Recent Advances in Modeling and Simulation of Plasma Material Interactions

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Graduate and Undergraduate students

VLT Conference Call

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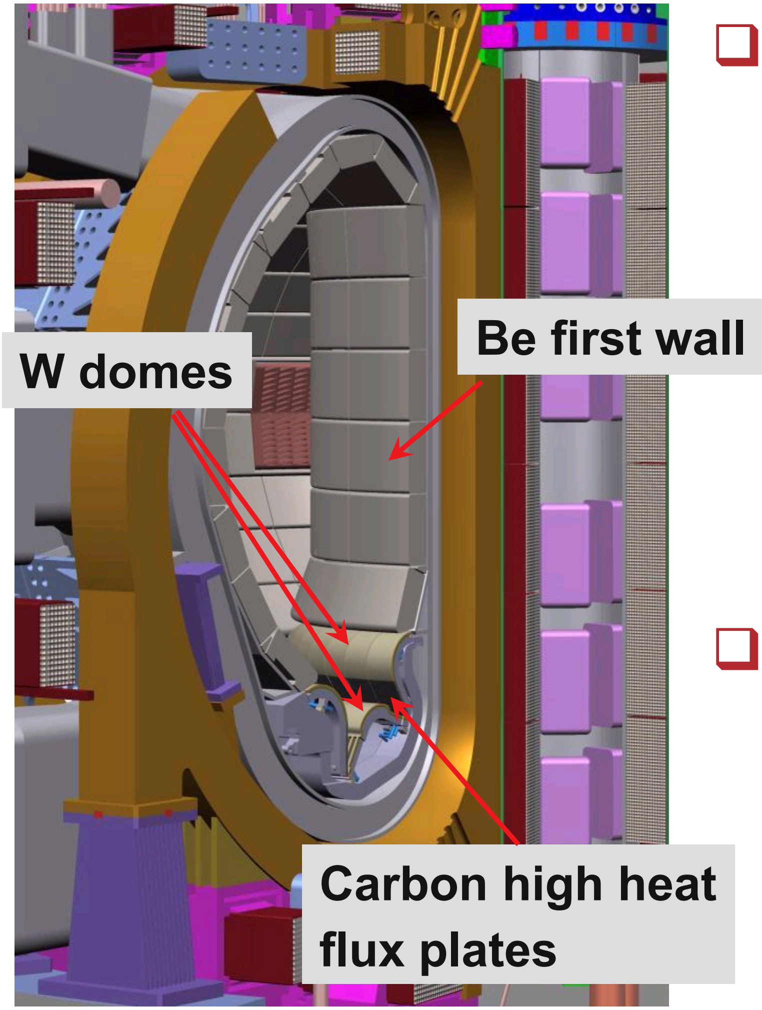
Outline

- **Status of Modeling & Simulations**
- **Disruptions & Edge-Localized Modes (ELMs)**
- **Melt Layer Erosion during Disruptions/ELMs**
- **Vertical Displacement Events (VDEs)**
- **Runaway Electrons and mitigation methods**
- **Surface evolution of mixed plasma facing materials**

Plasma Transient / Instabilities: PMI Key Concerns



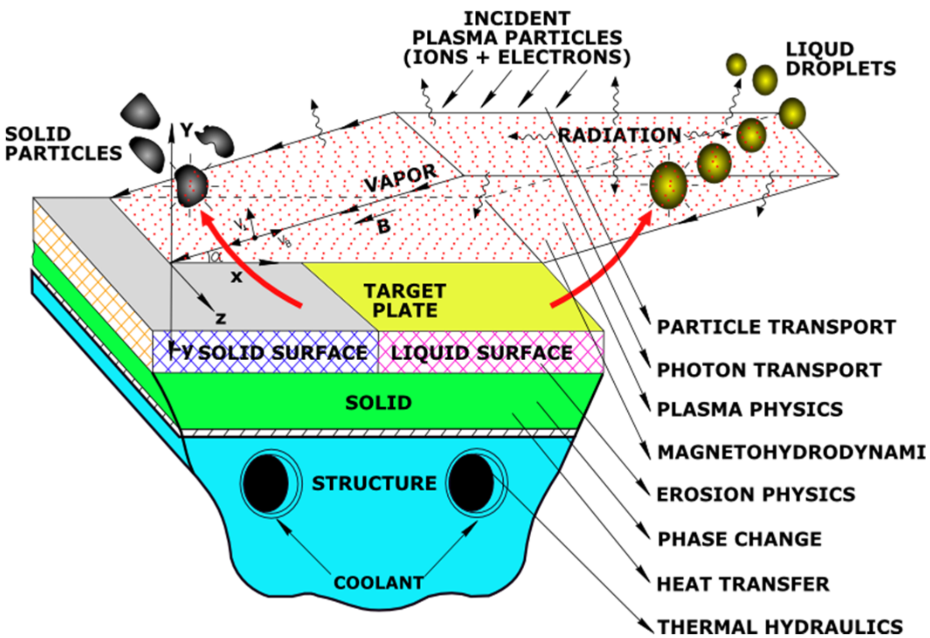
- **Major events for surface and structural response to plasma transients:**

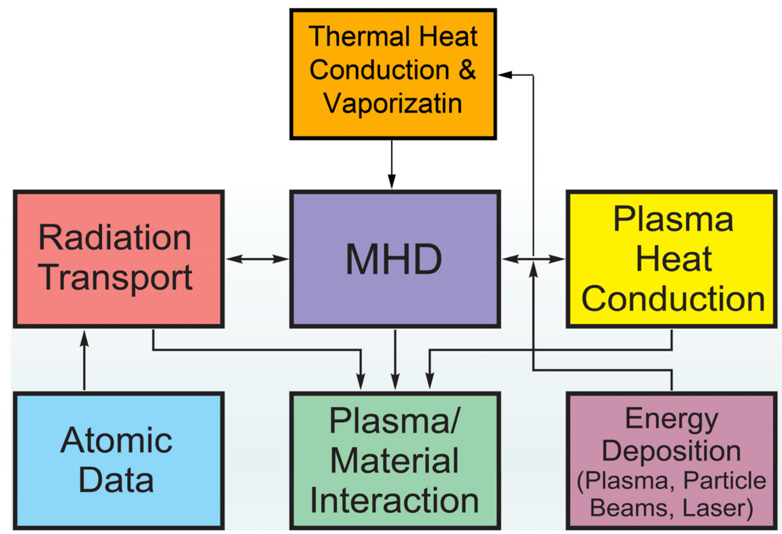
  (1) Edge Localized Modes (ELM's)
  (2) Disruptions
  (3) Vertical Displacement Events (VDE's)
  (4) Runaway electrons

- **Key concerns:**

  -- *Wall Coating/Chamber erosion lifetime*
  -- *PFC structural integrity*
  -- *Plasma contamination*

Simulation of Wall / Diveror Evolution





HEIGHTS Modeling Capabilities

- 3D MHD target evolution for various geometries
- 3D Implicit heat conduction in plasma; Explicit scheme for heat conduction in target
- 3D Monte Carlo models and Discrete models for radiation transport
- 3D Monte Carlo model for energy deposition/absorption in liquid, vapor, and plasma
- Moving boundaries with receding surface in 3D geometry
- Parallelized version of HEIGHTS based on MPI

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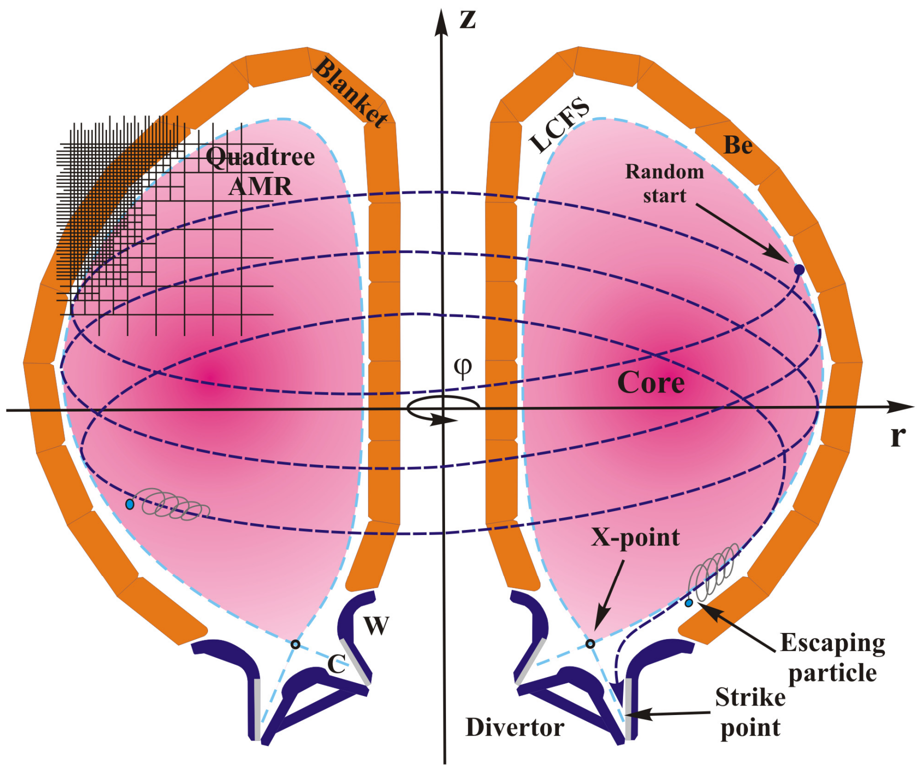
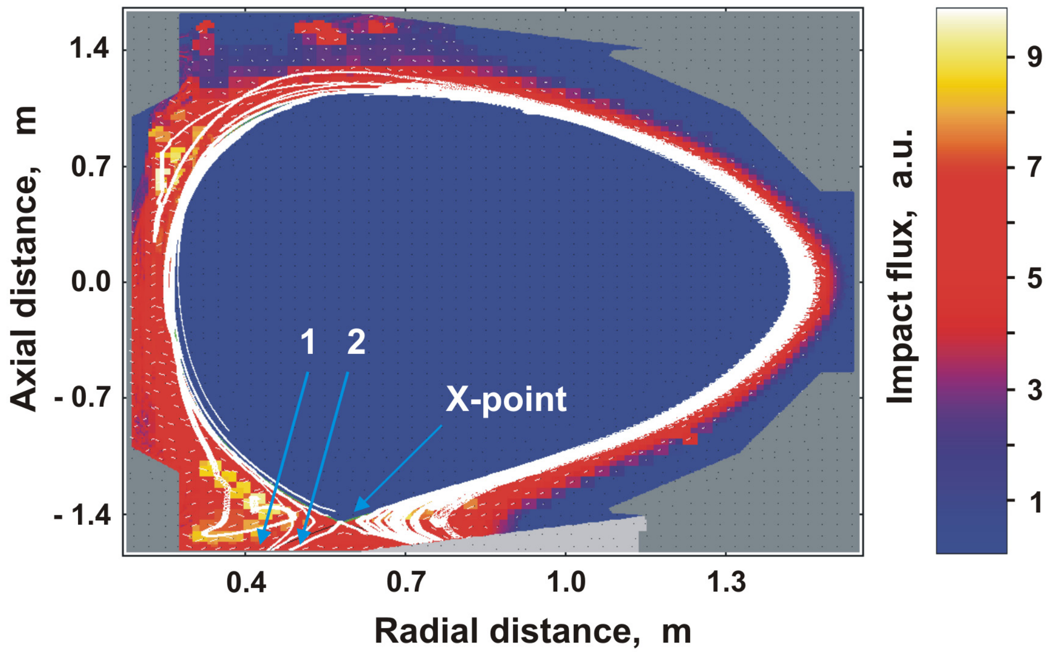
Multi-Scale 3D Approach



1. **Quadtree AMR for MHD:**
   - 5-Layer hierarchy
   - Fit any tokamak wall design
   - Automatic mesh configuration
   - Regions of interest refinement
2. **Undersurface processes:**
   - Extra layer of surface refinement for erosion and vaporization modeling
   - Monte Carlo calculations of plasma-wall interaction
3. **Integration into HEIGHTS models:**
   - Core particles escaping to SOL
   - Magnetic diffusion and plasma conduction
   - Radiation transport
4. **Parallel calculations:**
   - Automatic segmentation on sub-domains
   - Processors load distribution with subdomains size

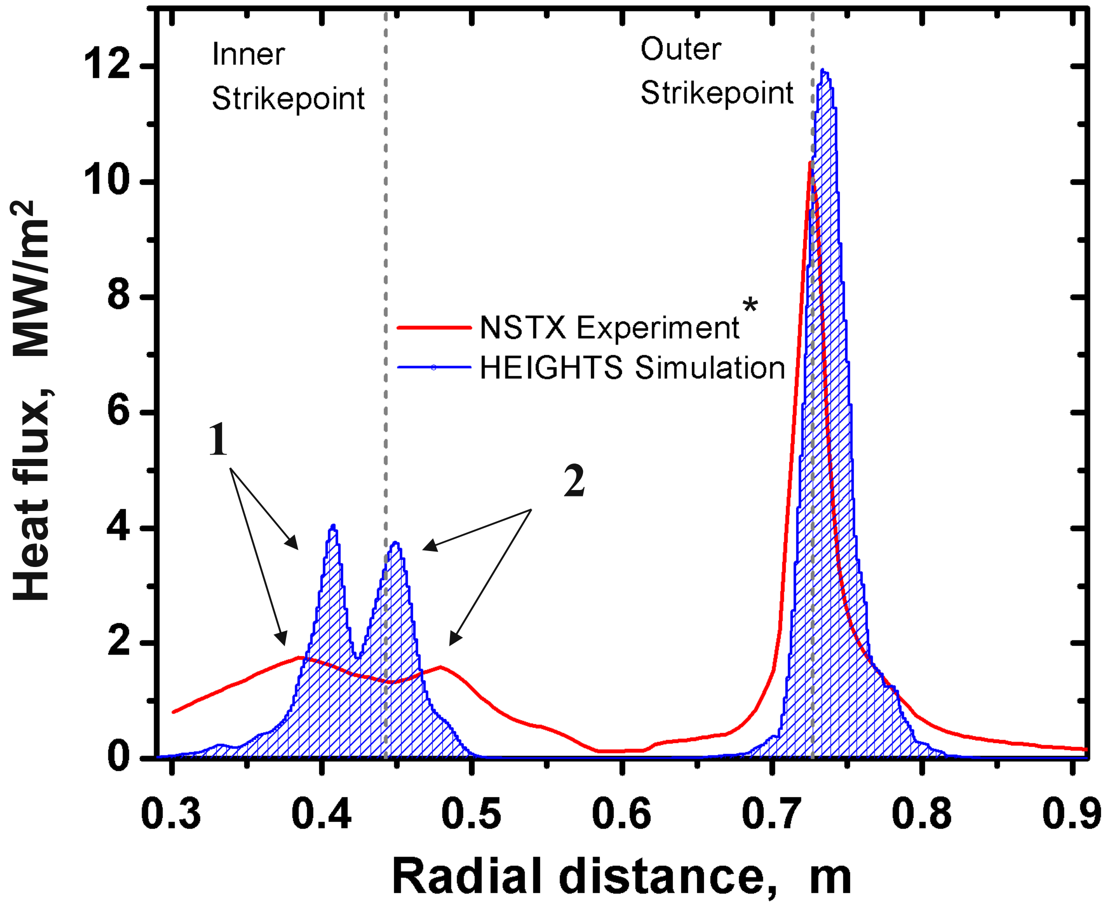
Escaping Core Plasma Particles



1. **Equations of motion in full 3D:**
   - Local magnetic field in cell
   - Local electric field in cell
   - Gradient and curvature drift
2. **Evolution from core escaping to:**
   - Deposition into surface
   - Vapor or edge plasma merge
   - Return to core

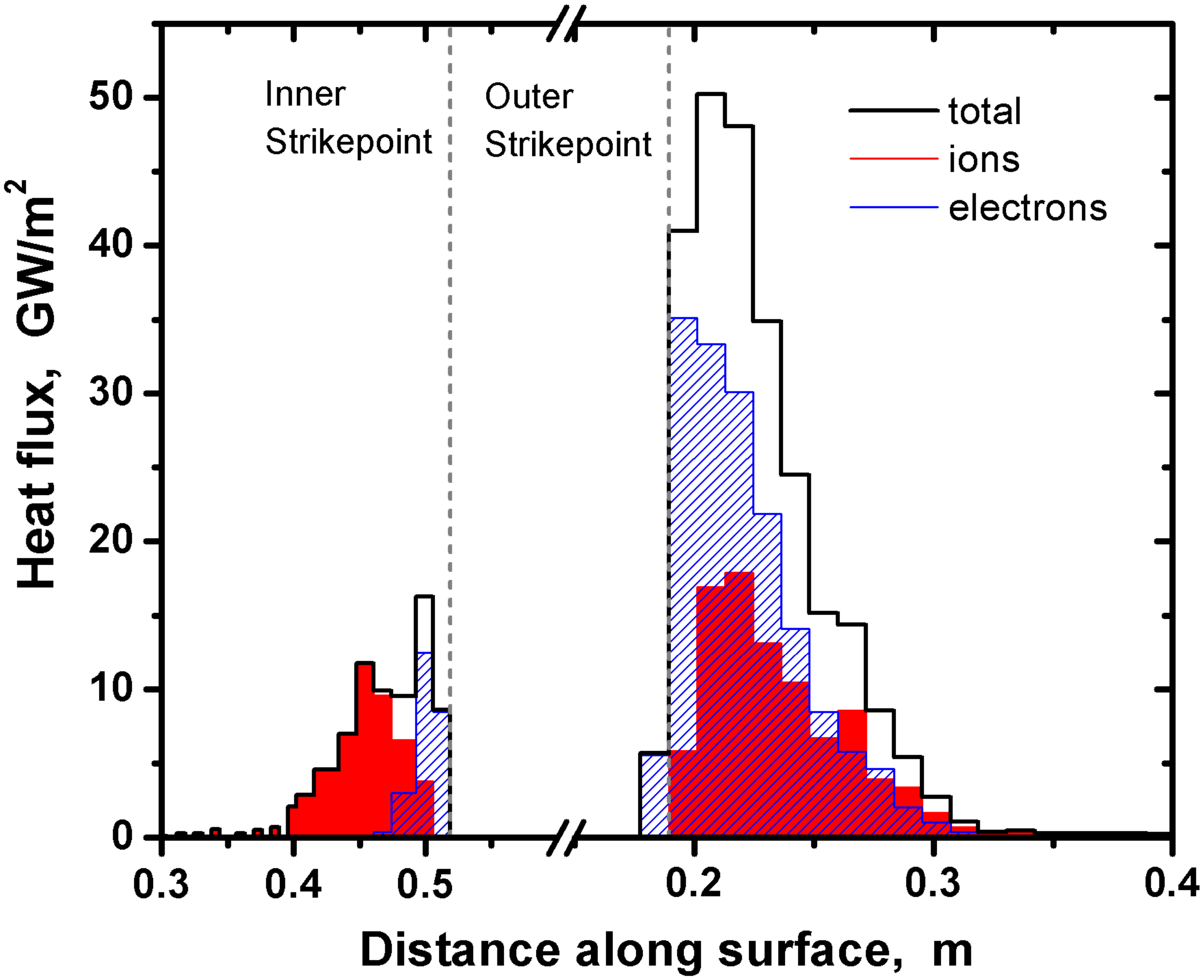
1. **Scatterings due to:**
   - Electron-electron, electron-nuclear
   - Ion-nuclear, Bremsstrahlung
   - Photo- and Compton absorption
   - Auger relaxation
2. **MC model for ELM or disruption:**
   - Initial distribution along core surface
   - Power time evolution
   - Source for MHD equations

Benchmarking – Flux to NSTX Divertor



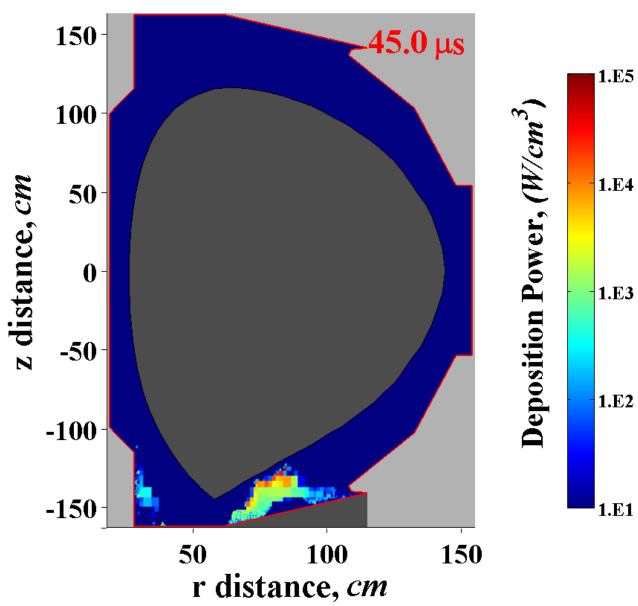
* Mastrovito D. *et al* Rev. Sci. Instrum. 74 5090 (2003)

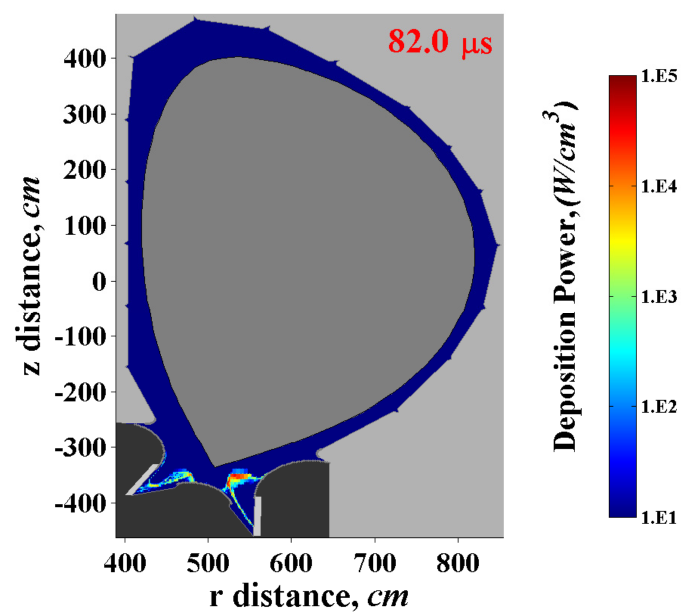
ITER Divertor Simulation



Escaped Particles Energy Deposition & Shielding Effect

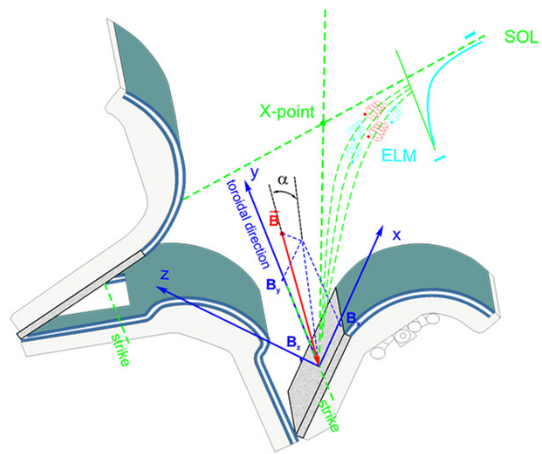
NSTX **ITER**

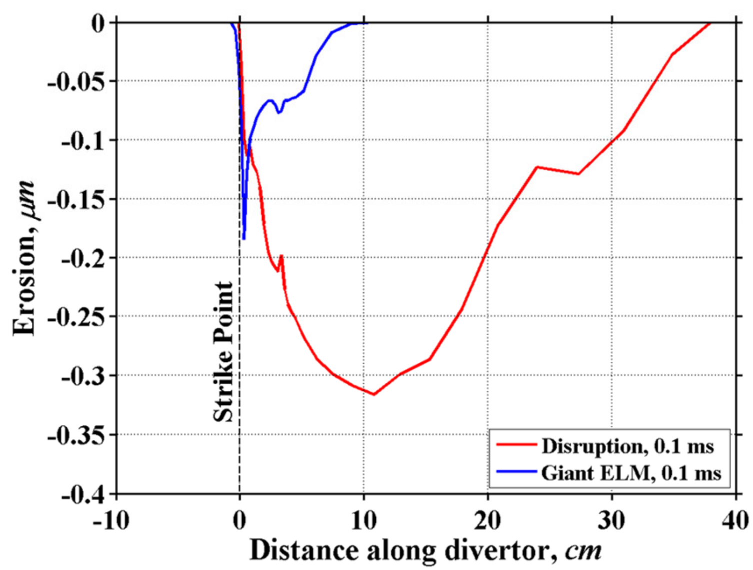


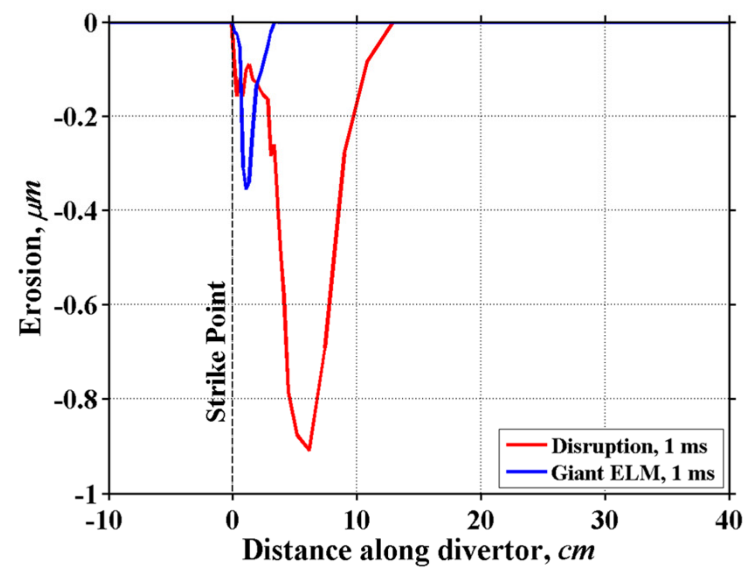


- ❑ Escaped core particles deposit energy in plasma clouds as it moves. As a result, the spatial profile of Divertor surface temperature varies during impact time.

Erosion of ITER Carbon Divertor Plate

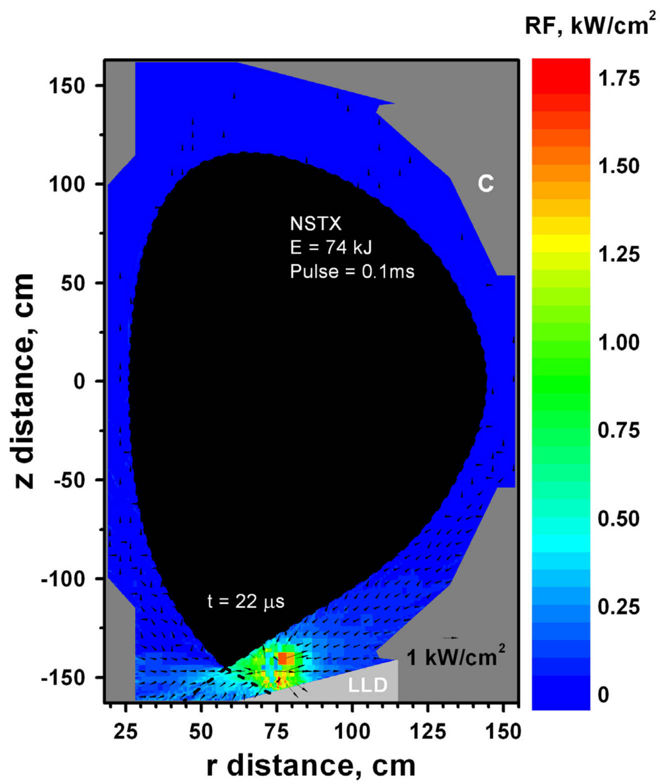




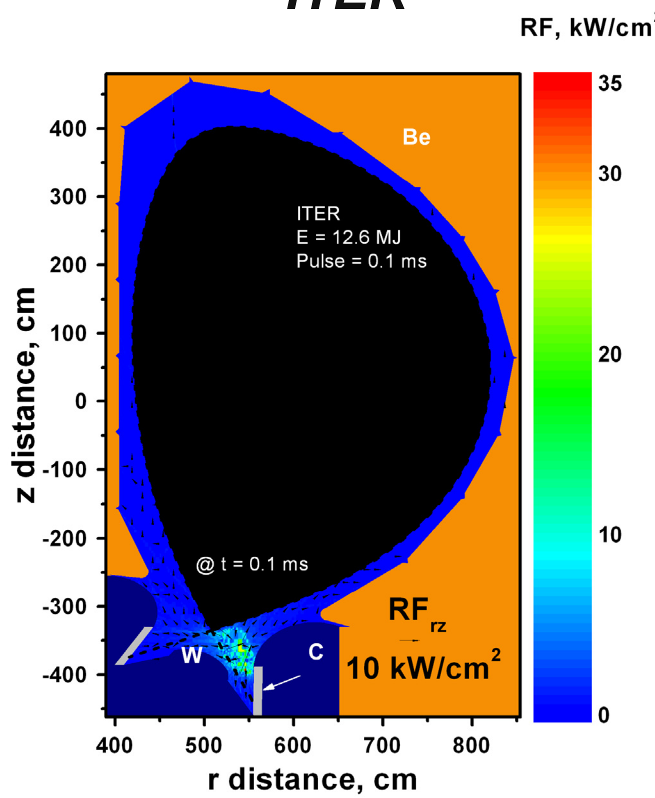


Radiation Fluxes of Divertor Produced Plasma

NSTX



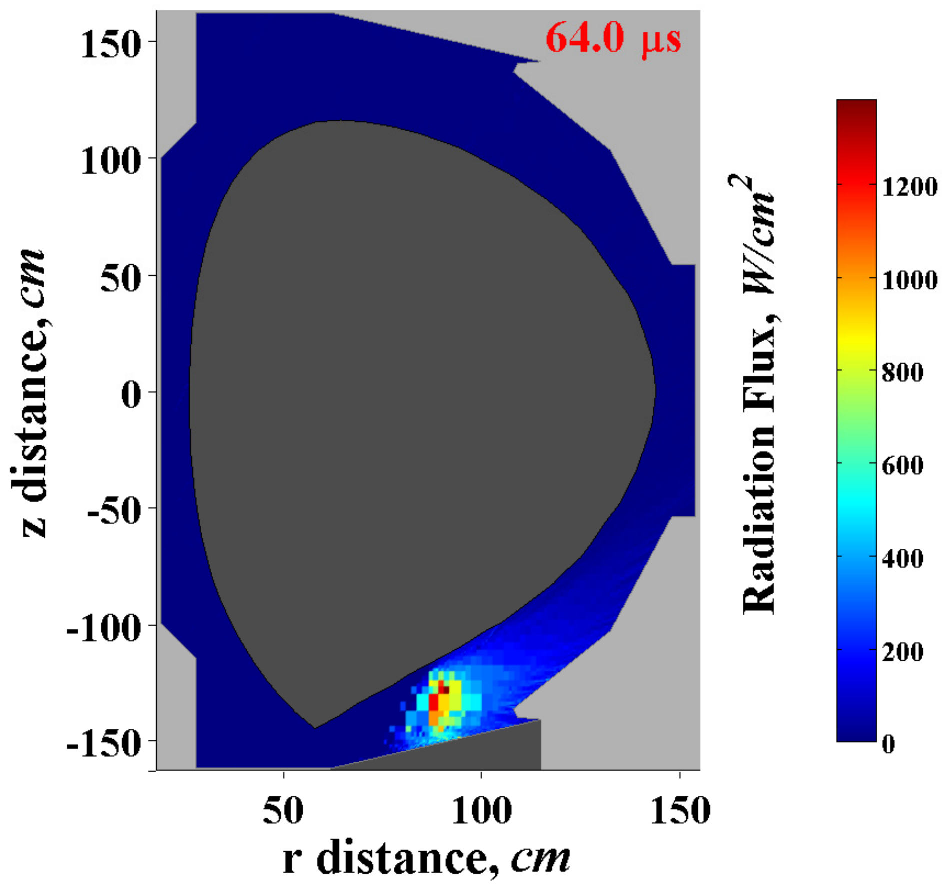
ITER



- ❑ NSTX calculated low radiation fluxes of up to 2 kW/cm^2 for disruption energy of = 74 kJ in comparison to initial plasma impact fluxes will NOT cause serious damage to nearby components in comparison to ITER ELM and disruption conditions.

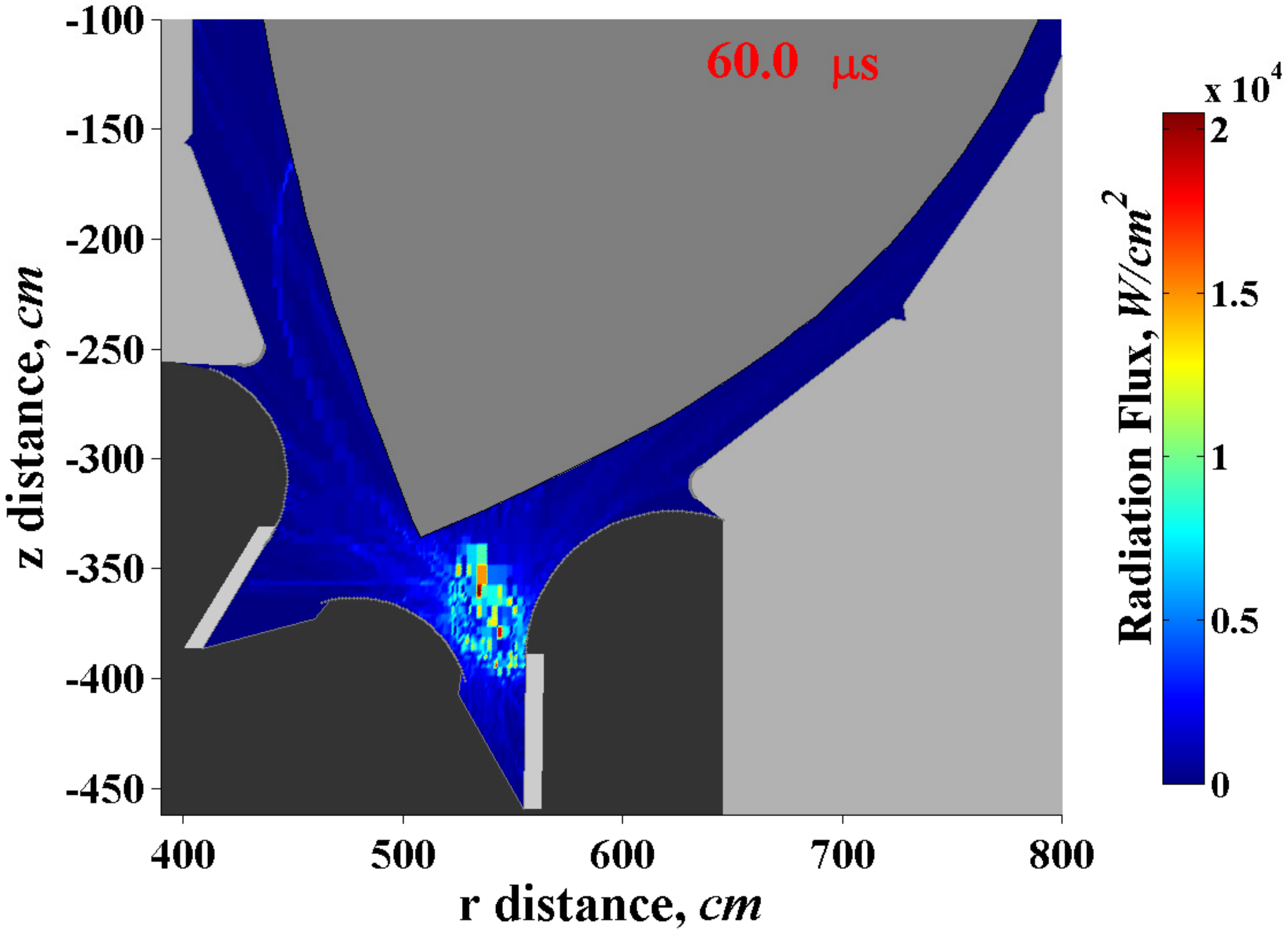
Radiation Fluxes of Divertor Produced Plasma

NSTX

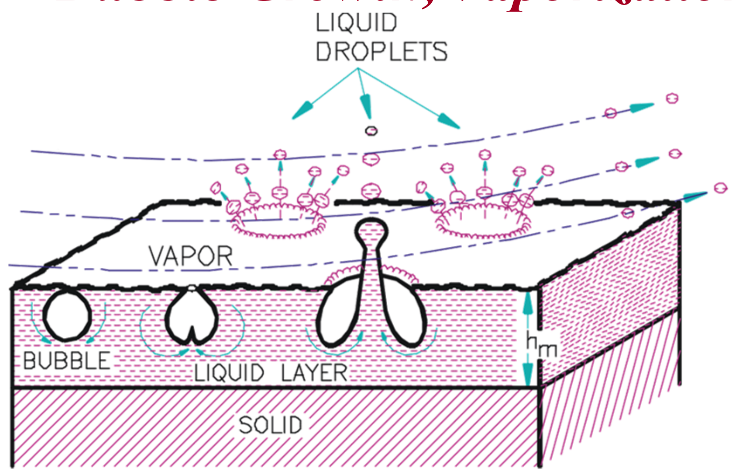


Radiation Fluxes of Divertor Produced Plasma

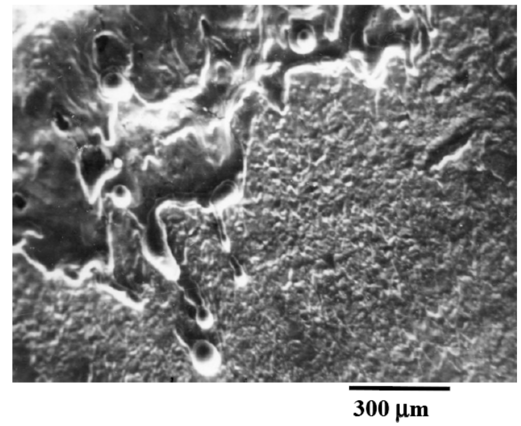
ITER



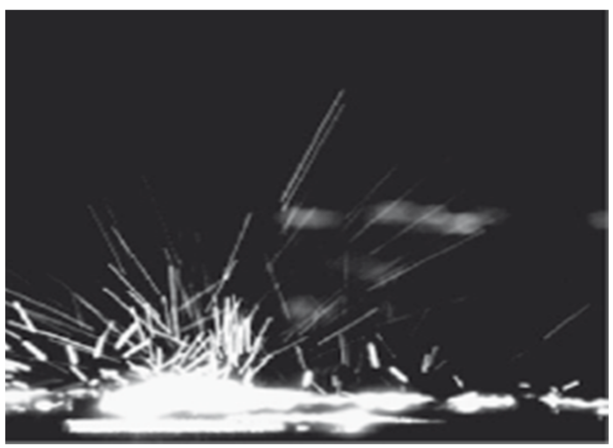
Melt-Layer Loss during Disruptions
Bubble Growth, Vaporization and Loss by Incident Plasma Wind



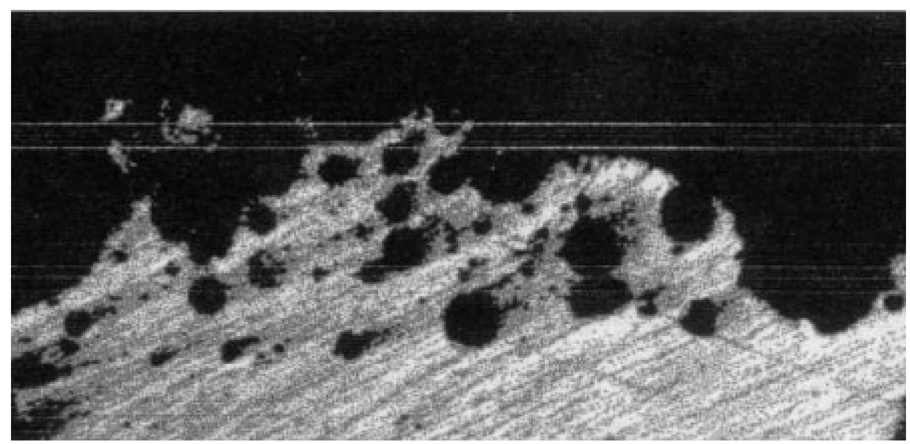
Hassanein et al., *J. Nucl. Mater.* 241 (1997) 288



MK-200: Safronov et al., PAST 8 (2002) 27



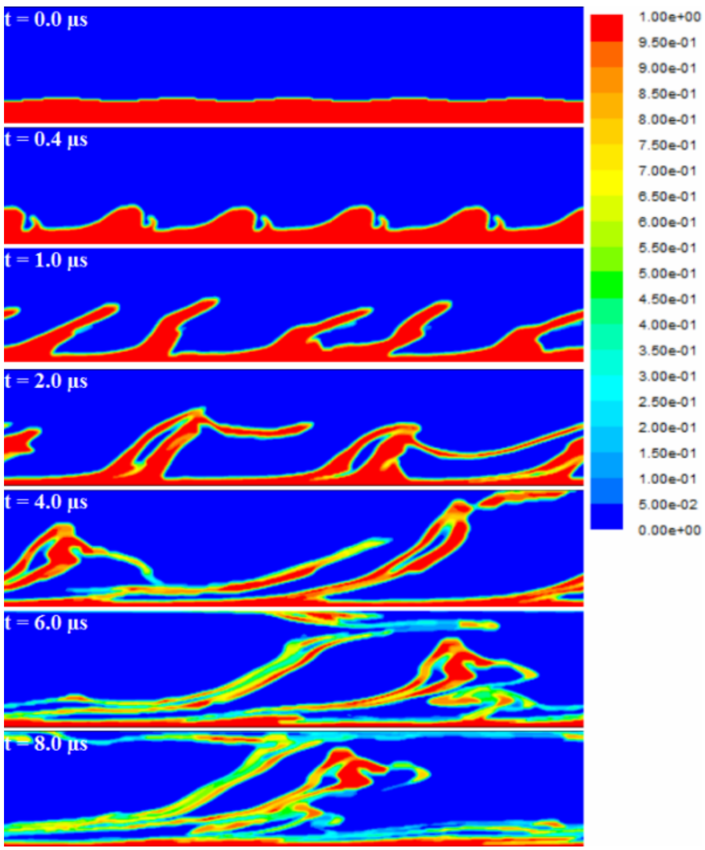
QSPA Kh-50: Garkusha et al., *J. Nucl. Mater.* 390 (2009) 814



VIKA: Litunovsky et al., *Fusion Eng. Des.* 49 (2000) 249

Modeling & Simulation of Plasma-Melt Flow

Plasma-liquid interface develops instabilities in plasma flow environments



- **Small liquid tungsten plumes developed at the wave crests**
- **Then elongated liquid tungsten ligaments penetrating into the plasma**
- **Then lengthening, thinning, and collisions of melt ligaments with capture of small pockets of the plasma**
- **Highly irregular topological structures of liquid tungsten patterns with breaks and holes**

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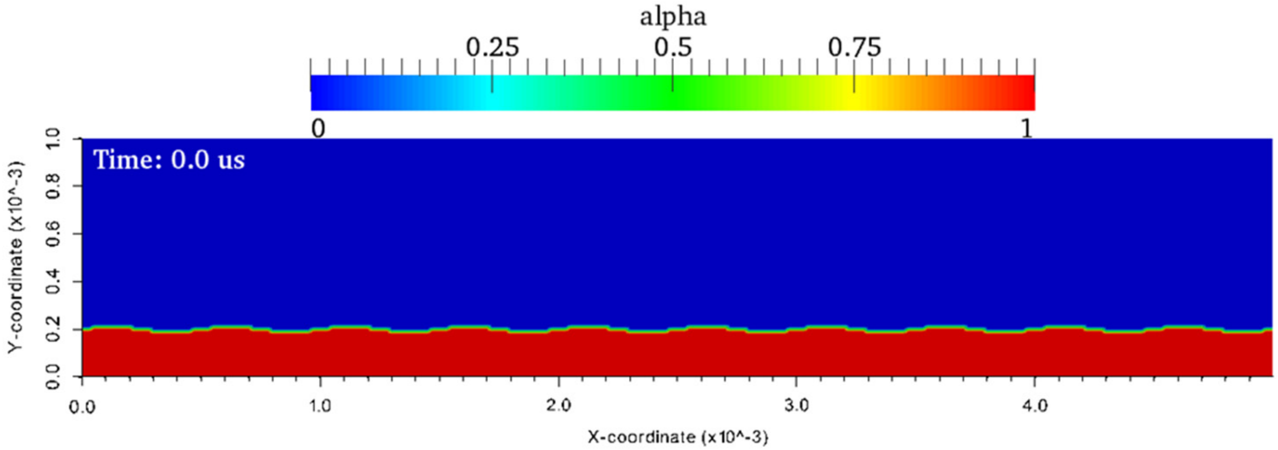
Modeling & Simulation of Plasma-Melt Flow



$N_p = 10^{20}\ \mathrm{m}^{-3}$

$h_m = 200\ \mu\mathrm{m}$ $V_p = 10\ km/s$ $\mu_p = 10^{-5}\ \mathrm{kg/(m\ s)}$ $T_m = 3695\ K$

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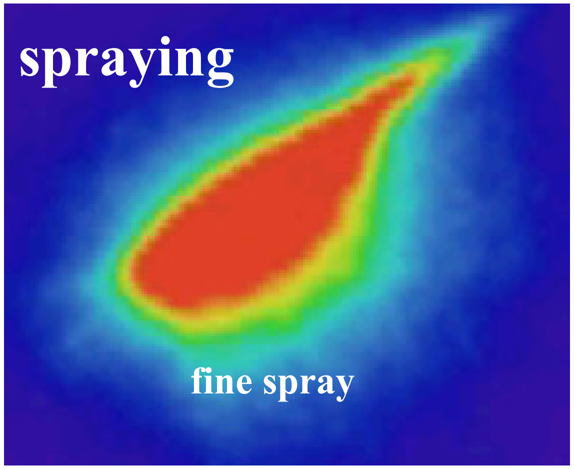
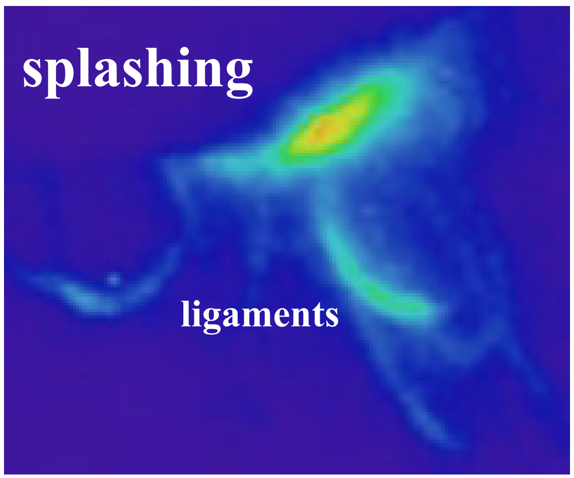
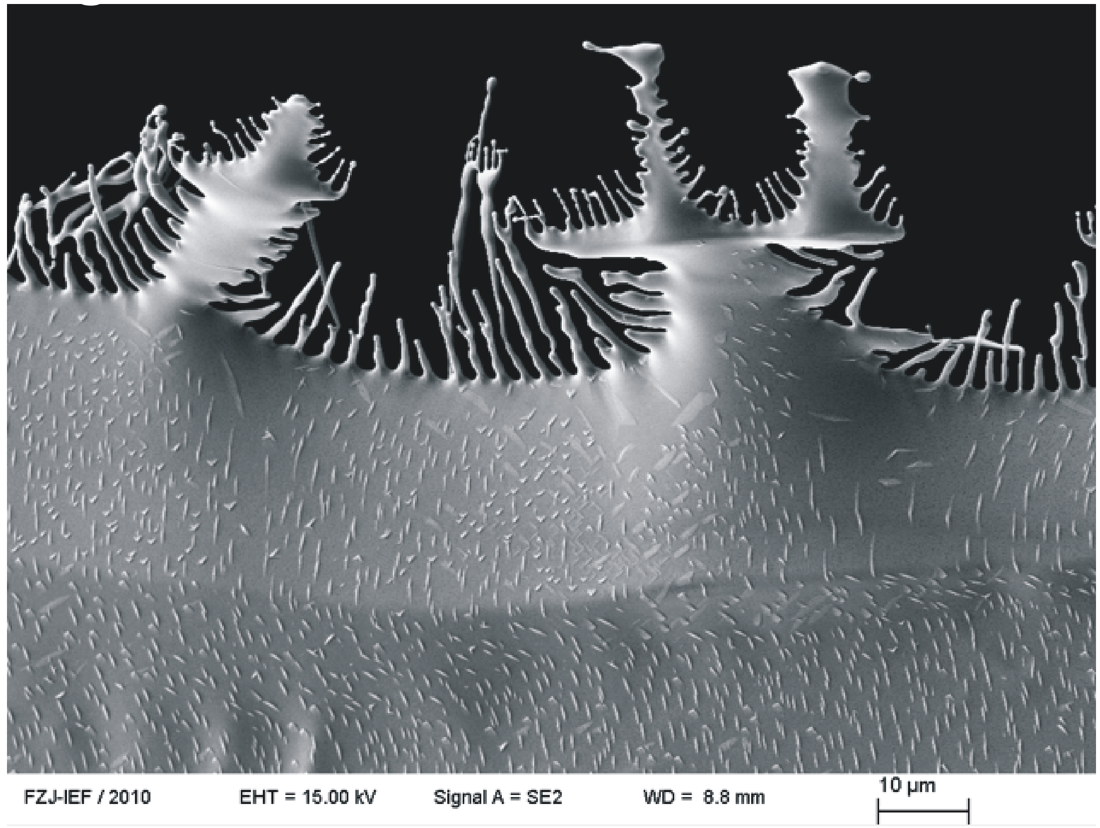
Benchmarking - Melt Layer Spraying and Splashing in TEXTOR

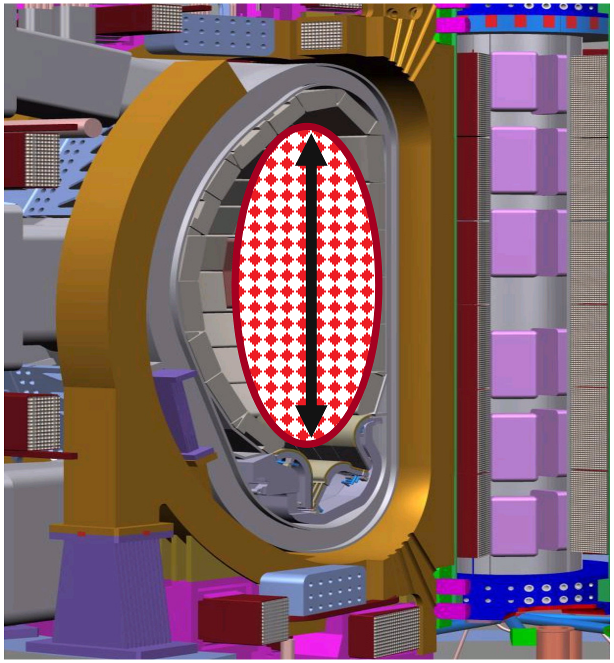


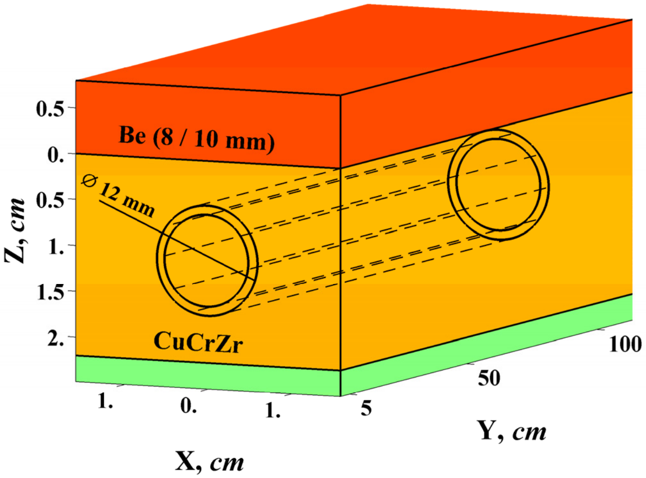


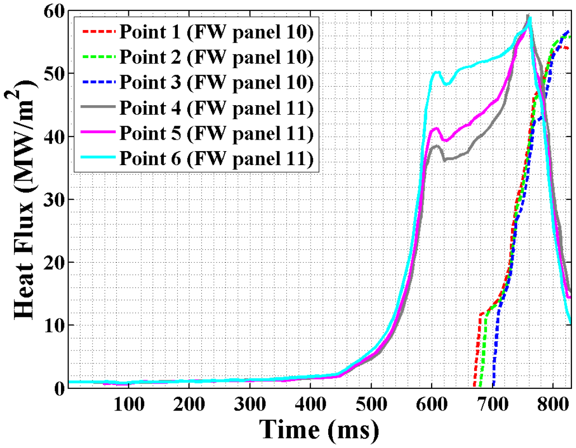


Coenen et al., *J. Nucl. Mater.* 415 (2011) S78; Coenen et al., *Nucl. Fusion* 51 (2011) 083008; *Nucl. Fusion* 51 (2011) 113020.

Modeling of VDE







Normal Heat Flux (NHF) panels in ITER and heat loads during upward VDE (before TQ) for six selected points on FW 10 and FW 11 panels

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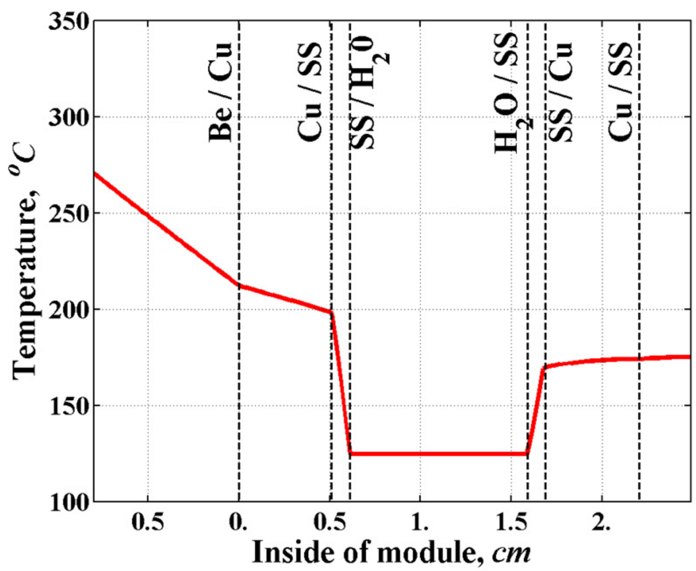
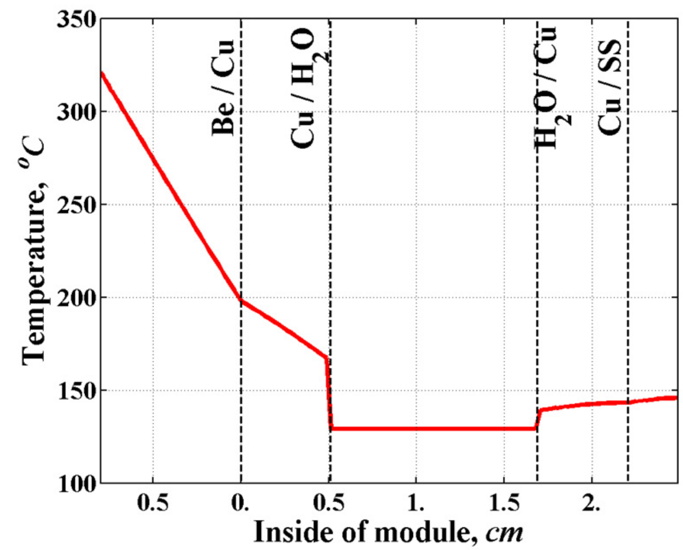
Steady-state Temperature distribution in NHF panels



Steady-state temperature distribution inside the module with 8 mm Be armor and with SS tube, 1 MW/m^2 steady-state heat flux (inlet water temperature of 115 ^{o}C)



Steady-state temperature distribution inside the module with 8 mm Be armor and without SS tube, 2 MW/m^2 steady-state heat flux (inlet water temperature of 115 ^{o}C)

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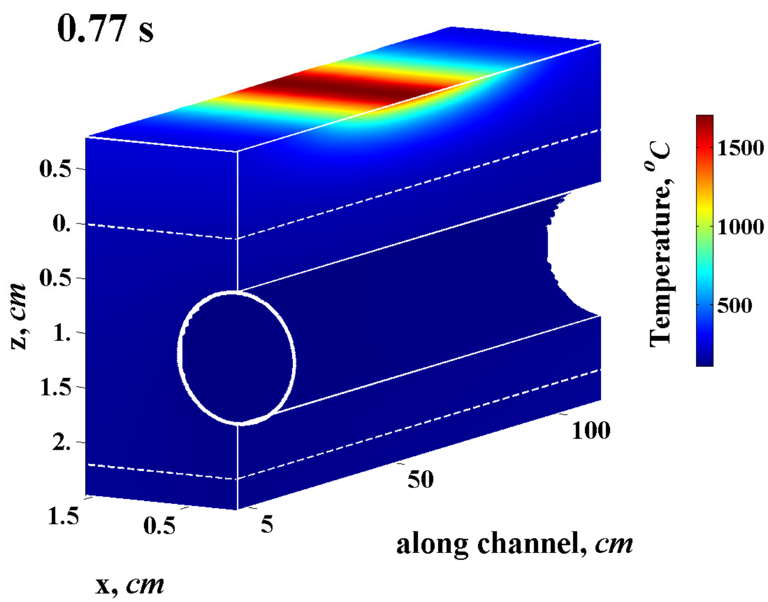
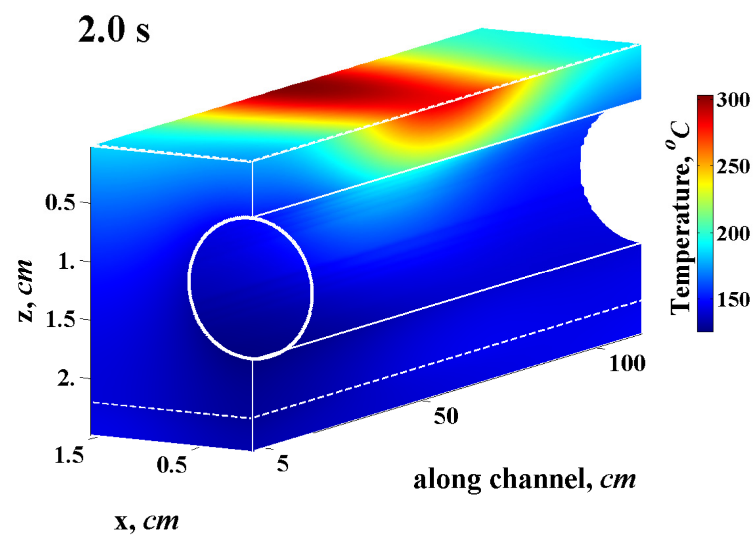
Temperature distribution in NHF panel without SS pipe Gaussian profile for maximum VDE heat load before TQ



Temperature distribution in panel at the peak of heat load before TQ



Temperature distribution in copper sink due to VDE heat load (2 MW/m^2 was used for steady-state heat flux)

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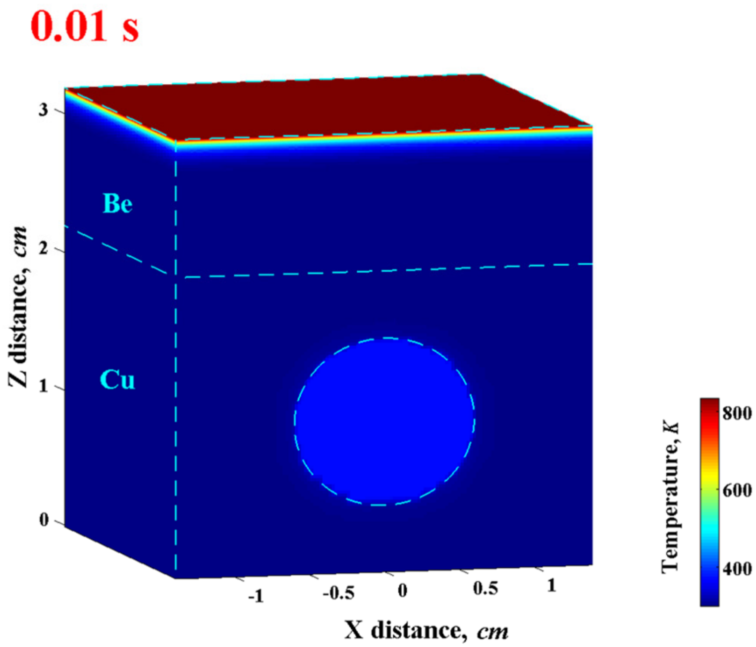
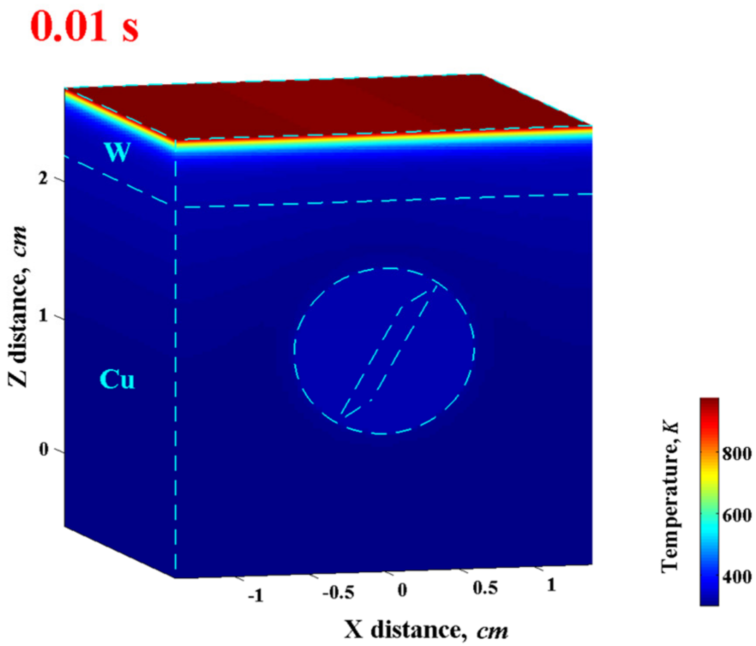
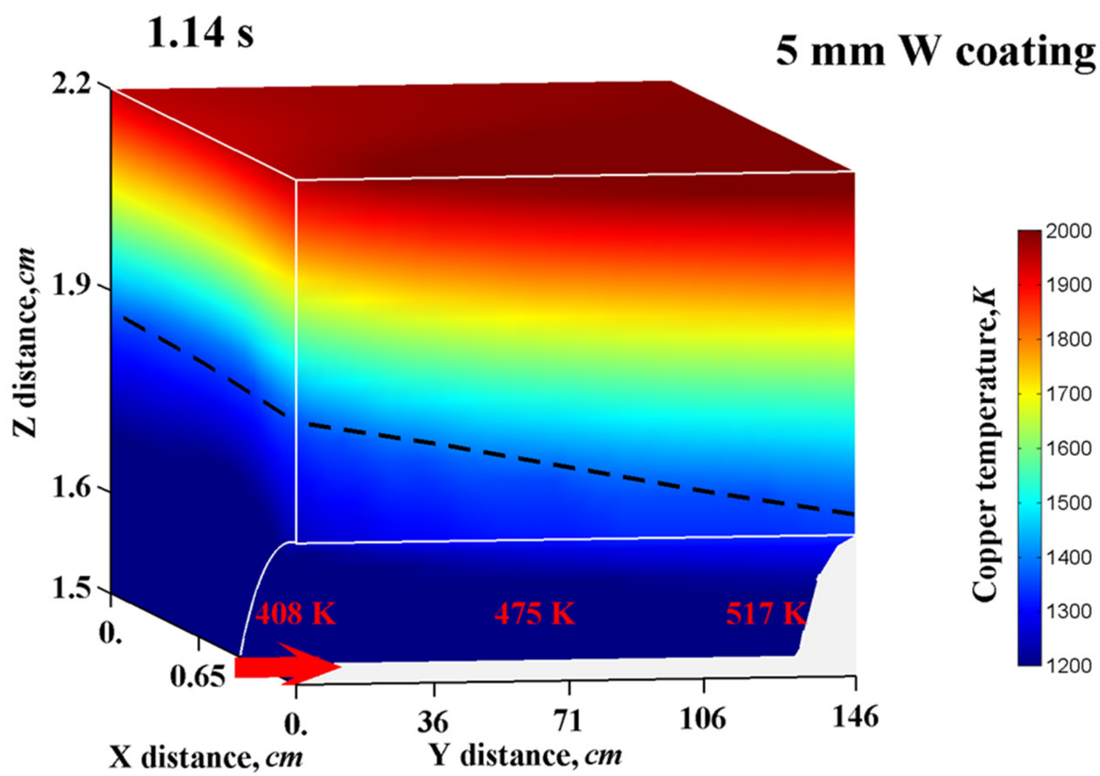
First Wall under Heating – Be and W armor





60 MJ/m^2, 0.5 s

Temperature Distribution in Cu and Water Coolant (60 MJ/m² Plasma Energy Impact during 0.5s for Structure with 5 mm W Coating)



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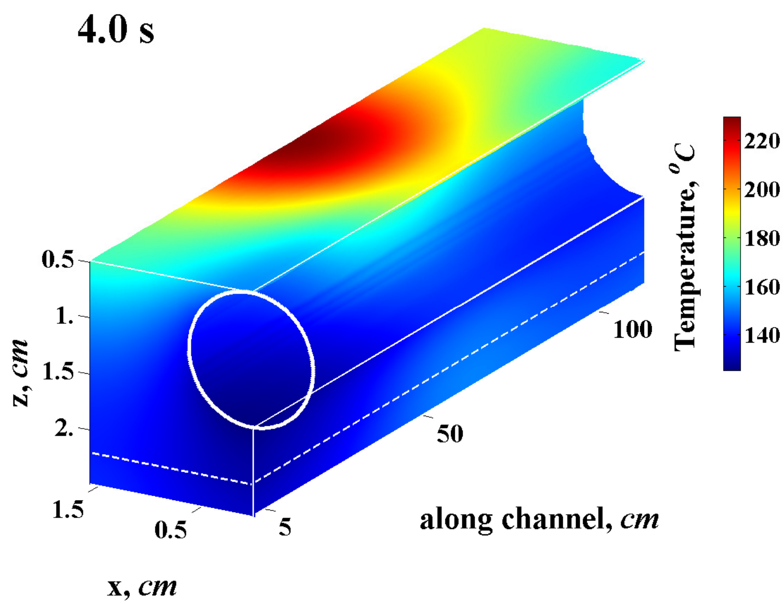
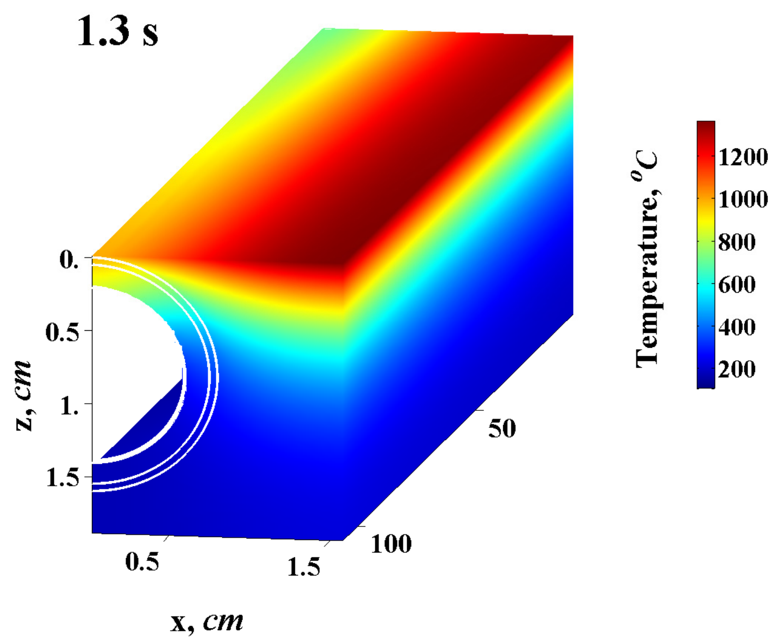
Temperature distribution on coolant walls due to upward and downward VDE

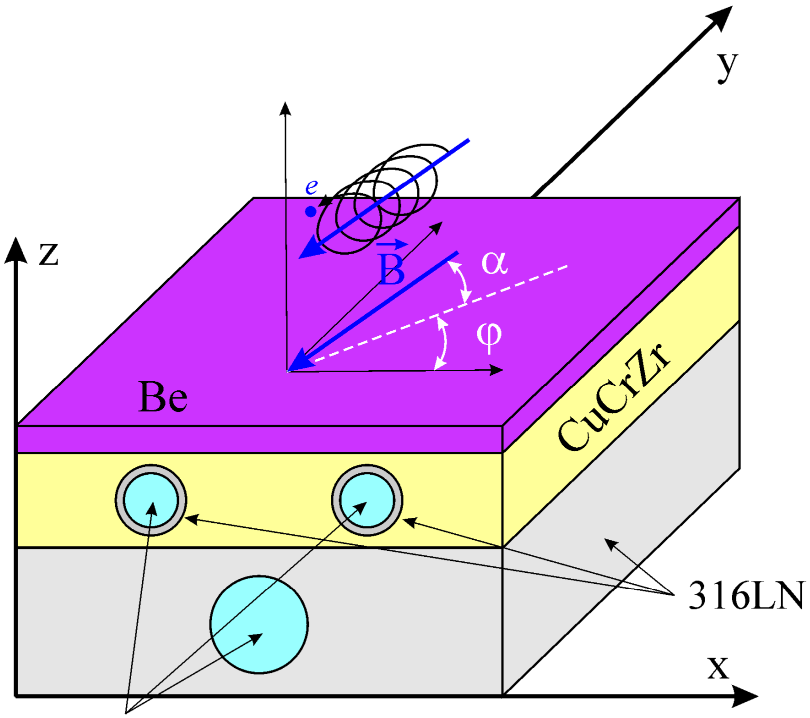


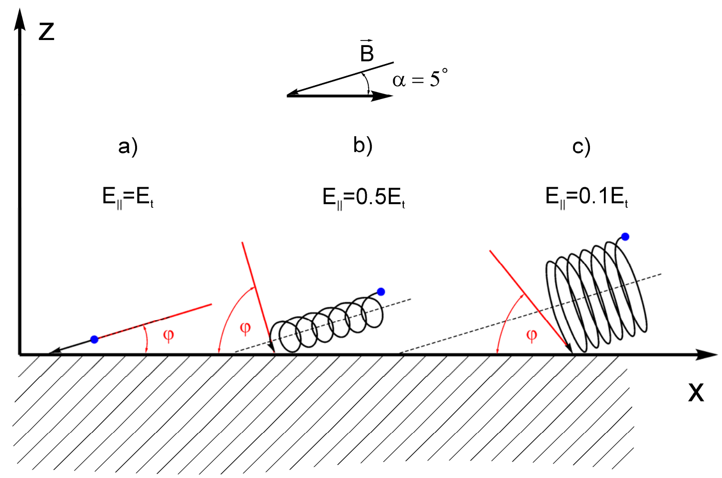


Temperature distribution on coolant wall of panel 11 due to VDE heat load (using predicted time history of pre-TQ heat flux) and followed 2 MW/m^2 steady-state heat flux

Temperature distribution in lower part of W monoblock and Cu tube wall and interlayer after VDE heat load (60 MJ/m^2 in 0.5 s) and followed 5 MW/m^2 steady state heat fluxes

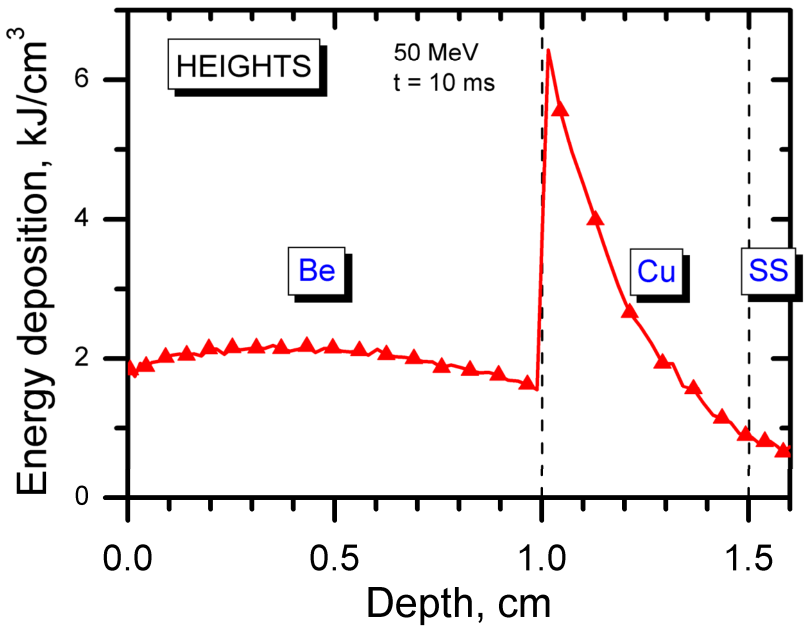
Detail Analysis of Runaway Electrons Energy Deposition and Structural Response → Very Serious!



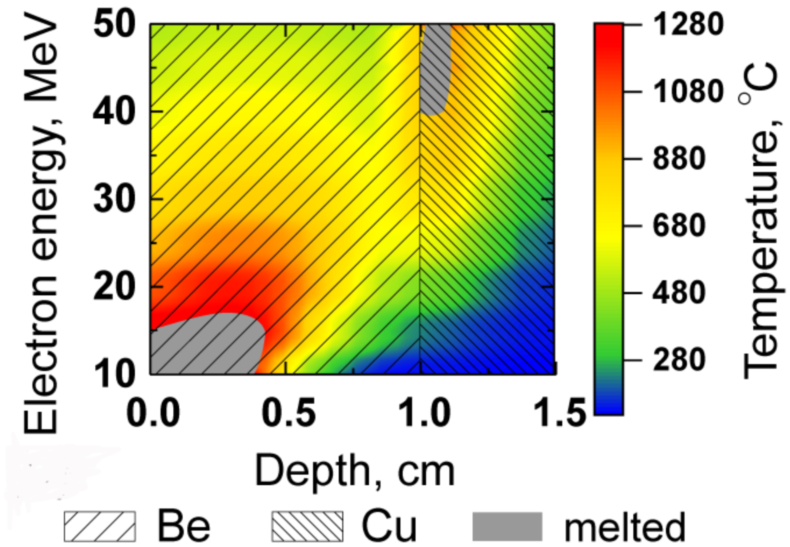


$E_t = 50$ MeV
B = 5-8 T
Time = 10 ms
Energy Density 50 MJ/m2

Modeling of Runaway Electrons Energy Deposition and Structural Response



Energy Deposition of 50 MeV Runaway Electrons → Structural Damage



Temperature and melting layer (grey) of target as a function of the electron incident energy for Be armor directly at normal axis above the coolant tube, magnetic field angle is 5 deg, energy ratio 0.1, and impact duration 0.01 s

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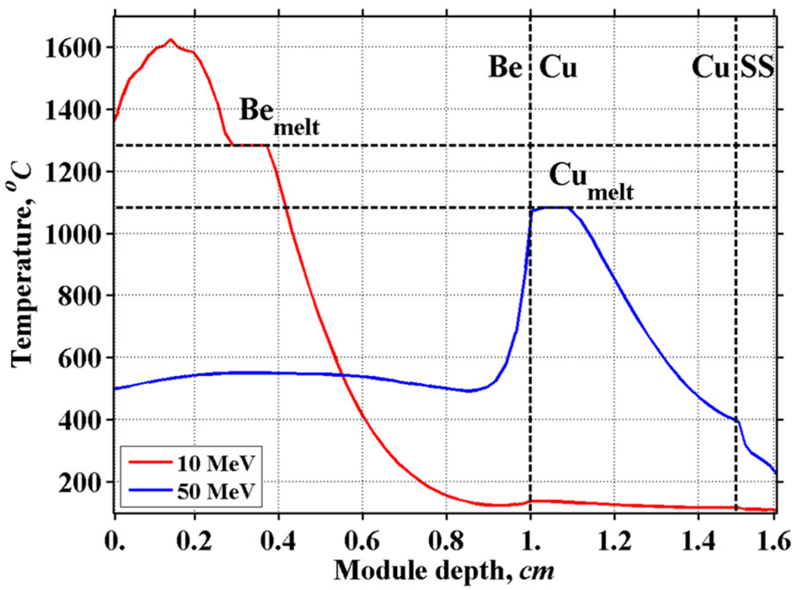
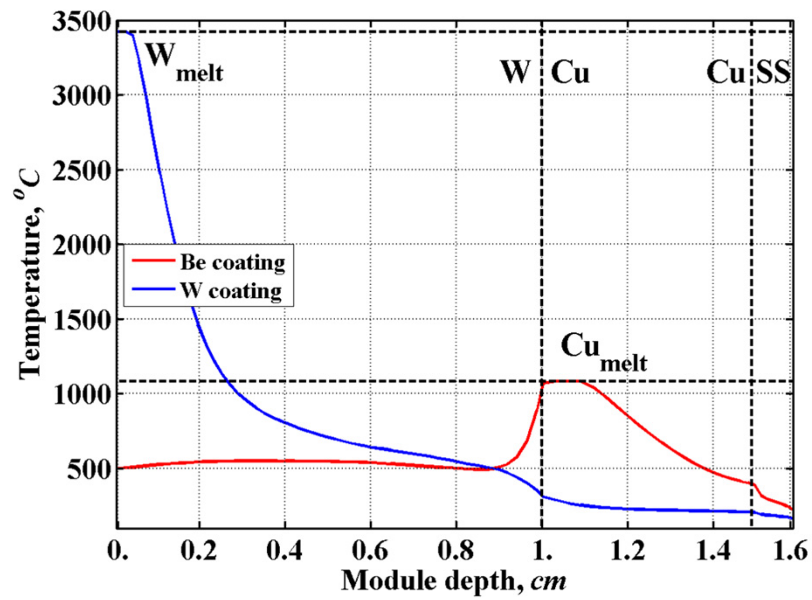
Temperature Rise in Structures with Be and W coating due to RE Deposition



Temperature rise in Be and Cu structure due to RE energies of 10 and 50 MeV (50 MJ/m² deposited in 10 ms)



Temperature rise in W and Cu structure due to RE energies of 50 MeV (50 MJ/m² deposited in 10 ms)

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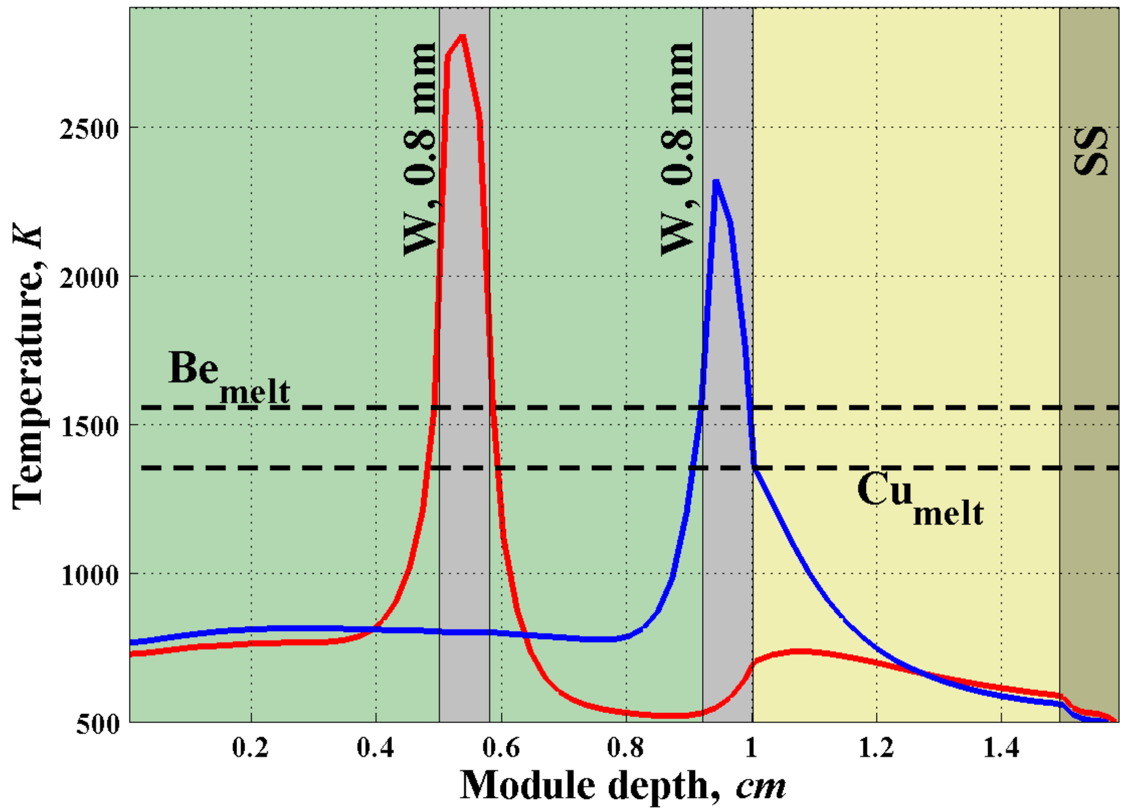
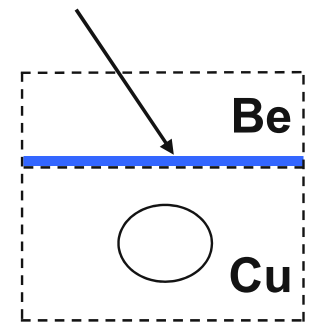
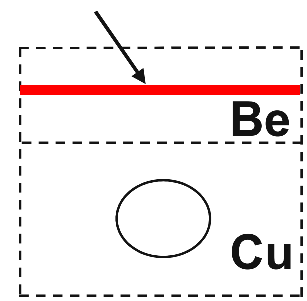
Influence of Tungsten Layer Location on Be and Cu Temperature







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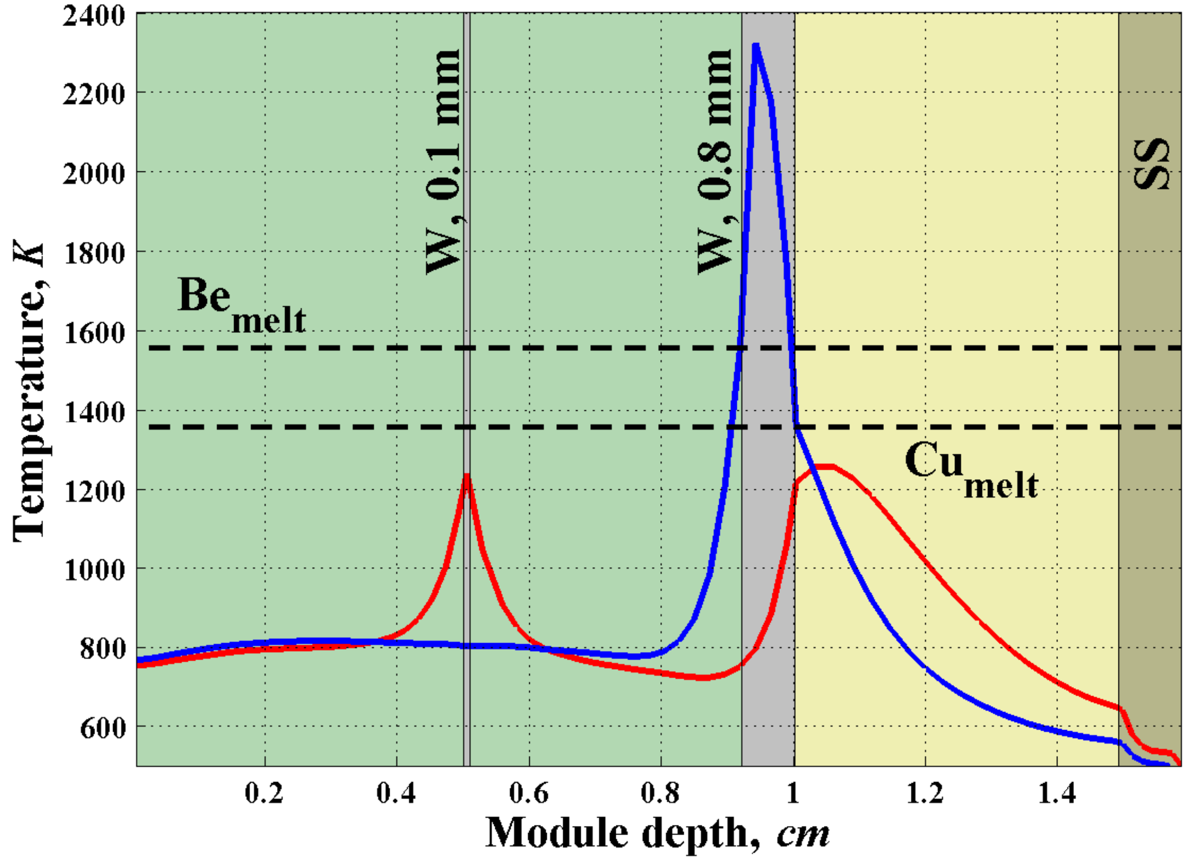
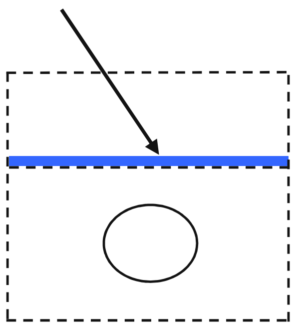
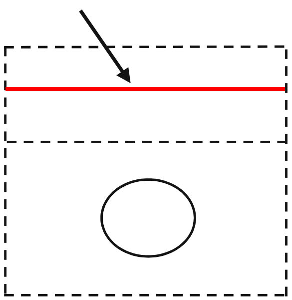
Influence of Tungsten Layer Location on Be and Cu Temperature



W of 0.8-mm thick



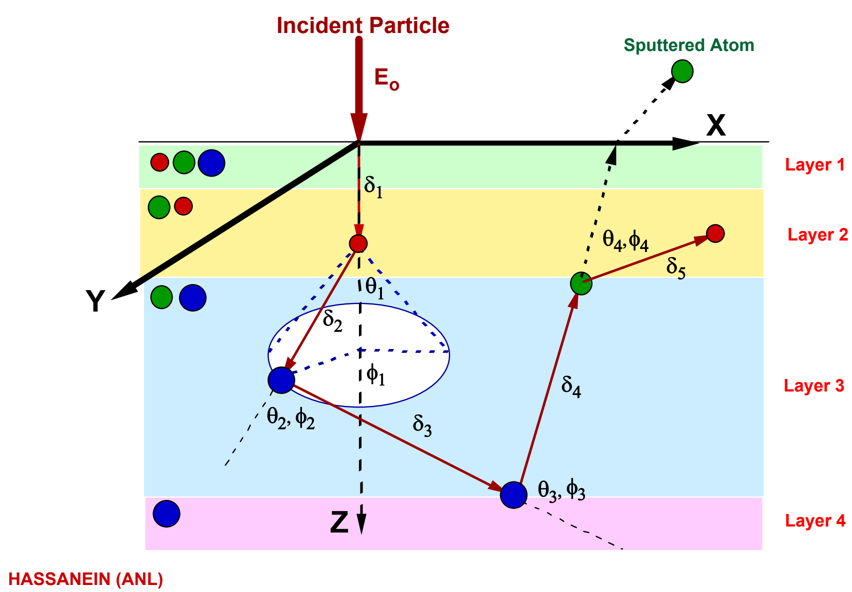
W of 0.1-mm thick

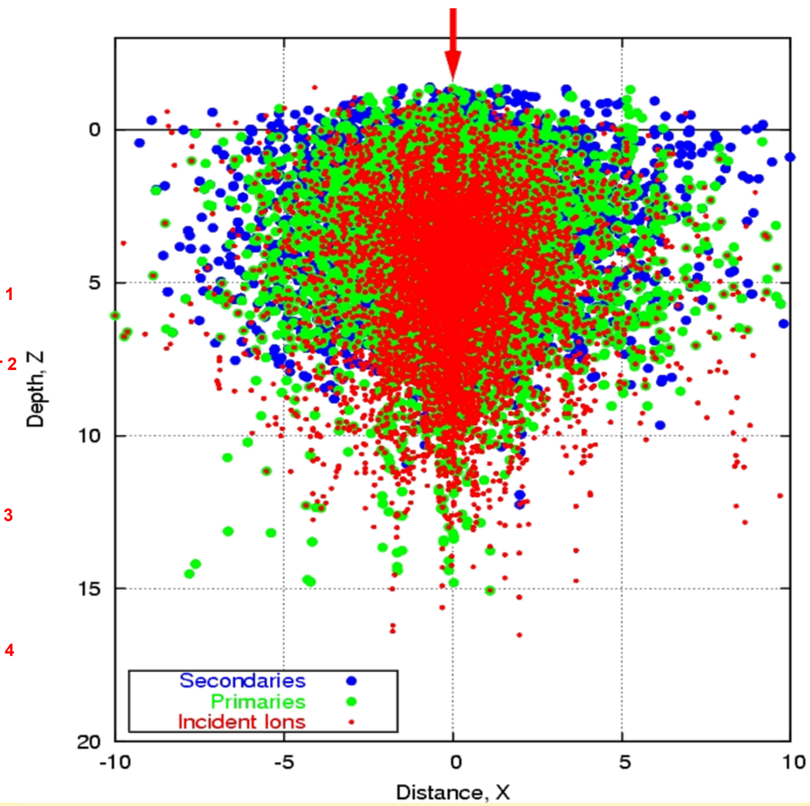


HEIGHTS Dynamic Simulation of Particle Beam Mixing with Target Materials—ITMC-DYN Code

Ion Transport in Materials and Compounds

ITMC Code





- **Fully 3D multi-beam on multi-target/layer compositions**
- **Moving boundary conditions for sputtering erosion or surface growth**

ITMC-DYN: multi-component, surface evolution

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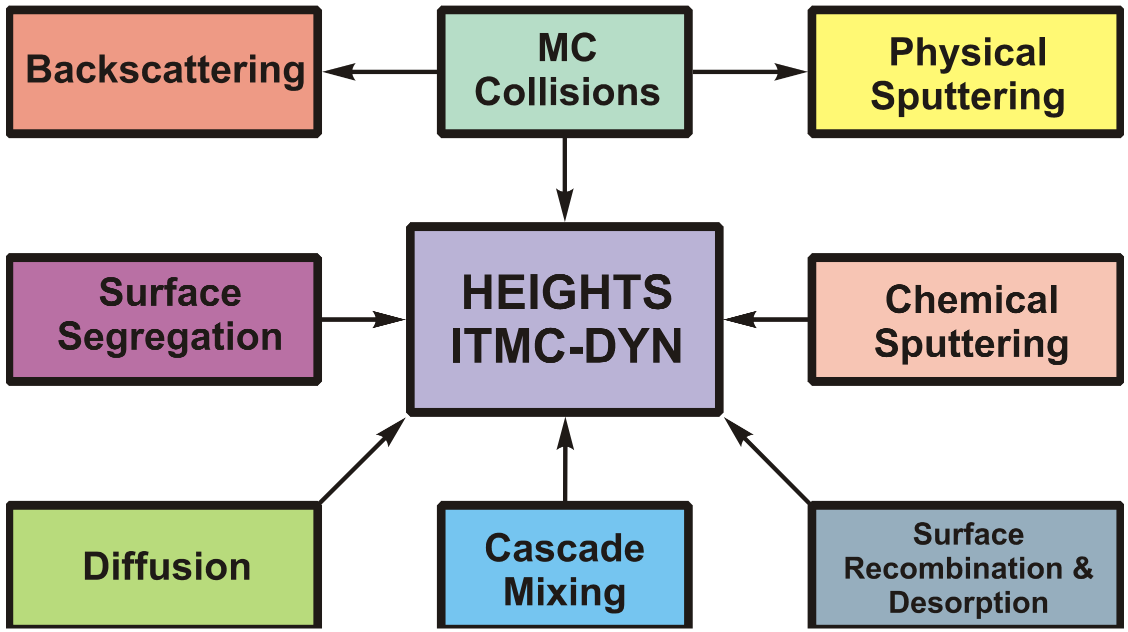
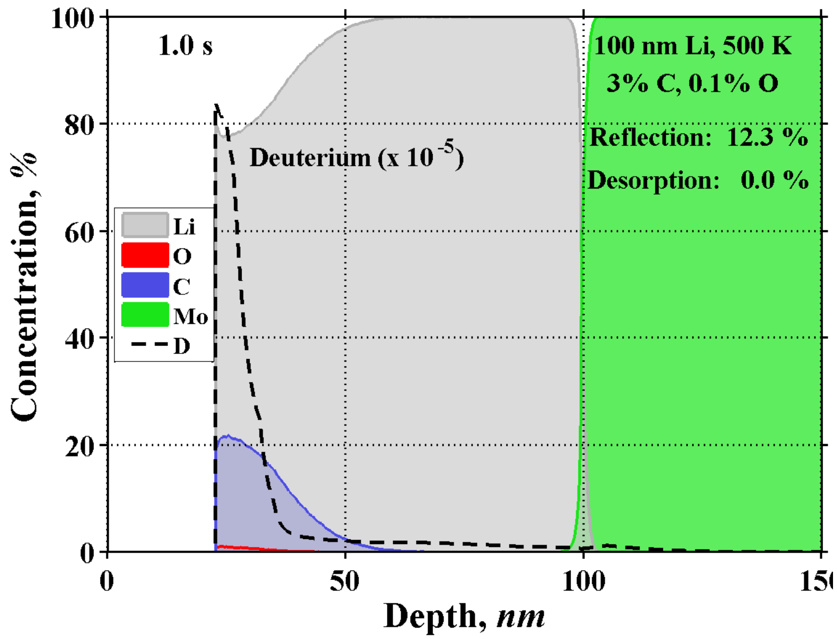
ITMC-DYN Integrated Modeling

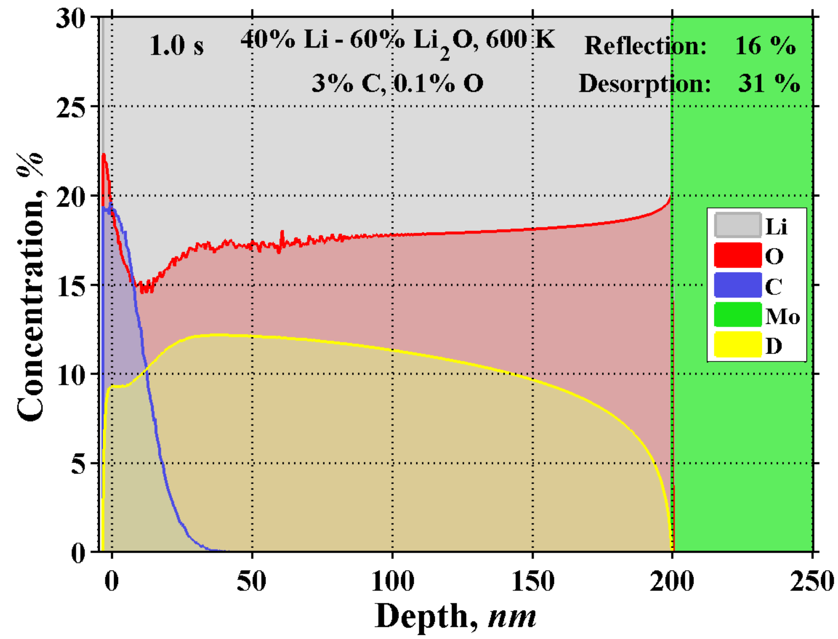


- Collision models are integrated with detail models of time-dependent processes including atom diffusion and segregation.
- Surface segregation models are implemented and explained recent experimental results.

Deuterium diffusion and desorption in pure and contaminated Li surface



100 nm Li on Mo substrate



200 nm Li with 20% of O in form of lithium oxide on Mo substrate

10^{22} $m^{-2}s^{-1}$ 1 keV deuterium flux, 3% 3 keV carbon ions, 0.1% 3 keV oxygen ions

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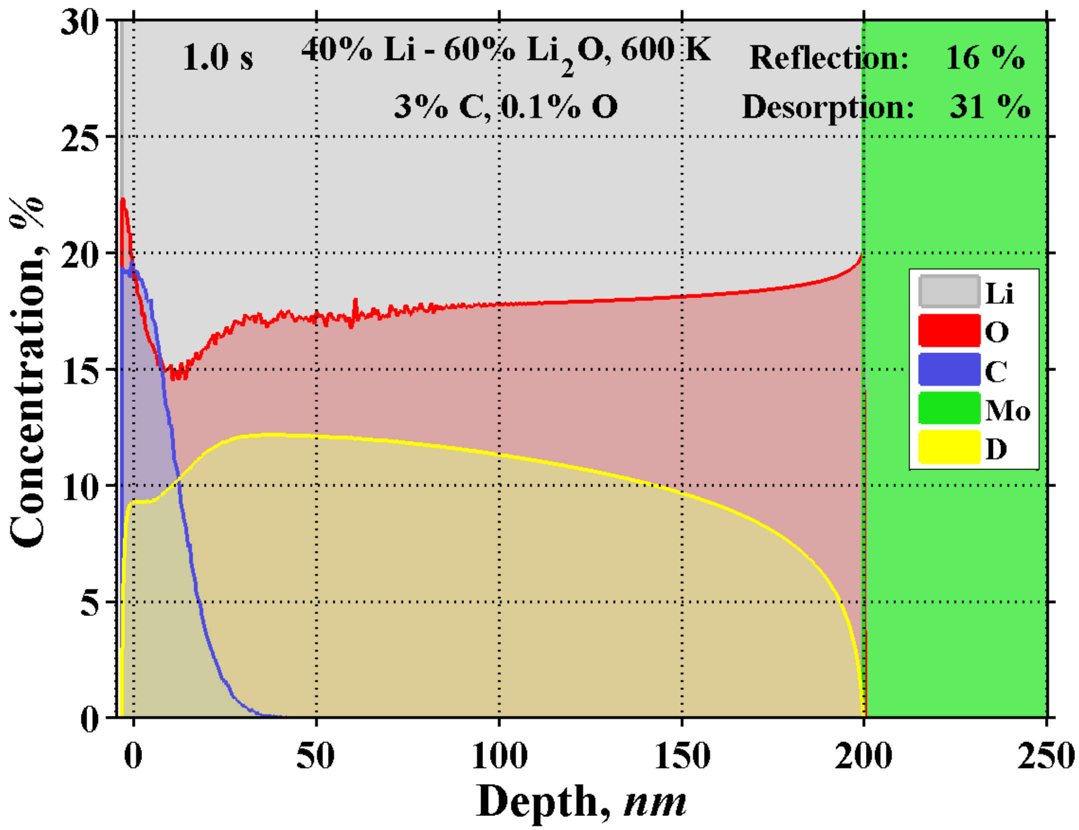
Deuterium diffusion and desorption in contaminated Li surface



10^{22} $m^{-2}s^{-1}$ 1 keV deuterium flux, 3% 3 keV carbon ions, 0.1% 3 keV oxygen ions

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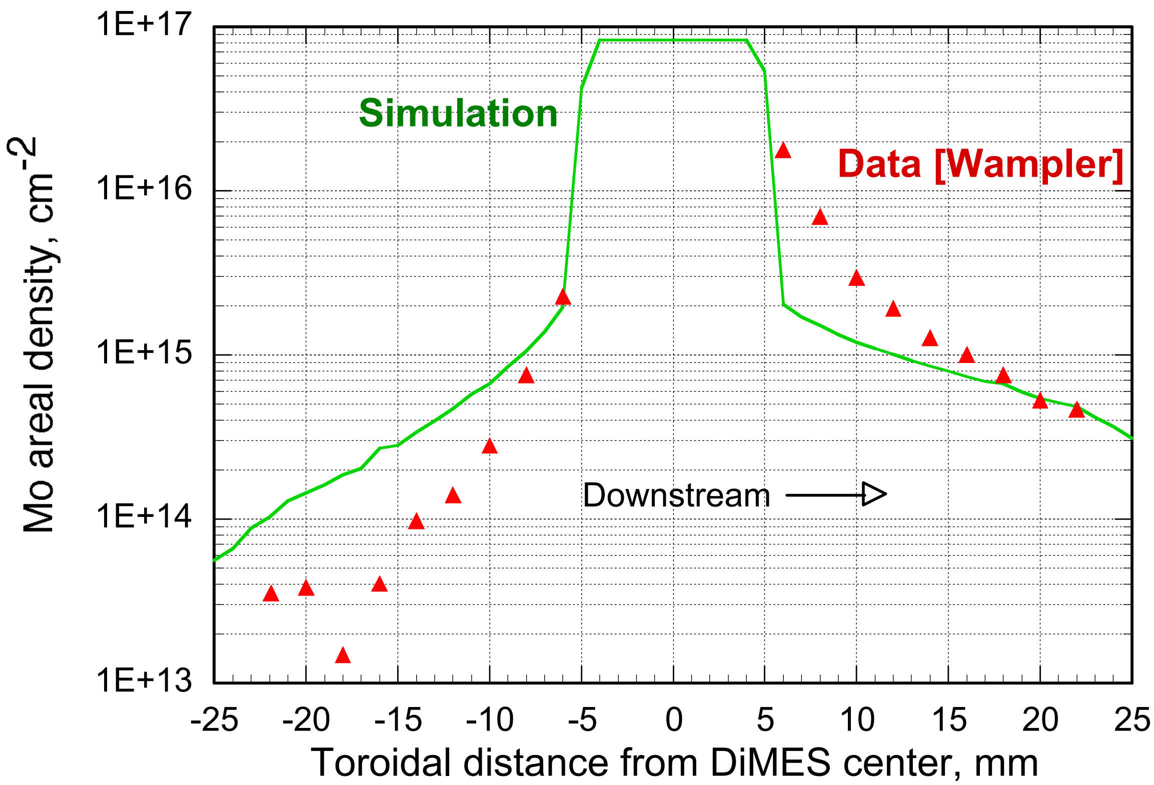
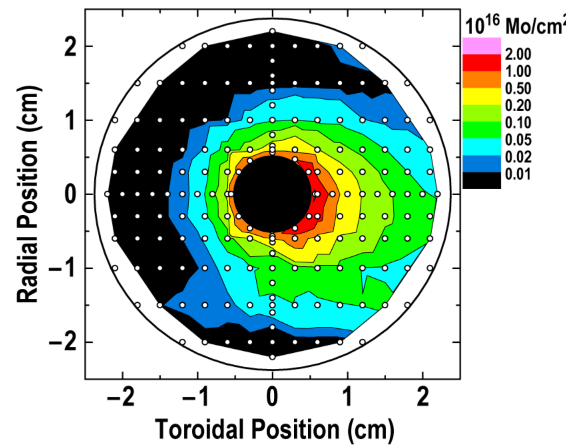
PURDUE NUCLEAR ENGINEERING

DIII-D Molybdenum Transport Experiment Analysis





2D map of Mo deposited on the complete 5 cm diameter graphite surface in the experiment (D.L. Rudakov, et al., 24th IAEA Fusion Energy Conference, 2012)

Code/data comparison; Mo areal density along DIII-D toroidal direction, through probe center.

REDEP/WBC erosion/redeposition code package coupled to the HEIGHTS ITMC/DYN mixed-material formation/response code

Recent Publications in 2012

1. A. Hassanein, V. Sizyuk, G. Miloshevsky, and T. Sizyuk, "**Can Tokamaks PFC Survive a Single Event of any Plasma Instabilities?**", PSI-20 (2012), Journal of Nuclear Materials, accepted.
2. G. Miloshevsky and A. Hassanein, "**Splashing and Boiling Mechanisms of Melt Layer Losses of PFCs During Plasma Instabilities**", PSI-20 (2012), Journal of Nuclear Materials, accepted.
3. V. Sizyuk and A. Hassanein, "**Integrated Self-Consistent Analysis of NSTX Performance during Normal and Disruptive Operation**", PSI-20 (2012), Journal of Nuclear Materials, accepted.
4. J. N. Brooks, A. Hassanein, T. Sizyuk, "**Advanced Simulation of Mixed-Material Erosion/Evolution and Application to Mo, C, Be, W Containing Plasma Facing Components**", PSI-20 (2012), Journal of Nuclear Materials, accepted.
5. T. Sizyuk and A. Hassanein, "**Dynamic Evolution of Plasma Facing Surfaces in NSTX: Impact of Impurities and Substrate Structure on Fuel Recycling**", PSI-20 (2012), Journal of Nuclear Materials, accepted.
6. P.C. Stangeby, D.L. Rudakov, W.R. Wampler, J.N. Brooks, N.H. Brooks, D.A. Buchenauer, J.D. Elder, A. Hassanein, A.W. Leonard, A.G. McLean, A. Okamoto, T. Sizyuk, J.G. Watkins, and C.P.C. Wong, "**An Experimental Comparison of Gross and Net Erosion of Mo in the DIII-D Divertor**", PSI-20 (2012), Journal of Nuclear Materials, accepted.
7. D.L. Rudakov, P.C. Stangeby, N.H. Brooks, W.R. Wampler, J.N. Brooks, D.A. Buchenauer, J.D. Elder, M.E. Fenstermacher, A. Hassanein, C.J. Lasnier, A.W. Leonard, A.G. McLean, R.A. Moyer, A. Okamoto, T. Sizyuk, J.G. Watkins, C.P.C. Wong, "**Measurements of Net versus Gross Erosion of Molybdenum Divertor Surface in DIII-D**", 24th IAEA Fusion Energy Conference (2012), Nuclear Fusion, to be published.
8. T. Sizyuk, A. Hassanein, M. Ulrickson, "**Thermal analysis of new ITER FW and divertor design during VDE energy deposition**", Accepted for publications in FED, Dec. 2012.
9. V. Sizyuk and A. Hassanein, "**Integrated self-consistent 3D Monte Carlo kinetic model to predict divertor heat and particle flux profiles in Tokamaks**", Submitted to NF, Nov. 2012.