# *Advanced integrated modeling of transient effects on Tokamak PFCs*

***Valeryi Sizyuk***

***Ahmed Hassanein***

***School of Nuclear Engineering, Purdue University***

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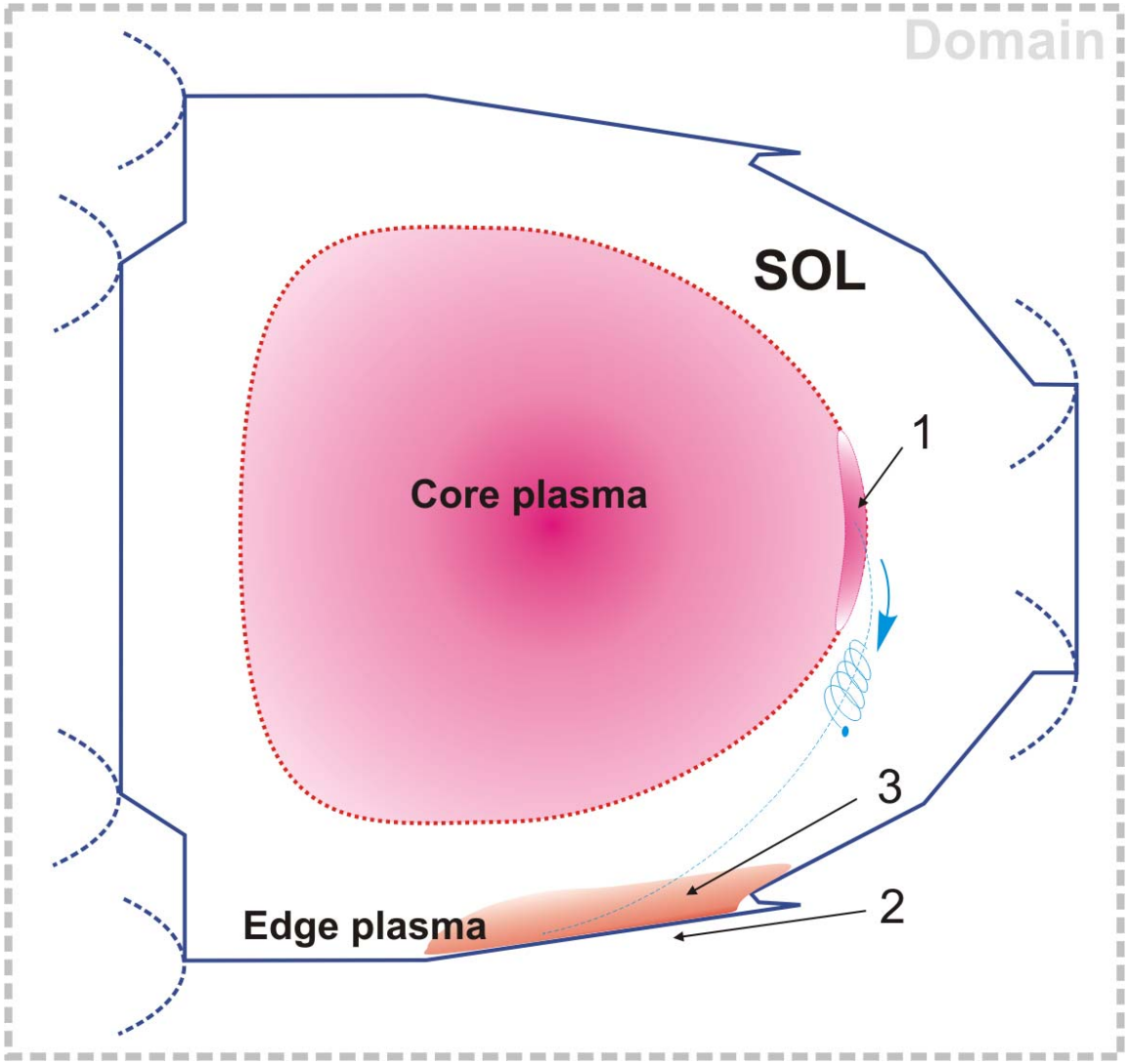
# *Outline*

- **HEIGHTS Integrated Approach**
- **Integration of Divertor Nearby Area**
- **Simulation Results**
- **HEIGHTS Upgrade and Current Status**
- **Summary**

# Physical Processes, an Integrated Approach




1. **MC model for escaped core particles**:
   - ELM and disruption conditions;
   - Energy deposition into walls
   - Energy deposition into plasma
2. **Device surface processes**:
   - Heat load;
   - Heat conduction;
   - Vaporization
3. **Edge plasma physics**:
   - MHD of plasma;
   - Magnetic diffusion
   - Heat conduction;
   - Radiation transport

# Physical Processes, an Integrated Approach

- Monte Carlo gyrokinetic model for the ELM and disruption particles:
  - *3D equations of motion in magnetic and electric fields;*
  - *Evolution of the initial and secondary particles (ions, electrons, photons);*
  - *All scattering processes including Bremsstrahlung, Compton absorption, photoabsorption, Auger relaxation;*
  - *3D energy deposition profiles in solid, vapor and plasma on unstructured mesh (UM)*
- MHD of the edge plasma in entire SOL:
  - *Total variation diminishing scheme in Lax-Friedrich formulation (UM);*
  - *Magnetic field divergence correction (UM);*
  - *Implicit algorithm for magnetic diffusion. Sparse matrix solvers (UM)*
- Thermal conduction:
  - *Implicit algorithm for edge plasma. Sparse matrix solvers (UM);*
  - *Explicit schemes for component materials. Surface extra refinement;*
  - *Vaporization model for component surfaces (UM)*
- Radiation transport in edge plasma:
  - *Weighted Monte Carlo algorithm;*
  - *More than 3500 spectral groups for the divertor plasma;*
  - *Full 3D simulation (UM)*
- Unstructured mesh:
  - *Five layers geometry adaptive refinement;*
  - *Device wall surfaces extra refinement*

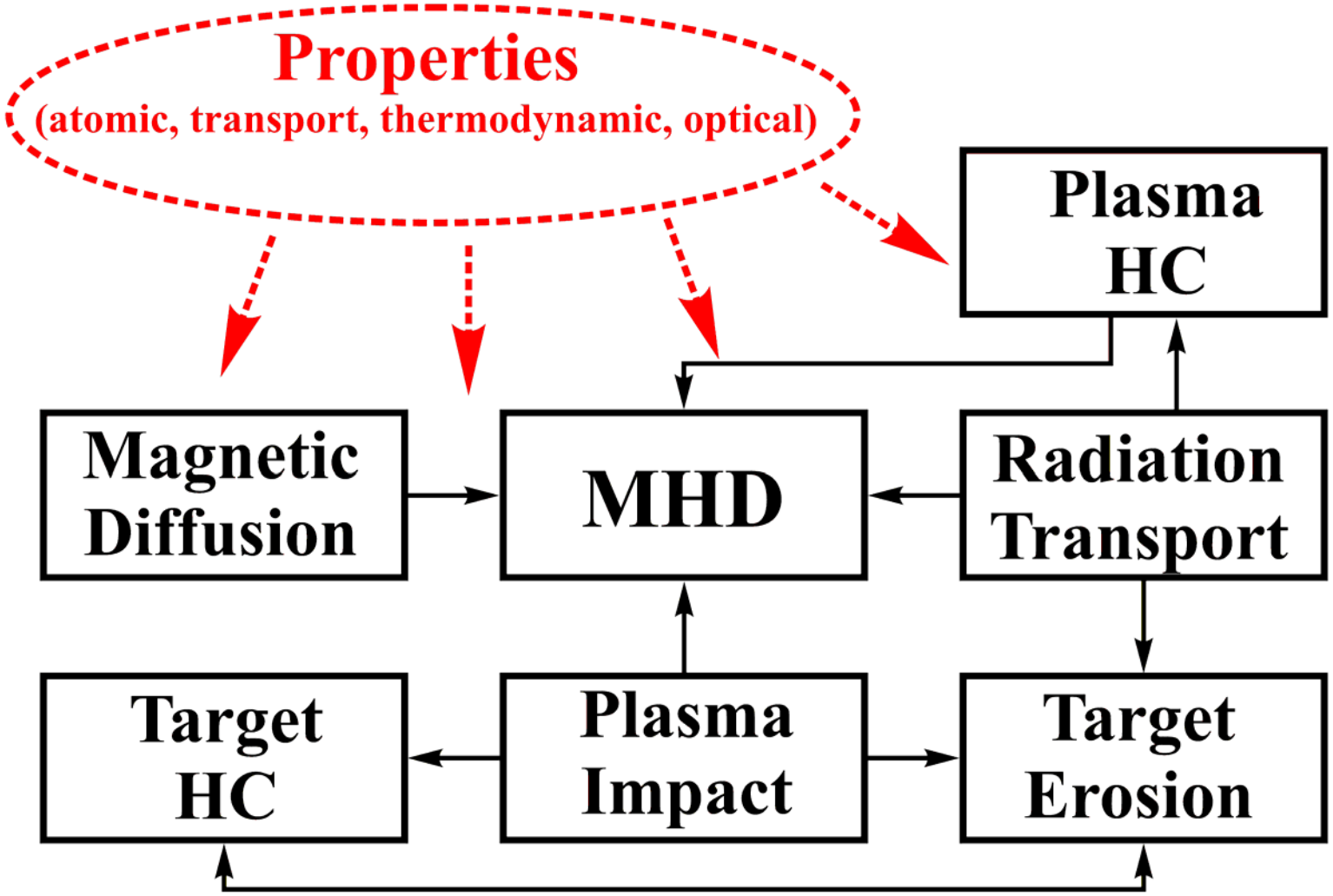
**New**

# Research Objectives

**Damage of Tokamak components should be simulated in actual device configuration and realistic operating conditions**

- Entire SOL should be modeled:
  - *Complex character of core plasma particles escape and motion in SOL;*
  - *Distribution of disrupted core particles on component surfaces;*
  - *Radiation transport problem;*
  - *Magnetic field gradient and curvature drift;*
  - *Radial electric field*
- Unstructured mesh is important solution for:
  - *Complex design of tokamak components;*
  - *Device size scale (meters) vs. edge plasma MHD scale (100 $\mu$m)*
- Extra refinement for surfaces:
  - *Energy deposition depth of core plasma particles ~ 10 $\mu$m;*
  - *Erosion surfaces scale ~ 1 $\mu$m*
- MPI parallelization of HEIGHTS:
  - *Large computational domain can be separated into sub-domains;*
  - *Great scalability of Monte Carlo computational blocks*

# HEIGHTS Structure



# Edge Plasma General Equations Set

$$\frac{\partial \rho}{\partial t}+\frac{1}{r}\frac{\partial}{\partial r}(r\rho v_r)+\frac{\partial}{\partial z}(\rho v_z)=Q_m^{vap}$$

$$\frac{\partial \rho v_r}{\partial t}+\frac{1}{r}\frac{\partial}{\partial r}\left[r\left(\rho v_r^2-\frac{B_r^2}{4\pi}\right)\right]+\frac{\partial p_t}{\partial r}+\frac{\partial}{\partial z}\left(\rho v_r v_z-\frac{B_r B_z}{4\pi}\right)=\frac{\rho v_\varphi^2}{r}-\frac{B_\varphi^2}{4\pi r}$$

$$\frac{\partial \rho v_\varphi}{\partial t}+\frac{1}{r}\frac{\partial}{\partial r}\left[r\left(\rho v_\varphi v_r-\frac{B_\varphi B_r}{4\pi}\right)\right]+\frac{\partial}{\partial z}\left(\rho v_\varphi v_z-\frac{B_\varphi B_z}{4\pi}\right)=\frac{\rho v_\varphi v_r}{r}-\frac{B_\varphi B_r}{4\pi r}$$

$$\frac{\partial \rho v_z}{\partial t}+\frac{1}{r}\frac{\partial}{\partial r}\left[r\left(\rho v_z v_r-\frac{B_z B_r}{4\pi}\right)\right]+\frac{\partial}{\partial z}\left(\rho v_z^2+p_t-\frac{B_z^2}{4\pi}\right)=0$$

$$\frac{\partial e_h}{\partial t}+\frac{1}{r}\frac{\partial}{\partial r}\{r[v_r(e_h+p_h)]\}+\frac{\partial}{\partial z}[v_z(e_h+p_h)]=Q_{en}^{vap}+Q_{hc}+Q_J+Q_{imp}+Q_{rad}$$

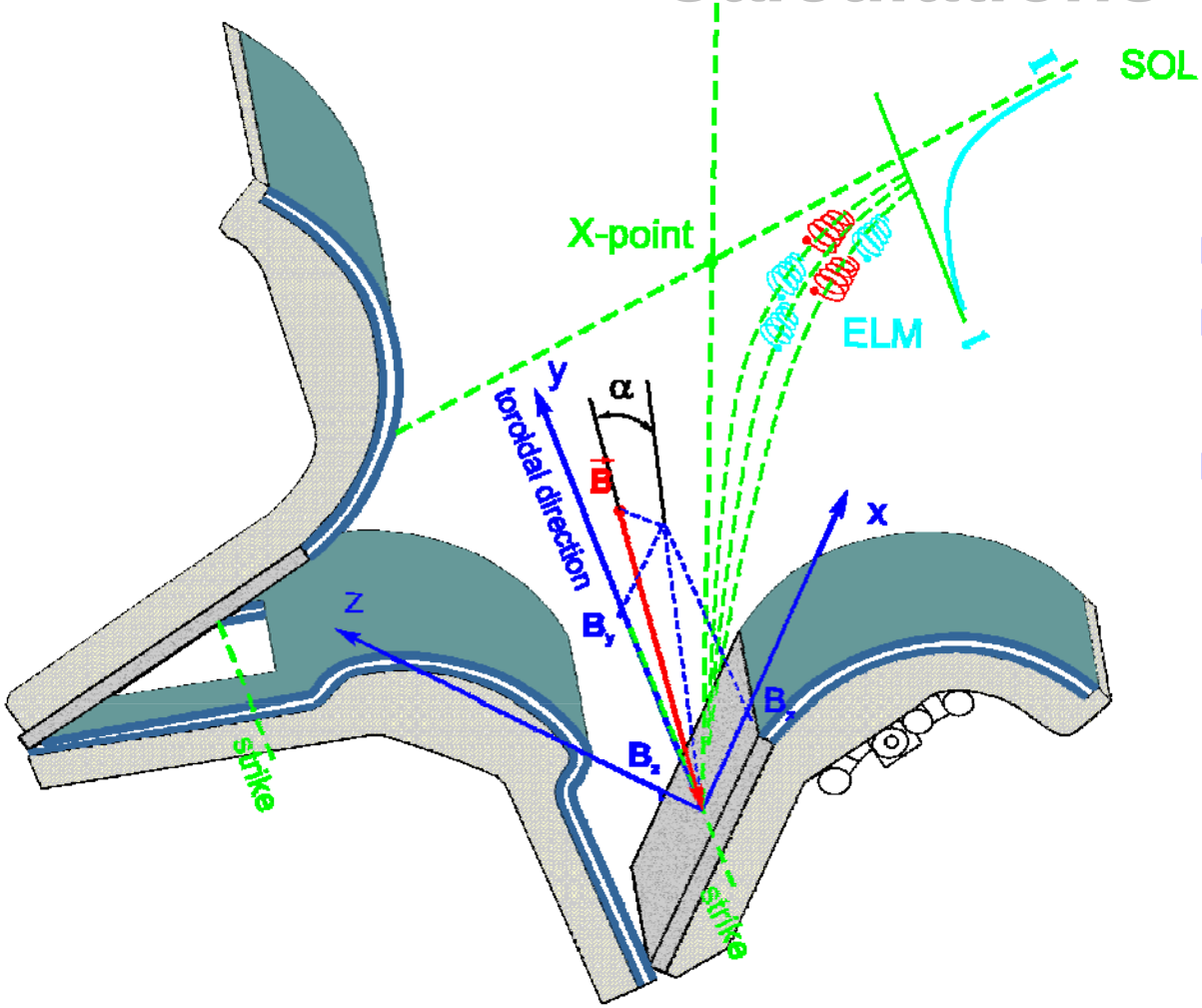
$$\frac{\partial B_r}{\partial t}+\frac{\partial}{\partial z}(v_z B_r-B_z v_r)=Q_r^{mdiff}$$

$$\frac{\partial B_\varphi}{\partial t}+\frac{\partial}{\partial z}(v_z B_\varphi-B_z v_\varphi)=Q_\varphi^{mdiff}$$

$$\frac{\partial B_z}{\partial t}+\frac{1}{r}\frac{\partial}{\partial r}[r(v_r B_z-B_r v_z)]=Q_z^{mdiff}$$

$\rho$ - density; $v$ – velocity; $B$ – magnetic field; $p$ – pressure; $Q_{hc}$ - thermal conduction; $Q_{rad}$ - radiation transport; $Q_J$ - Joule heat term; $Q_m^{vap}$, $Q_{en}^{vap}$ - target vaporization; $Q_{imp}$ - SOL plasma impact, $Q^{mdiff}$ - magnetic diffusion terms.

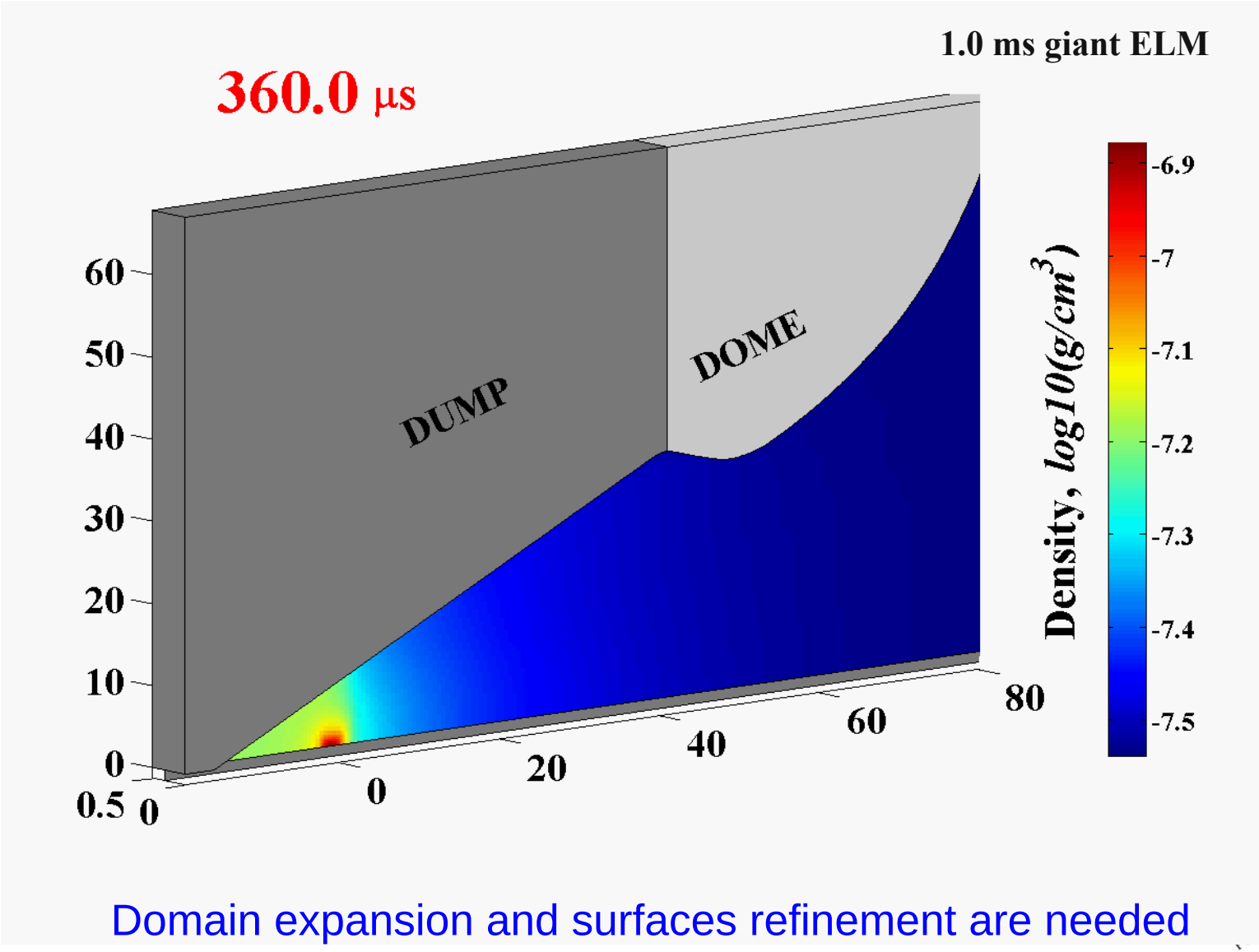
# Previous Local Implementation of Calculations




- Nearby divertor area domain
- Coarse mesh for curvilinear component surfaces
- Local Cartesian coordinate system

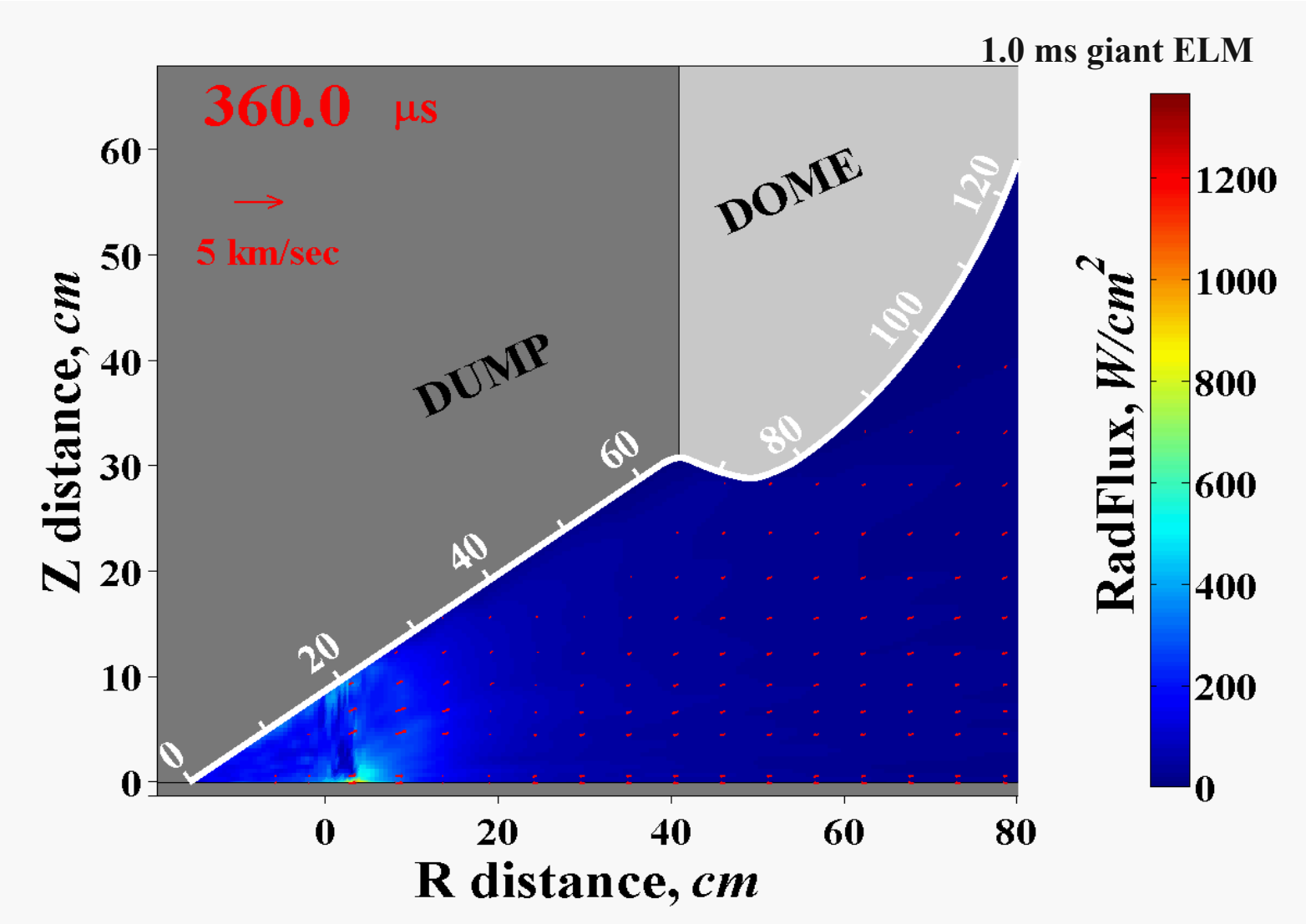
J. Palmer *et al.*, Recent developments towards ITER 2001 divertor maintenance, *Fusion Engineering and Design*, **75-79** 583 (2005)

# Divertor Plasma Density Evolution




Domain expansion and surfaces refinement are needed

# Radiation Fluxes Evolution

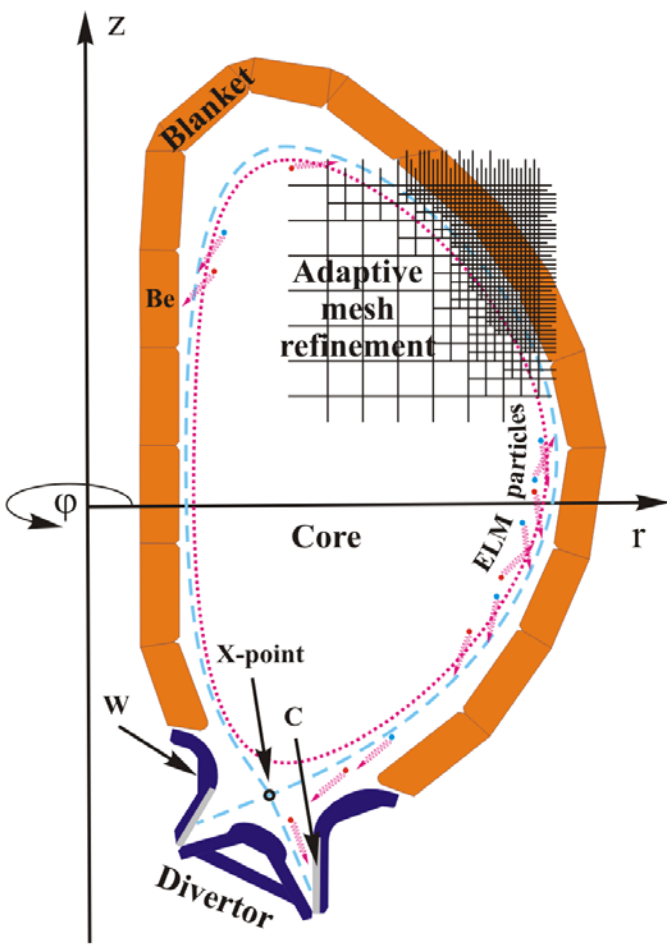


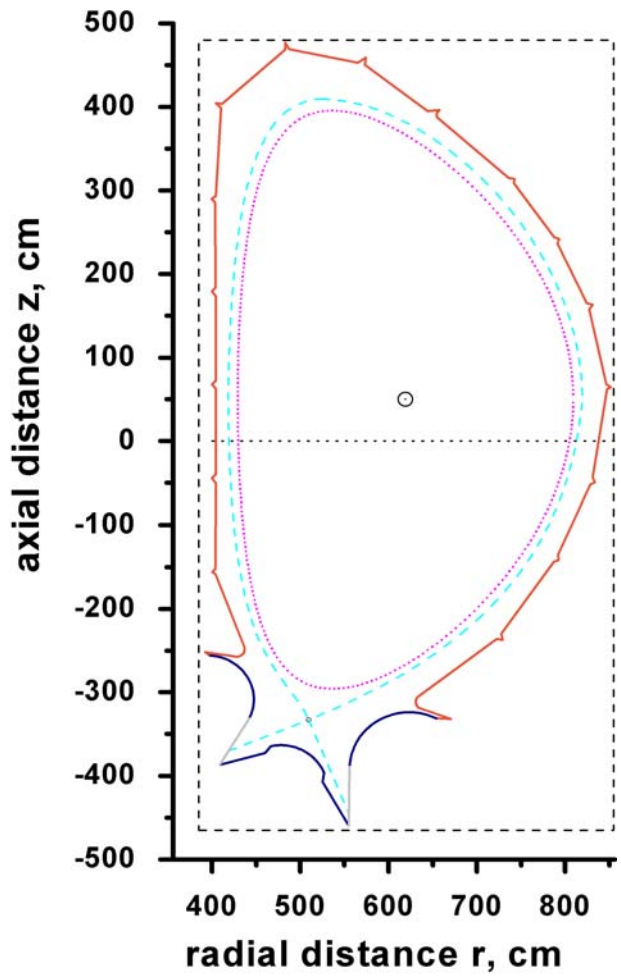

Domain expansion and surfaces refinement are needed

# Publications


1. V. Sizyuk and A. Hassanein, Integrated models to study the impact of ELMs and disruptions on lithium in the NSTX divertor, *Journal of Nuclear Materials*, (2011) in press.
2. E.M. Hollmann et al, Plasma-surface interaction during tokamak disruptions and rapid shutdowns, *Journal of Nuclear Materials*, (2011) in press.
3. A. Hassanein, T. Sizyuk, V. Sizyuk, G. Miloshevsky, Impact of various plasma instabilities on reliability and performance of tokamak fusion devices, *Fusion Engineering and Design*, vol. 85, N7-9, pp. 1331-1335, 2010.
4. V. Sizyuk and A. Hassanein, Damage to nearby divertor components of ITER-like devices during giant ELMs and disruptions, *Nuclear Fusion,* vol. 50, N11, p. 115004, 2010.
5. V. Sizyuk and A. Hassanein, Self-consistent analysis of the effect of runaway electrons on plasma facing components in ITER, *Nuclear Fusion*, vol. 49, N9, p. 095003, 2009.

# New Approach of Calculations (ITER)

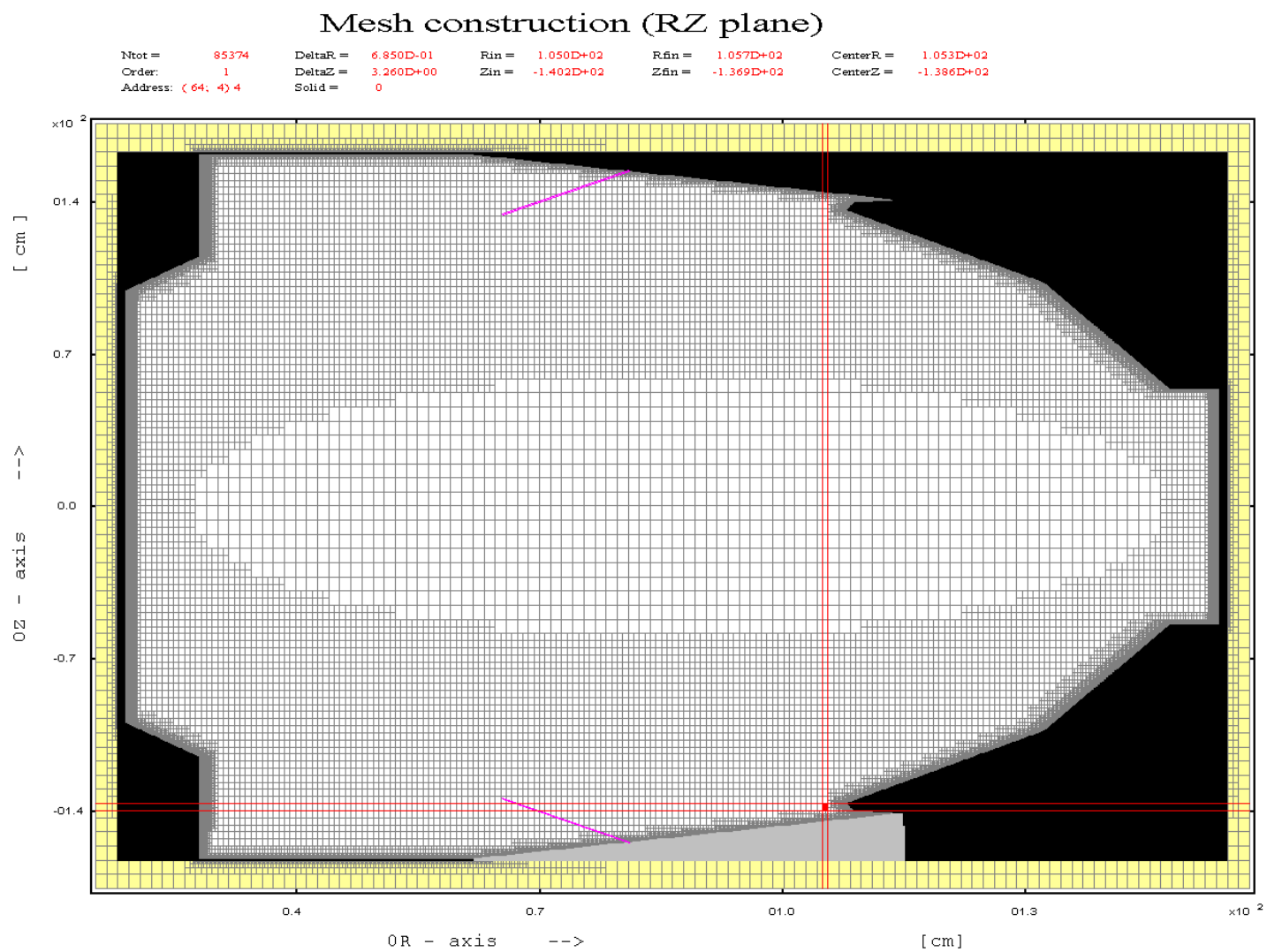


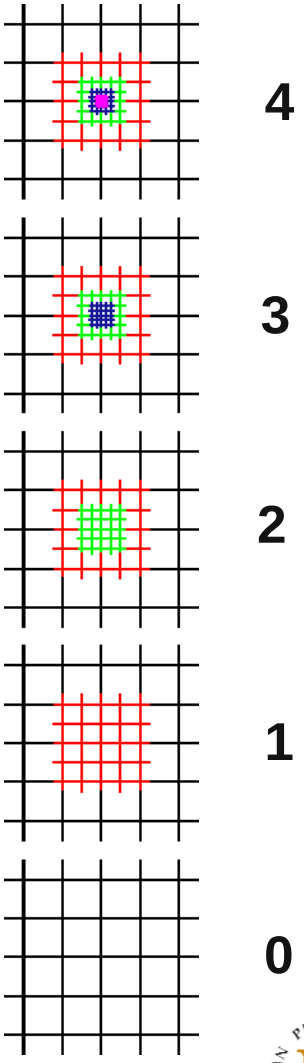




- AMR for the complex design of surfaces
- AMR decreases calculation time with better accuracy
- Extra refinement for surfaces heat load and erosion
- 3D Cylindrical coordinate system
- Whole SOL computational domain
- Accurate simulation of core particles escape to SOL

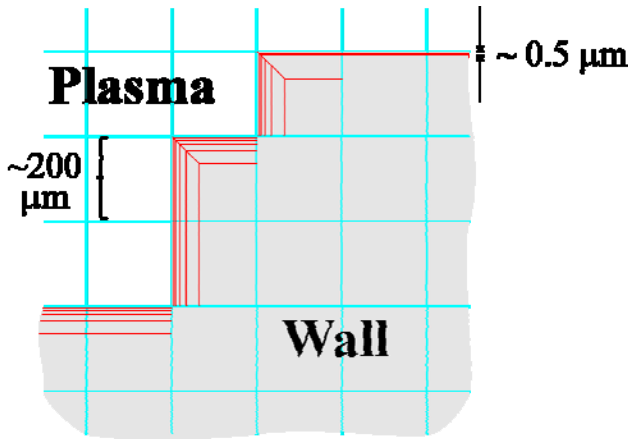
Device design: R. Aymar, *Fusion Eng. Des.* **55** 107 (2001).
Plasma core form: W.M. Stacey, *Phys. Plasmas* **16** 032506 (2009)

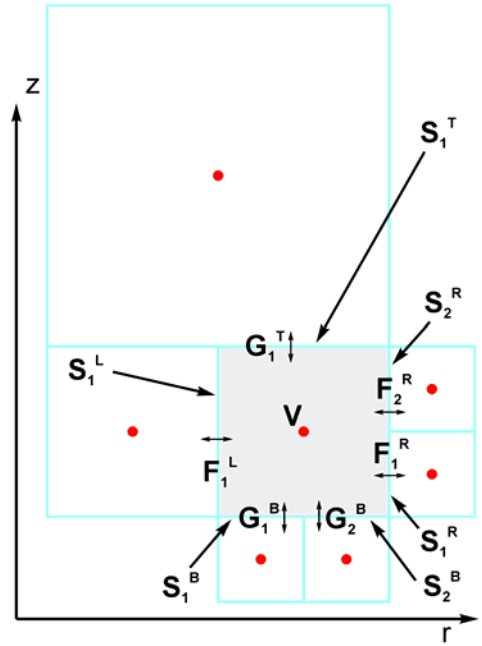
# 5-Layers Geometry Levels of AMR (NSTX)



# Wall Extra Refinement (Unstructured Mesh)



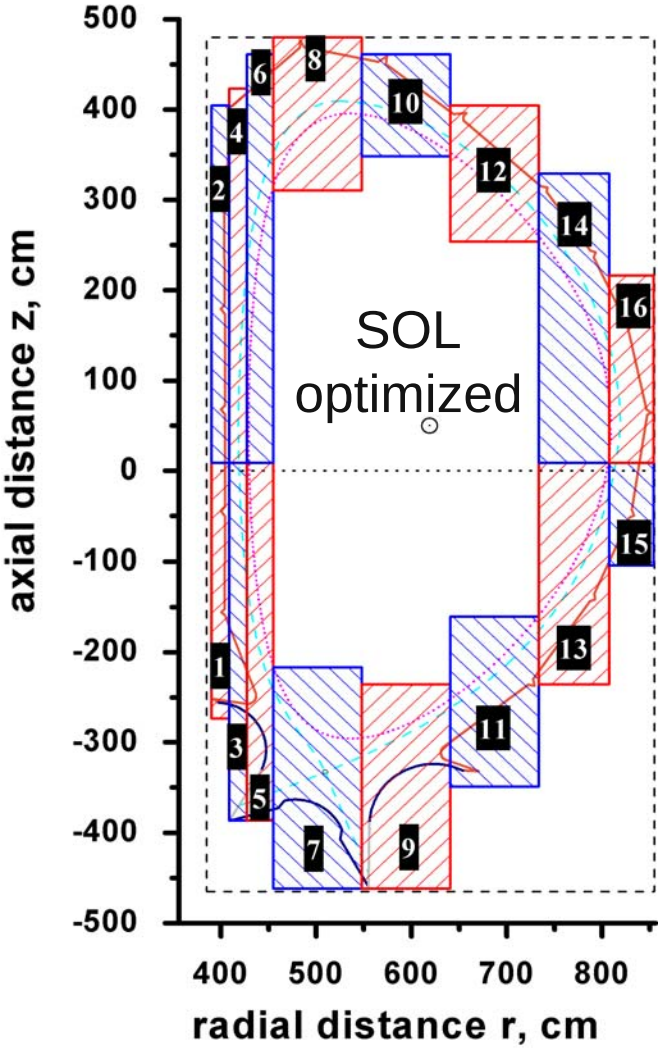



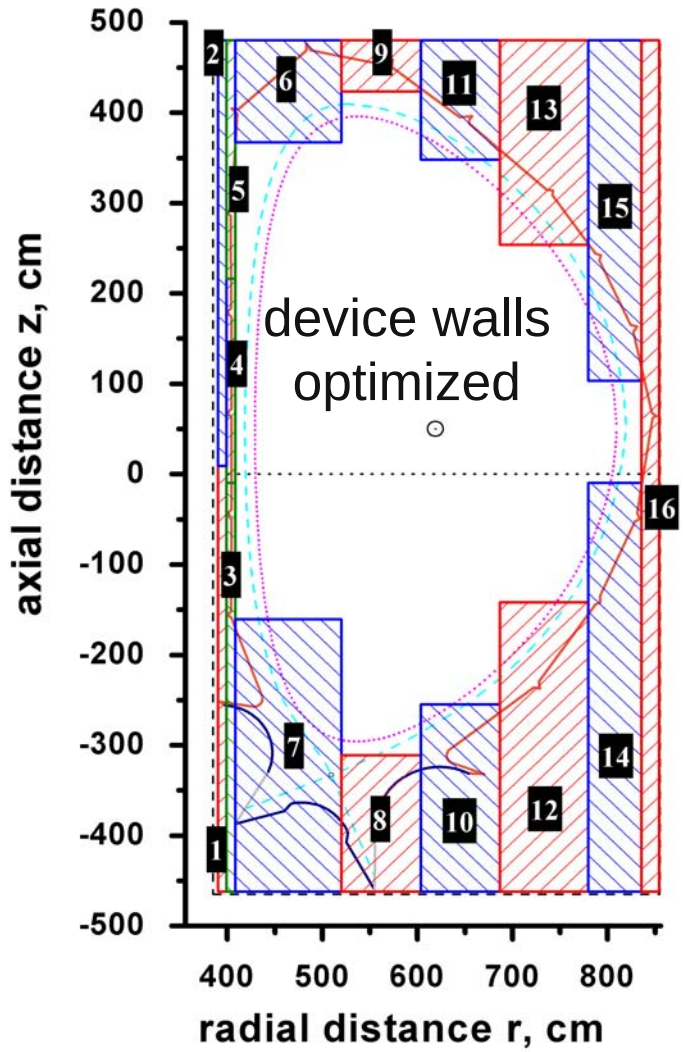

- Finite volume approach for unstructured mesh
- Limit in two side neighbors
- Extra refinement for surfaces heat load and vaporization
- Scale different: ~ 100-200 µm for plasma and ~ 0.5-1.0 µm for device walls

$$\mathbf{U}^{n+1} = \mathbf{U}^{n} - \frac{\Delta t^{n}}{V}\left(\sum_{i=1}^{N^R}\mathbf{F}_i^R S_i^R - \sum_{i=1}^{N^L}\mathbf{F}_i^L S_i^L + \sum_{i=1}^{N^T}\mathbf{G}_i^T S_i^T - \sum_{i=1}^{N^B}\mathbf{G}_i^B S_i^B\right) -$$

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

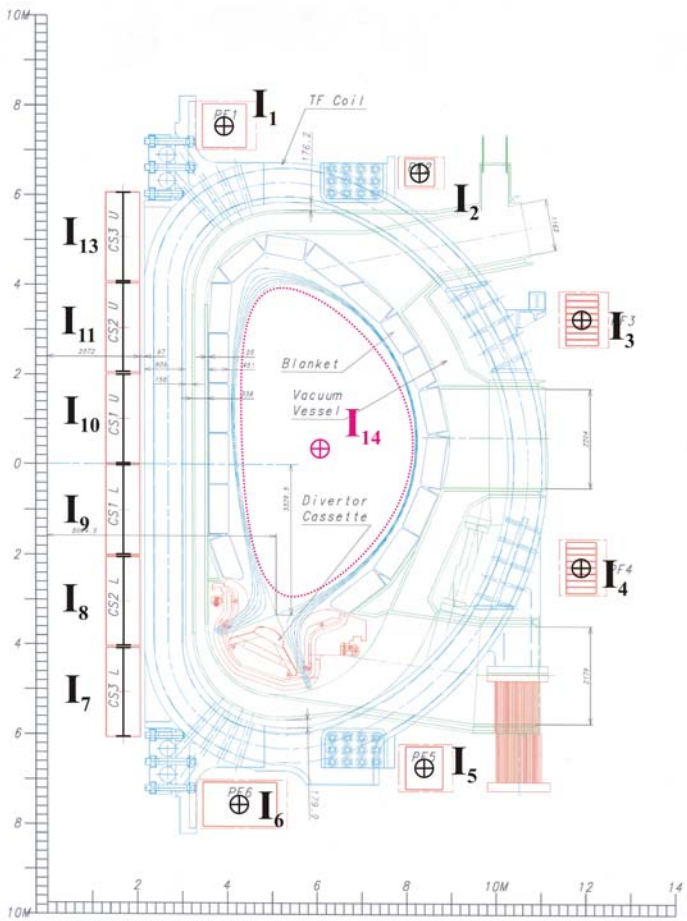
# MPI Subdomain Distributions (16 procs)

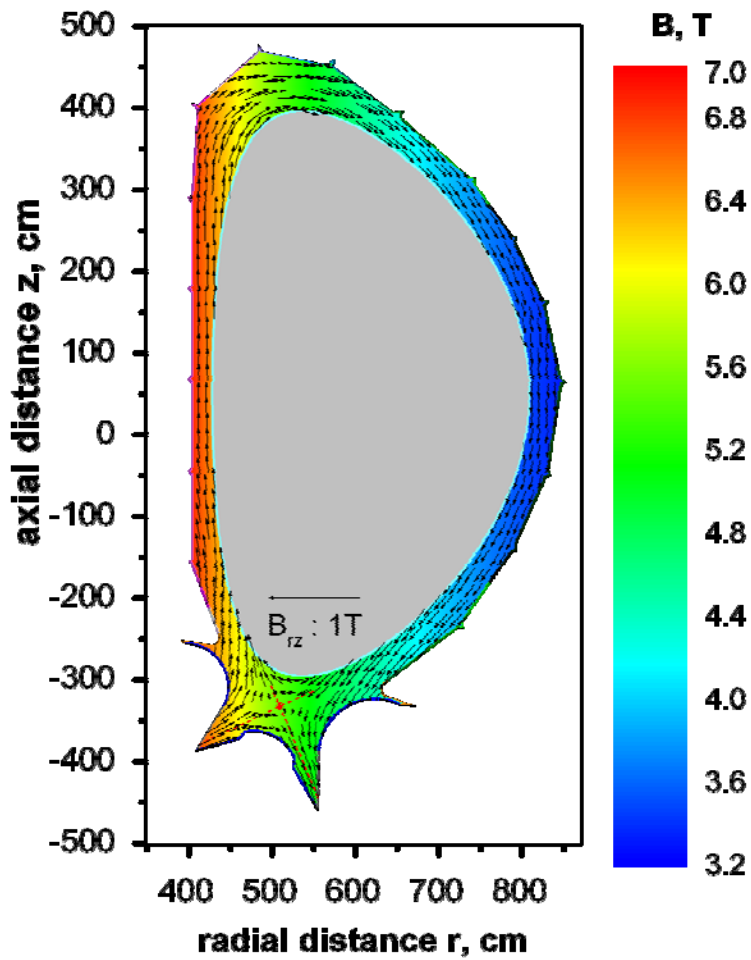



- Automatic partitioning of domain on processors subdomains
- Separate processors for plasma MHD domain and solid heat conduction domain
- Equal processors load distribution via cell numbers in subdomains

# Magnetic Field Initialization (ITER)

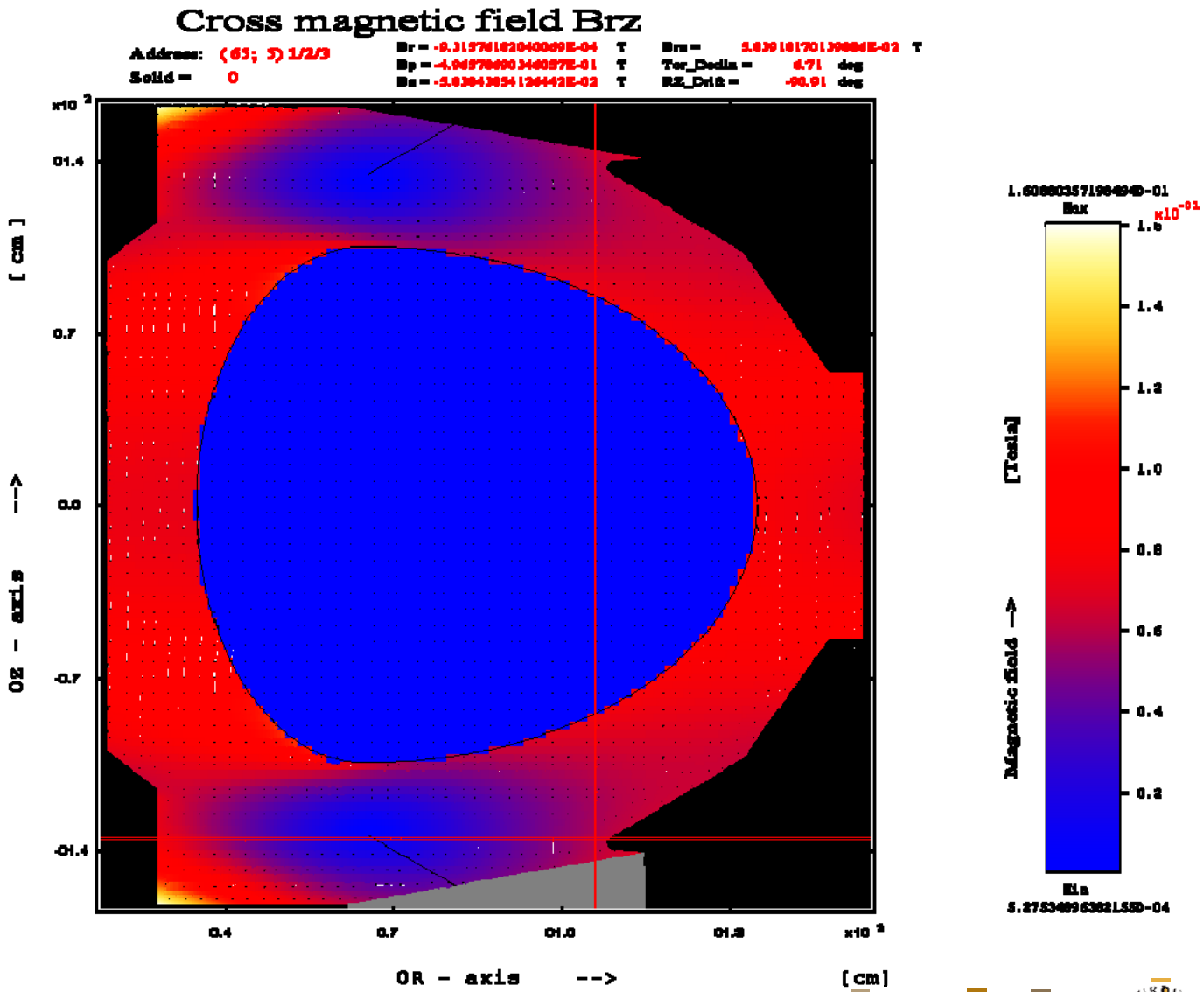



Magnetic field at strike point: B = 5 T
Sliding angle at strike point: $\alpha$ = 5 deg
Coils location:
R. Aymar, *Fusion Eng. Des.* **55** 107 (2001).

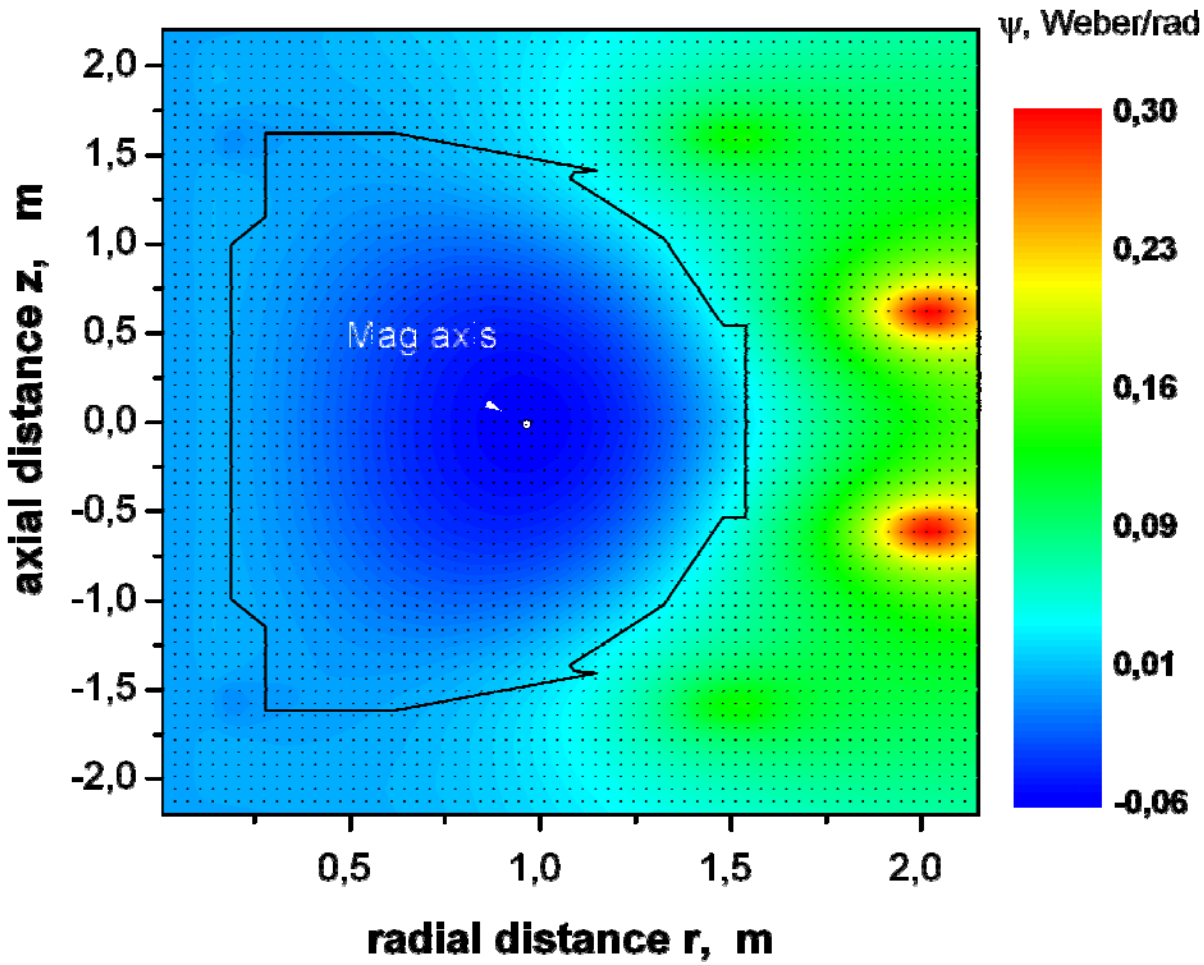
EQSDK files as the initial conditions source

# Magnetic Field Initialization (NSTX)

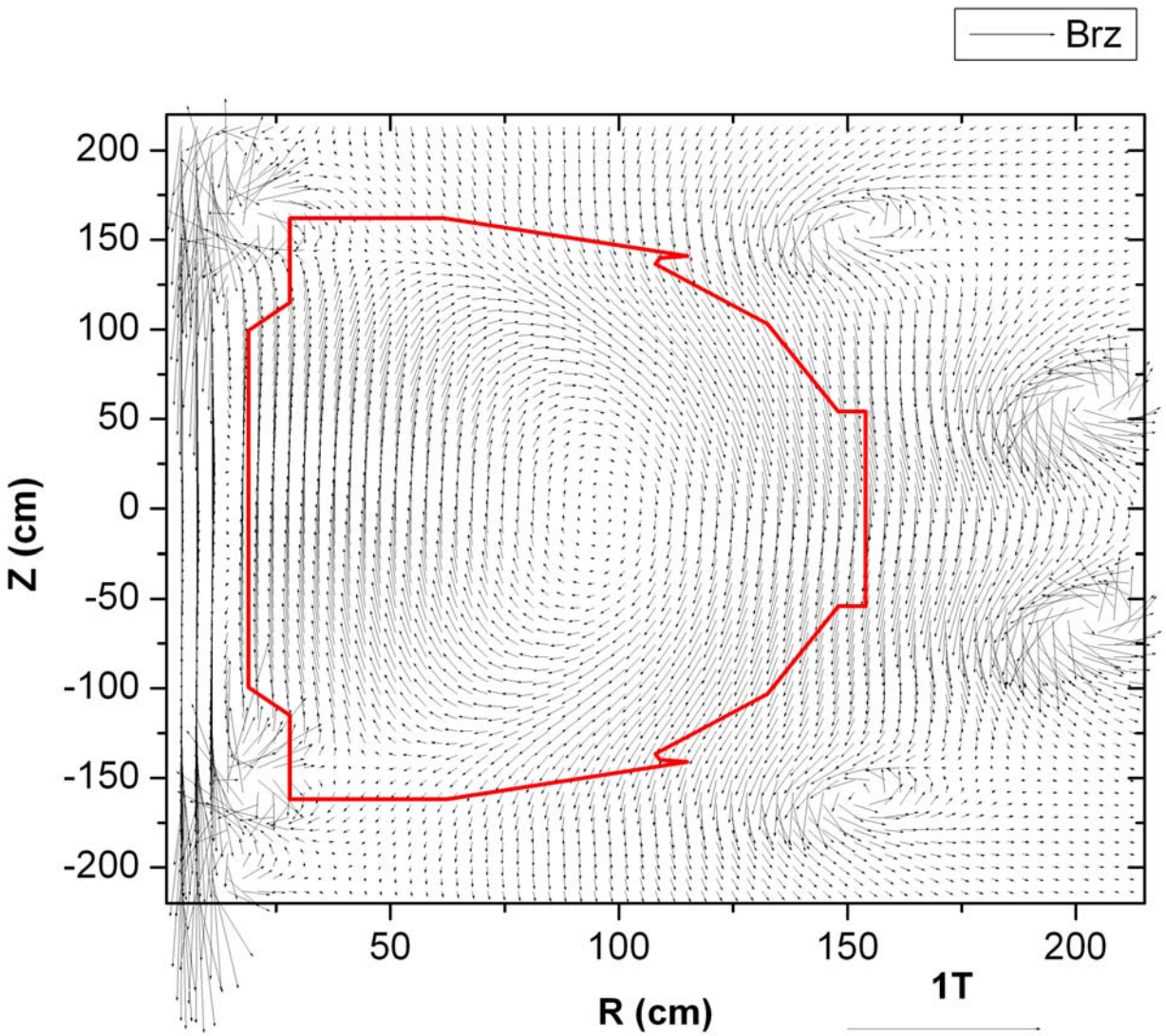


# Magnetic Field Initialization using EQDSK

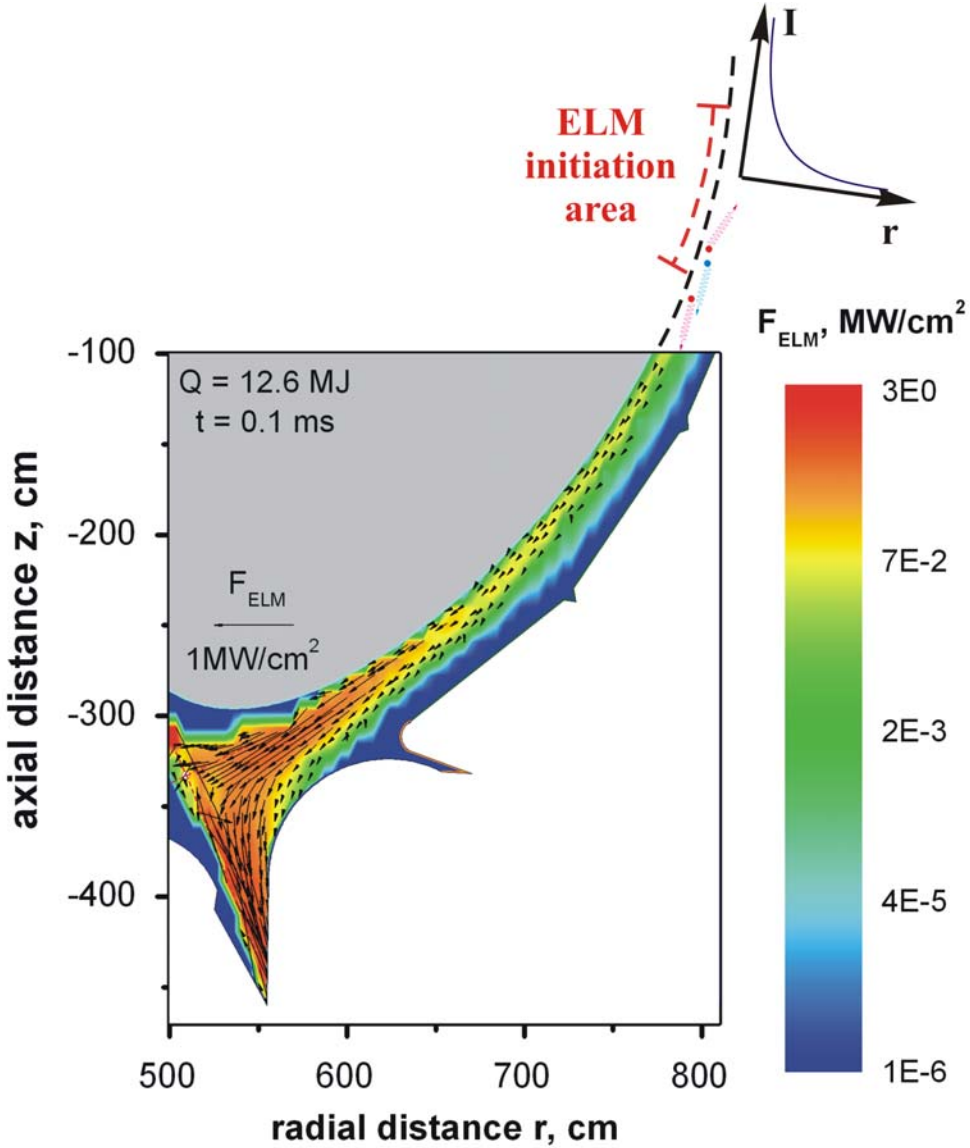
$$\vec{\mathbf{B}} = \frac{1}{r}\frac{\partial \Psi}{\partial z}\vec{i}_r + B_\varphi \vec{j}_\varphi - \frac{1}{r}\frac{\partial \Psi}{\partial r}\vec{k}_z$$



# Magnetic Field Initialization using EQDSK



# MC Simulation of Core Particles Escape



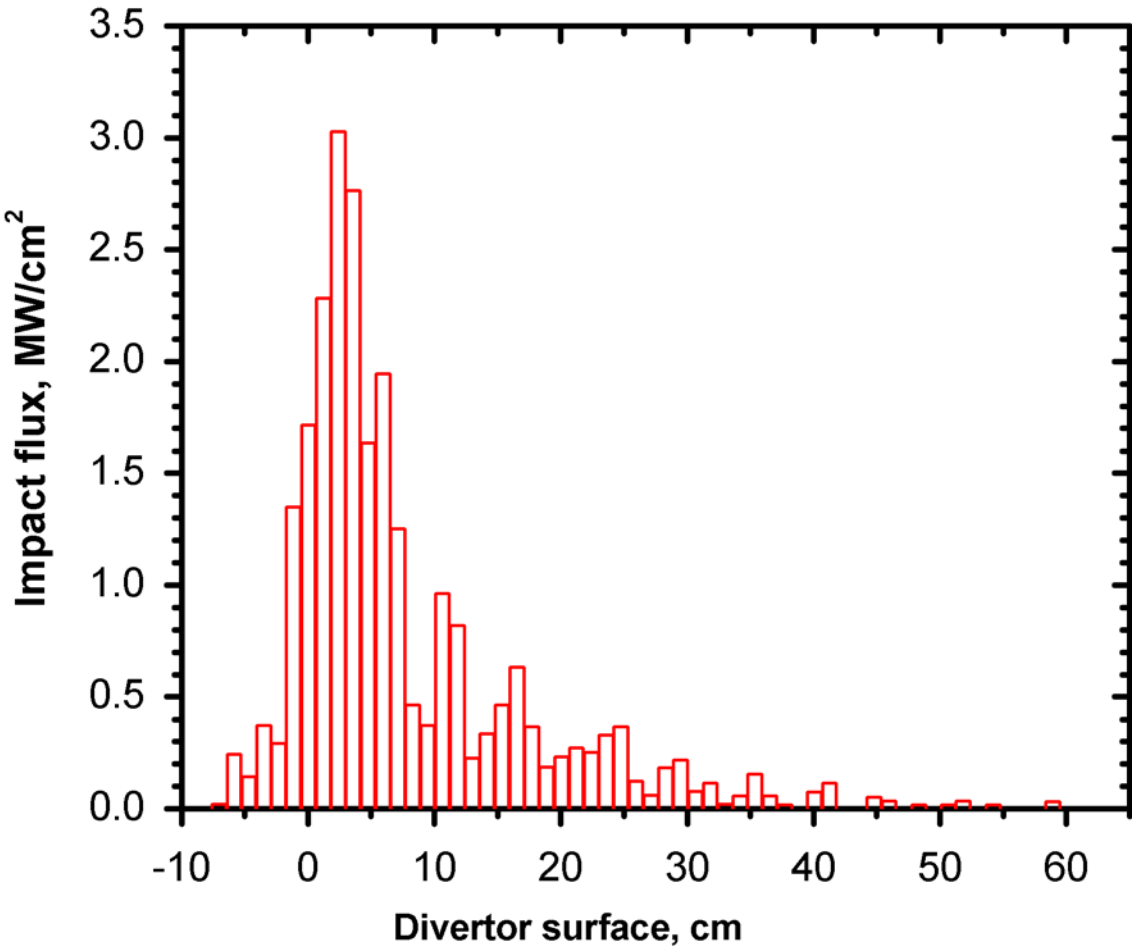

**Simulation provided for ITER ELM parameters:**

$Q_{ELM}$ = 12.6MJ
$t_{pulse}$ = 0.1 ms
$B_{strike\ oint}$ = 5.0 T
$\alpha_{sliding}$ = 5.0 deg

**ELM source:**
exponential distribution on r-axis, e-fold = 1.0 cm

- ❑ Accurate ELM and disruption modeling: distribution in space and time
- ❑ Actual device geometry
- ❑ Full 3D simulation
- ❑ Taking into account both magnetic and electric fields drifts

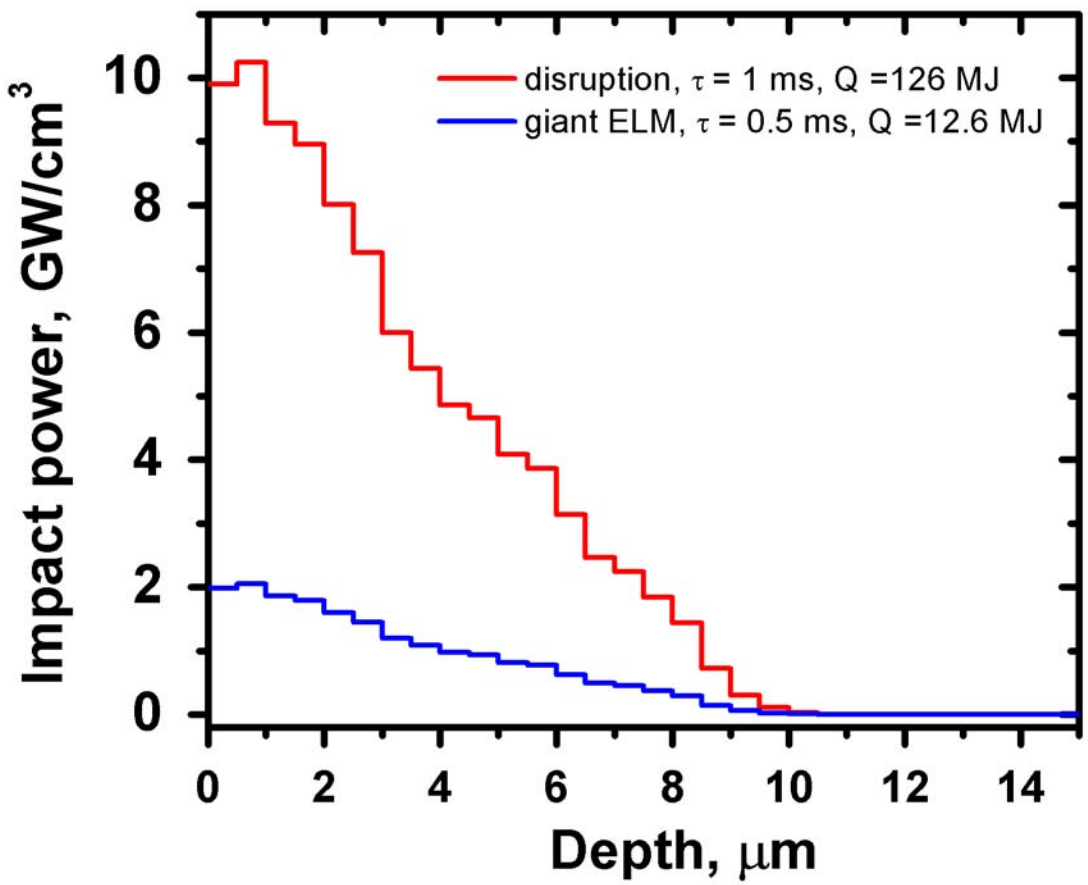
# Integrated Divertor ELM Flux (ITER)




- First calculation without plasma shielding of divertor heat flux
- Exponential surface profile
- In agreement with previous calculations of local geometry
- Maximum flux is slightly lower because part of escaped core particles returned to core due to drift!

Divertor flux profile was simulated for the ELM impact energy Q = 12.6 MJ by the pulse duration $\tau$ = 0.1 ms. The core border plasma temperature T = 3.5 keV. E-fold of initial space distribution of ELM particles at the core border $L_{ef}$ = 1.0 cm.

# Spatial Energy Deposition in Divertor (ITER)




- Maximal depth of the energy deposition is ~10 μm (for 3.5 keV plasma)
- For accurate heat load calculation, extra refinement scale should be ~ 0.5-1.0 μm
- In agreement with previous results of local calculation

Spatial energy deposition into carbon divertor at the strike point. Distributions are shown for disruption parameters (Q = 126 MJ, $\tau$ = 1 ms) and for ELM (Q = 12.6 MJ, $\tau$ = 0.1 ms). The impact plasma temperature T = 3.5 keV. Magnetic field B = 5.0 T, sliding angle at the strike point $\alpha$ = 5 deg.

# Summary and Conclusion

- HEIGHTS models and computer codes are revised and applied to plasma evolution modeling in ITER-like devices during the giant ELM and disruptions
- Physical and computational models are expanded to describe evolution of edge plasma in entire SOL area
- Unstructured mesh with adaptive refinement was incorporated into HEIGHTS to achieve higher accuracy with reasonable computational time
- The implemented mesh has five layers of cell sizes and logical block for the device geometry adaptive refinement. Extra refinement (~ 0.5 μm) is applied to surface cells to provide sufficient accuracy of surface erosion and evolution

# Summary and Conclusion (Cont.)

- Both mathematical models and HEIGHTS package structure have parallel implementation.
- The new developed gyrokinetic block allows simulating particles escape from core plasma via generation of initial particles at core border section. Influence of radial electric field on generated particles motion is taken into account
- We simulated ELM and disruption plasma incident fluxes using ITER actual geometry and predicted initial impact parameters. The simulated results are in good agreement with our previous localized calculations
- Now new HEIGHTS is ready for full integrated simulation of transient events in full 3D and for realistic reactor geometry!