasma
- ELMs in future Tokamaks can be simulated in plasma guns and z-/theta-pinch devices.
- Plasma contaminations!

| Event | Repetition | Duration [ms] | Energy dump [$MJ/m^2$] | Power flux [$GW/m^2$] |
|---|---|---|---|---|
| Disruption | Low | 1-10 | $10\text{-}10^2$ | $10^2$ |
| A giant ELM | >1 Hz | 0.1-0.5 | 1-3 | 1-10 |
| VDE | Low | $10^2\text{-}10^4$ | 20-60 | 0.01-0.1 |

# Particle & Energy Fluxes during ELMs

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

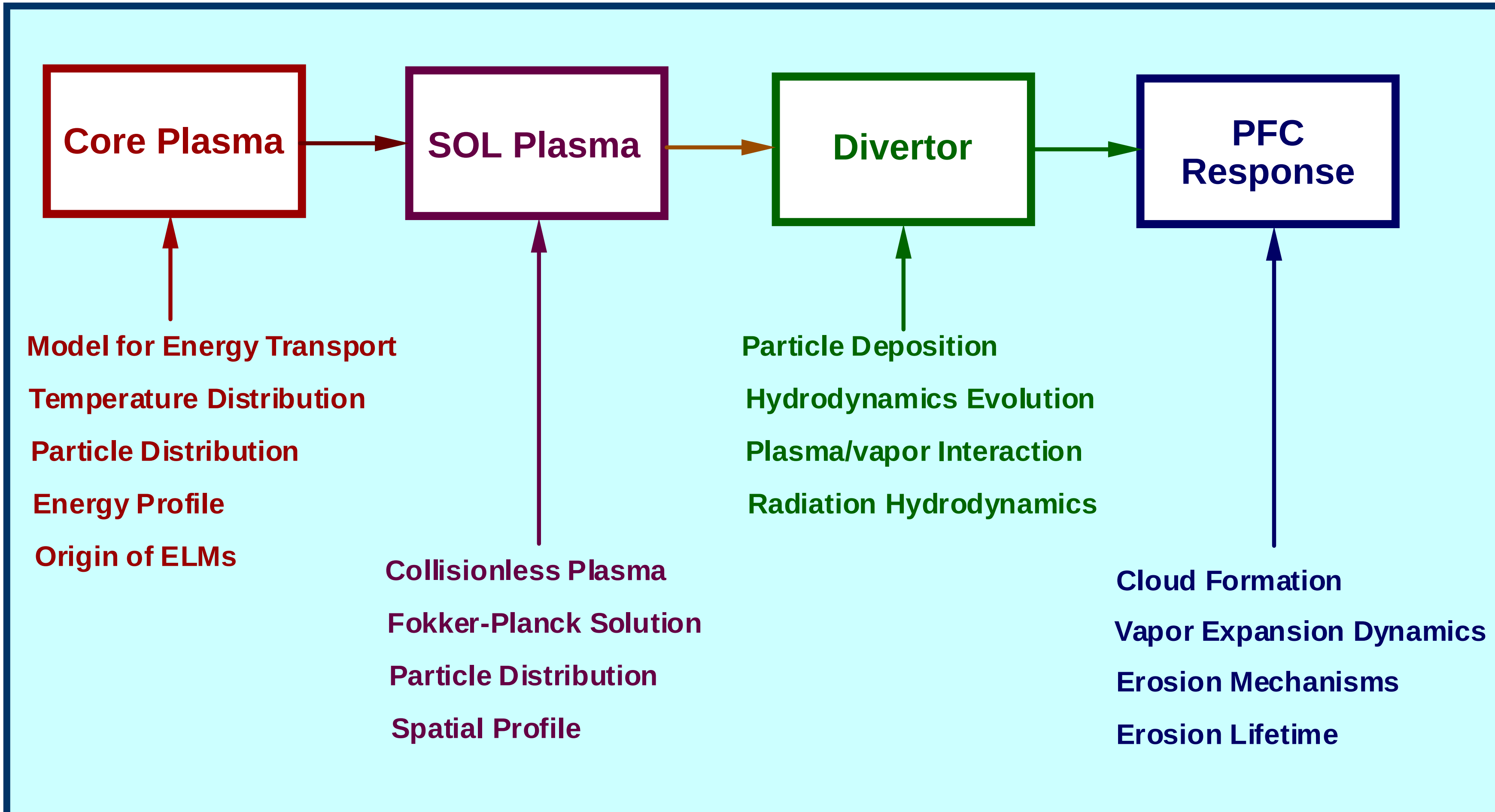
$$\xi = \eta \frac{\tau_E}{\tau_{ELM}} = 50 - 500$$

**( for 1% to 10%)**

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

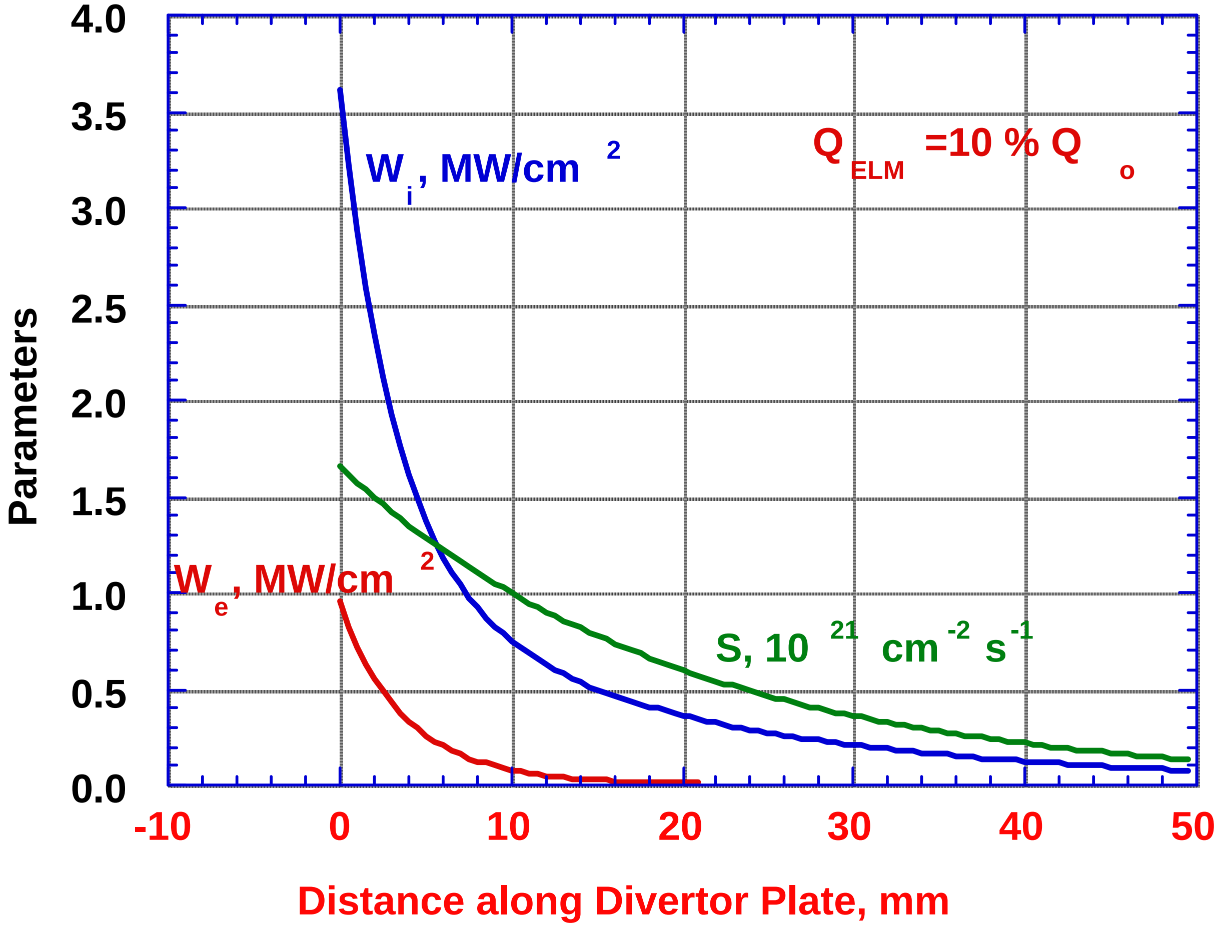
- **To predict these losses and contamination of core plasma, integrated problems must be solved: core plasma ejection, dynamics of particles in SOL, and interaction of particle and heat fluxes with divertor plate.**

# *Modeling Stages of ELMs in HEIGHTS*

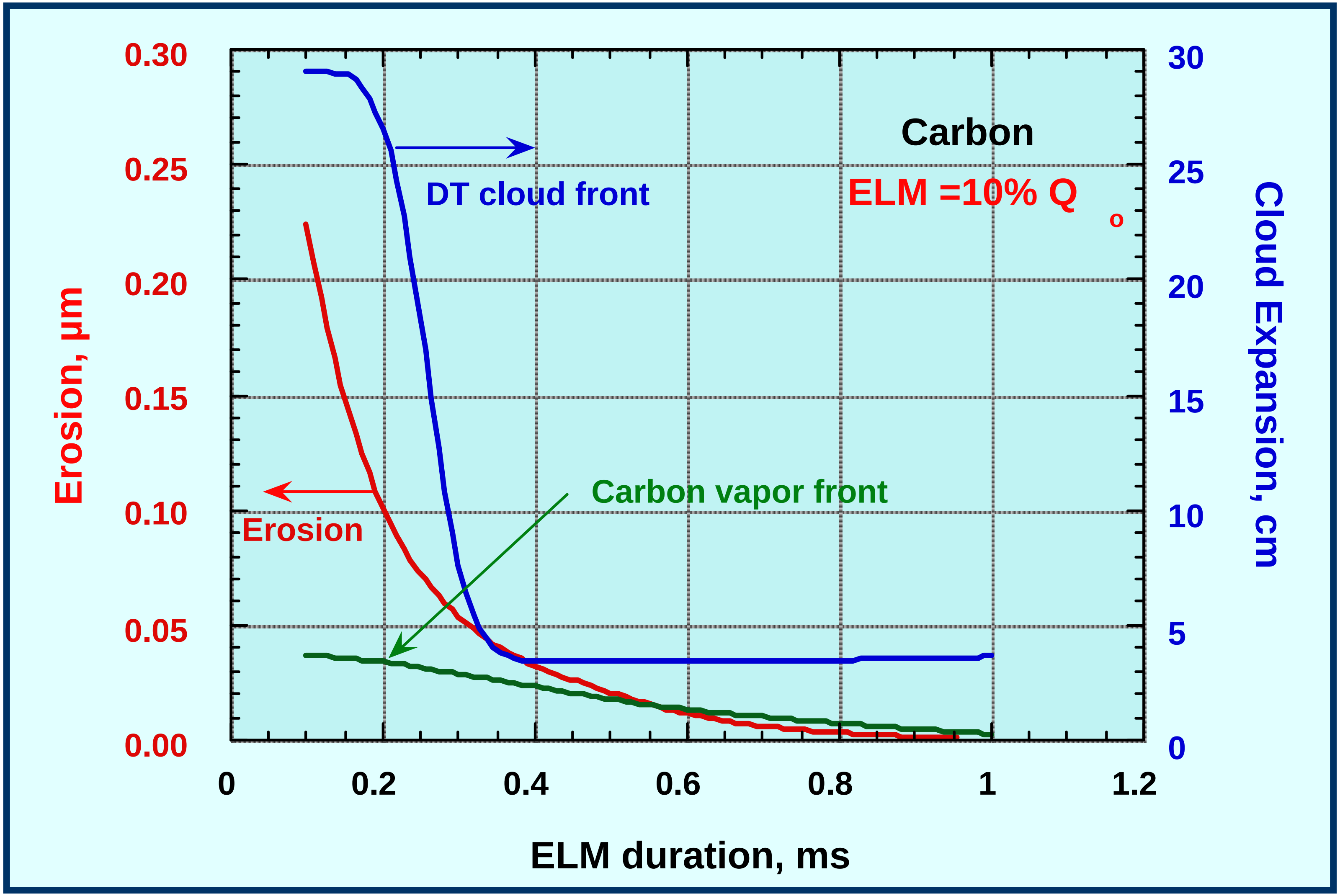



Hassanein (ANL)

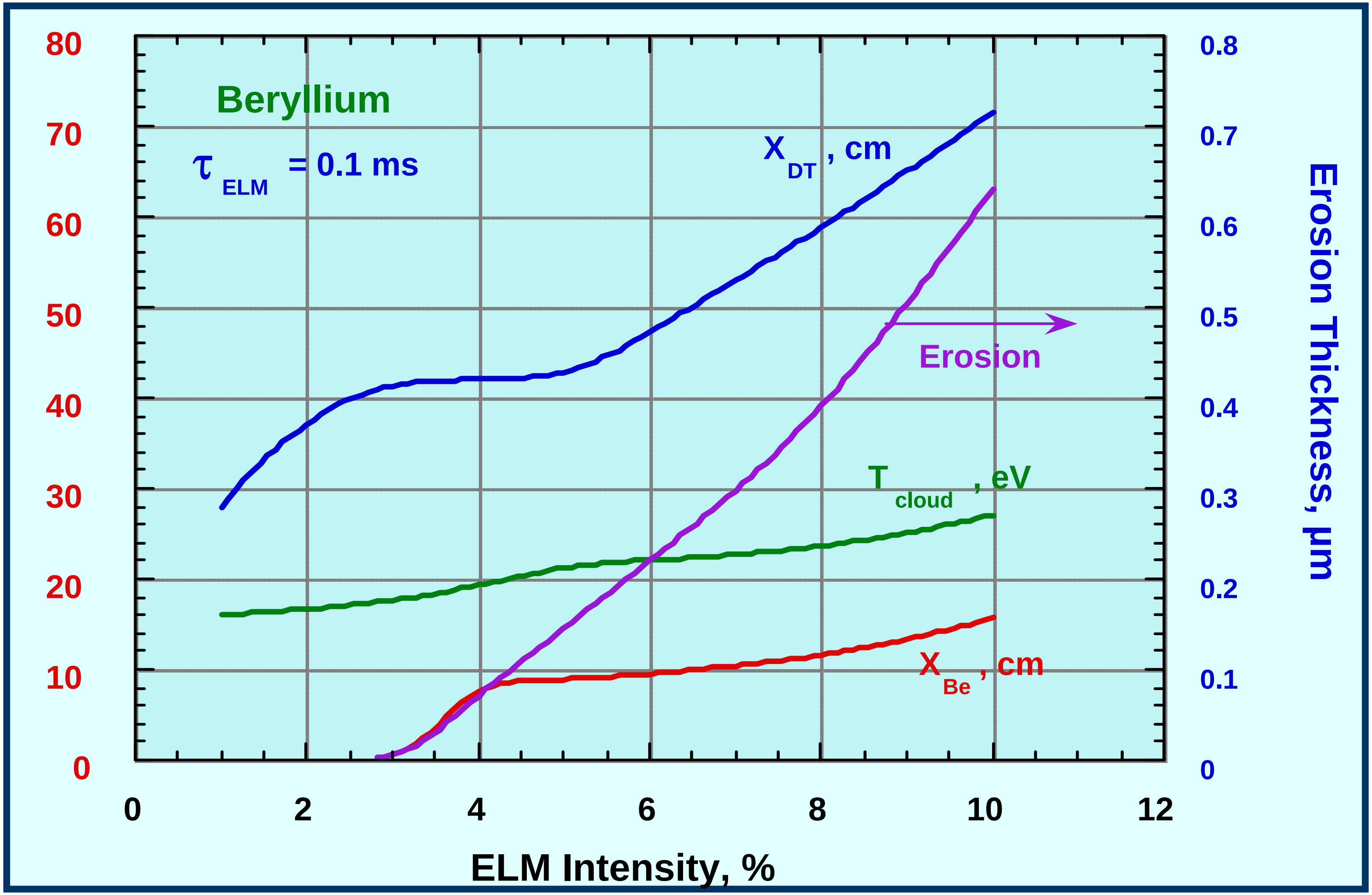
# Spatial Distribution of Particle and Heat Fluxes during ELMs



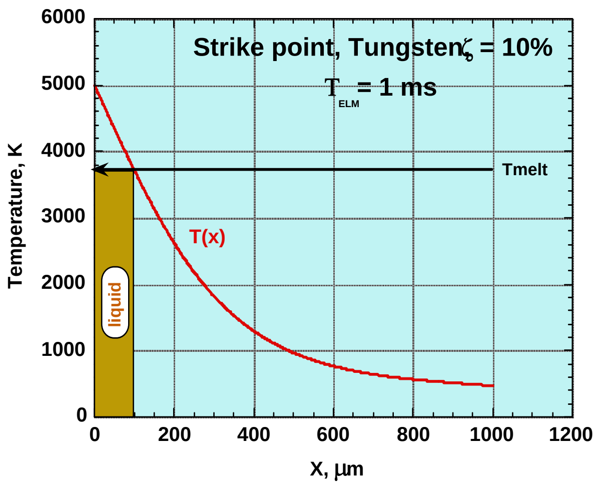
# HEIGHTS Calculation of Material Erosion and Cloud Expansion during ELMs



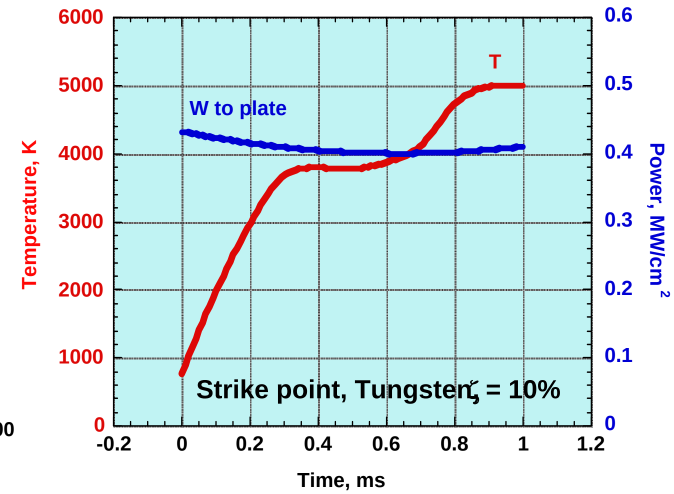
# HEIGHTS Calculation of Be Response and Erosion during ELMs at Different Intensities



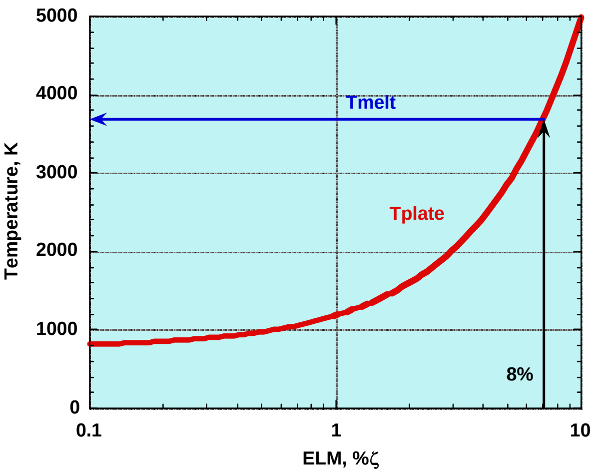
# Response of Tungsten Divertor Plate to Giant ELM (Q = 10%)




Temperature at t =1 ms



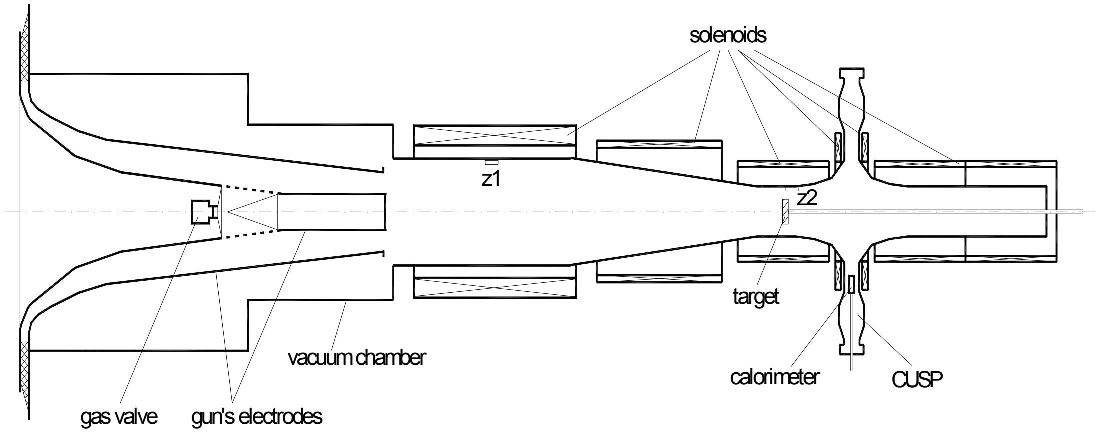

Surface temperature as function of time.

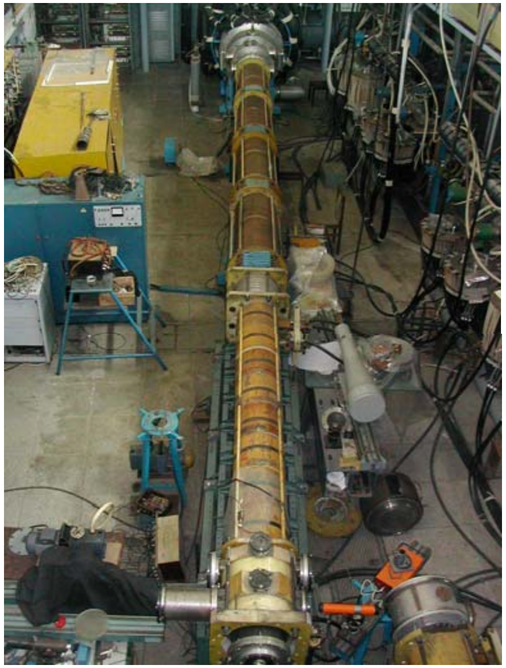



Surface temperature as function of ELM intensity

**For low ELM intensity (<8%), surface temperature does not reach the melting temperature**

# *MK-200 TRINITI facility*

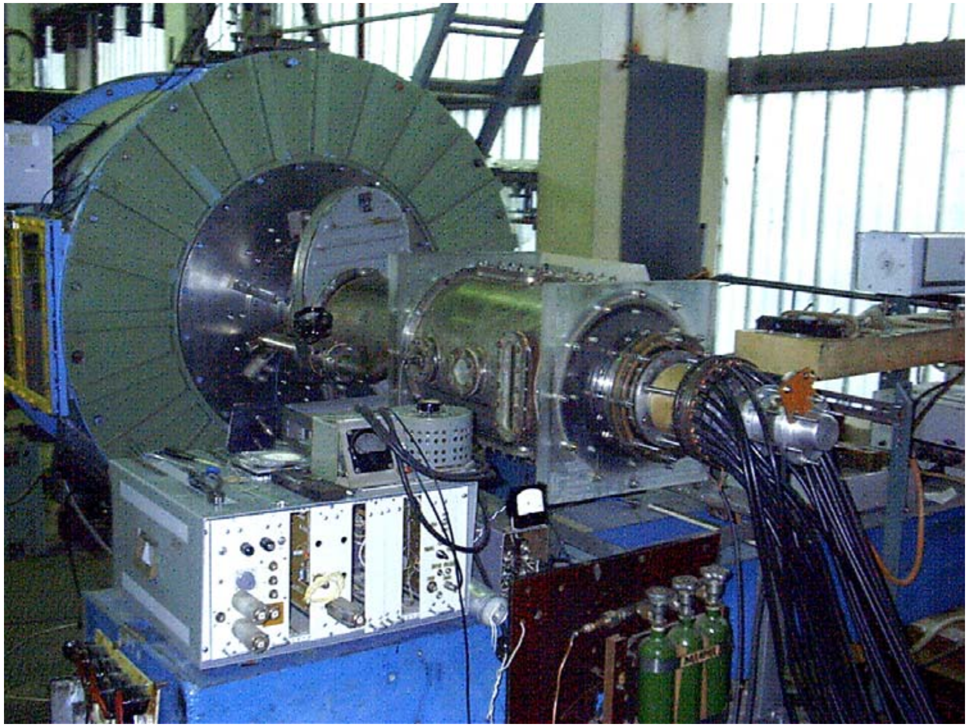


## Plasma stream parameters at target position

| | |
|---|---|
| Energy density | Q = 1.5 kJ/cm$^2$ |
| Power density | W= 100 – 150 MW/cm$^2$ |
| Pulse duration | $\tau$ = 7 - 15 $\mu$s |
| Ion energy | $E_i$ = 1 keV |
| Plasma density | n > $10^{16}$ cm$^{-3}$ |
| Impact pressure | P = 80 – 120 atm |
| Stream diameter | D = 5 cm |

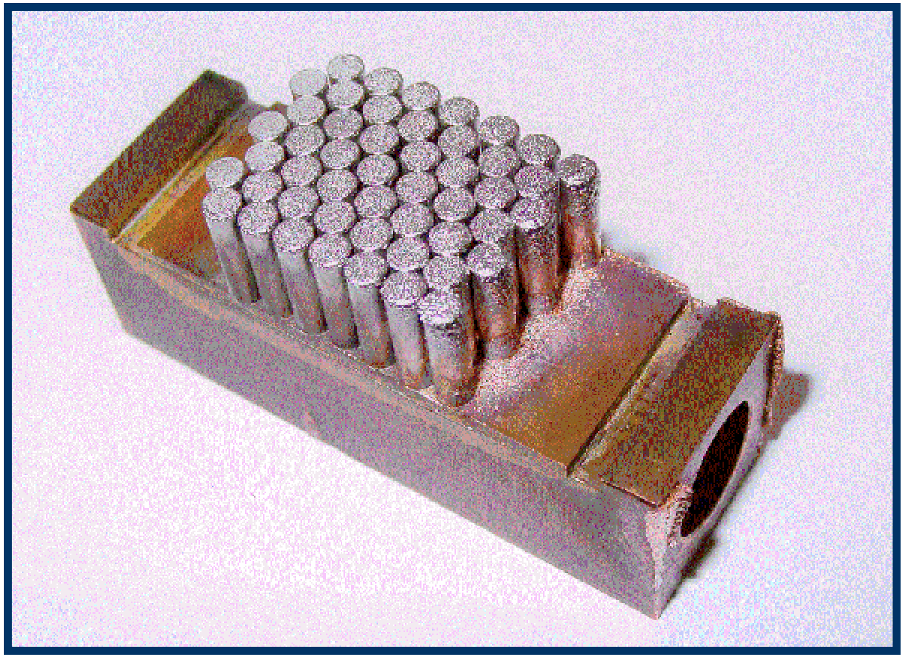
# QSPA-TRINITI facility



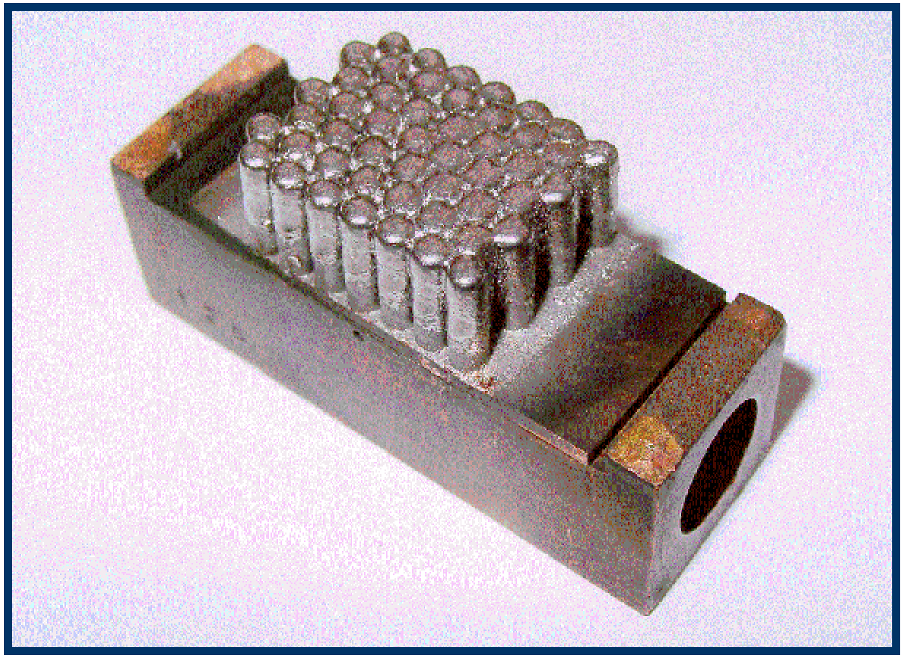
**Plasma stream parameters at target position**

| | |
|---|---|
| Energy density | $Q = 0.5 - 1\ kJ/cm^2$ |
| Power density | $W = 1 – 3\ MW/cm^2$ |
| Pulse duration | $\tau = 500\ \mu s$ |
| Ion energy | $E_i = 0.1\ keV$ |
| Plasma density | $n > 10^{16}\ cm^{-3}$ |
| Temperature | T = 10 eV |
| Stream diameter | D = 4 cm |

# *Melt Layer Erosion of Tungsten Brush Samples*



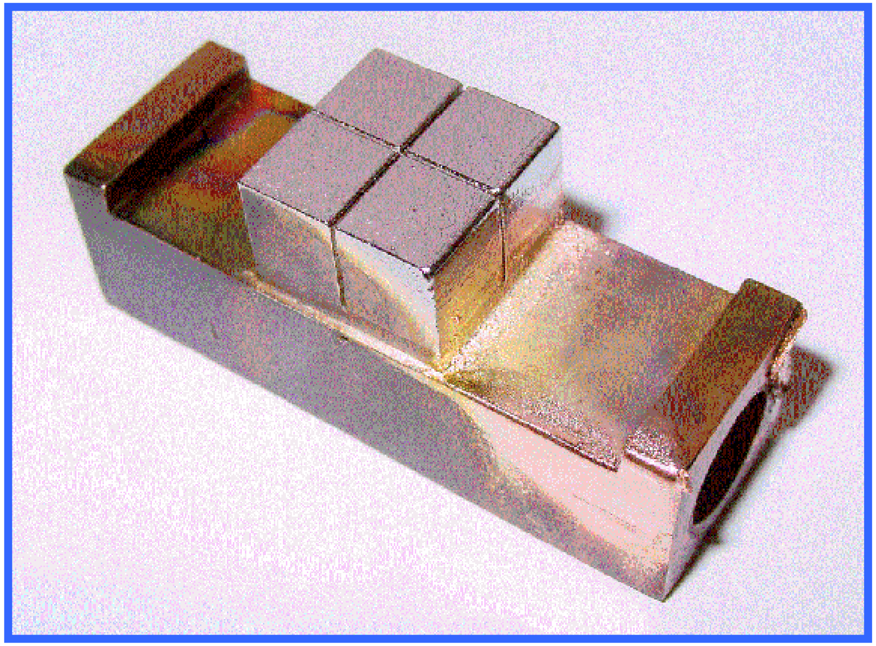
**50 ELM loads at MK-200UG facility**



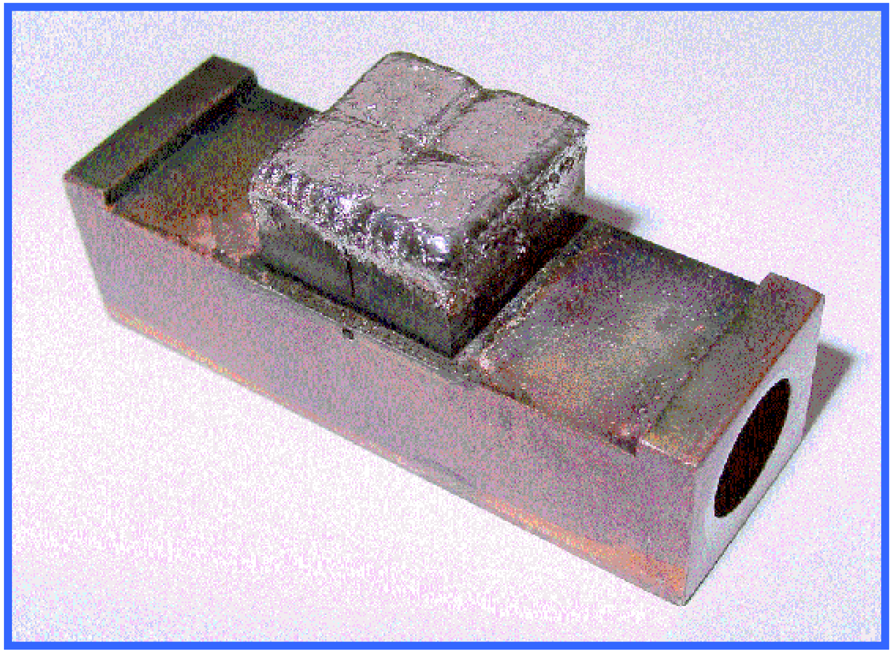
**20 ELM loads at QSPA facility**

(TRINITI, Russia)

# Melt Layer Erosion of Tungsten Block Samples



50 ELM loads at MK-200UG facility



20 ELM loads at QSPA facility

# *What We Learned From Plasma Gun Simulations*

- Plasma tests have shown that W metal erosion is dominated by melt motion.  Melt motion of metals is accompanied by droplet splashing.

- Weight loss measurements of all exposed materials demonstrate little contribution of evaporation process to metals erosion..

- Tungsten targets show lowest erosion in comparison with other metals. Nevertheless melt layer motion and surface cracking are the main factors responsible for tungsten damage.

- For ITER disruptions and giant ELMs, longer duration of plasma heat load and Lorentz force action may significantly add to the melt motion.

# Core Plasma Contamination during ELMs

- **The problem of core plasma contamination could be serious.**
- **Despite that even giant ELM may not be so dangerous of direct contamination of core plasma during ELMs, because expansion of cloud is not large and front part of cloud closer to separatrix (X-point) consists of mainly DT.**
- **There are two other reasons for contamination:**
  - **a) Contamination during SOL reconstruction and**
  - **b) Impurities diffusion along Private Flux Region (PFR).**

# Core Plasma Contamination

## (a) Reconstruction of SOL

- **After ELM, the front part of cloud consists of DT+He plasma while impurities are concentrated nearby the plate surface. Characteristic time of cloud particles motion in SOL is less than the time, $\tau_{\perp}$ , of diffusion (reconstruction time) from core plasma to rebuilt core edge with the removed "peel" depth , ΔR , of ten cm and SOL**

$$\tau_{II} = \frac{L}{Vs} \approx 5\ ms << \tau_{\perp} = \frac{\Delta R^2}{D} \approx 50\ ms$$

- **The reconstruction of tokamak plasma edge after ELMs requires more detail studies.**

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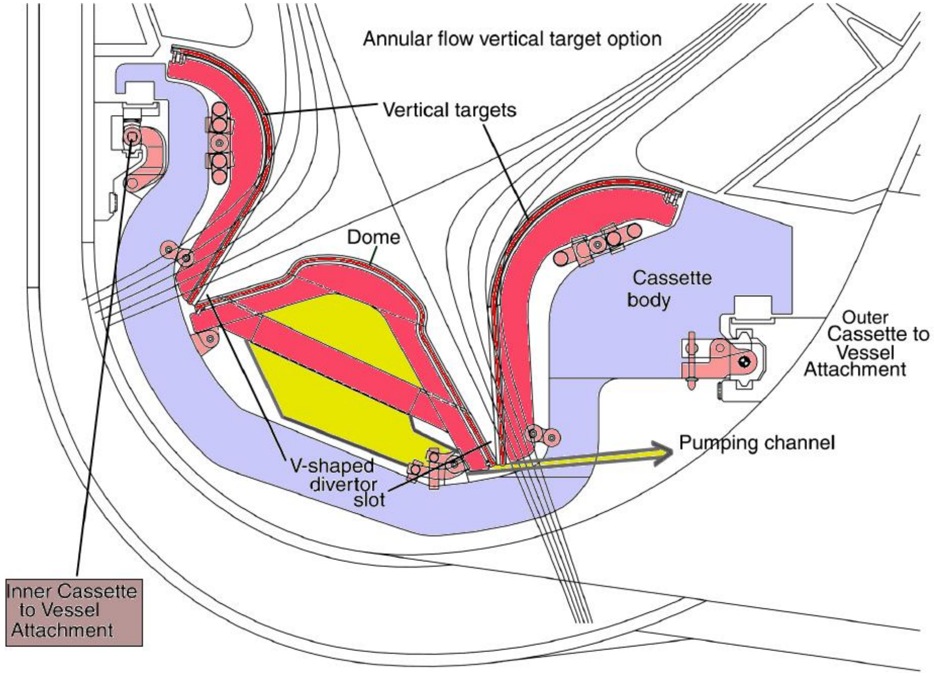
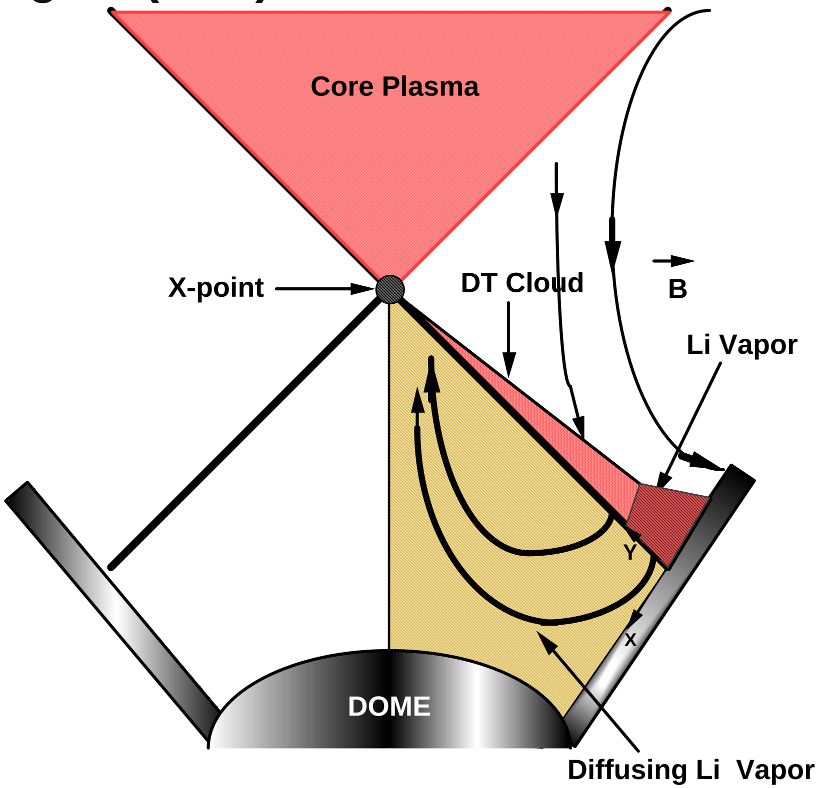
# Dynamics of Vapor Cloud Plasma in the Private Flux Region

## (b) Diffusion

- Vapor divertor plasma (Li, W, Be, C) is lost due to diffusion across the Separatrix into the  Private Flux Region (PFR)



# *Summary of Contamination*

1. **The plasma cloud during ELMs consists mostly of DT plasma.**

2. **This DT plasma with high temperature ($T_{DT}$ = 40-70 eV) keeps the underneath eroded vapor plasma with lower temperature ($T_C$=10-20 eV).**

3. **The vapor (carbon) plasma can diffuse across Separatrix into the private flux region and be the main mechanism of (carbon) vapor leakage and contamination.**

4. **Carbon impurities reaches the X-point for time of 100 ms much longer than ELMs time of 0.1-1 ms and could penetrate into core plasma.**

5. **Contamination of core plasma is governed by pumping and absorption of vapor plasma by components in PFR.**

6. **Need more detail analysis for the interaction of eroded material with PFR materials, pumping, and bulk plasma.**

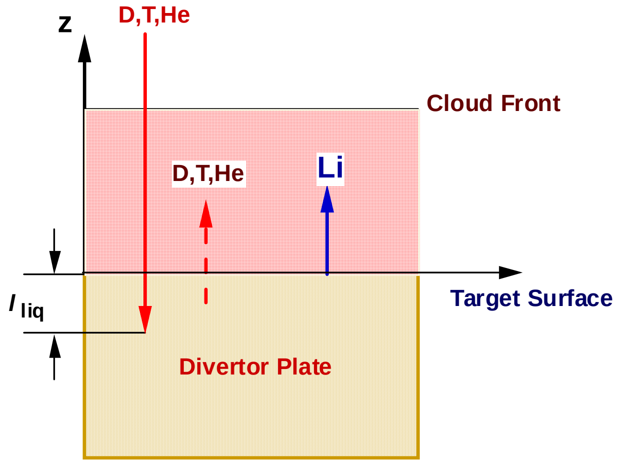
# *Mitigations of Disruptions and ELMs*

**HEIGHTS Analyzed the Following Options:**

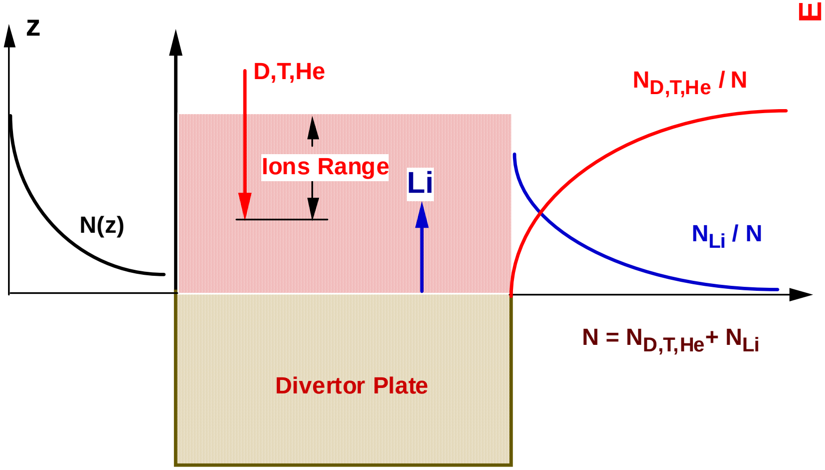
1. **Liquid Metals as PFCs**

2. **Injection of Inert Gases**

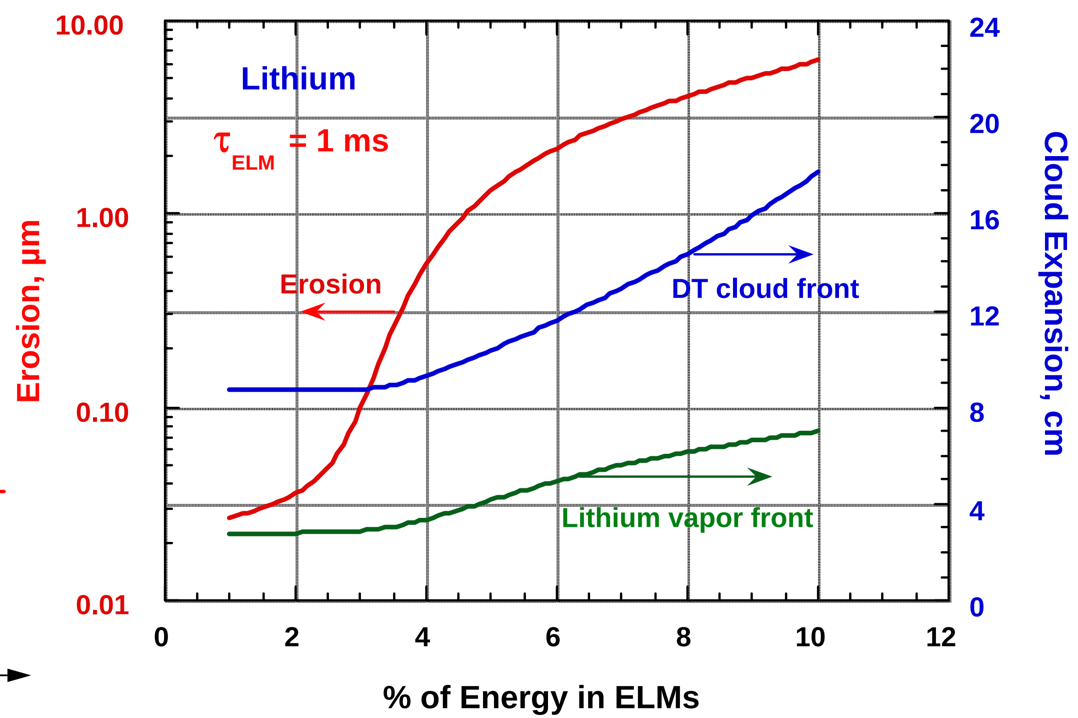
# *Lithium Surface under ELM Load*




**Initial Stage of Cloud Formation**




**Mixing Stage**



# *Summary of Mitigation Studies*

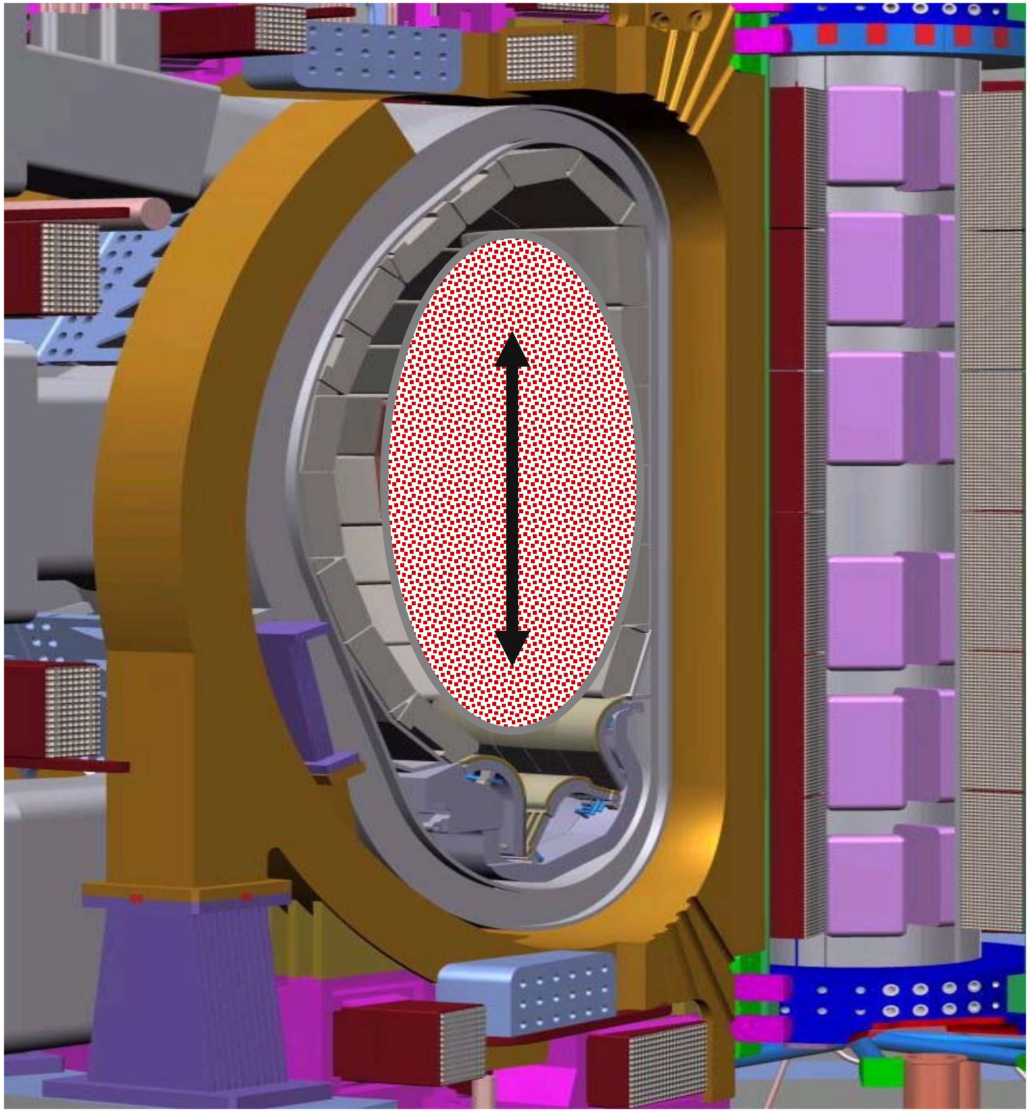
**1. Refractory divertor materials such as tungsten will need noble gas puff to prevent melting and consequences of splashing and cracks formation. For low power ELMs, gas puff would also be desirable to decrease sputtering erosion.**

**2. Shielding effect of noble gas cloud is less efficient than self shielding of light elements (Li, Be, C) due to low radiation power.**

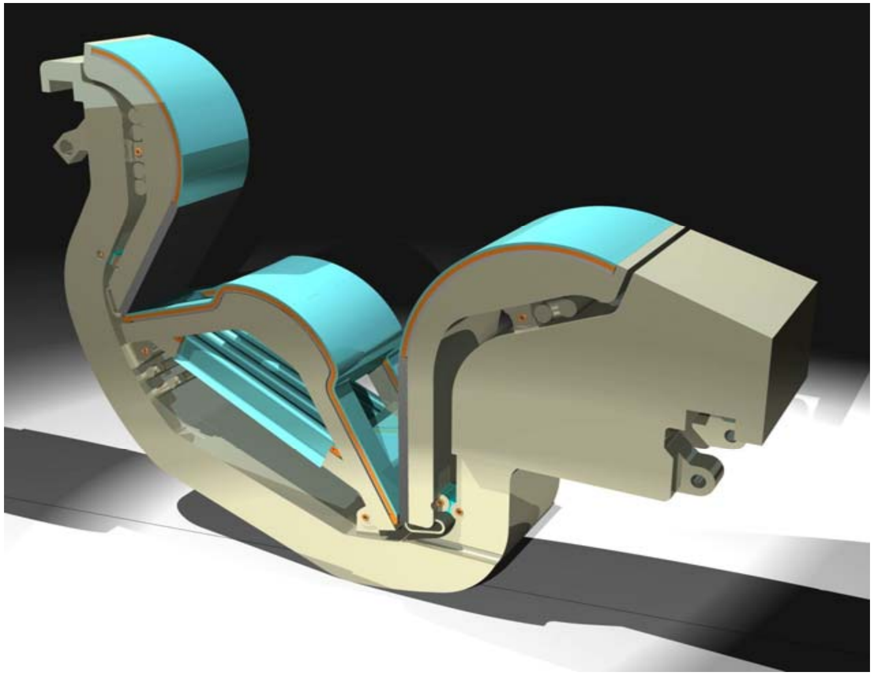
**3. A serious concern has to do with whether or not the injected gas can be retained in the divertor area. Diffusion across the PFR can be significant and cause core contaminations. This could lead to DISRUPTIONS!!**

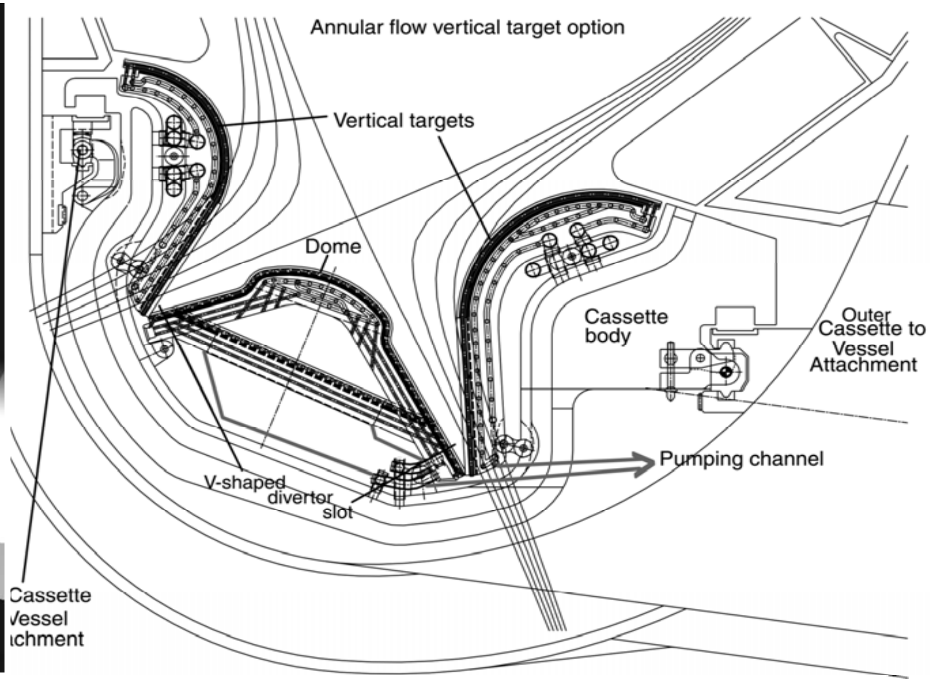
**4. Contamination of core plasma via both the SOL and PFR after ELMs and during the SOL reconstruction requires more detail studies.**

# III. Vertical Displacement Events (VDEs)



# Divertor Cassette Design and High Radiation Flux to Nearby Components





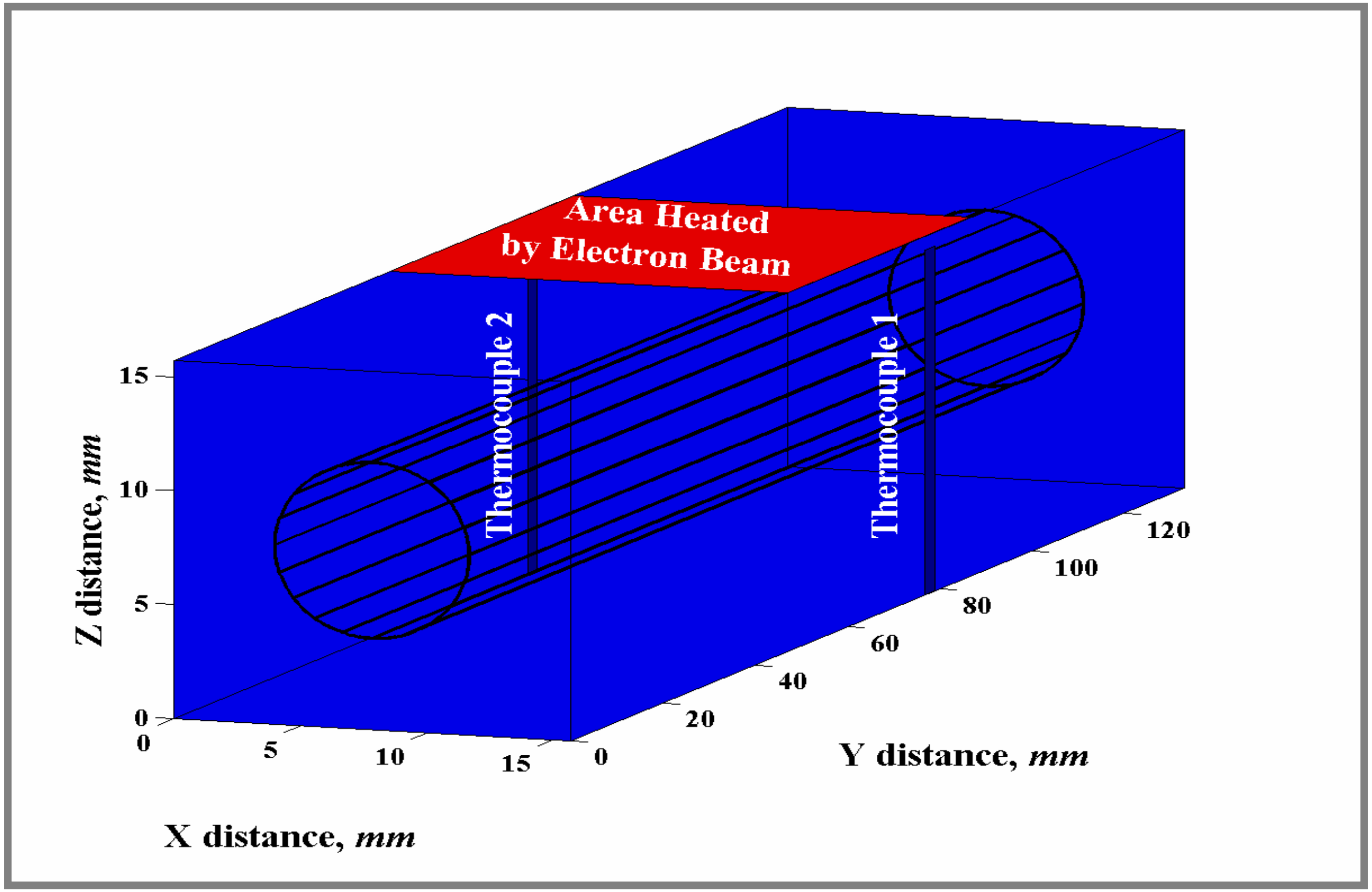
# *Characteristics of Transients*

## *III. Vertical Displacement Events*

- **Rare events but serious effects**
- **Energy density similar to disruptions 20-60 $MJ/m^2$**
- **Deposition time is much longer about 100-1000 ms.**
- **Complicated physics**:
  - **Less/no vapor shielding**
  - **Surface damage**
  - **Structural damage**
- **VDEs in future Tokamaks can be simulated in powerful electron beam devices**.

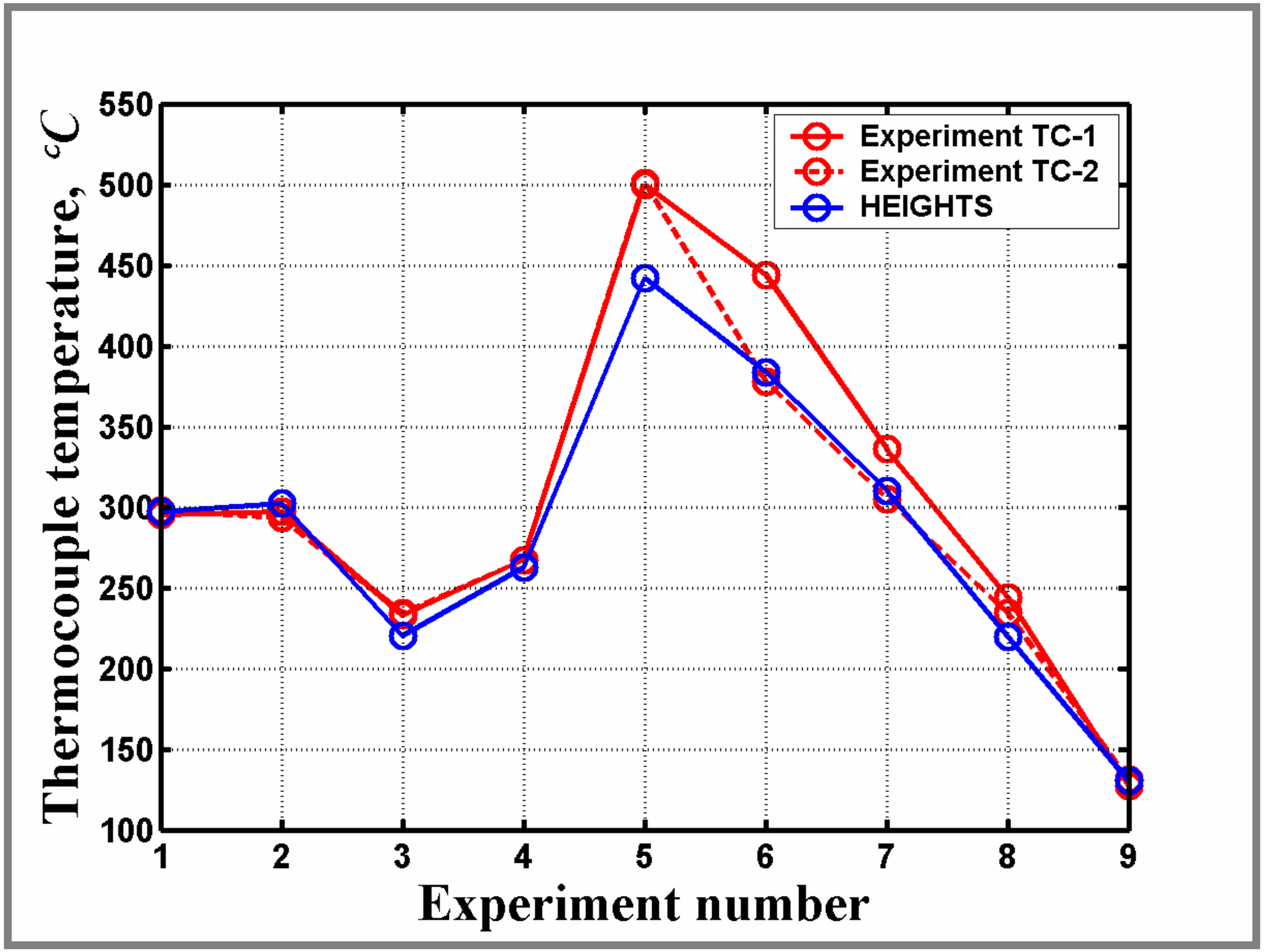
| Event | Repetition | Duration [ms] | Energy dump [$MJ/m^2$] | Power flux [$GW/m^2$] |
|---|---|---|---|---|
| Disruption | Low | 1-10 | $10\text{-}10^2$ | $10^2$ |
| A giant ELM | >1 Hz | 0.1-0.5 | 1-3 | 1-10 |
| VDE | Low | $10^2\text{-}10^4$ | 20-60 | 0.01-0.1 |

# HEIGHTS Benchmark of Laboratory Experiments

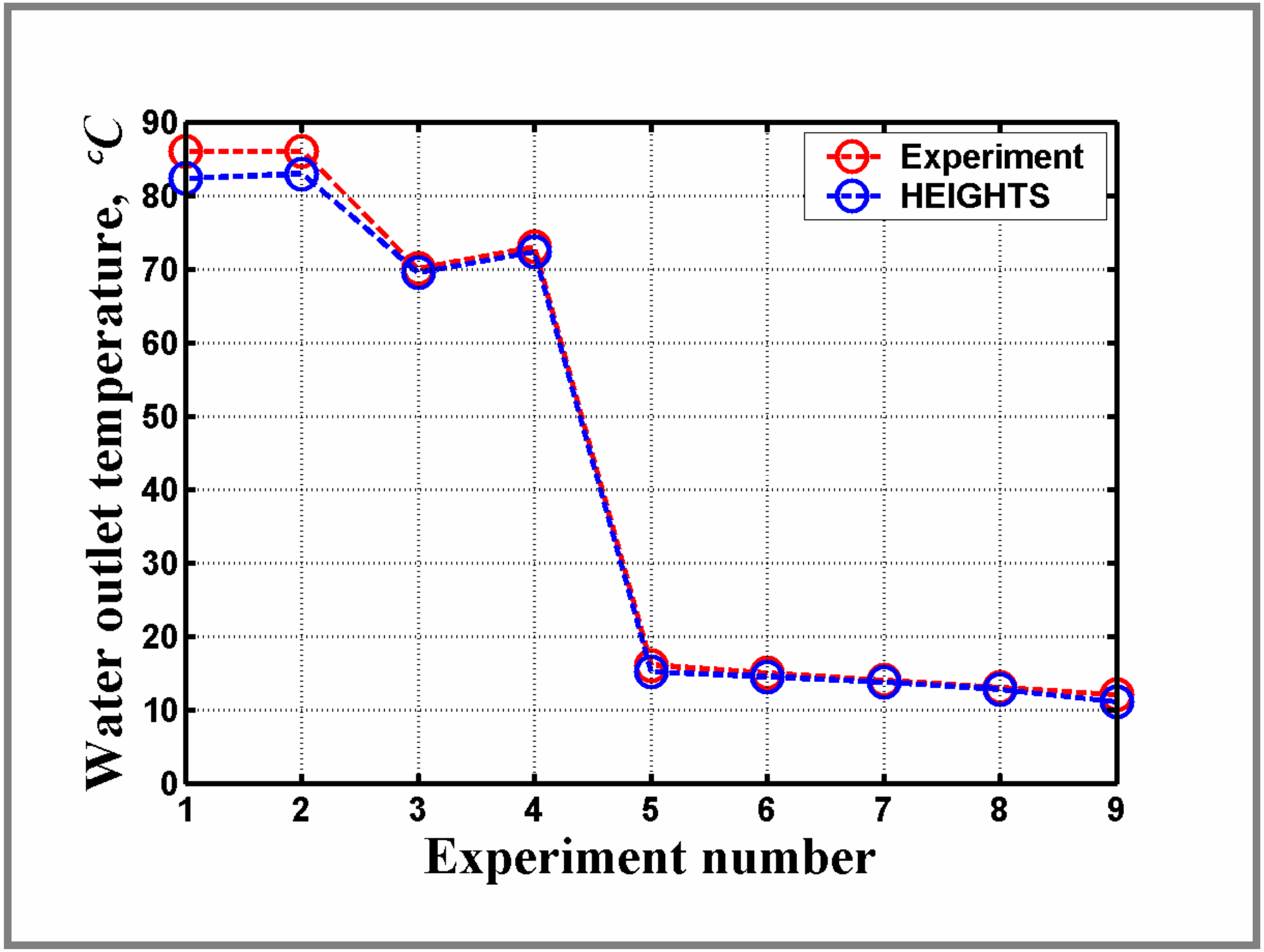



*Marshall, T.D., McDonald, J.M., Cadwallader, L.C., Steiner, D. "An experimental examination of the loss-of-flow accident phenomenon for prototypical ITER divertor channels of Y=0 and Y=2." Fusion Technology 37, (2000) p. 38-53.

# HEIGHTS Benchmarking

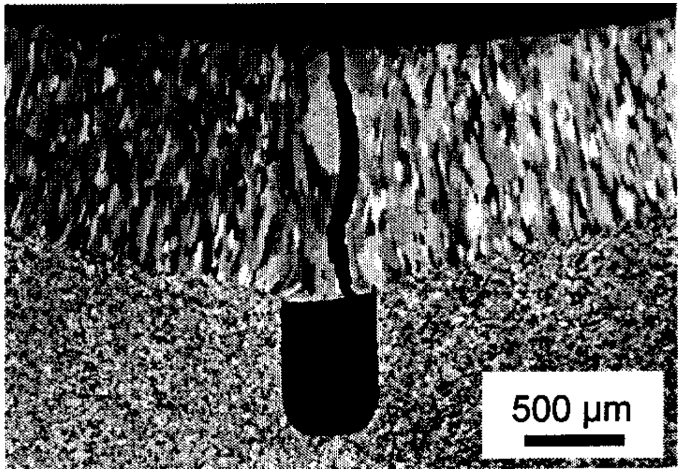


# *HEIGHTS Benchmarking*

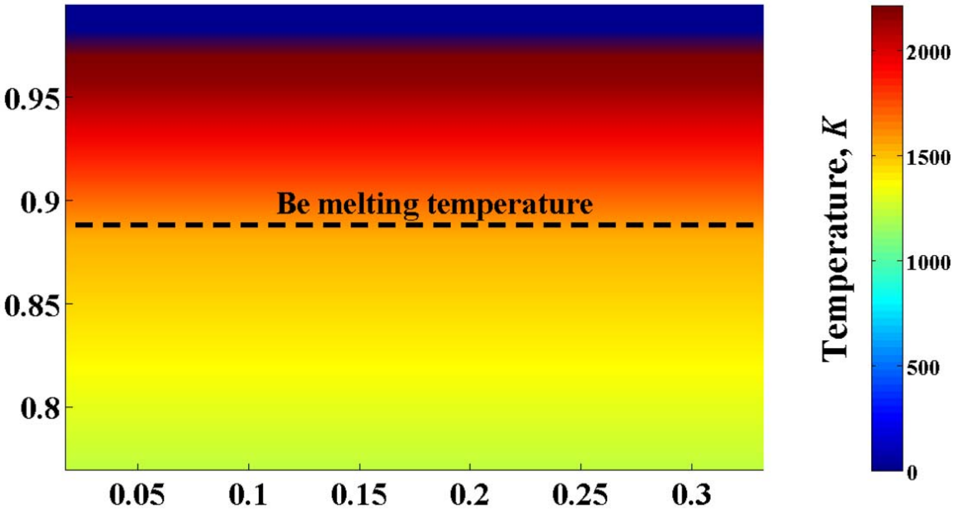


# *HEIGHTS Benchmarking of JET VDE Experiments*

**JET Experiment**

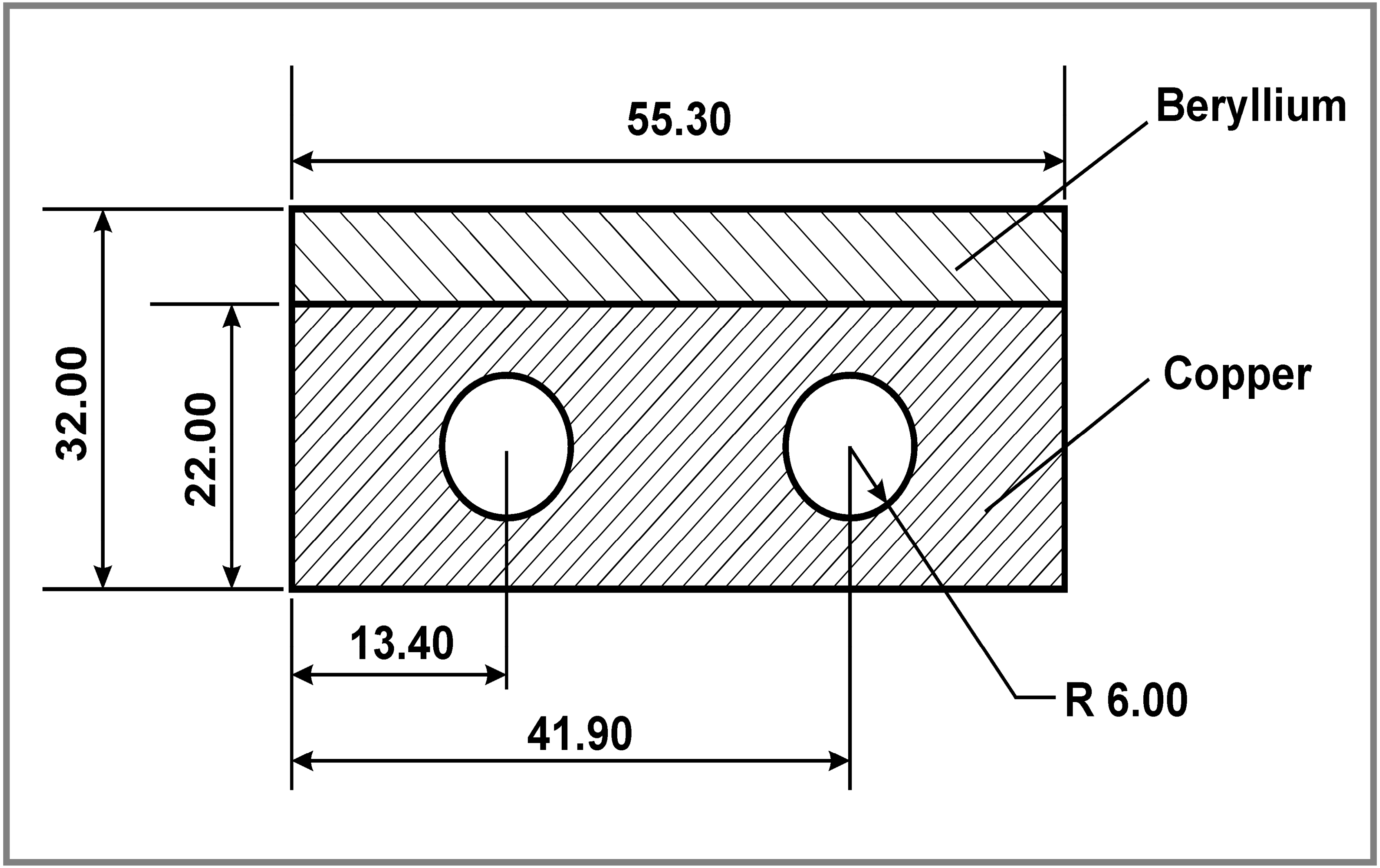



**HEIGHTS Simulation**

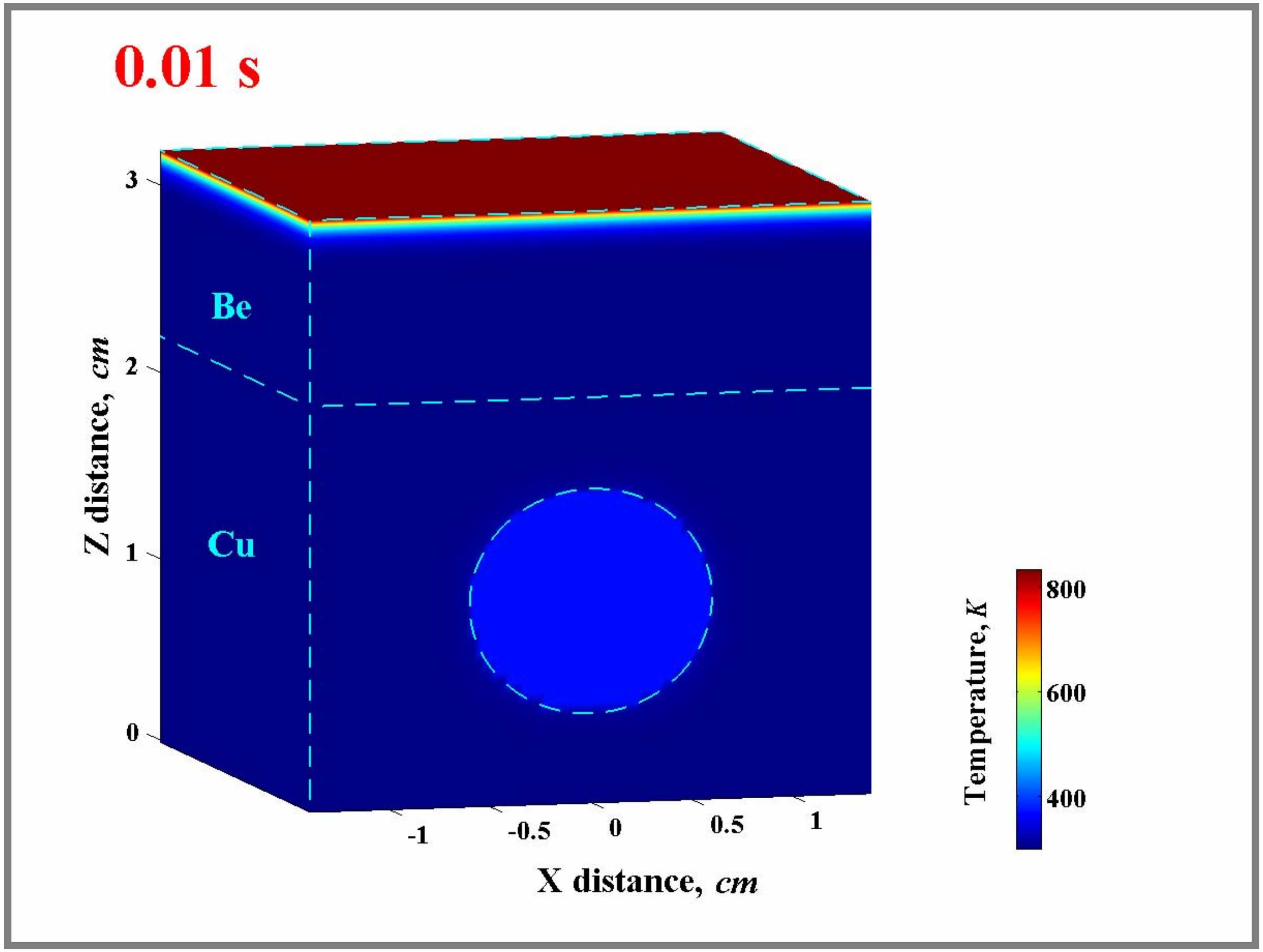



**Erosion and Melt layer thickness during Vertical Displacement Events (deposited energy density: 60 MJ/m$^2$, 1.0 s)**

# ITER PFC Module and Structural Design

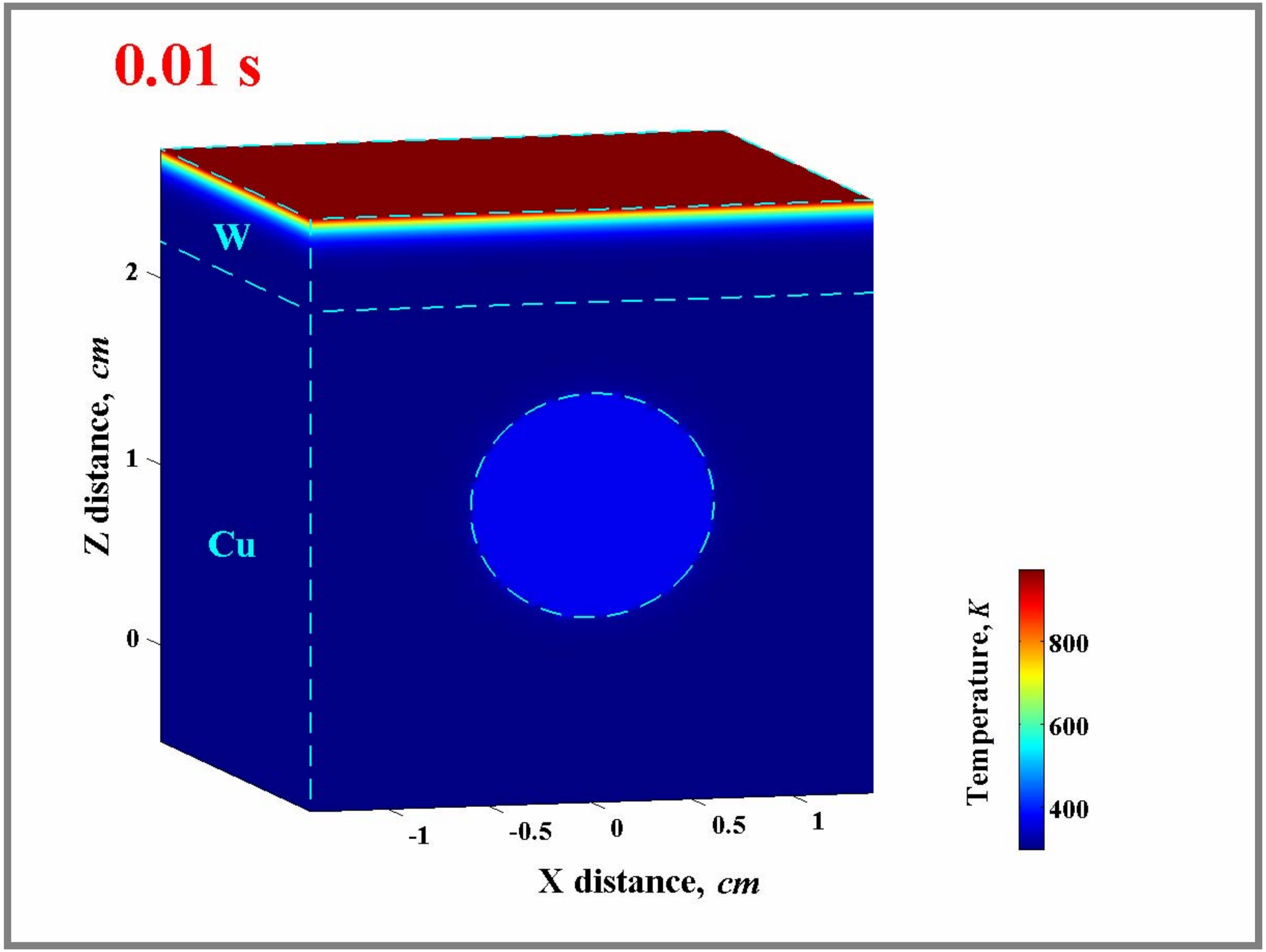


# Beryllium First Wall under VDE Heating



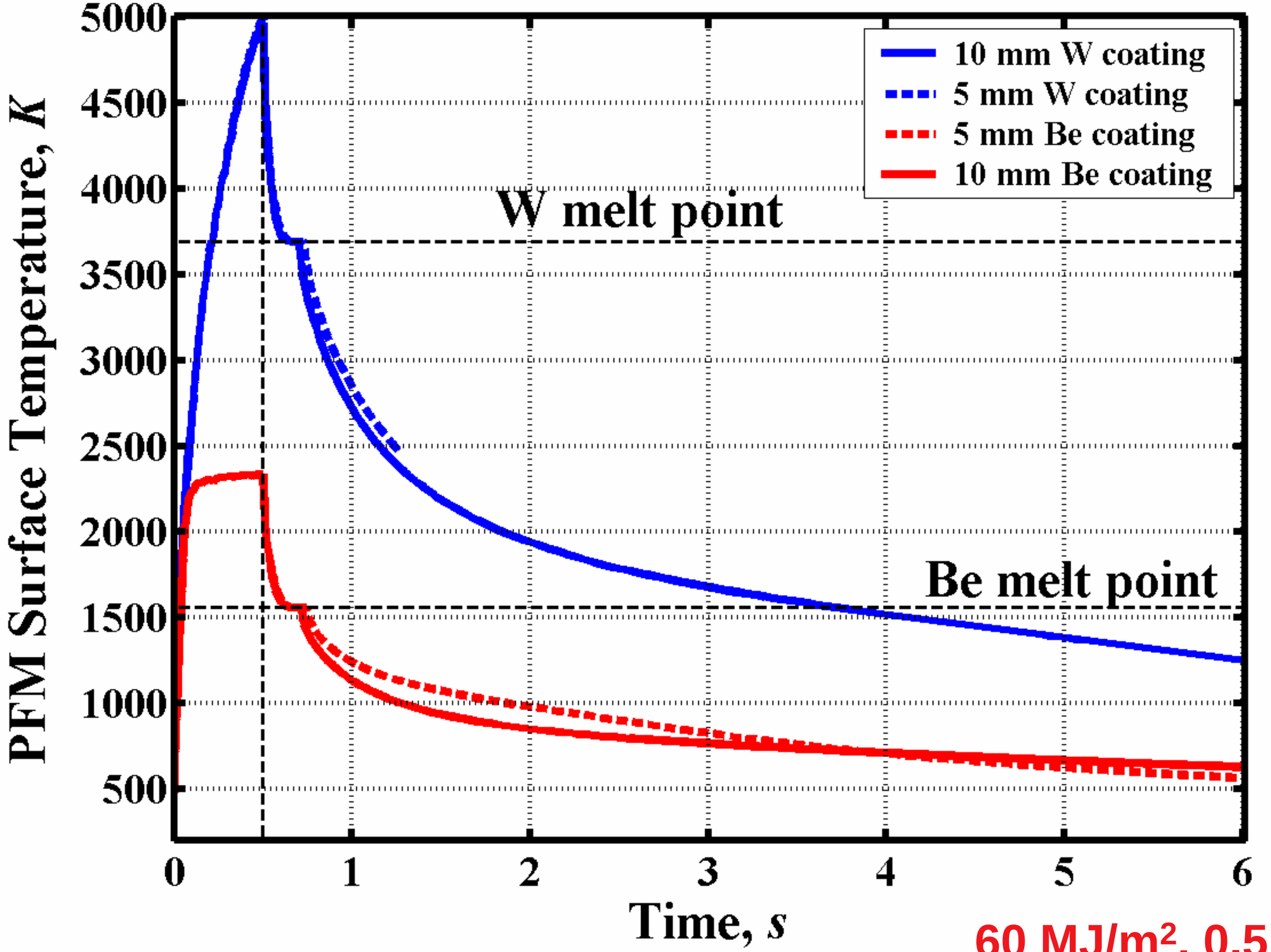

**60 MJ/m², 0.5 s**

# *Tungsten Wall under VDE Heating*



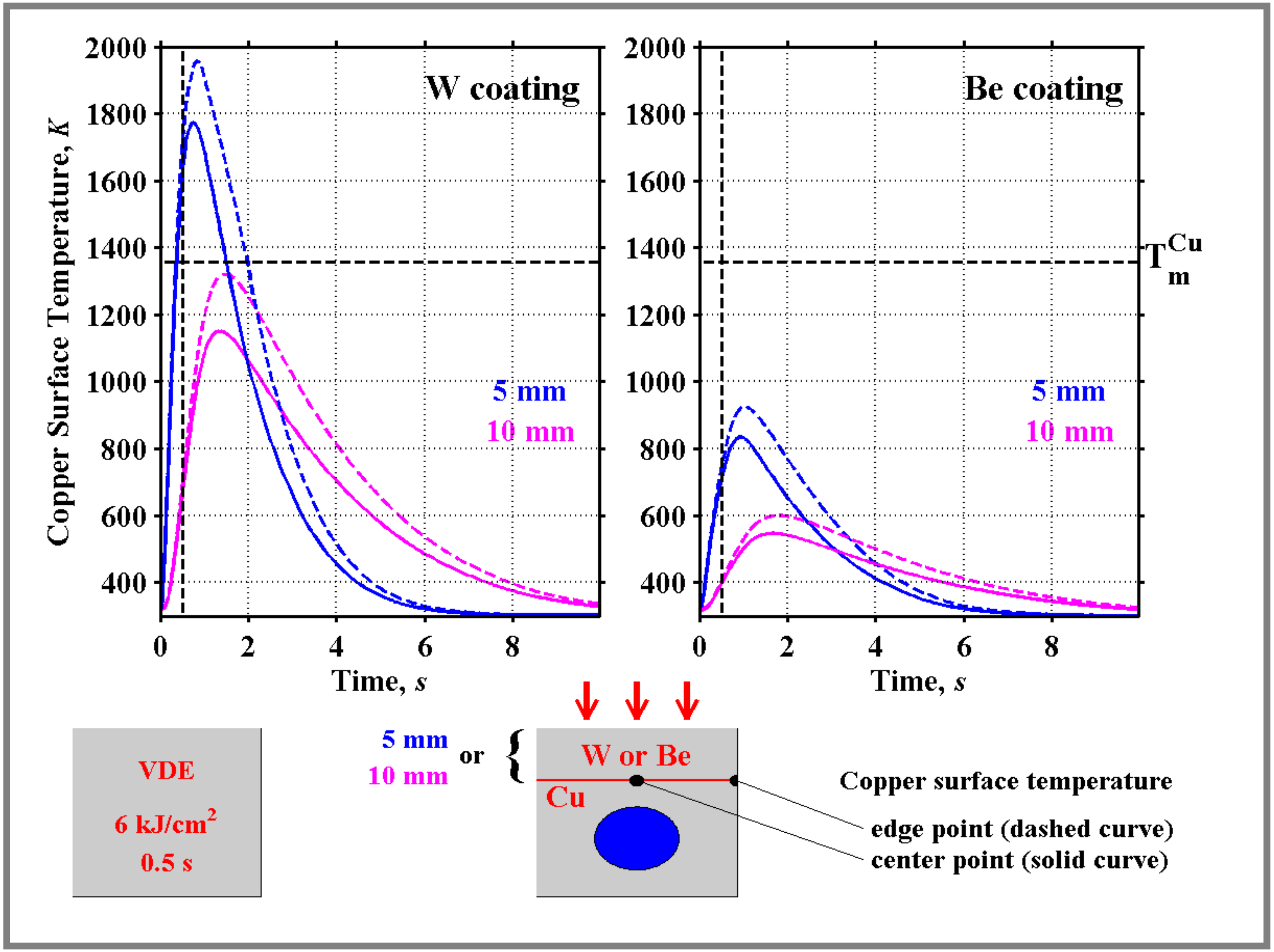

**60 MJ/m$^2$, 0.5 s**

# PFM Surface Temperature

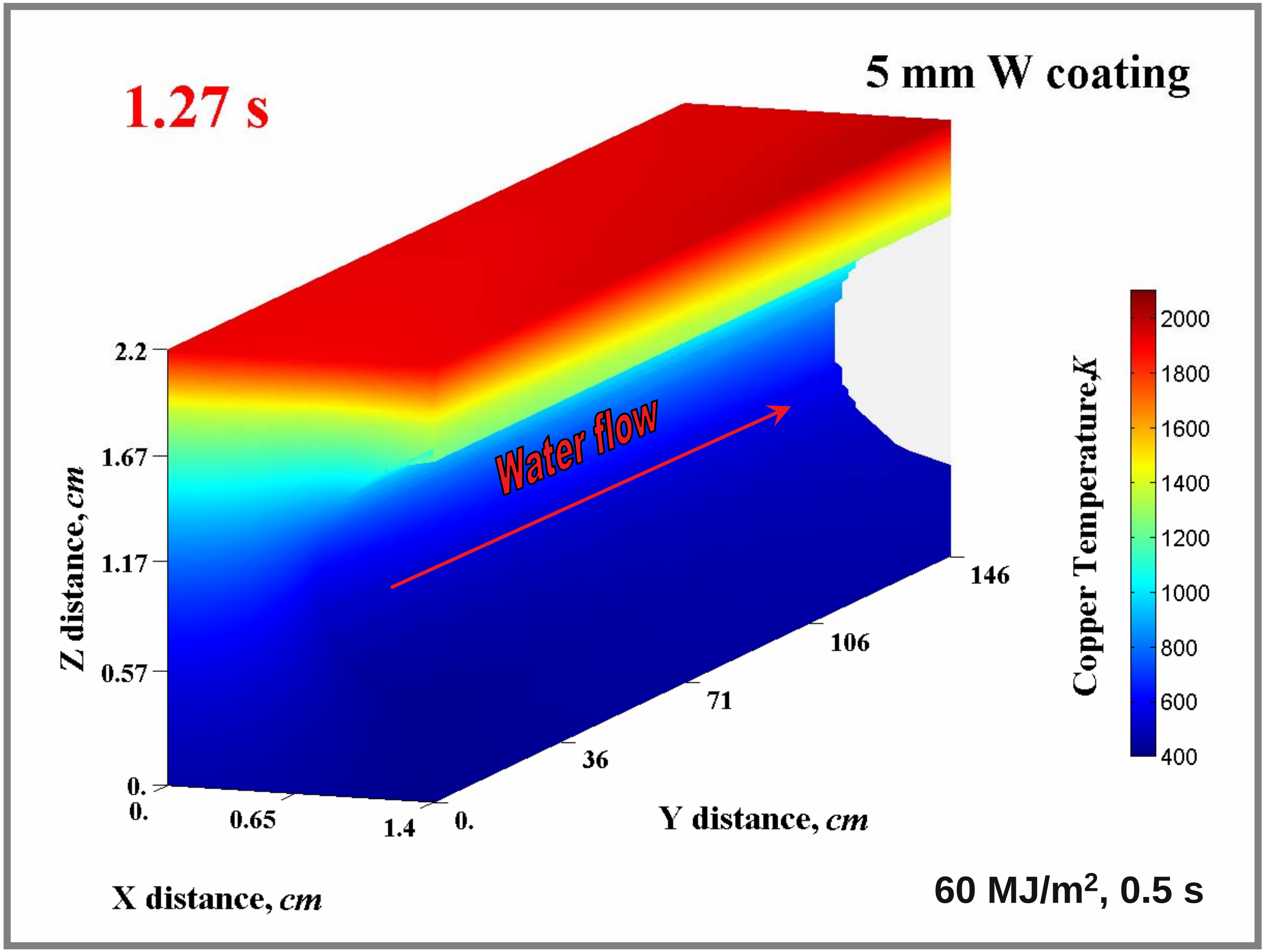



60 MJ/m², 0.5 s

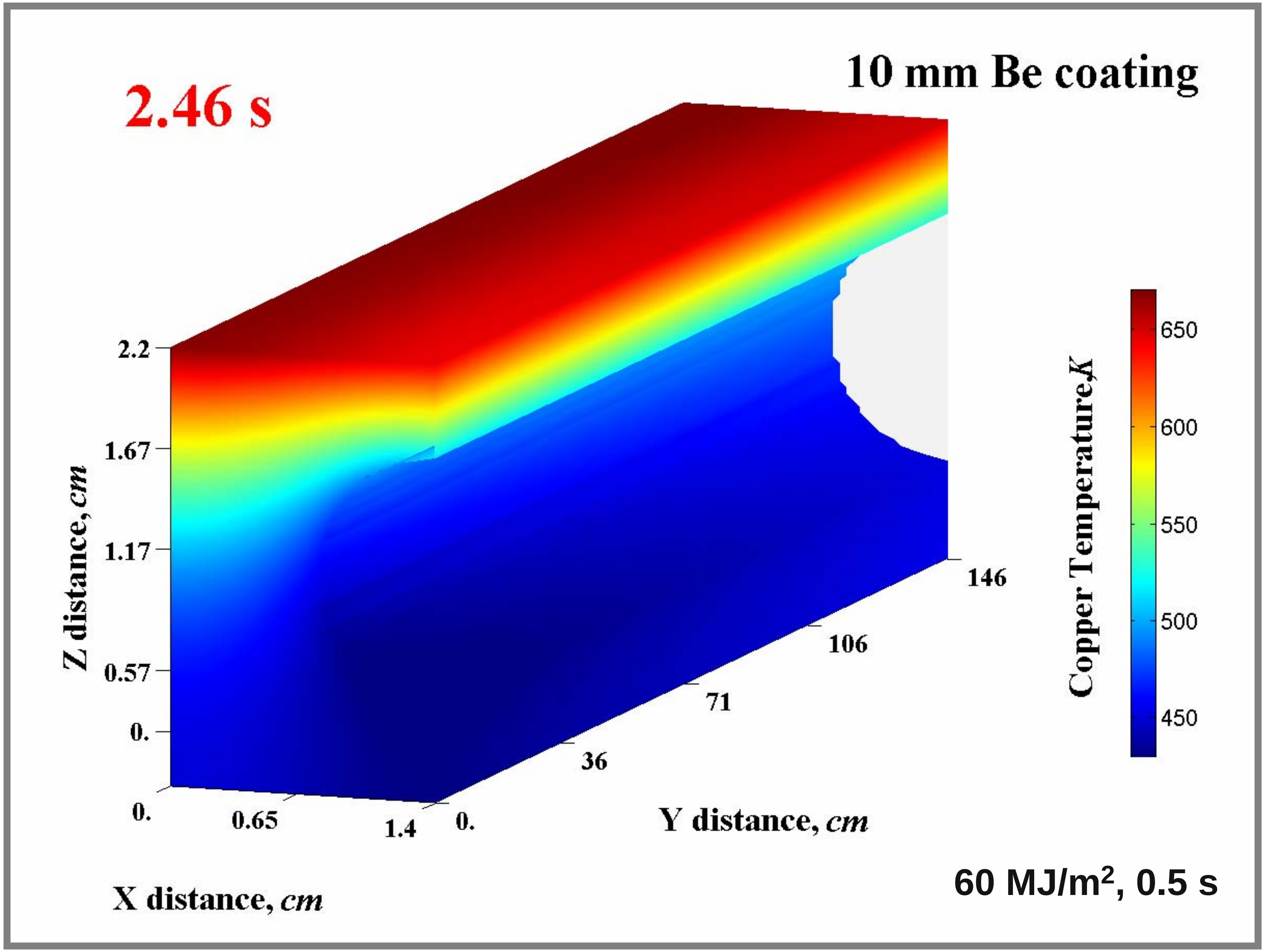
# Cu Structural Material Response



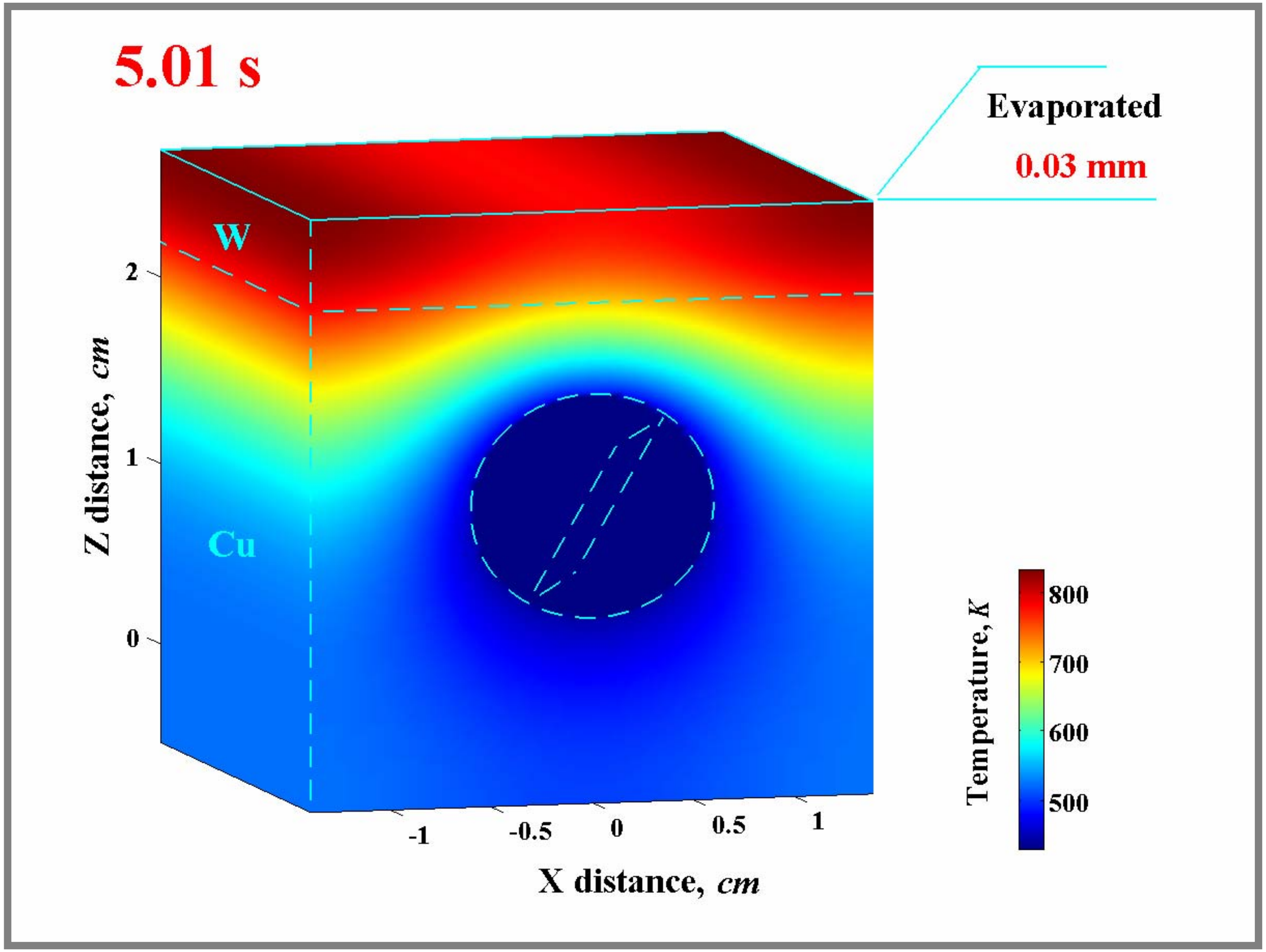
# Copper Temperature



# Copper Temperature



# *Wall under Heating in Swirl Tube*

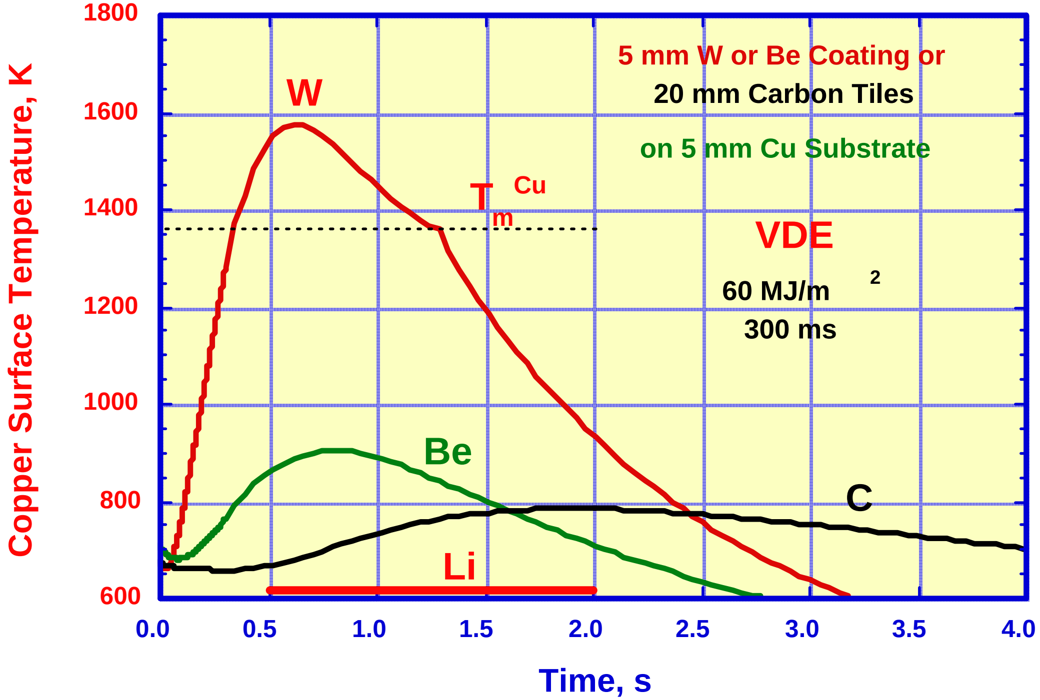


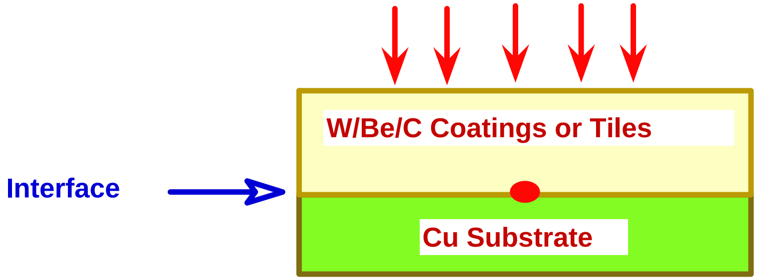

**60 MJ/m$^2$, 0.5 s**

# Summary of VDEs

- Although VDEs are rare events, operations in ITER-like device could result in serious damage to PFC coating and structural materials.
- Full 3-D model is developed to accommodate various PFC coatings and structural materials design modules and configurations using HEIGHTS-MFE package.
- Simulation experiments in laboratory and tokamaks (JET) showed excellent agreements with HEIGHTS.
- Significant surface vaporization losses and possible melting of copper structure can take place.
- Possible mitigation methods are the use of liquid metal such as Li to remove plasma incident power via surface vaporization or by the following Li

# Structural material response with Lithium Layer during VDEs



# General Conclusions

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