Comprehensive and Integrated Modeling of Plasma Instability Events

Valeryi Sizyuk

Ahmed Hassanein

School of Nuclear Engineering, Purdue University

Plasma Facing Components Meeting

June 20-22, 2011, PPPL, Princeton, NJ

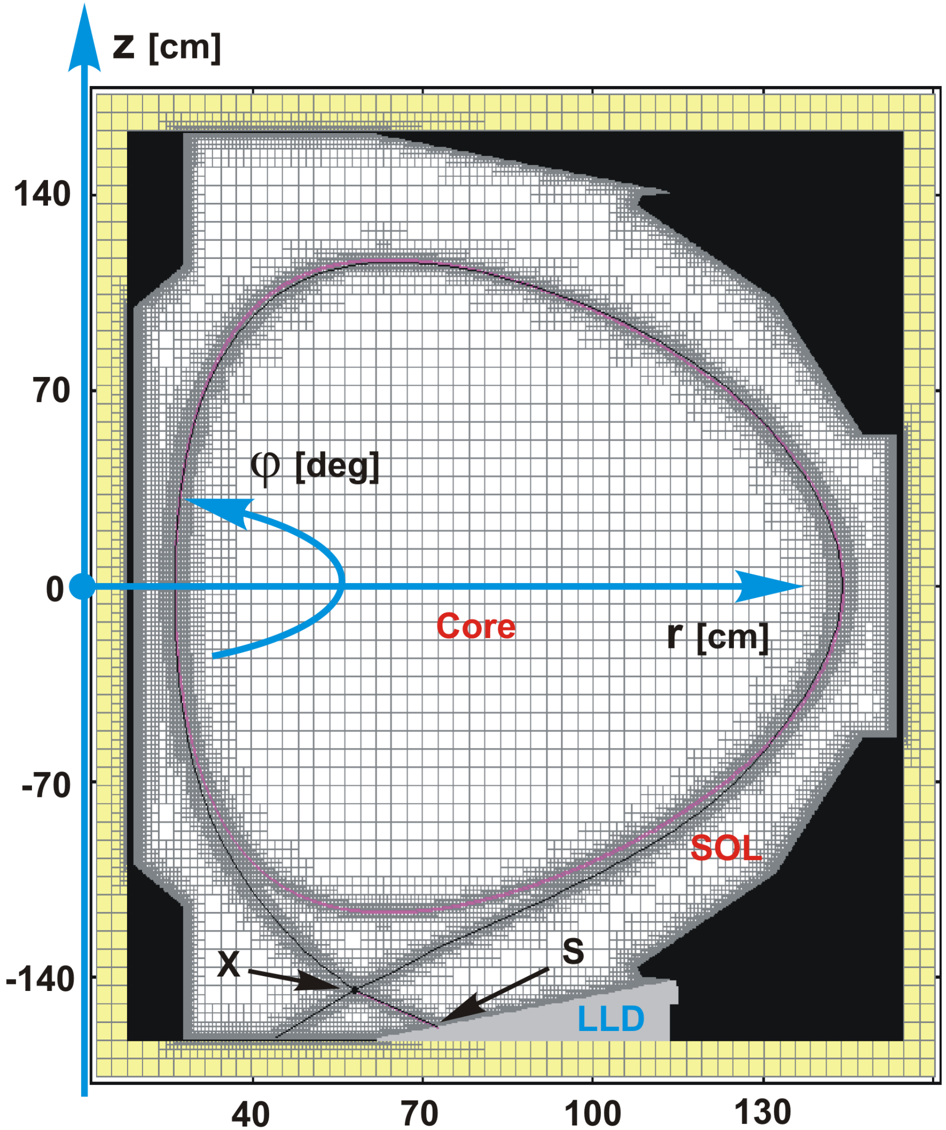
PURDUE NUCLEAR ENGINEERING

PURDUE UNIVERSITY

Outline

- HEIGHTS New Integrated Models & Design
- Application to NSTX and ITER
- Simulation Results
- Prospective New HEIGHTS Applications
- Summary

Quadtree Mesh in Poloidal Cross-Section



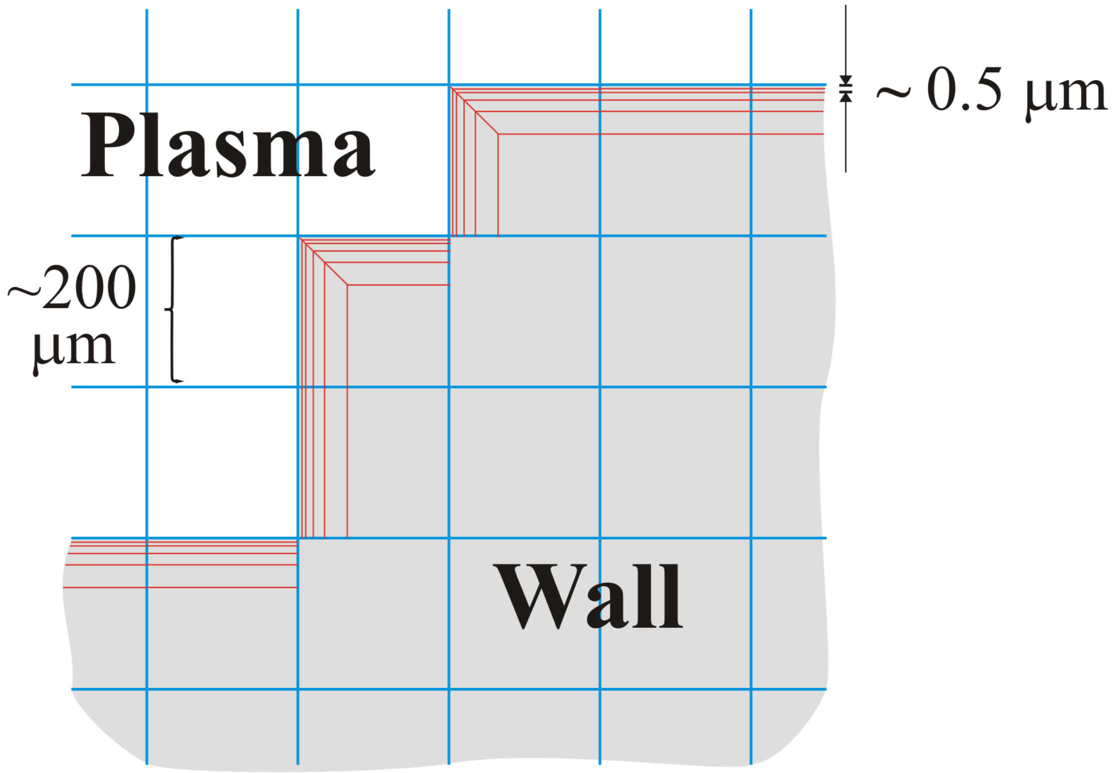
1. **Multi-scale capability:**
   - 5-Layer hierarchy
   - Surface extra refinement

2. **Device wall and regions AMR:**
   - Fit any tokamak wall design
   - Automatic mesh configuration
   - Regions of interest refinement

3. **Integration into HEIGHTS models:**
   - Core particles escaping
   - Walls heat load and erosion
   - Divertor plasma MHD
   - Magnetic diffusion and plasma HC
   - Radiation transport

4. **Parallel calculations:**
   - Automatic segmentation on sub-domains
   - Processor load distribution control with subdomains size

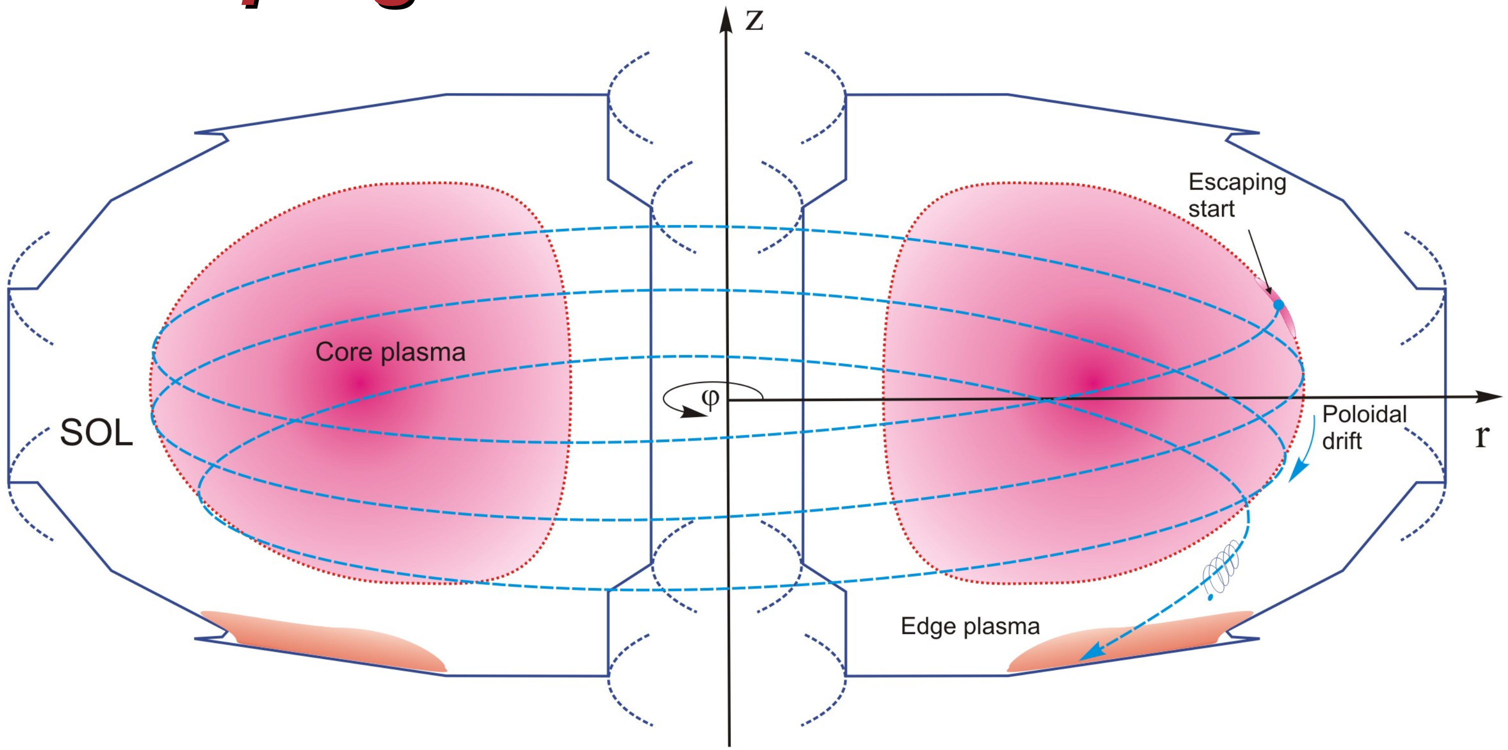
Surface Extra Refinement



Multiscale modeling:

- Device size, ~ [m]
- Plasma MHD cell, ~200 [µm]
- Surface processes, ~ 0.5 [µm]
- Distance between MC scatterings, ~ 25 [nm]

Escaping of 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

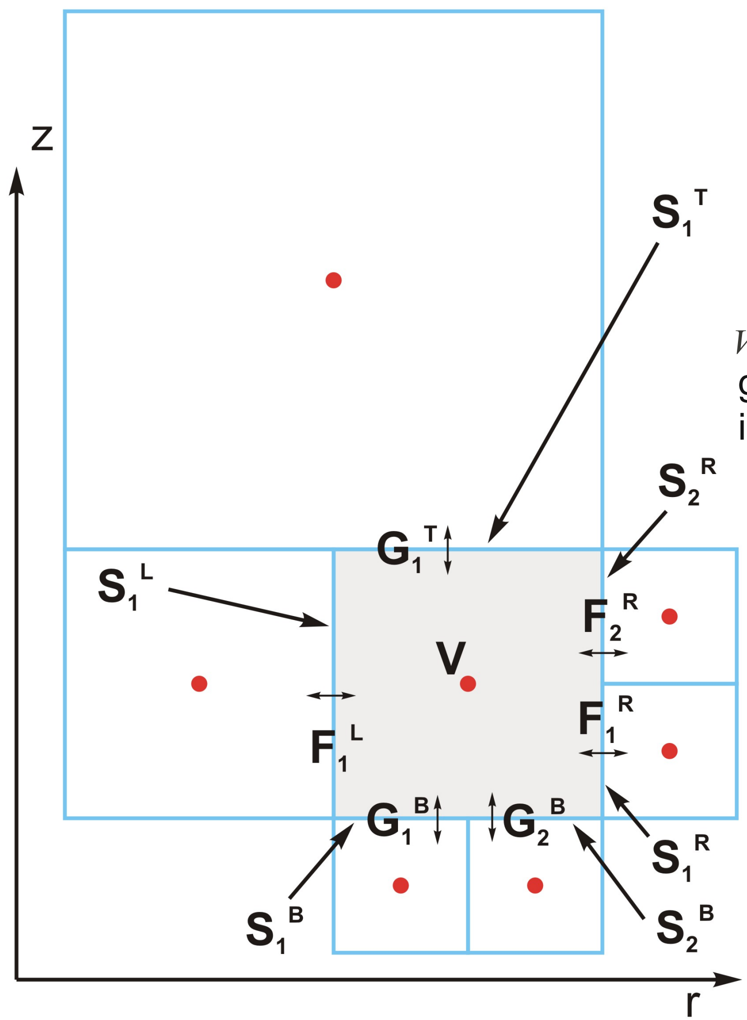
3. **Scatterings due to:**
   - Electron-electron, electron-nuclear
   - Ion-nuclear, Bremsstrahlung
   - Photo- and Compton absorption
   - Auger relaxation

4. **MC model for ELM or disruption:**
   - Initial distribution along core surface
   - Power time evolution
   - MHD equations right side source

Finite Volume Approach for AMR

$$U^{n+1}=U^{n}-\frac{\Delta t^{n}}{V}\left(\sum_{i=1}^{N^{R}}F_{i}^{R}S_{i}^{R}-\sum_{i=1}^{N^{L}}F_{i}^{L}S_{i}^{L}+\sum_{i=1}^{N^{T}}G_{i}^{T}S_{i}^{T}-\sum_{i=1}^{N^{B}}G_{i}^{B}S_{i}^{B}\right)-$$

$$-\Delta t^{n}\left(\sum_{i=1}^{N^{R}}P_{i}^{R}\frac{S_{i}^{R}}{V+\Delta V}-\sum_{i=1}^{N^{L}}P_{i}^{L}\frac{S_{i}^{L}}{V-\Delta V}-\Omega\right)$$

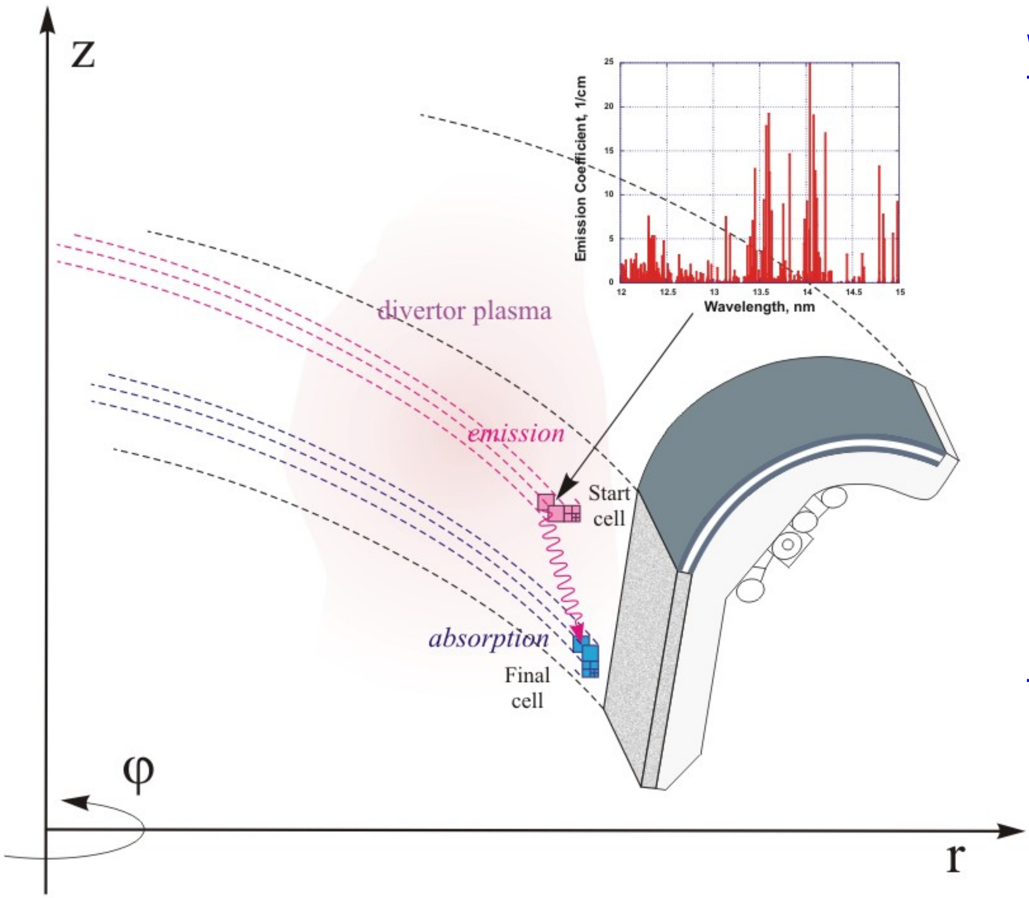


$V=\pi\left(r_R^2-r_L^2\right)$ is cell volume and $\Delta V=\pi\Delta r^{2}\Delta z$; is correction of geometrical cell volume due to cylindrical coordinate system and indexes L,R,B,T correspond to the left, right, bottom and top

Conservation laws for cell volume:

- Walls heat conduction and vaporization
- MHD evolution of vapor and plasma
- Magnetic field diffusion
- Heat conduction in plasma

Radiation Transport in Edge Plasma



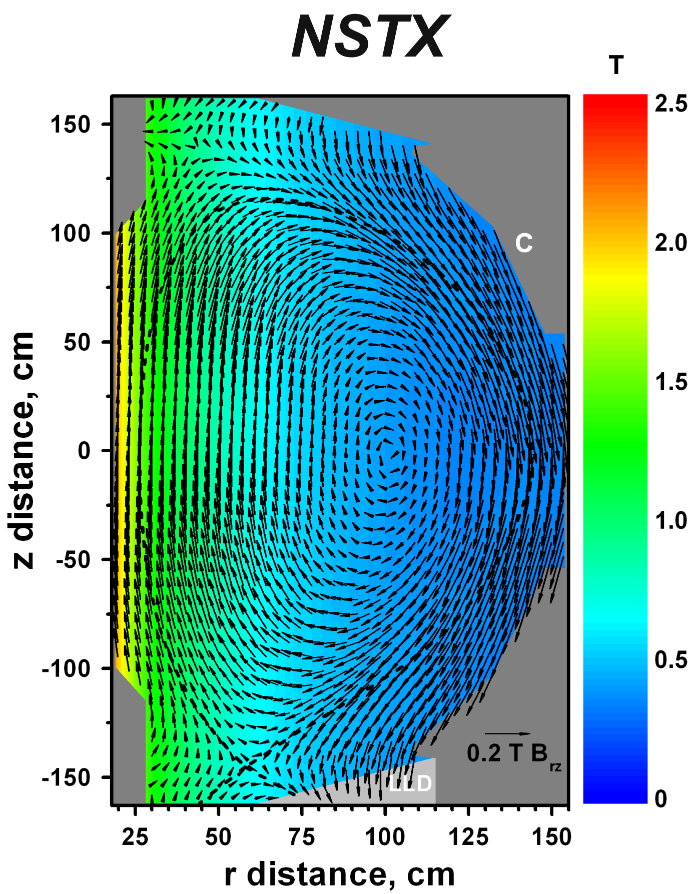
Weighted Monte Carlo Algorithm:

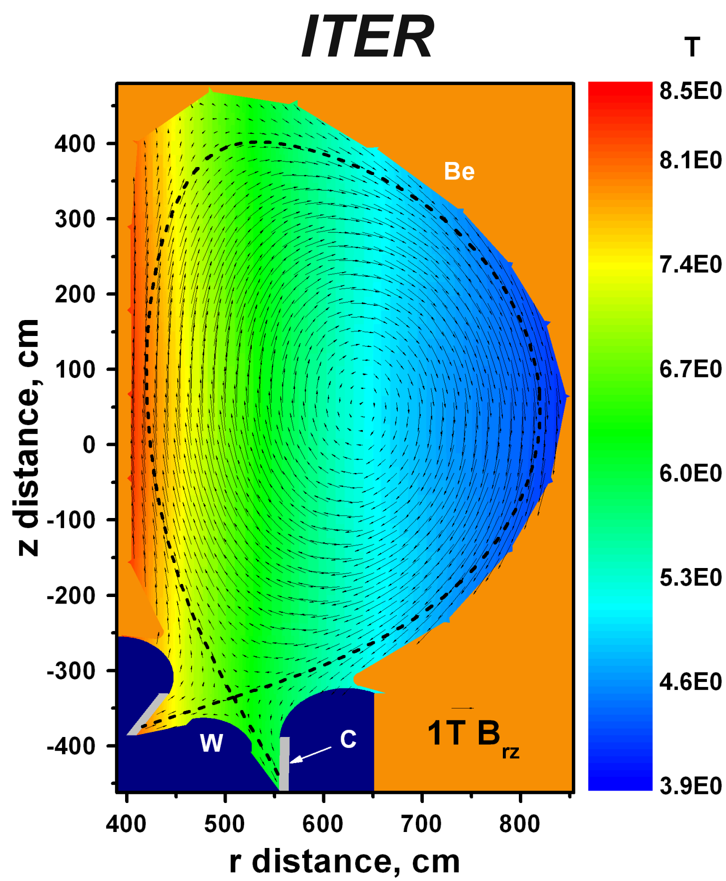
- Neglecting cold cell emission
- Ignoring emission and absorption in same cell
- Quadtree AMR
- Radiation flux deposition on all surfaces
- Correction of MHD solution and walls heat conduction

HEIGHTS Opacity Refinement:

- Carbon: 3800 spectral groups
- Lithium: 2800 spectral groups
- Tungsten: 9300 spectral groups

Magnetic Field Initialization

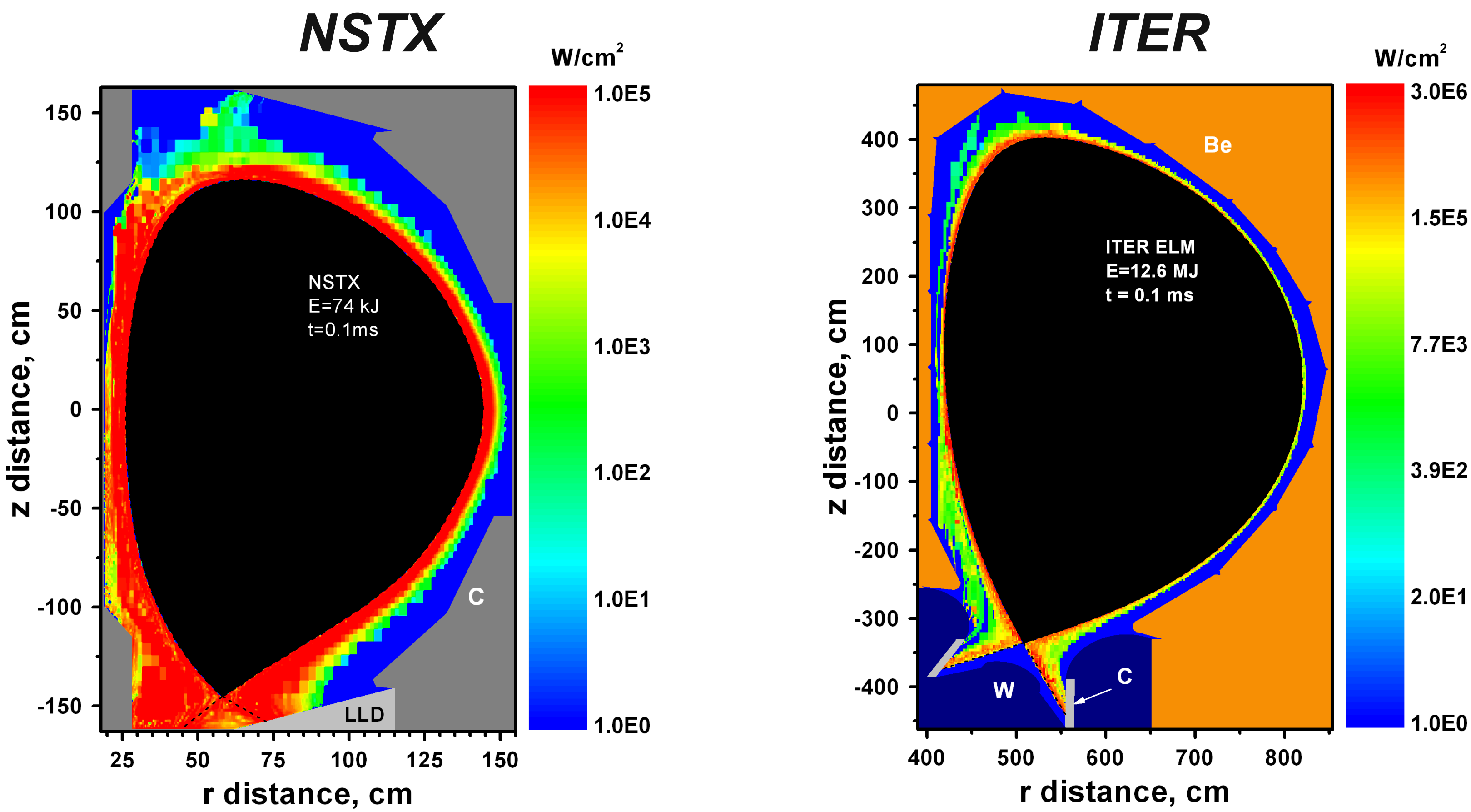




The initial magnetic field was reconstructed from the equilibrium EQDSK files for NSTX with liquid lithium divertor and ITER devices

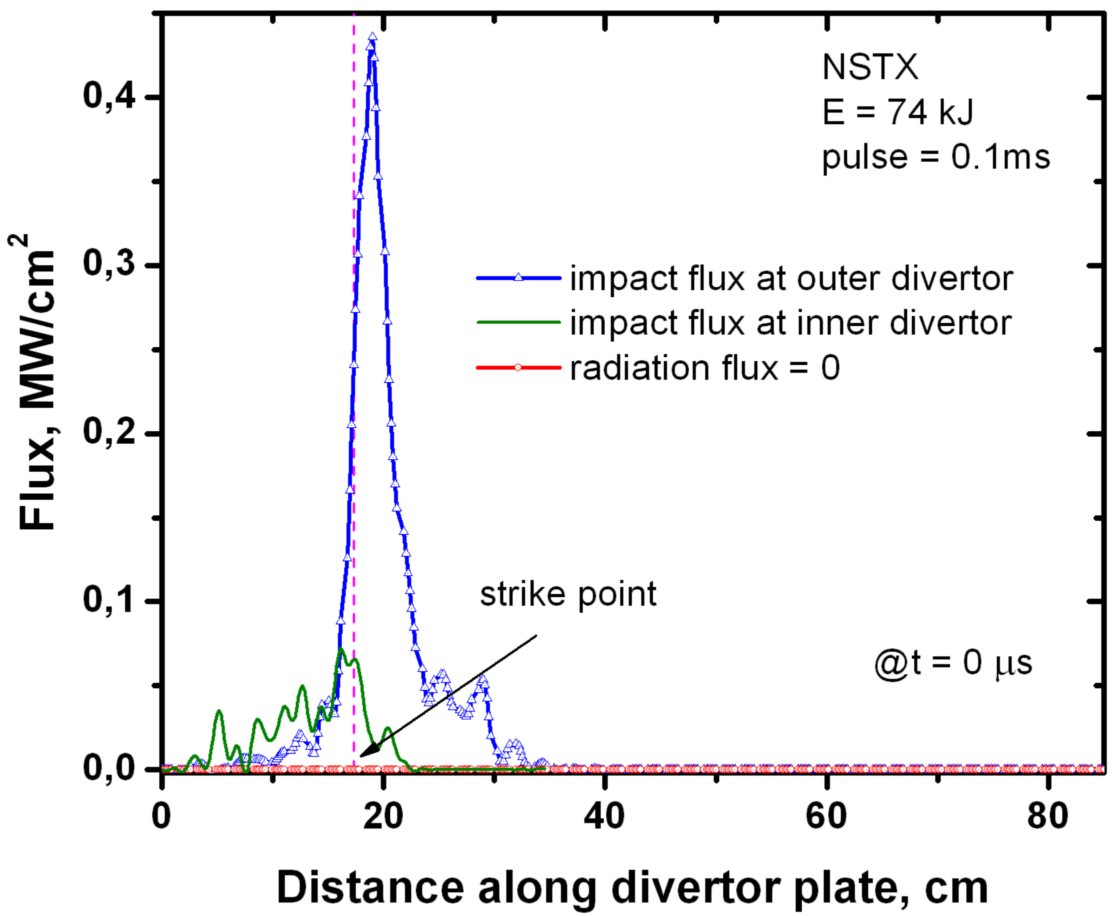
- D.P. Stotler et al., Contrib. Plasma Phys., **50** (2010) 368
- T.D.Rognlien et al., J. Nucl. Mater., **363-365** (2007) 658

MC Core Particles Escaping



We simulated in full 3D the evolution of escaped core plasma particles, i.e., starting from core border, gyration and scattering in SOL, and then penetration into device PFC.

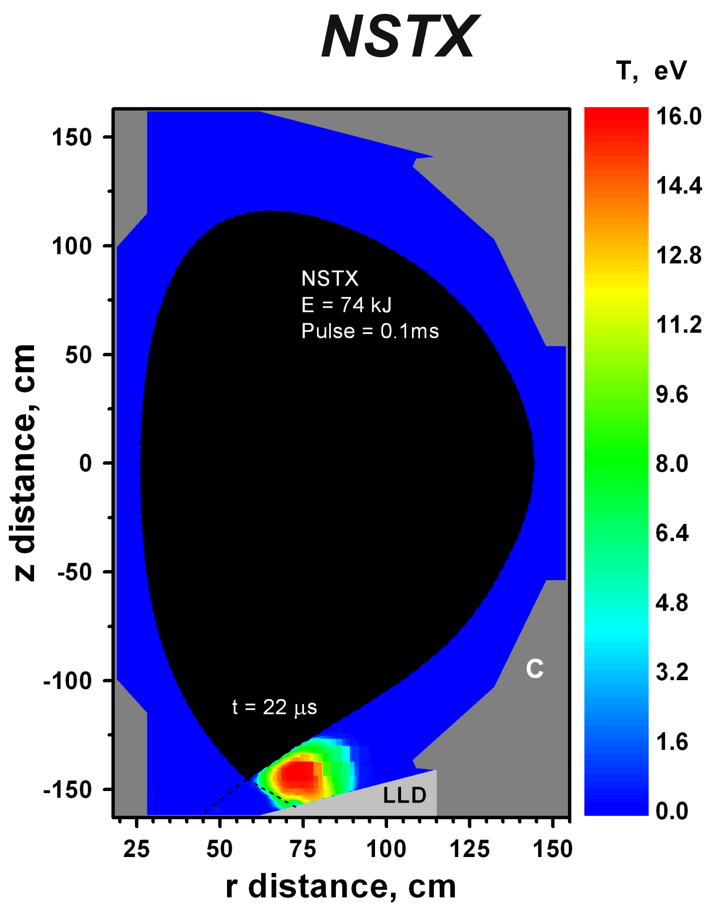
Initial Flux at NSTX LLD Surface

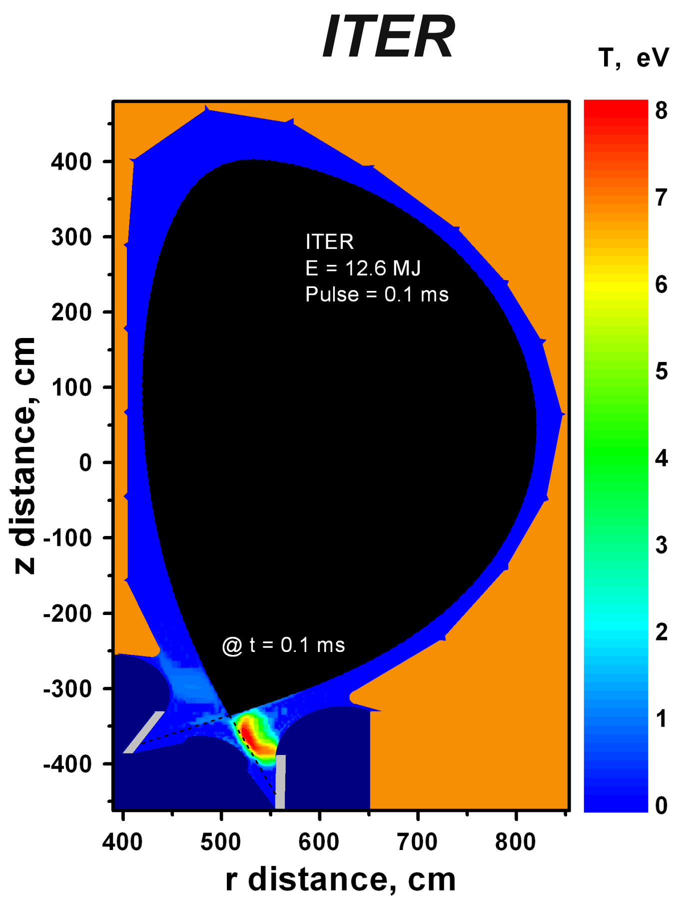


The initial distribution of plasma impact along lithium divertor in our new integrated design corresponds to our previous localized simulations

V.Sizyuk and A.Hassanein, J. Nucl. Mater., **415** (2011) S881.

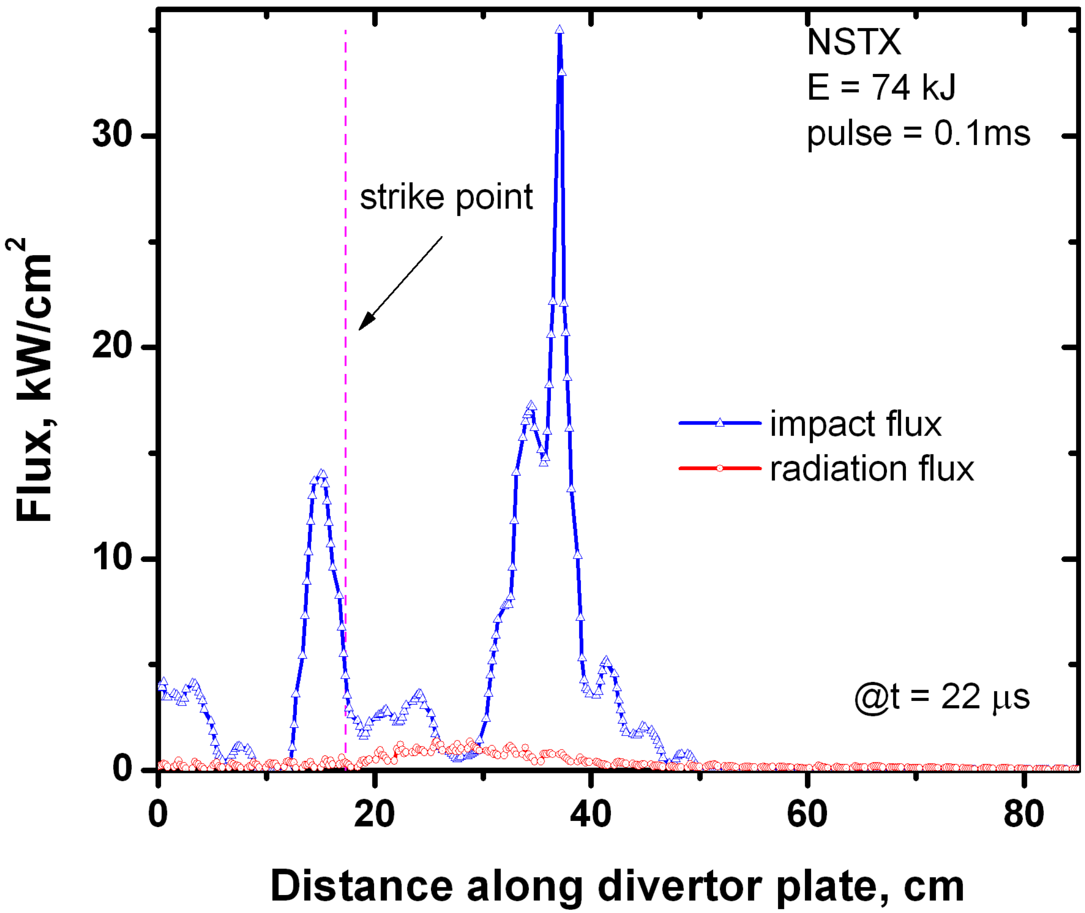
Plasma Cloud Formation





After plasma escaping starts, the drifting particles arrive at Li divertor strike-point location and initiates Li vaporization and plasma cloud formation.

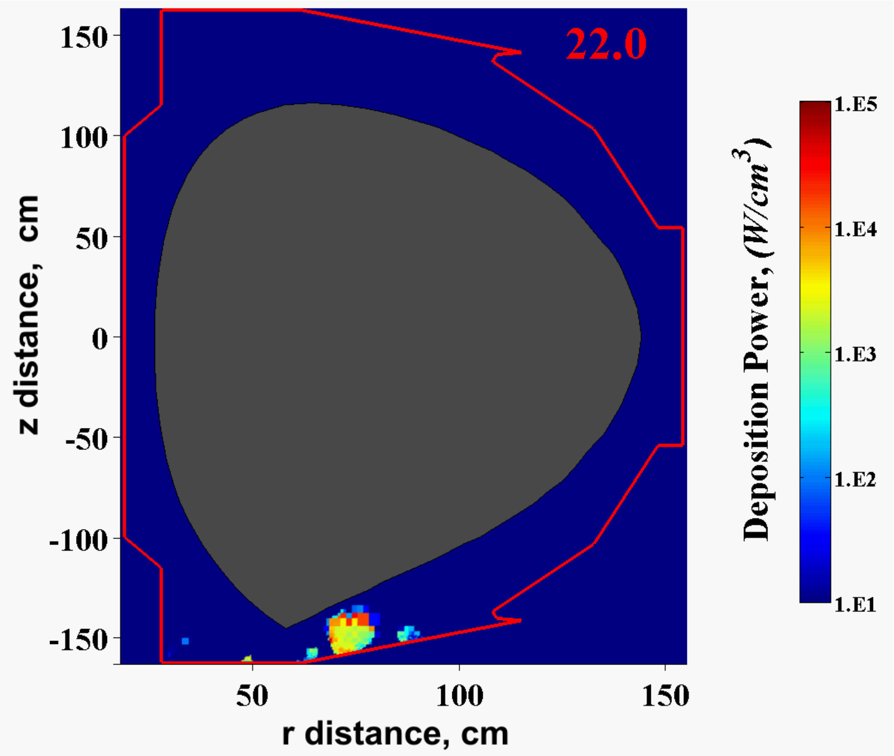
Plasma Shielding Effect



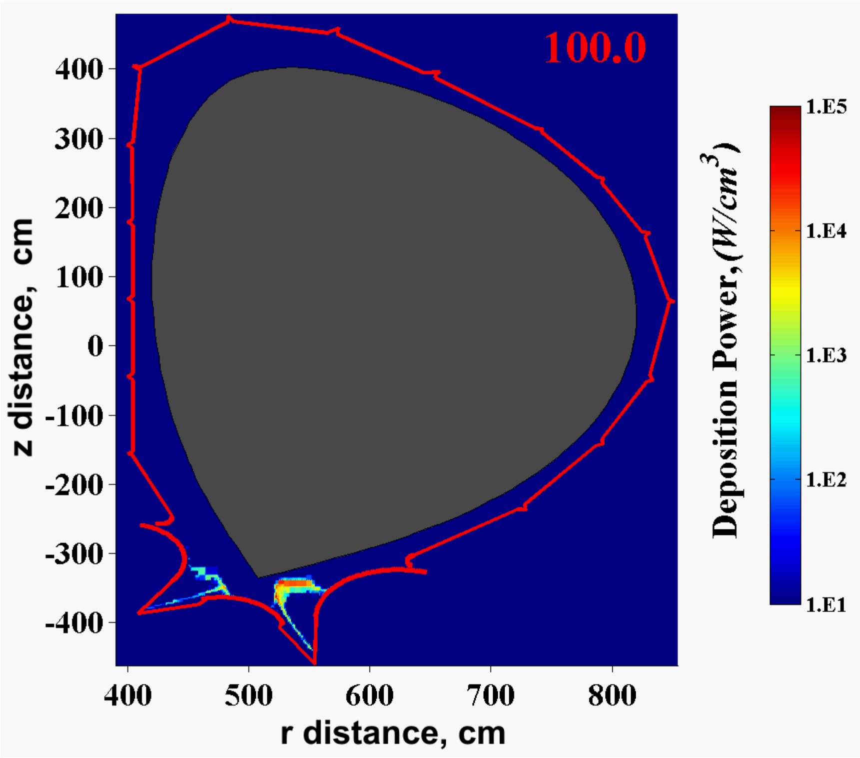
Because of evolving plasma-shielding effect, the impact power at the strike point is decreased and the peak of energy deposition changes location along the lithium surface. As a result, the spatial profile of lithium surface temperature varies during the impact time.

Escaped Particles Energy Deposition

NSTX

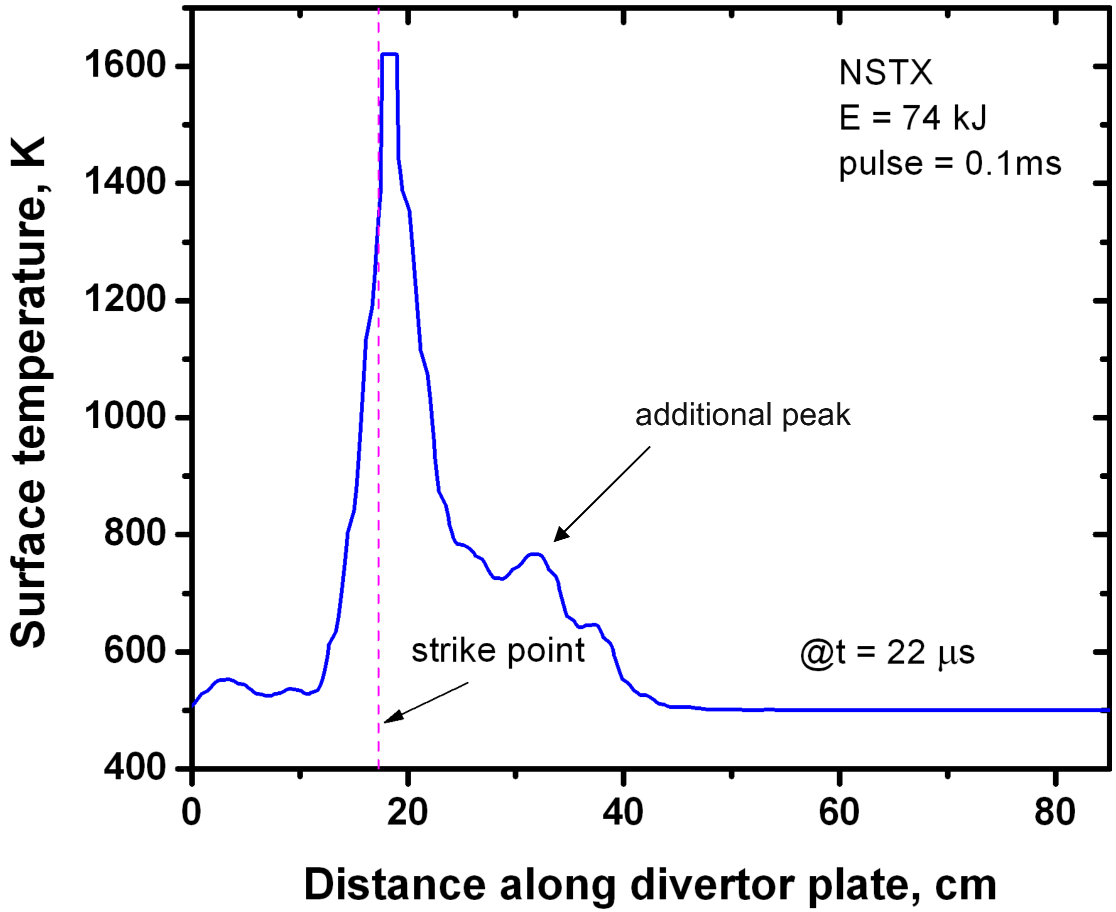


ITER



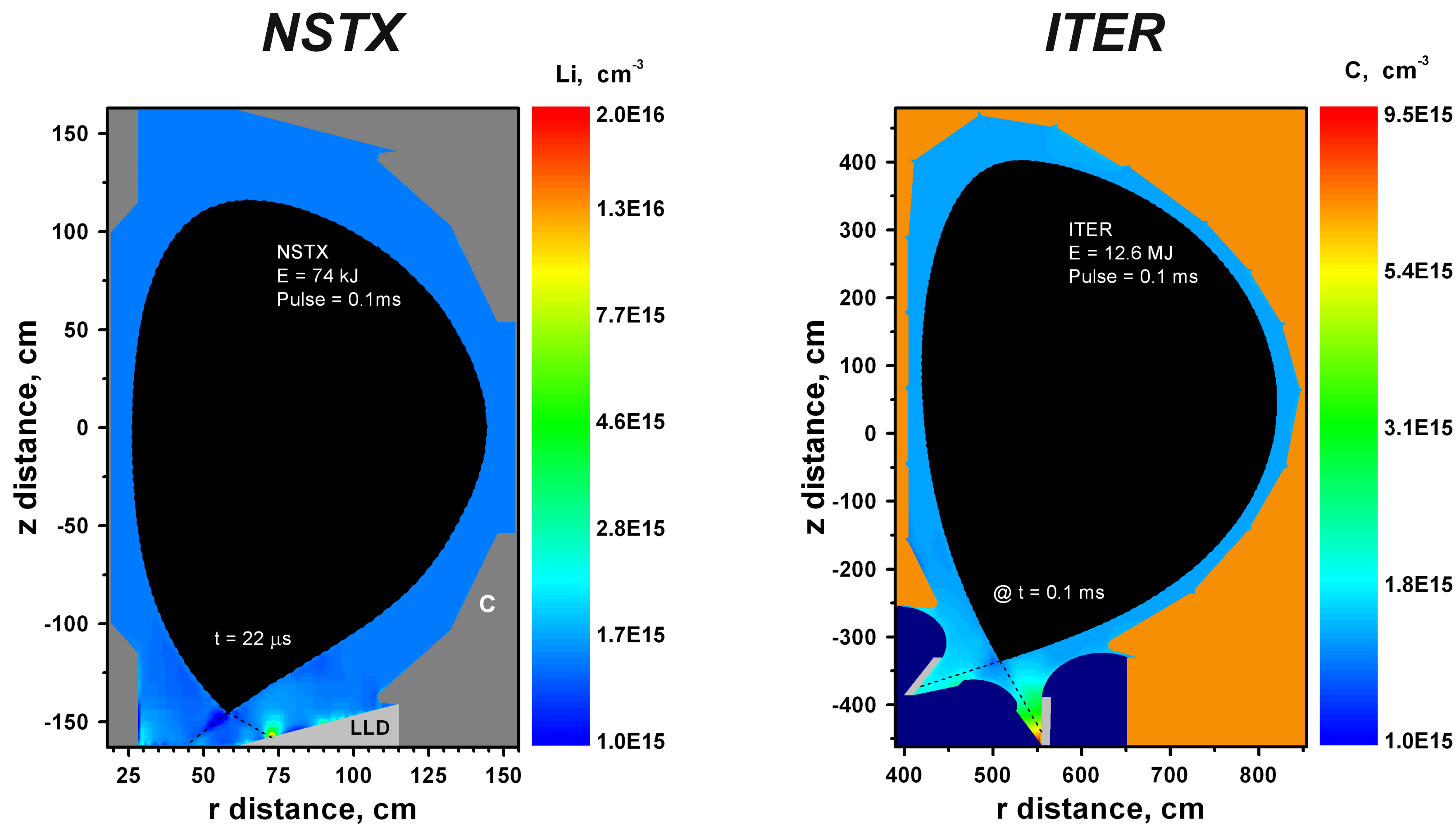
Escaped core particles deposit energy in plasma clouds as it moves. As result, the lithium surface temperature spatial profile varies during the impact time.

LLD Surface Temperature



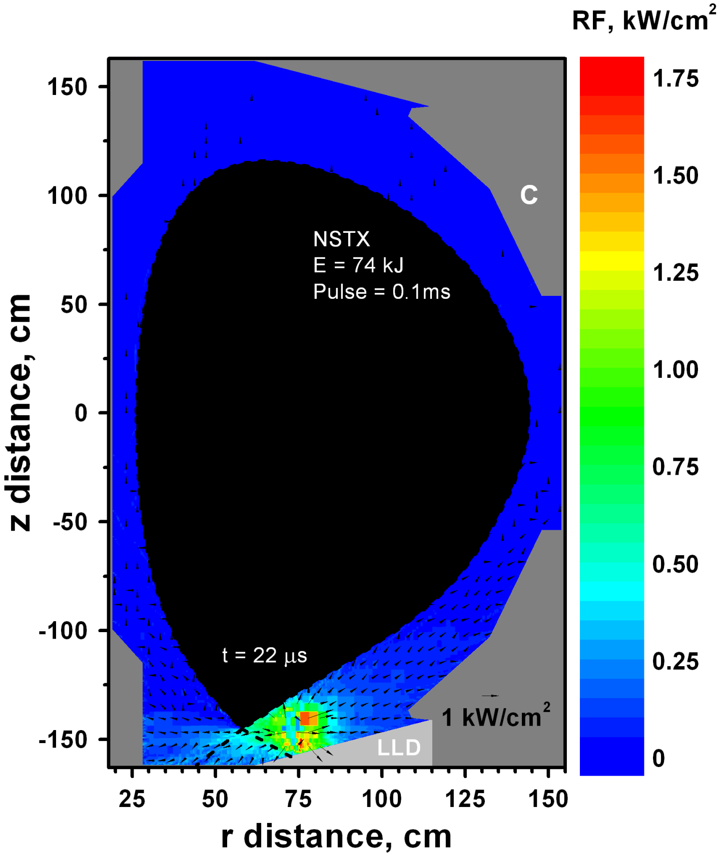
Initially, the vaporization area is located at the strike point but plasma shielding effect decreases impact energy at this location as shown in previous Slide. This explains the formation of the additional temperature peaks near the main maximum strike point.

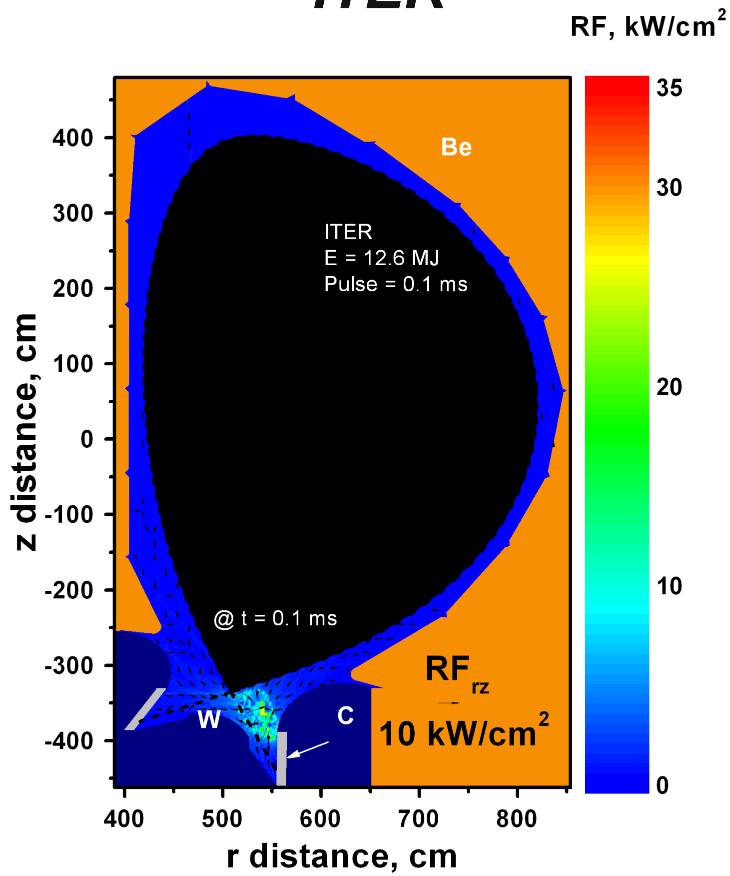
Divertor Plasma Expansion into SOL



The motion of the plasma density follows the magnetic field lines from the strike point to X-point and into the SOL zone along device walls.

Divertor Plasma Radiation Fluxes





The calculated low radiation fluxes of up to 2 kW/cm^2 for a 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.

Prospective New HEIGHTS Applications

- Precise prediction of device component heat load and spatial erosion profile
- Detail divertor plasma expansion into SOL and contaminations
- Calculation of edge plasma radiation output
- Modeling of new divertor and component designs (snow-flake, new materials application, etc.)
- Pellets and gas injection for mitigation and local effects

Summary and Conclusion

- The recent upgraded HEIGHTS package proved the necessity of integrating edge plasma transport in the expanded entire SOL domain

- The model and numerical methods are enhanced using adaptive mesh refinement (AMR) for fitting any arbitrary geometry of device walls and implementing nanoscale surface processes

- The implemented mesh has five layers of different cell sizes and logical block for AMR. Extra refinement (~ 0.5 μm) is applied to surface cells to provide sufficient accuracy of surface erosion and evolution

Summary and Conclusion (Cont.)

- Using actual geometry and magnetic field structure of NSTX and ITER we simulated in full 3D the evolution of escaped core plasma particles, i.e., starting from core border, gyration and scatterings in SOL, and then deposition into device PFC components
- Plasma magnetic diffusion, heat conduction, and radiation transport are also implemented using the quadtree grid hierarchy
- Lithium divertor heat load, surface erosion profile, and potential lithium contaminations drift were calculated for the First Time for the coupled system of inner and outer divertors interconnected through the SOL