Response of Plasma Facing Components to Different Plasma Instabilities

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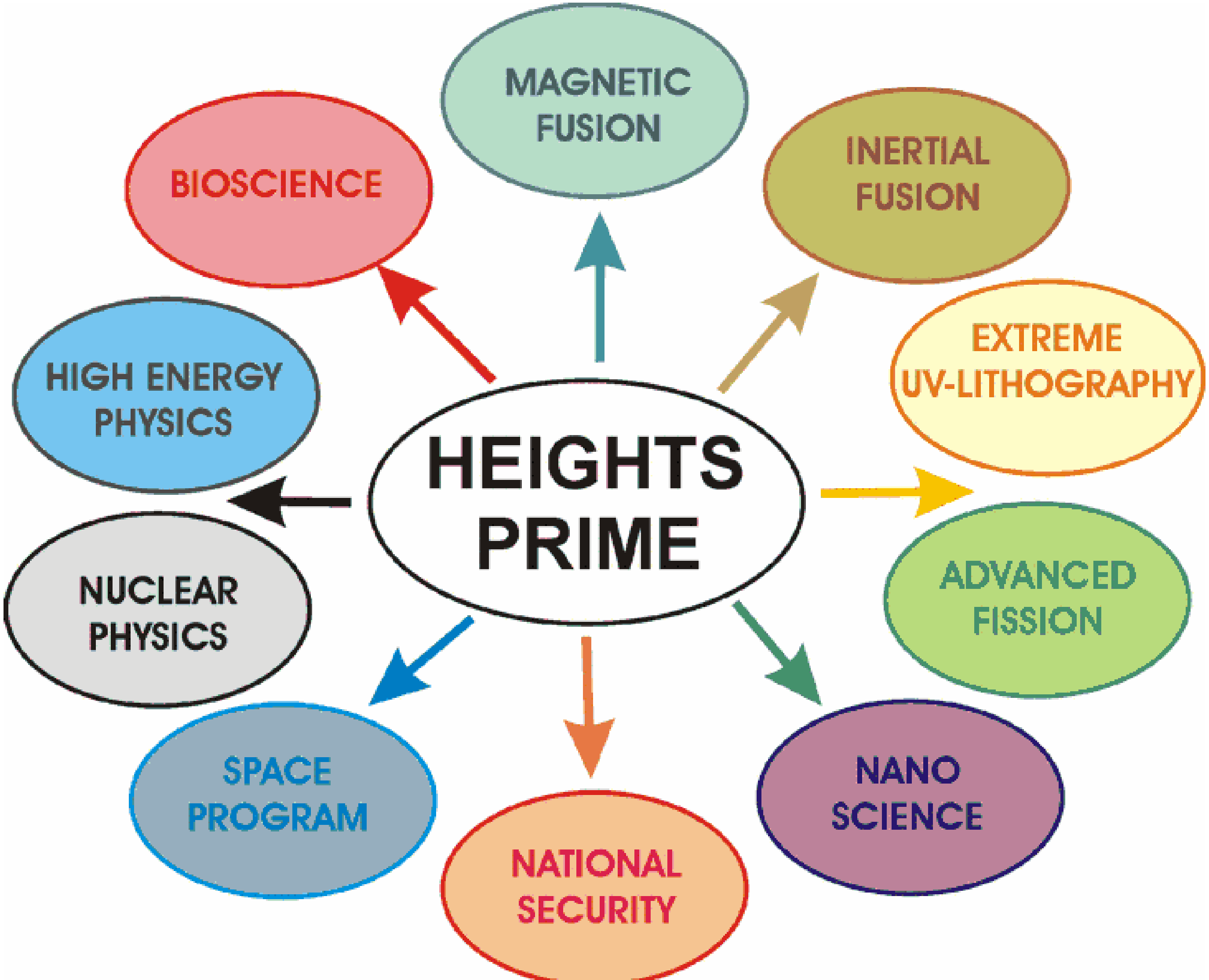
Outline

- Computational Research Activities
- Various Plasma Transient Events
- Disruption Modeling & Simulation
- Edge-Localized Modes (ELMs)
- Vertical Displacement Events (VDEs)
- PRIME Facilities & Simulated Experiments
- Summary & Conclusions

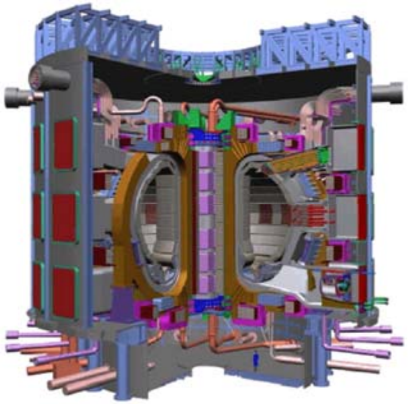
Computational Modeling



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/m2 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	10-10^2	10^2
A giant ELM	>1 Hz	0.1-0.5	1-3	1-10
VDE	Low	10^2-10^4	20-60	0.01-0.1

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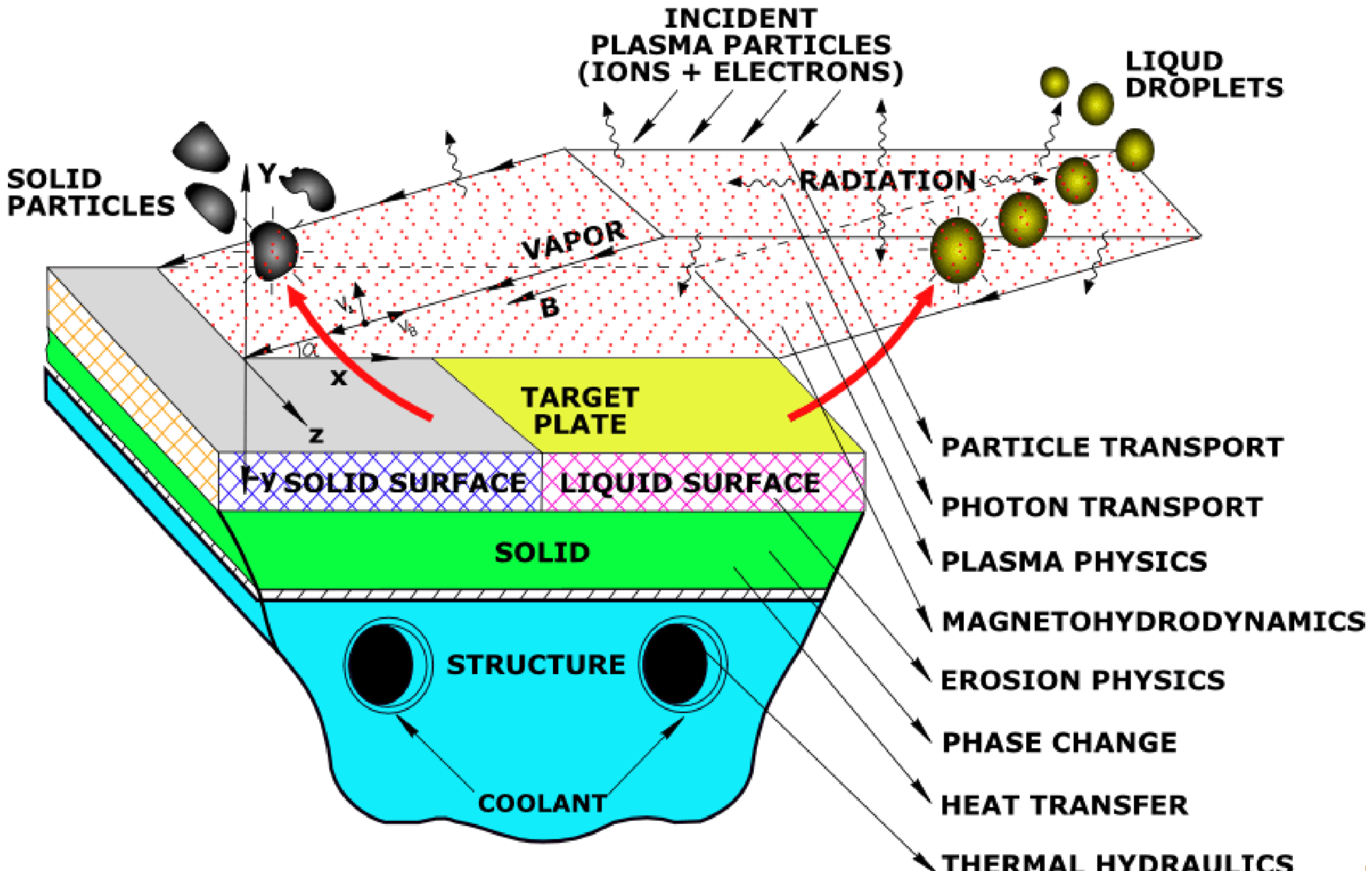
Models Involved in Predicting High-Intensity Plasma/Surface Interactions



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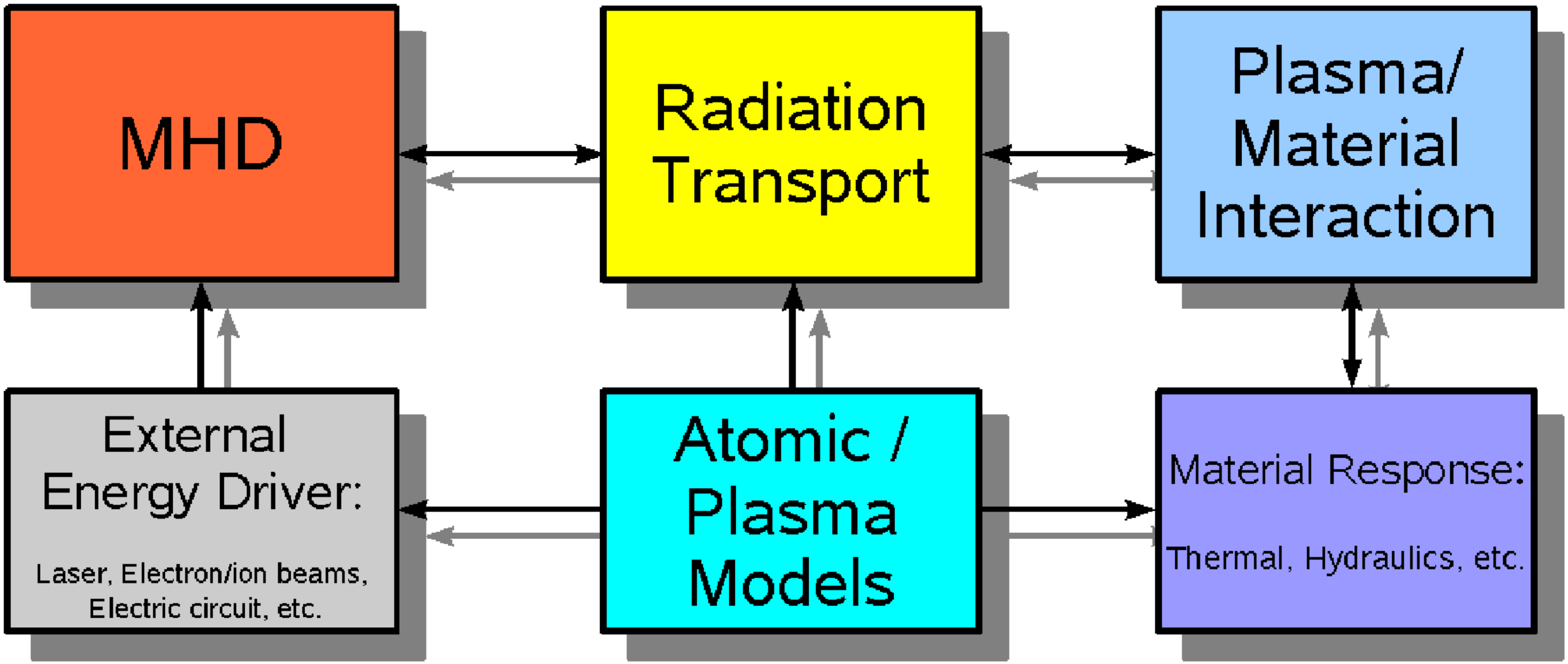
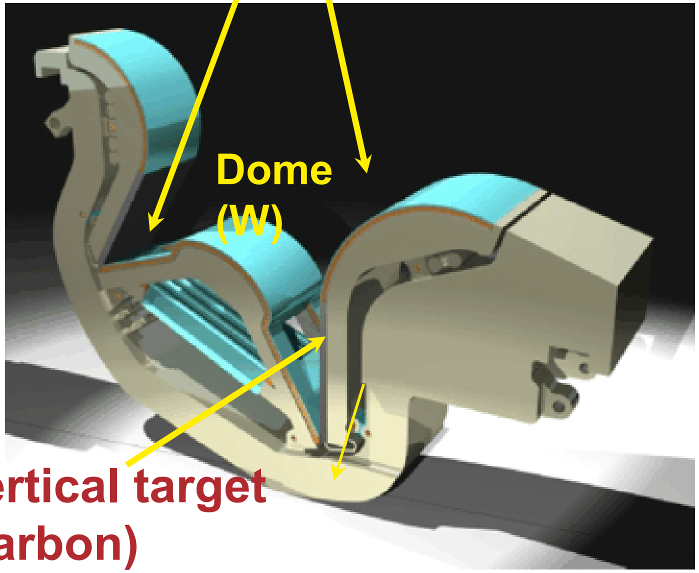
Integrated Simulation Package

HEIGHTS-Package: Comprehensive 3-D Simulation Project for Various Applications

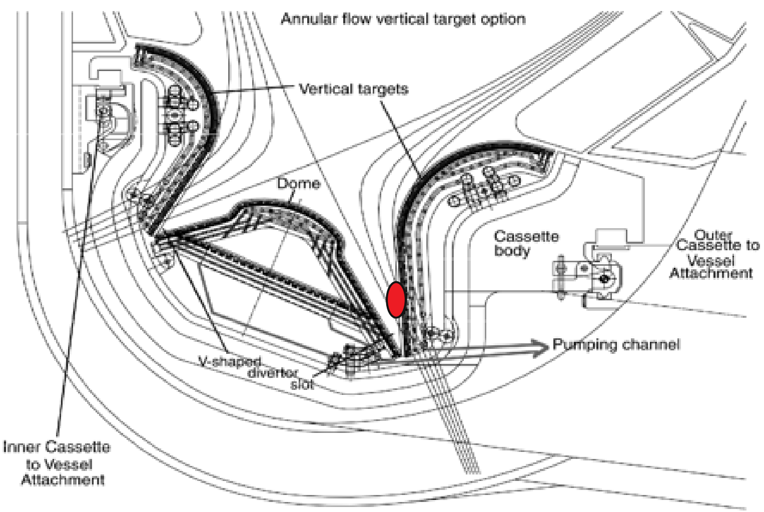


ITER Divertor Design

Vertical target (W part)



Vertical target
(carbon)



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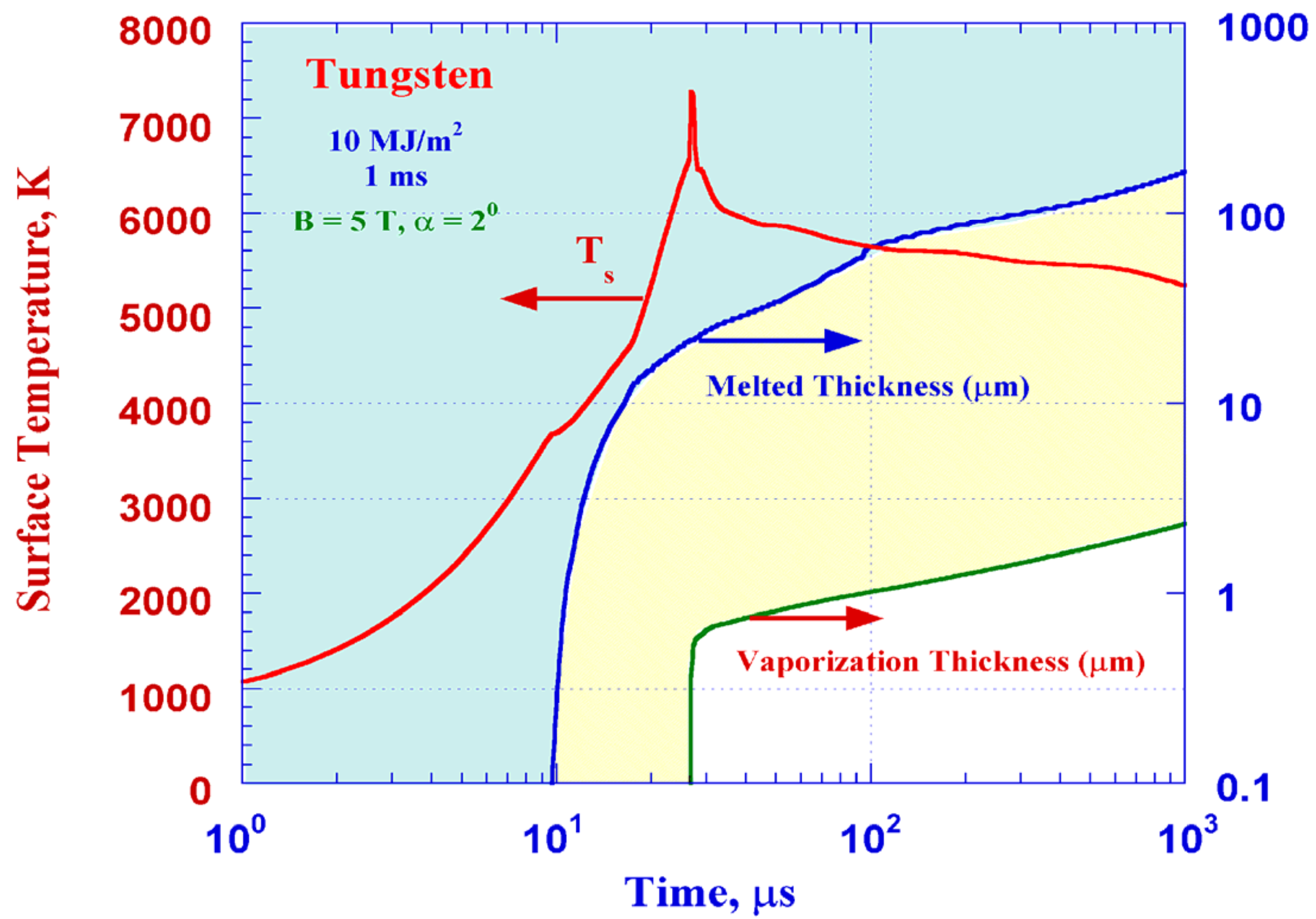
HEIGHTS Analysis of Tungsten Target Thermal Evolution during Intense Energy Deposition



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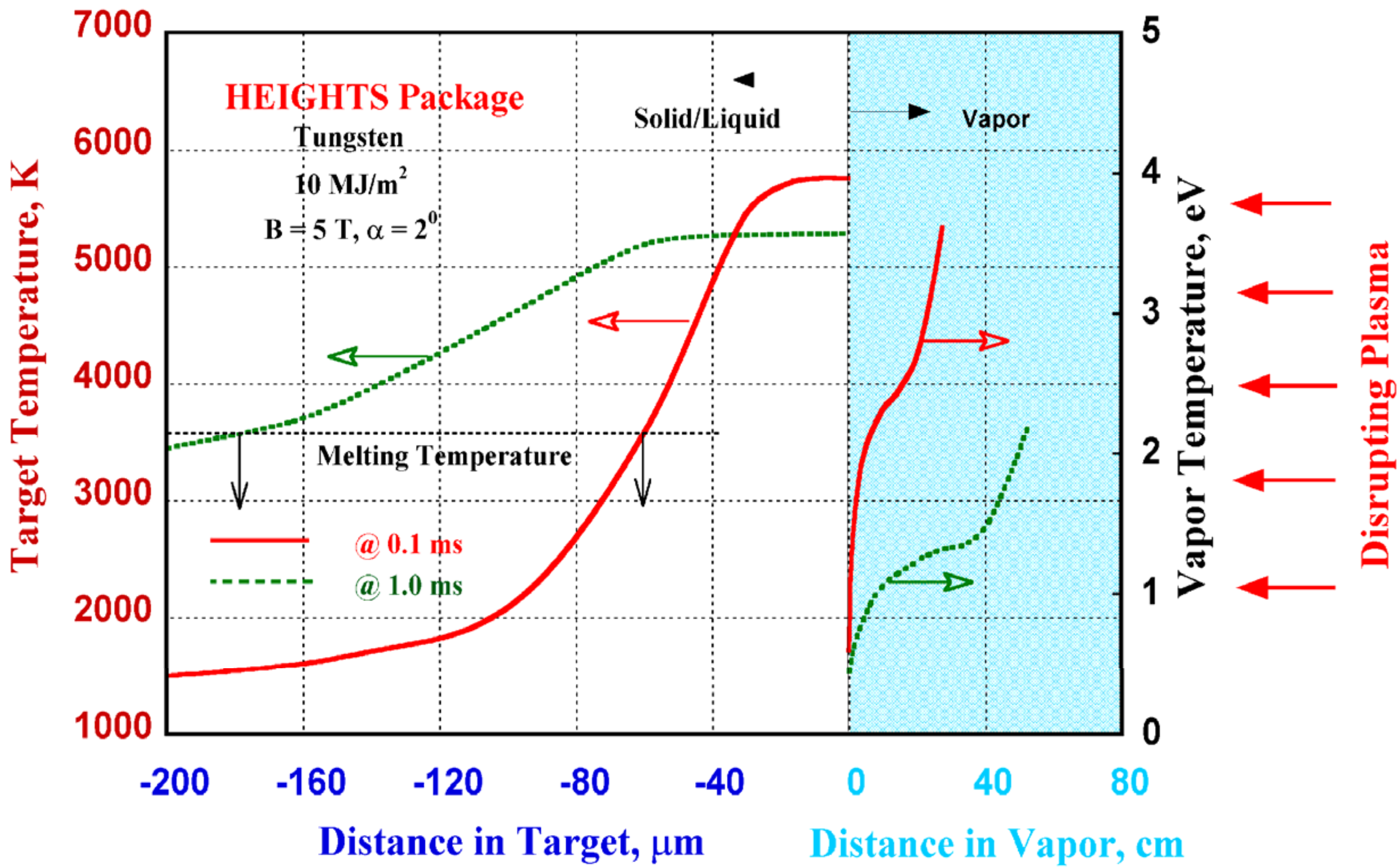
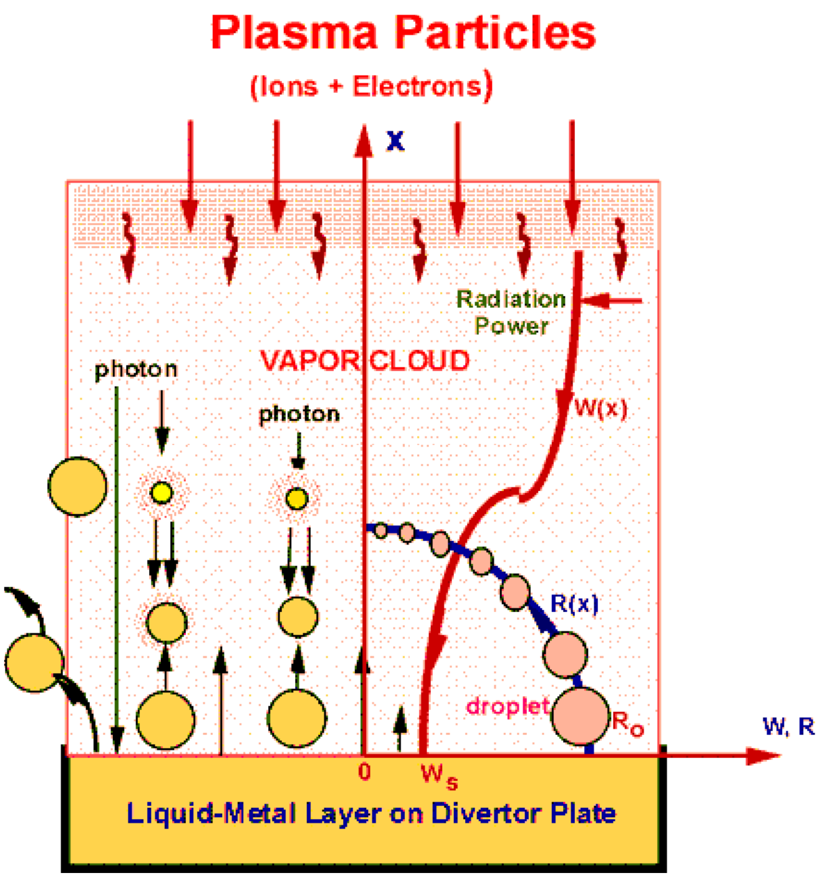
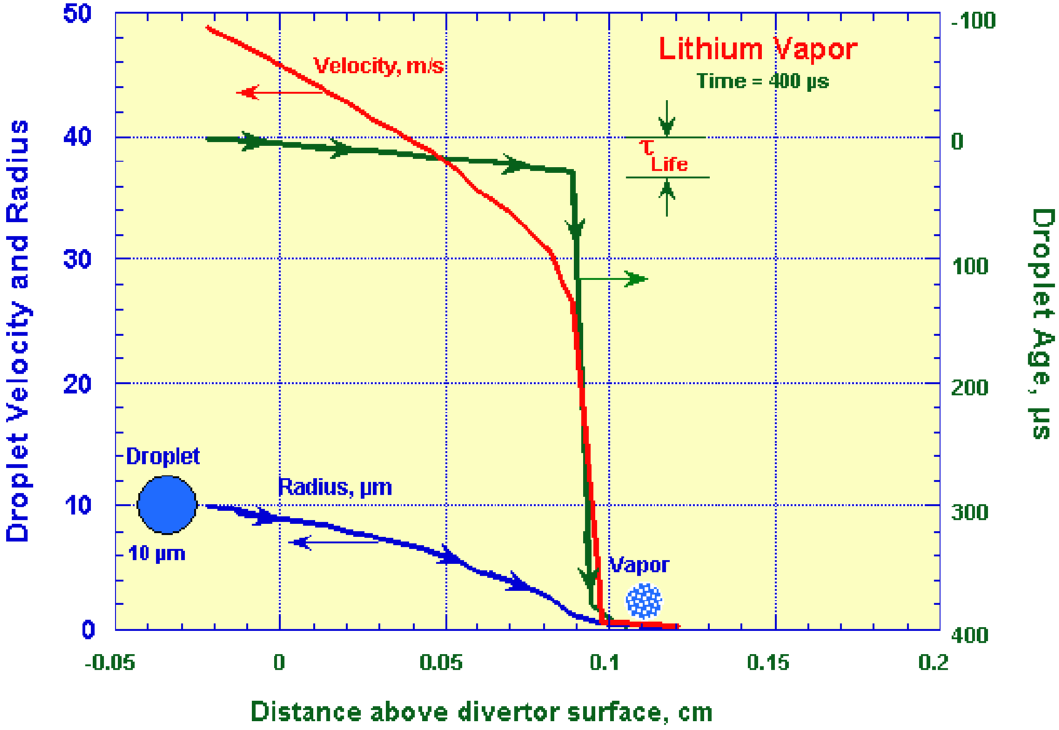
Spatial Evolution of Tungsten Solid-Liquid-Vapor Cloud Temperatures at Two Disruption Times

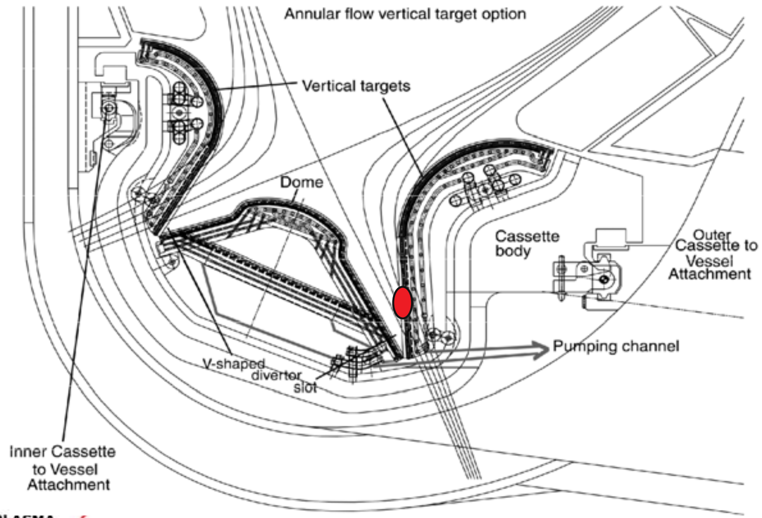


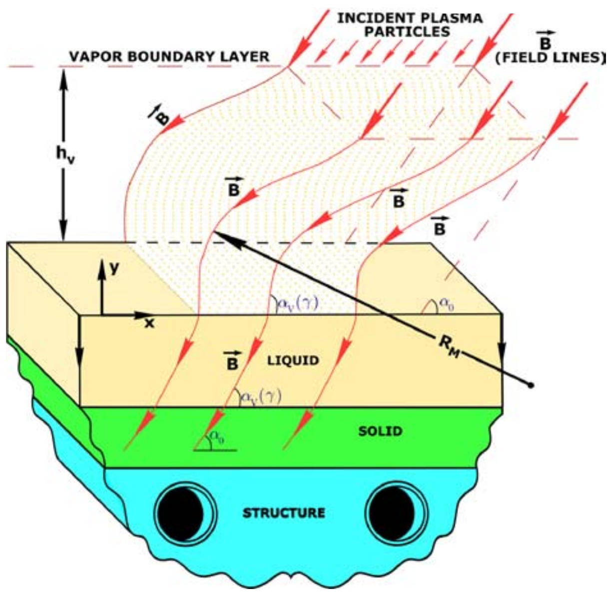
Evolution and lifetime of a macroscopic droplet moving in vapor cloud

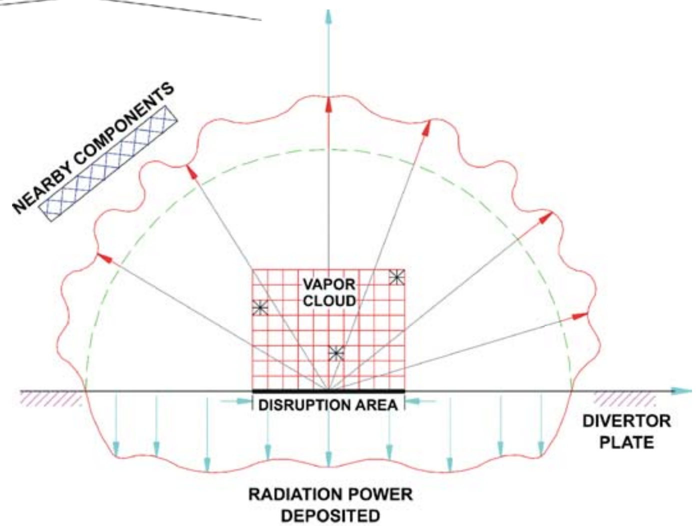




Other Issues Need to be Studied in Details







Instability under Inclined Magnetic Field

Effect of Secondary Radiation to Nearby Comp.

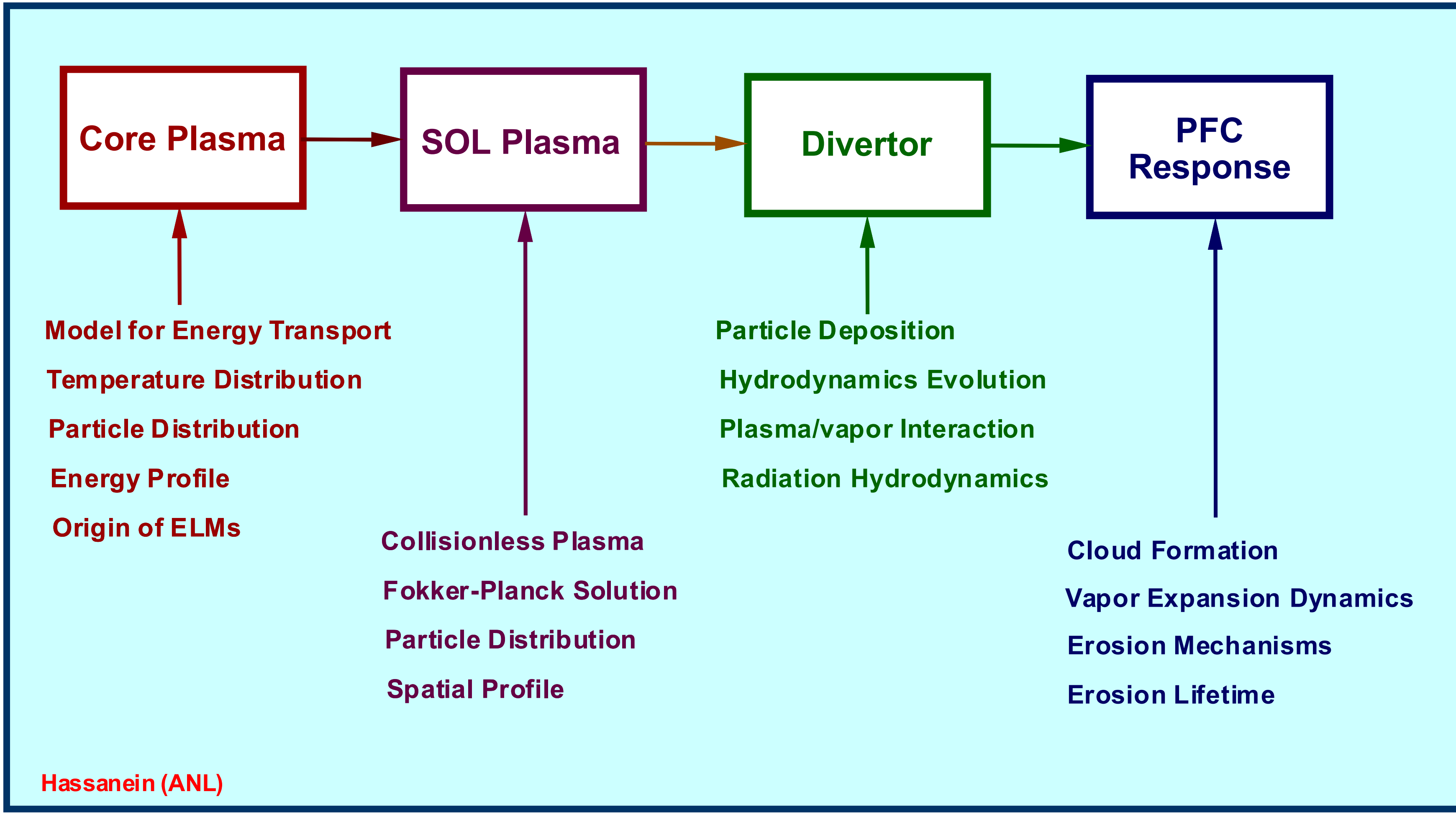
Characteristics of ELM Transients

II. Edge-Localized Modes

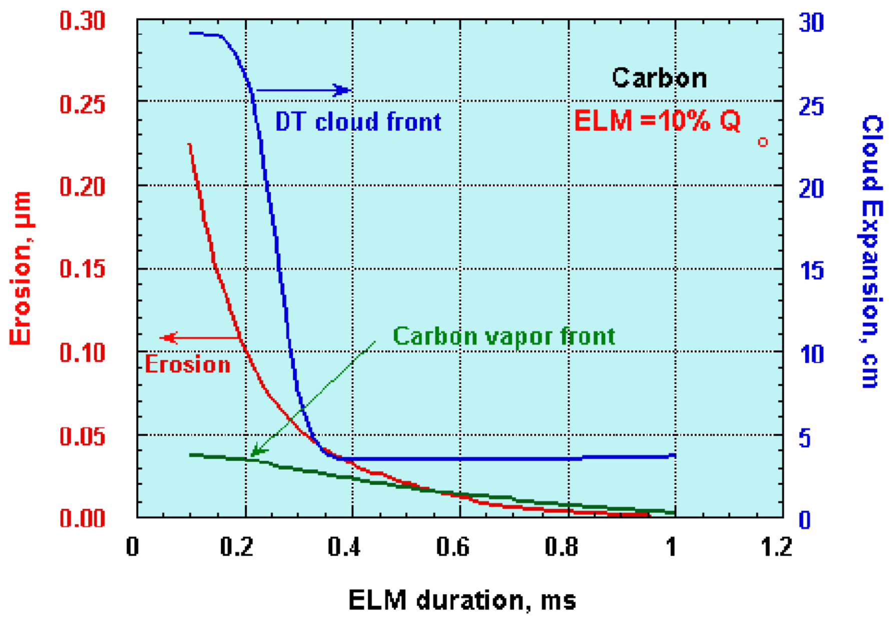
- Much more frequent and must be tolerated (1-10 Hz).
- Lower energy density about 1-3 MJ/m2 (up to 10% Qo).
- Deposition time is less than 1 ms.
- Complicated physics:
  - Lower density vapor cloud
  - Higher cloud temperature and velocity
  - Mixing effects of vapor and plasma
- ELMs in future Tokamaks can be simulated in plasma guns and z-/theta-pinch devices.
- Plasma contaminations!

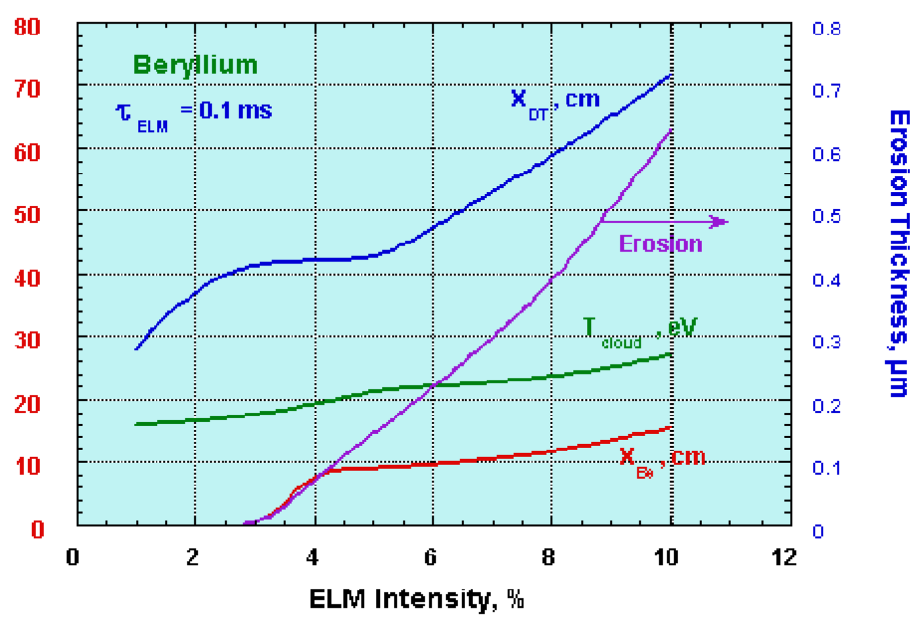
Event	Repetition	Duration [ms]	Energy dump [MJ/m^2]	Power flux [GW/m^2]
Disruption	Low	1-10	10-10^2	10^2
A giant ELM	>1 Hz	0.1-0.5	1-3	1-10
VDE	Low	10^2-10^4	20-60	0.01-0.1

Modeling Stages of ELMs in HEIGHTS



HEIGHTS Calculation of Material Erosion and Cloud Expansion during ELMs





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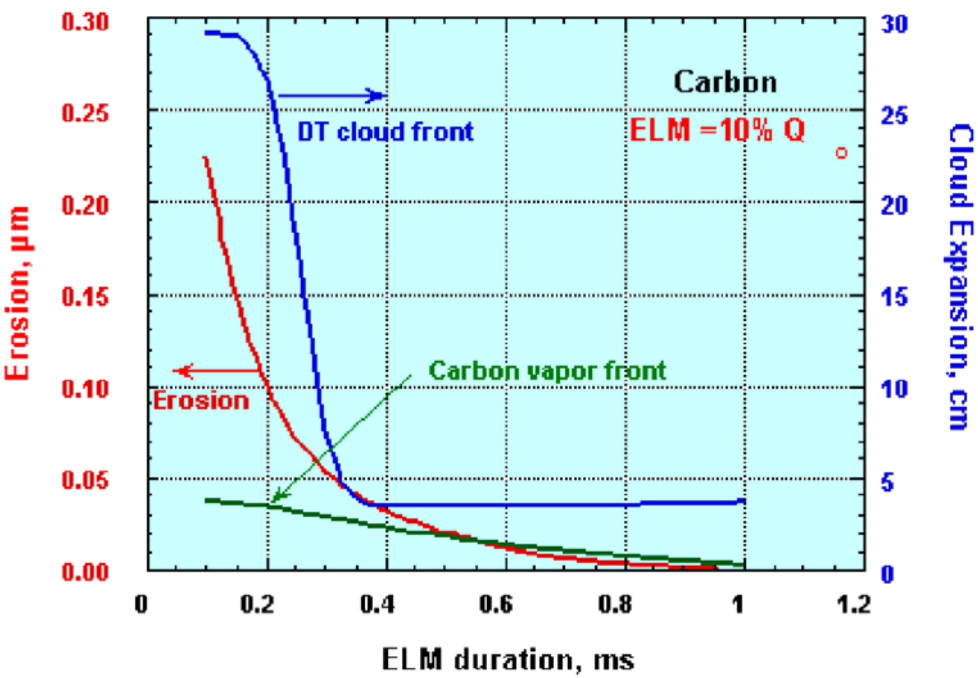
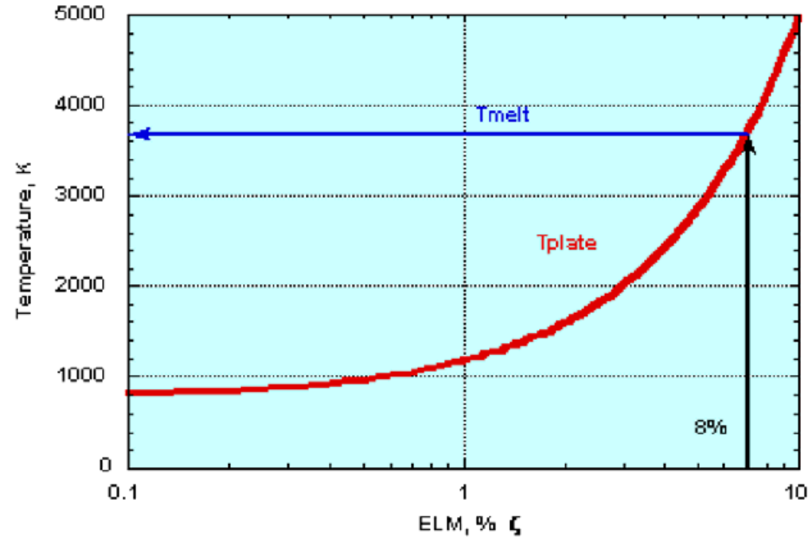
HEIGHTS Calculation of ITER Divertor Plate Response to Giant ELMs

Carbon



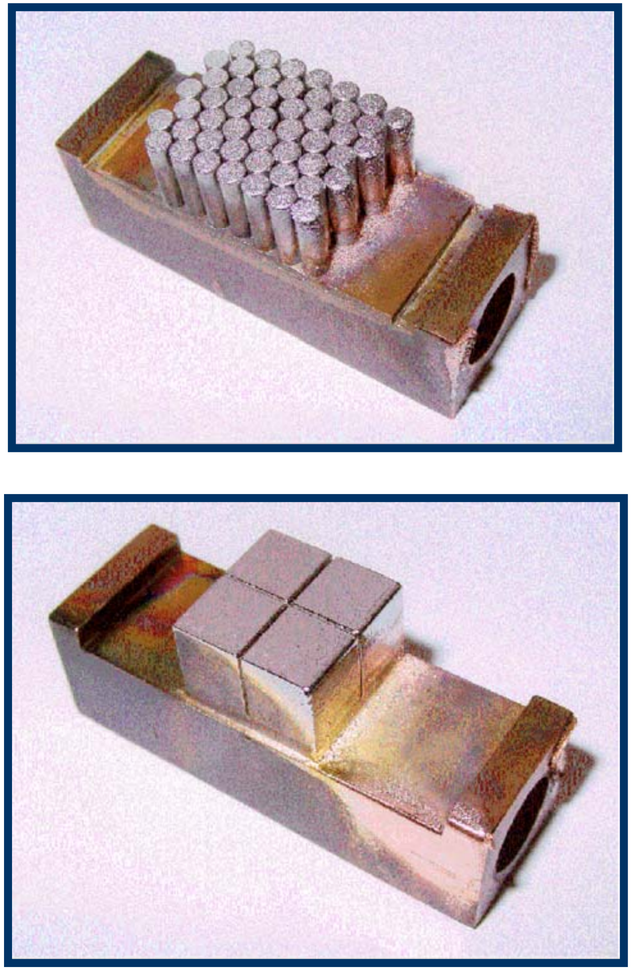
Tungsten



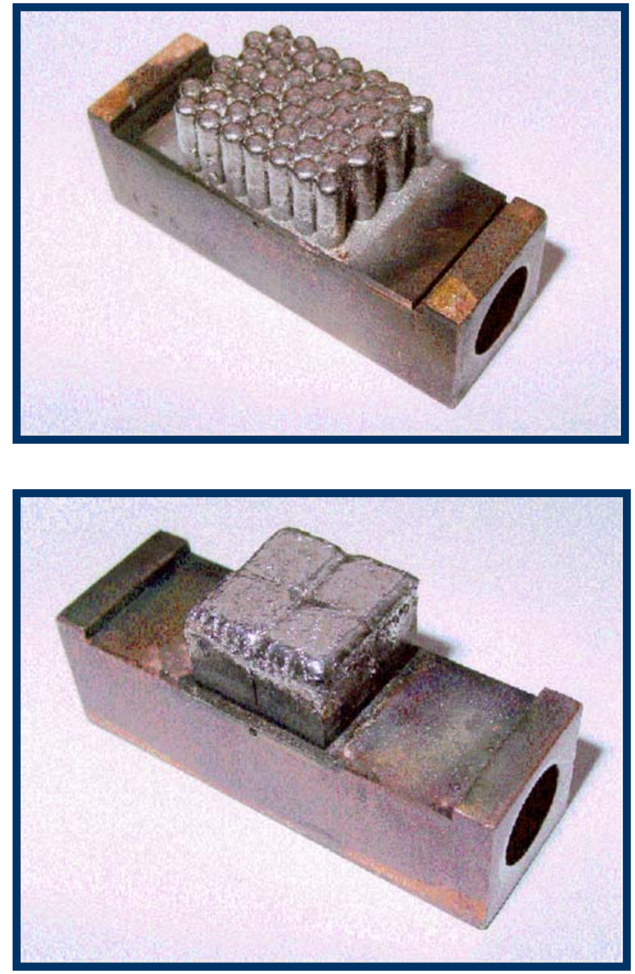
For lower ELM intensity (ζ<8%) (and > 0.5 ms duration), tungsten surface temperature does not reach melting temperature.

- **Carbon erosion too high for short ELM duration, may be “OK” for longer duration.** **(Core plasma contamination is an issue).**
- **Tungsten ELM erosion is dominated by melt-layer erosion.**

Melt Layer Erosion of Tungsten Brush Samples



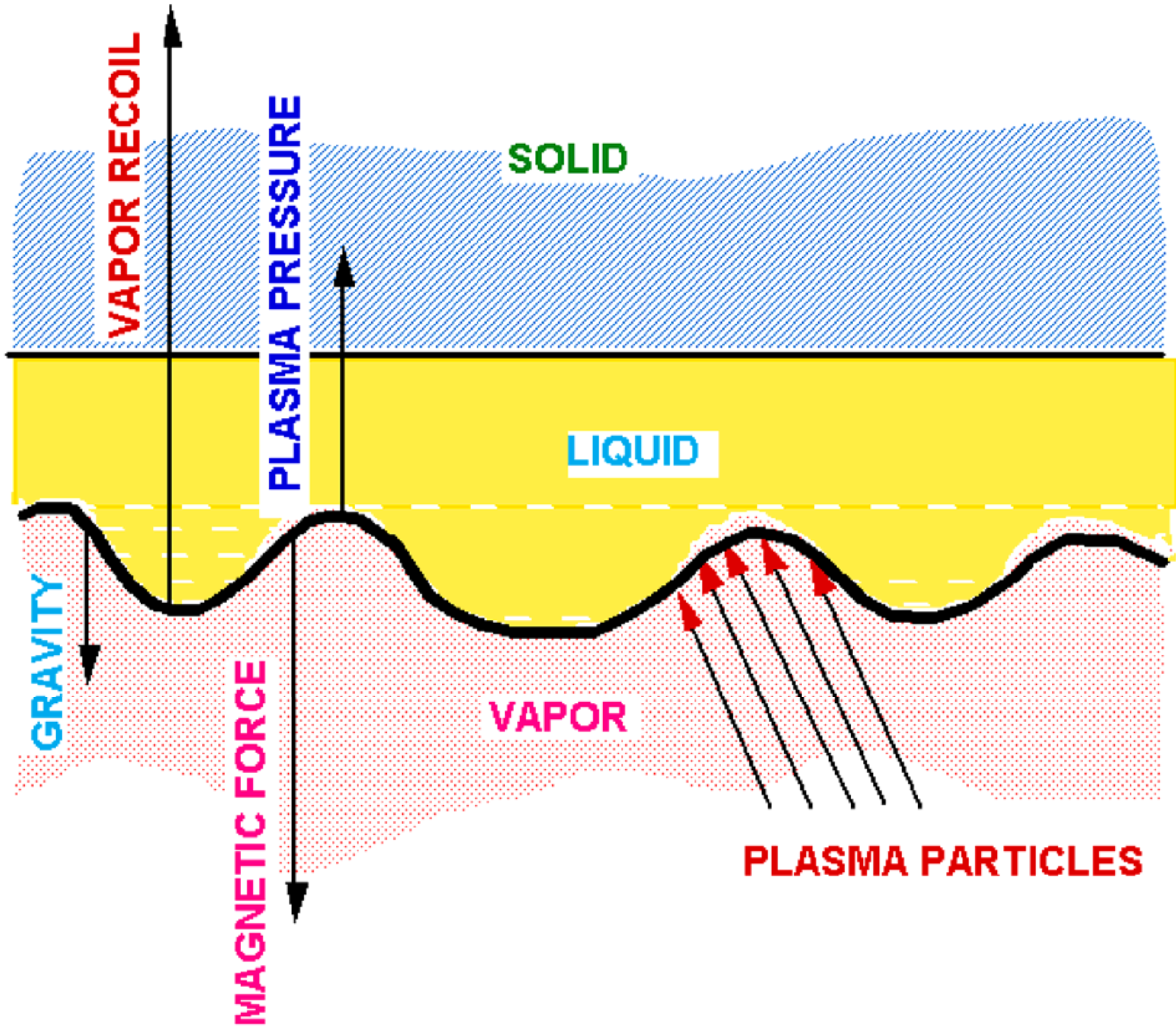
50 ELM loads at MK-200UG facility



20 ELM loads at QSPA facility

(TRINITI, Russia)

Various Forces Acting on Melt Layer during Plasma Instabilities



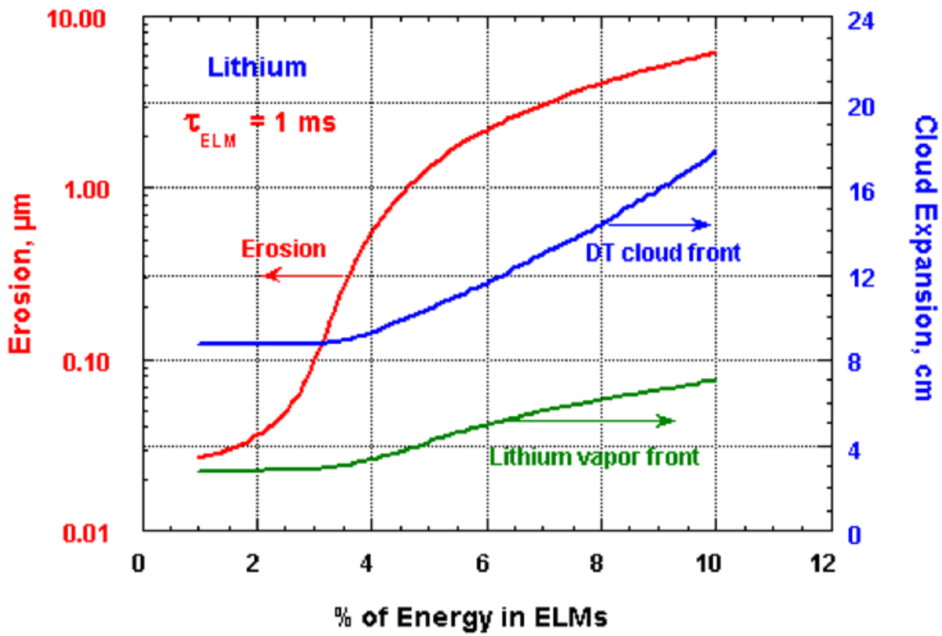
Mitigations of Disruptions and ELMs

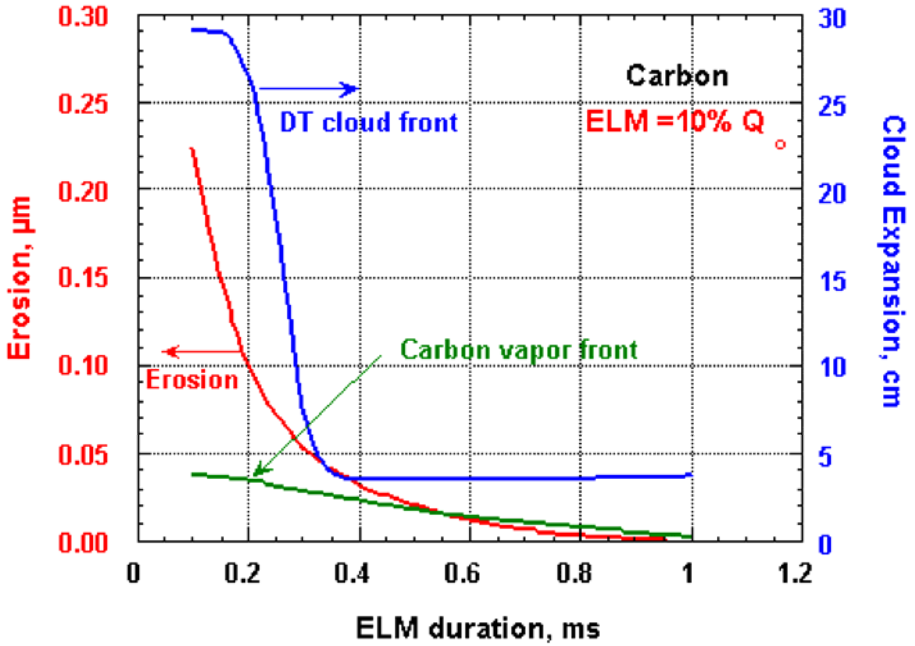
HEIGHTS Analyzed the Following Options:

1. Liquid Metals as PFCs

2. Injection of Inert Gases

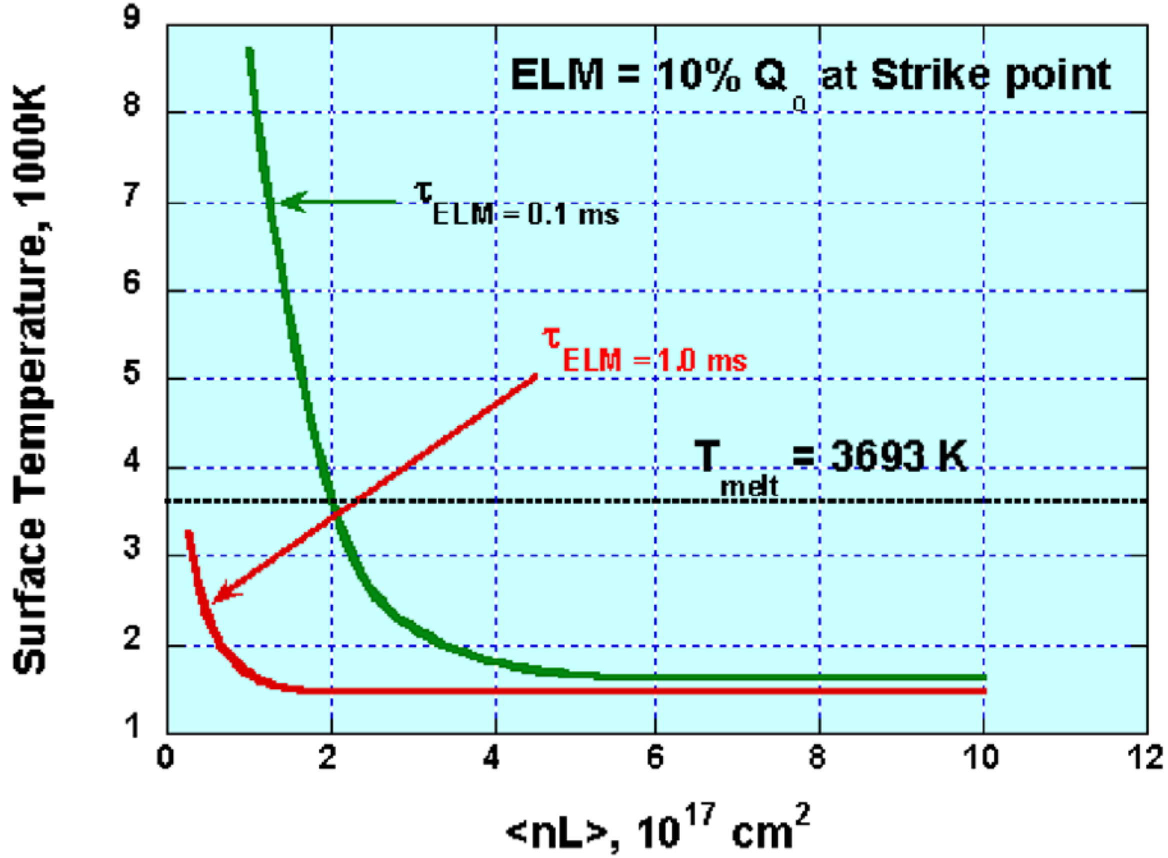
Lithium Surface under ELM Load





Mitigations by Neon Gas Injection

- Neon gas should have enough linear density, <nL>, to stop incoming plasma particles (ions and electrons) and reradiate significant part of their energy.
- Divertor surface temperature is given for different Ne gas density. Shielding efficiency is very low till <nL>=10^{17} cm^{-2} with asymptotic value of temperature T=1500 K.

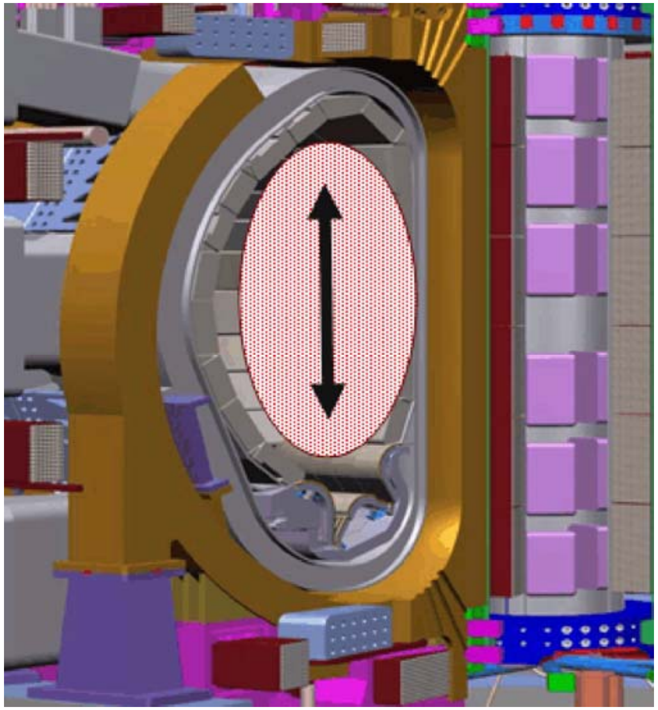


Core Plasma Contamination during ELMs

- Core plasma contamination can be serious.
- There are two other reasons for contamination:
  - a) Contamination during SOL reconstruction and
  - b) Impurities diffusion along Private Flux Region (PFR).

Characteristics of Transients

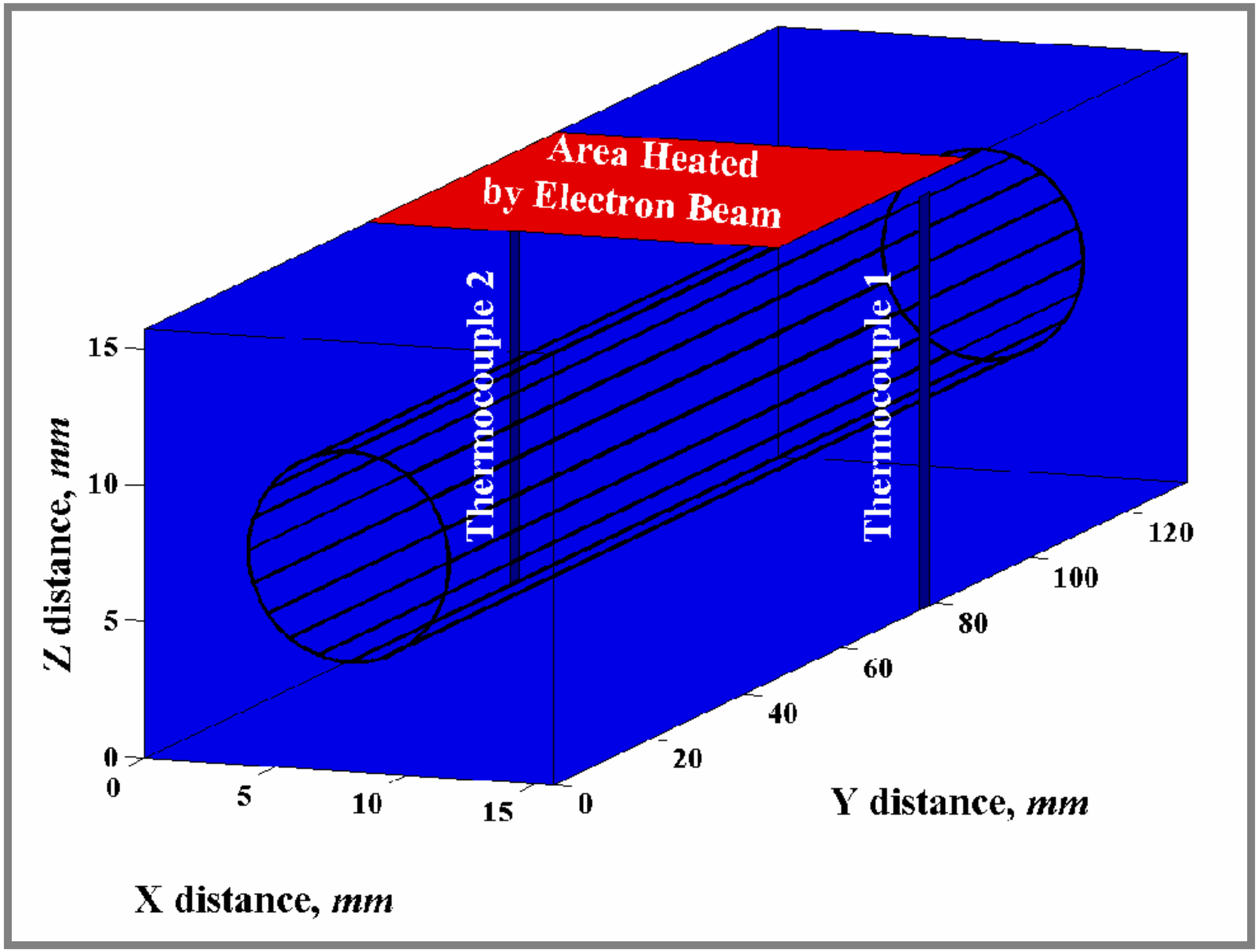
III. Vertical Displacement Events



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

- Rare events but serious effects
- Energy density similar to disruptions 20-60 MJ/m2
- Deposition time is much longer about 100-1000 ms.

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.

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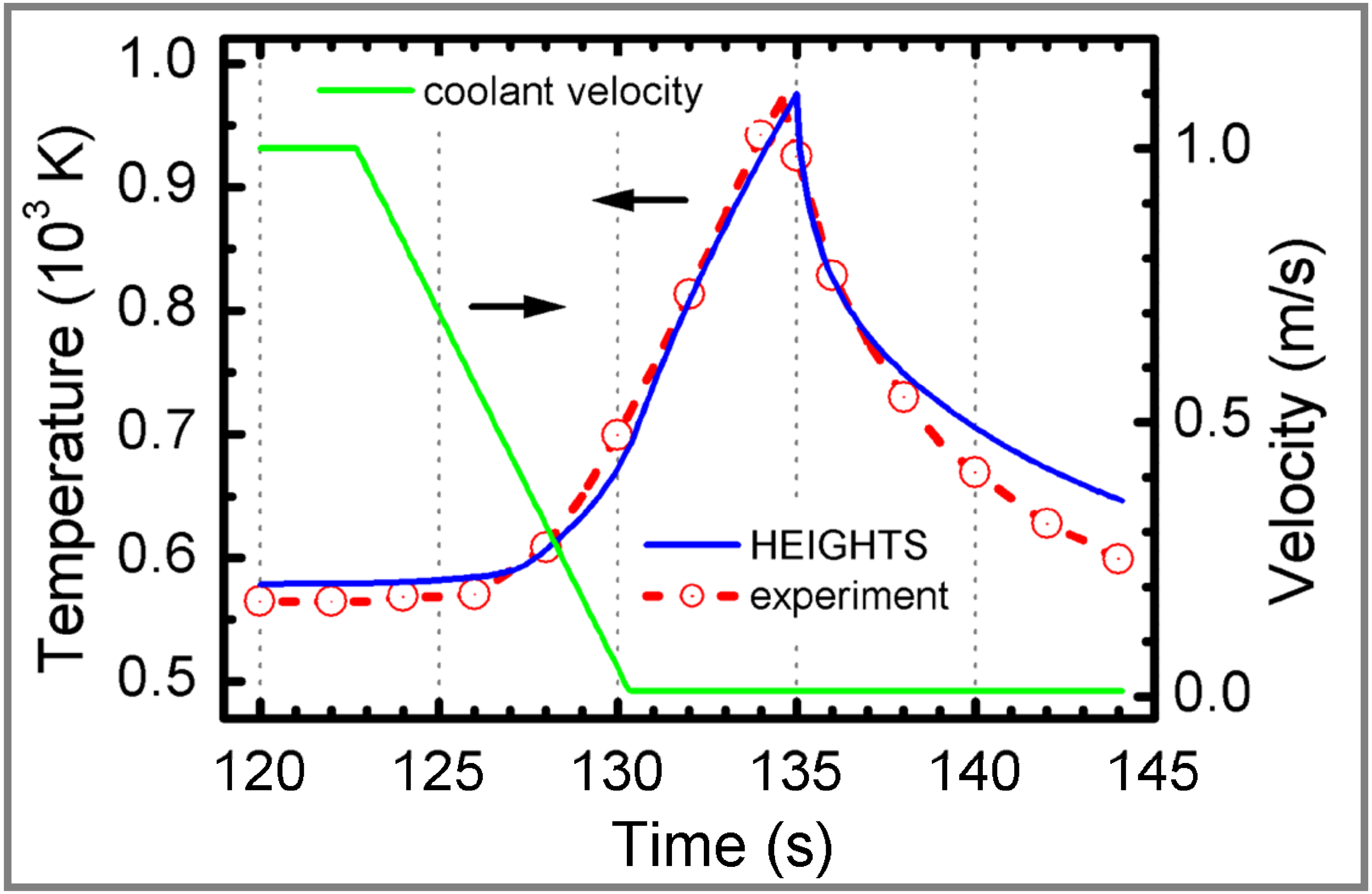
LOFA Modeling



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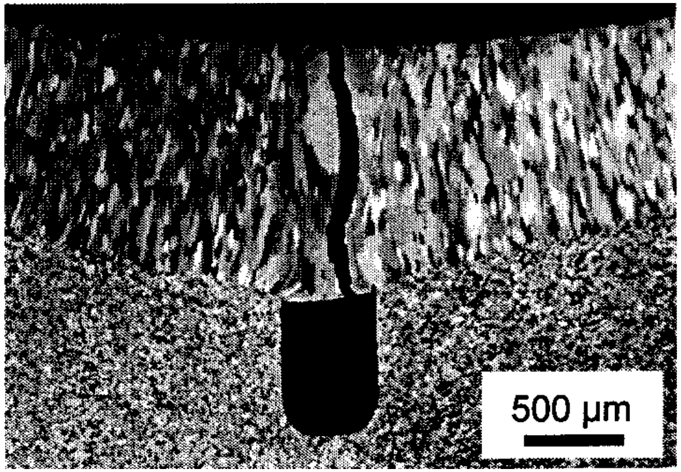
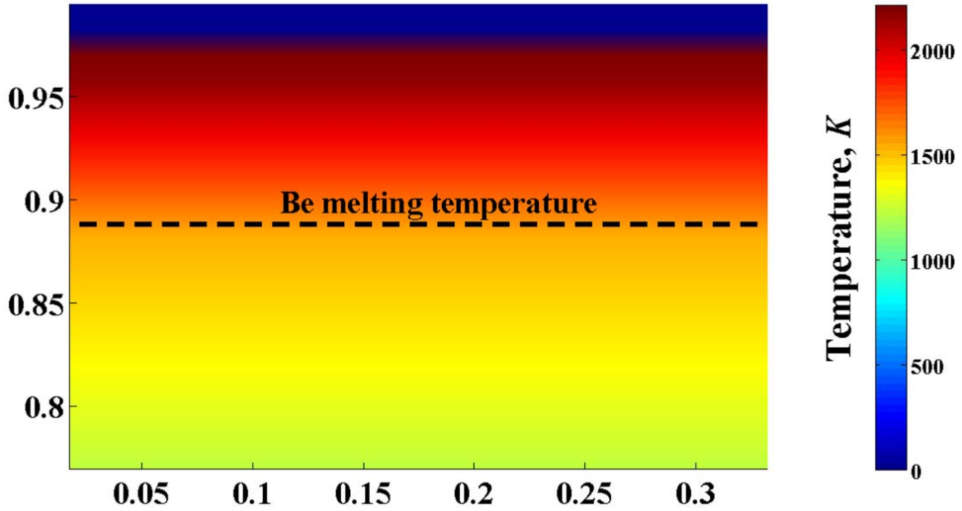
HEIGHTS Benchmarking of JET VDE Experiments

JET Experiment

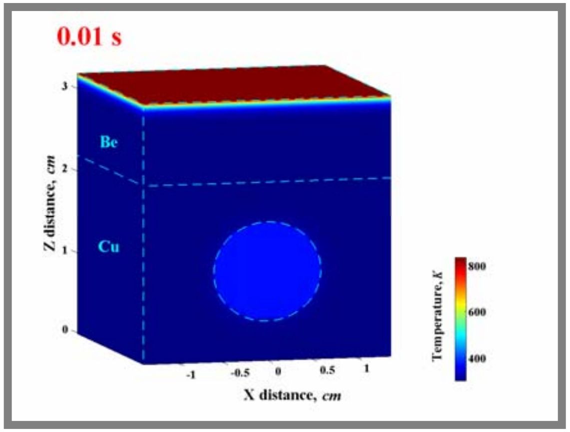


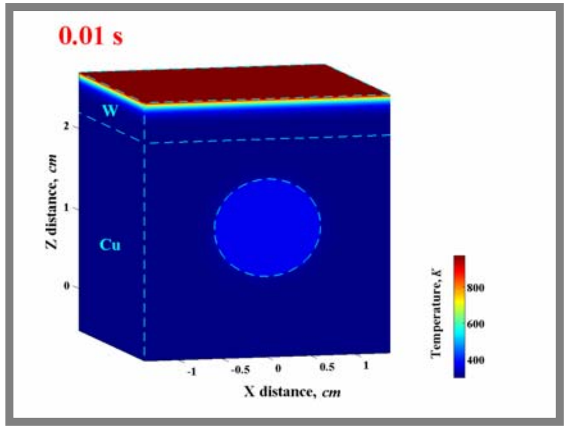
HEIGHTS Simulation

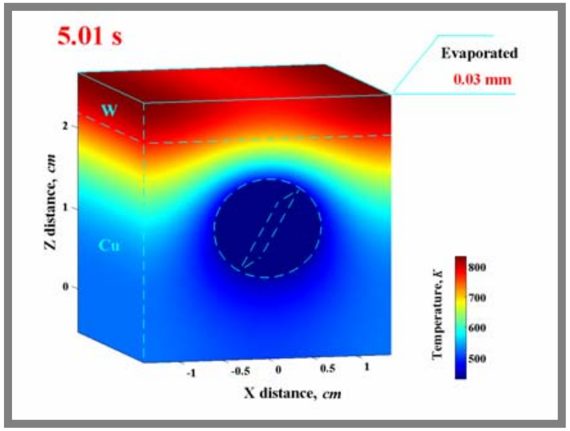


Erosion and Melt layer thickness during Vertical Displacement Events (deposited energy density: 60 MJ/m², 1.0 s)

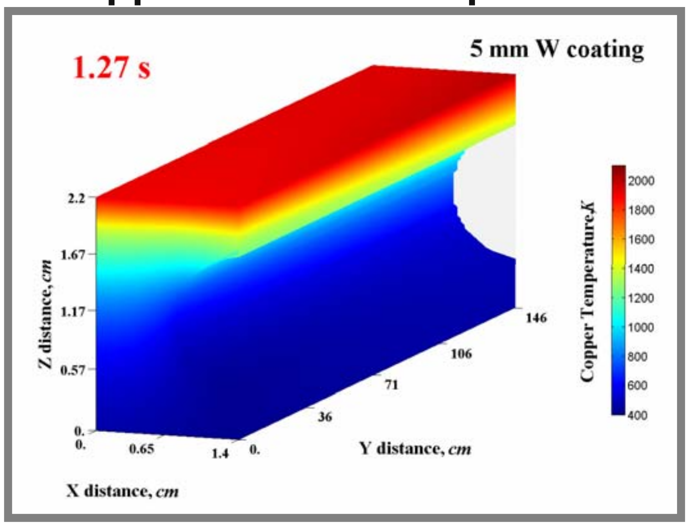
First Wall and Structural Response under VDE Heating



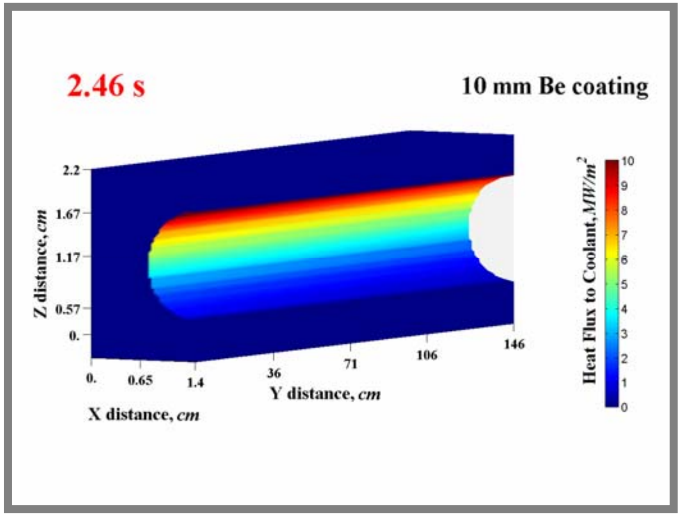




Copper Surface Temperature

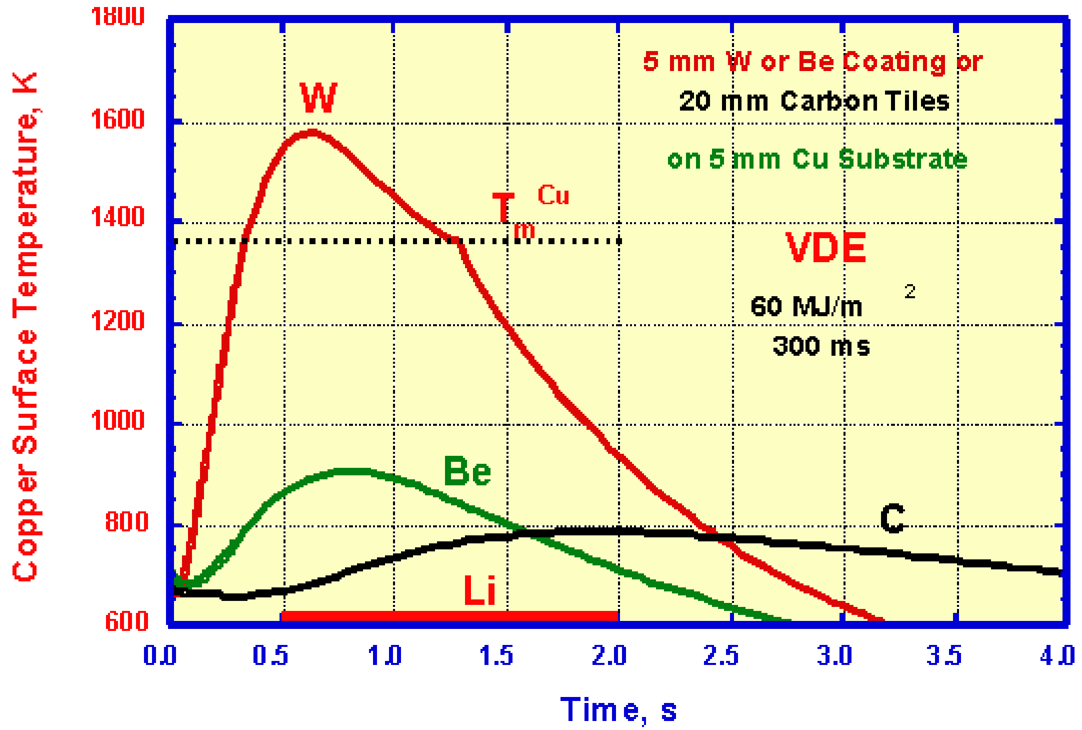


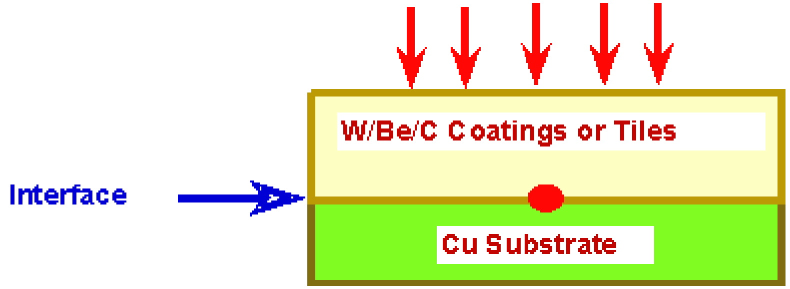
Heat Flux to Coolant



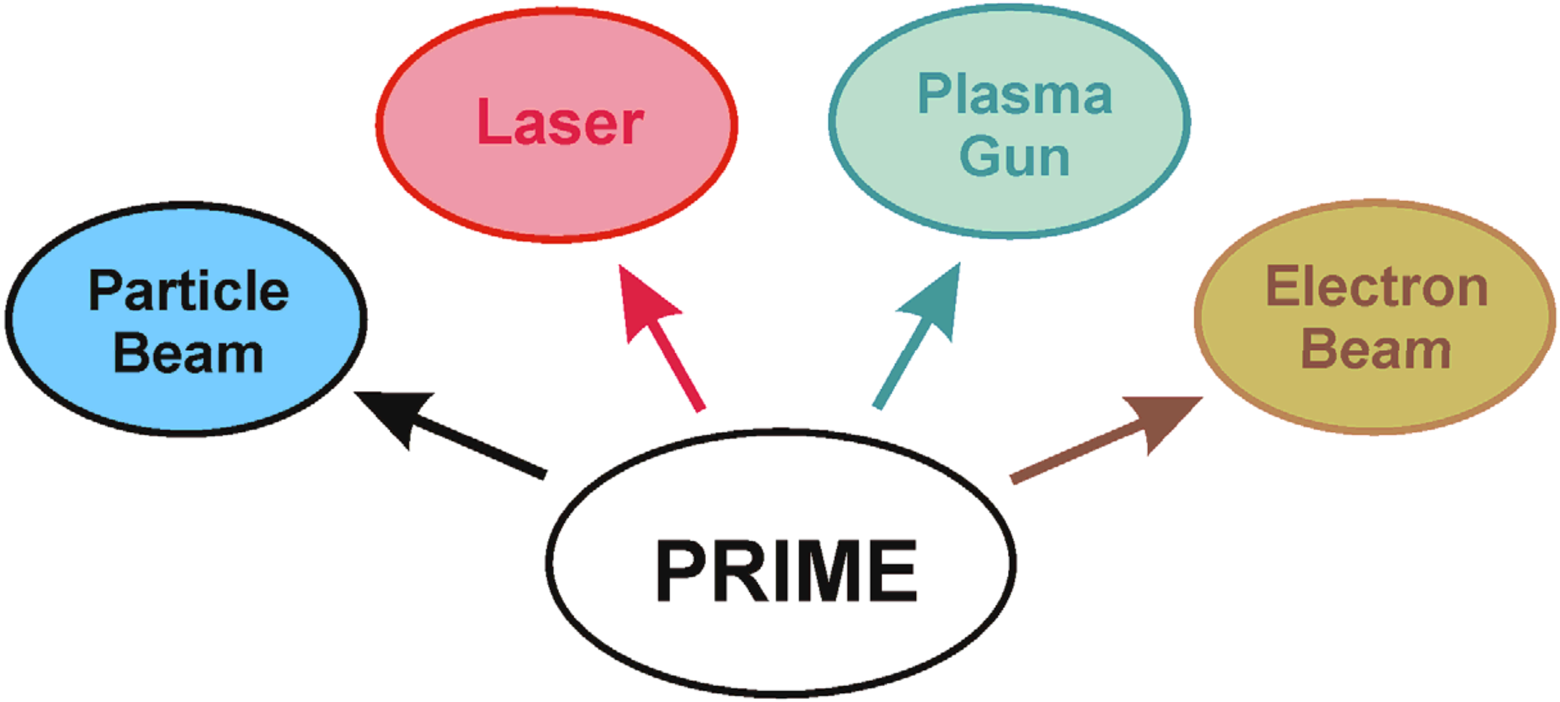
60 MJ/m^2, 0.5 s

Structural material response with Lithium Layer during VDEs





PRIME Experimental Facilities



Conclusions

- Plasma transients in tokamaks are serious events and may prevent successful and prolonged plasma operation
- Overall erosion damage to plasma instabilities (e.g. ELMs in normal operation; VDEs, and 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 (particularly Li) show promise in mitigating transients due to self-healing properties and pumping capabilities
- In ELM operation and using liquid metal or inert gas injection to mitigate giant ELMs, plasma contamination is very serious and can terminate plasma in a disruption
- ITER design should seriously address all issues regarding handling extremely large particle and heat fluxes under both normal and off-normal operation