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Presentation of SMITER

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Introduction

SMITER code package[1]:

- **graphical user interface (GUI) framework**
  - for power deposition mapping on tokamak plasma-facing components (PFC) in the full 3-D CAD geometry of the machine
  - Thermal modelling (based on Elmer Fem code, in progress)
  - Ray-tracing (based on Raysect code, in progress)
- The software package provides CAD model, CAD de-featuring for PFC surface ex-traction, meshing utilities, visualization (using an integrated ParaView module), Python scripting and batch processing, storage in hierarchical data files.

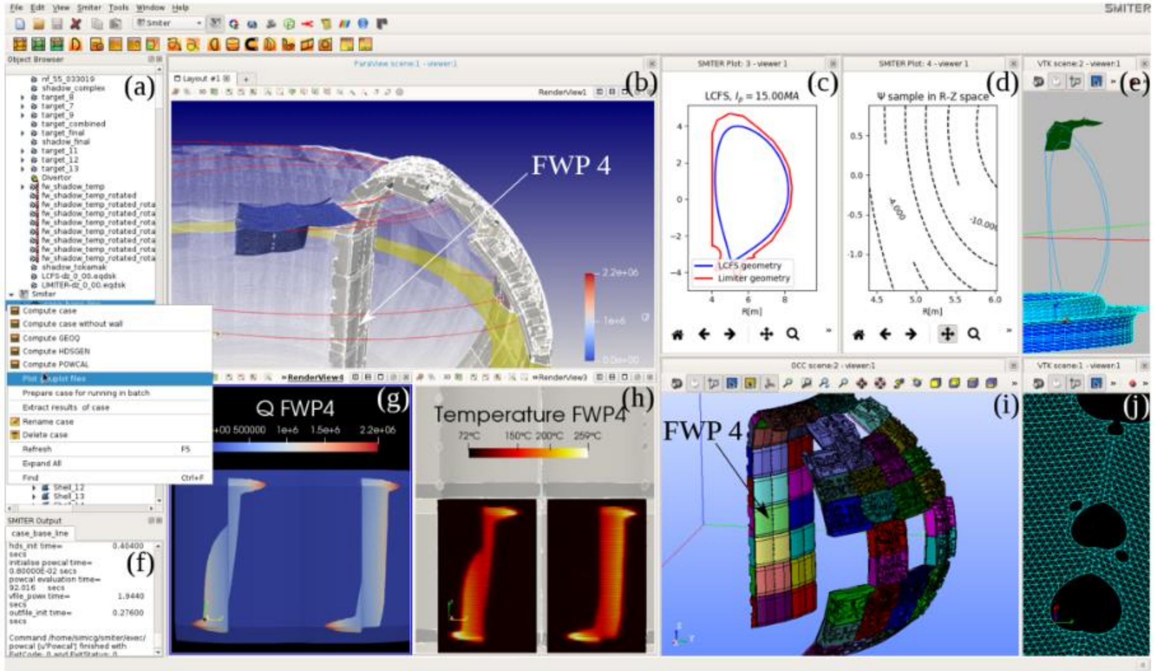


Figure 1: Illustration of the SMITER graphical user interface for ITER [1]. The code allows several run-cases in one study (a) to be run (f) in parallel on a compute cluster. ParaView window (b) shows resulting target top panels (blue), selected characteristic field lines (red), omp disk (yellow), a complete blanket sector CAD model from the Geometry module and a shadow mesh from the Meshing module (grey) augmented for an overall evaluation of run-case setup. The magnetic equilibrium with LCFS and Limiter/Wall geometry (c) and other details can be further analyzed with built-in 2D and 3D plots such as flux function detail (d). Triangular meshes (j) are the main run-case geometry setup (e) that are directly imported or meshed from CAD models (i) defeatured to retain only the required PFC surfaces for meshing with different algorithms and hypotheses. Resulting heat fluxes (g) on the ITER first wall panel number 4 (FWP4) can be further processed to get temperatures (h) using FEM thermal models of normal heat flux (NHF) or enhanced heat flux (EHF) cooling sub-structures.

[1] L. Kos et al, SMITER: A field-line tracing environment for ITER, Fusion Engineering and Design, Volume 146, Part B, 2019,

LeCAD

Design of First Wall Panels

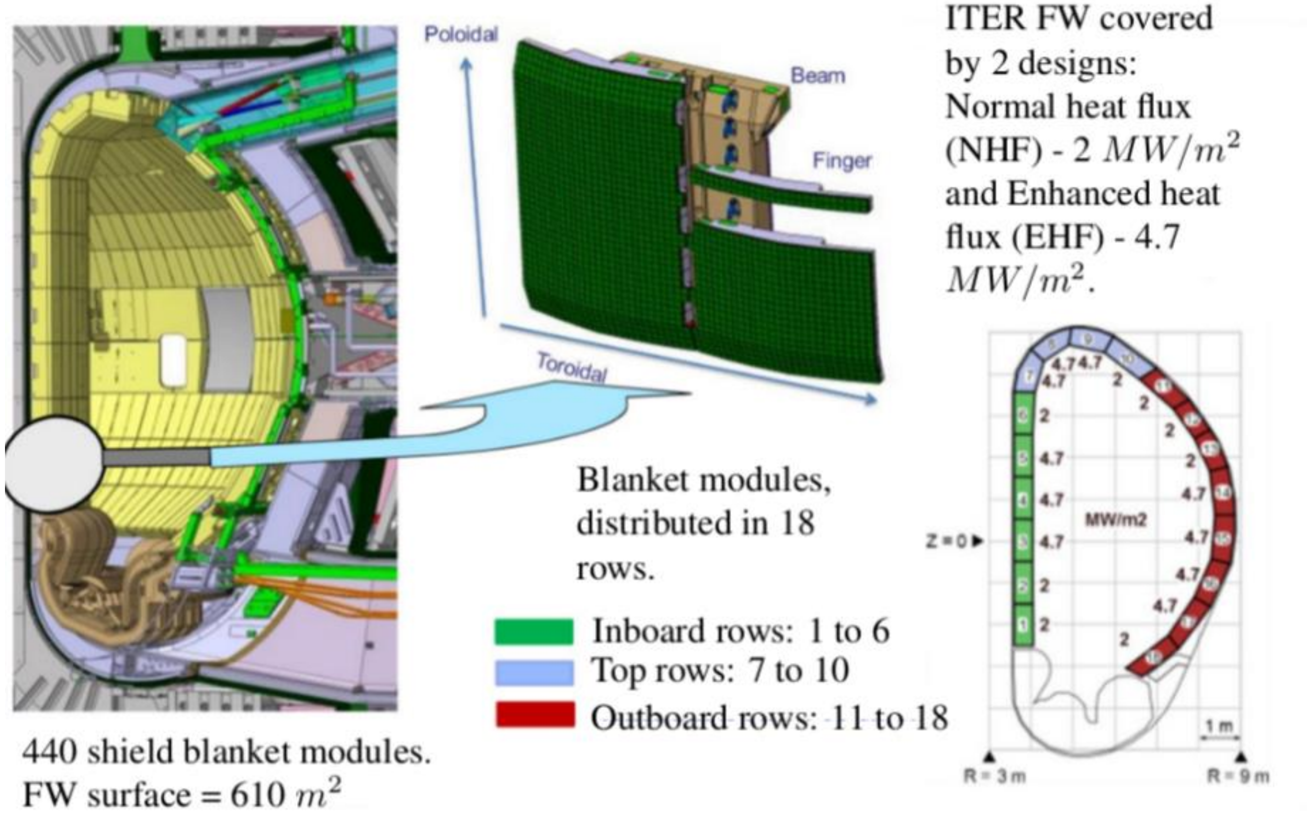
ITER panels are the main contributor in providing neutron shielding for the superconduction coils and vessel structure. Plasma facing surface is made towards minimizing the plasma contamination.

Main components:

- Strong steel beam, oriented in the
- poloidal direction
- Elongated plasma facing units
- called fingers

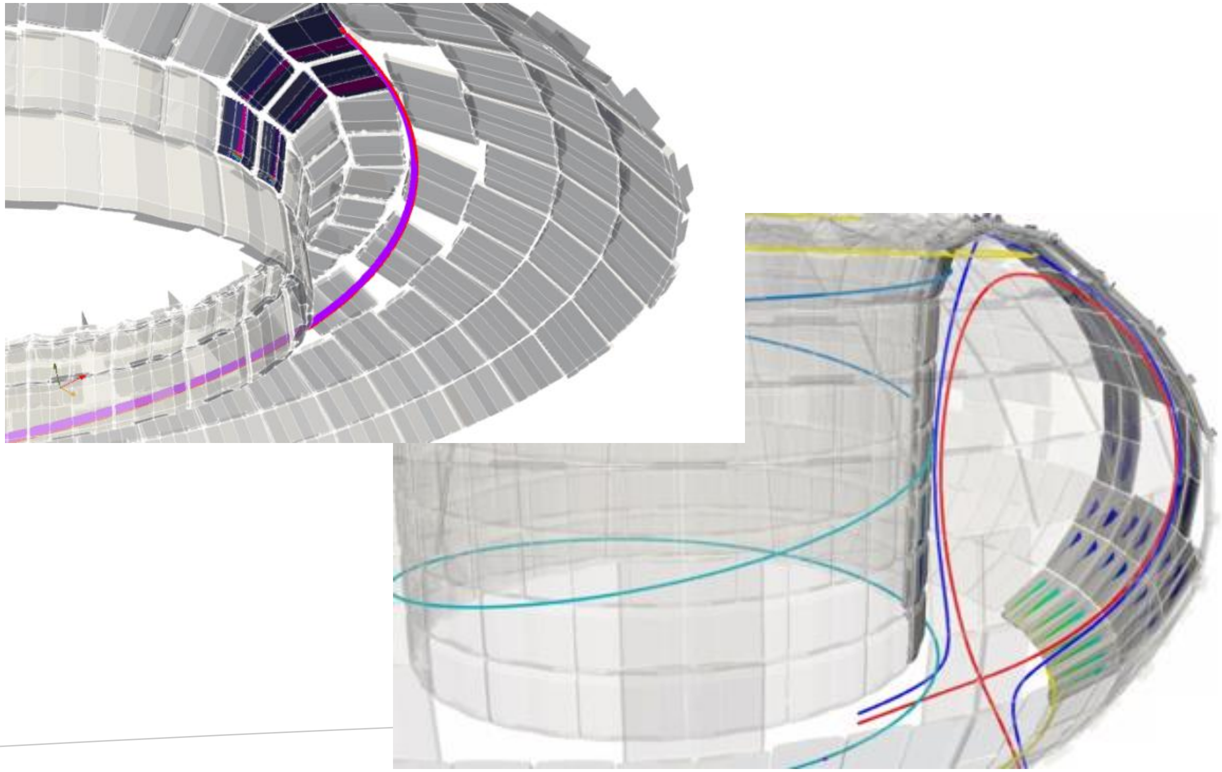
Two types of panels:

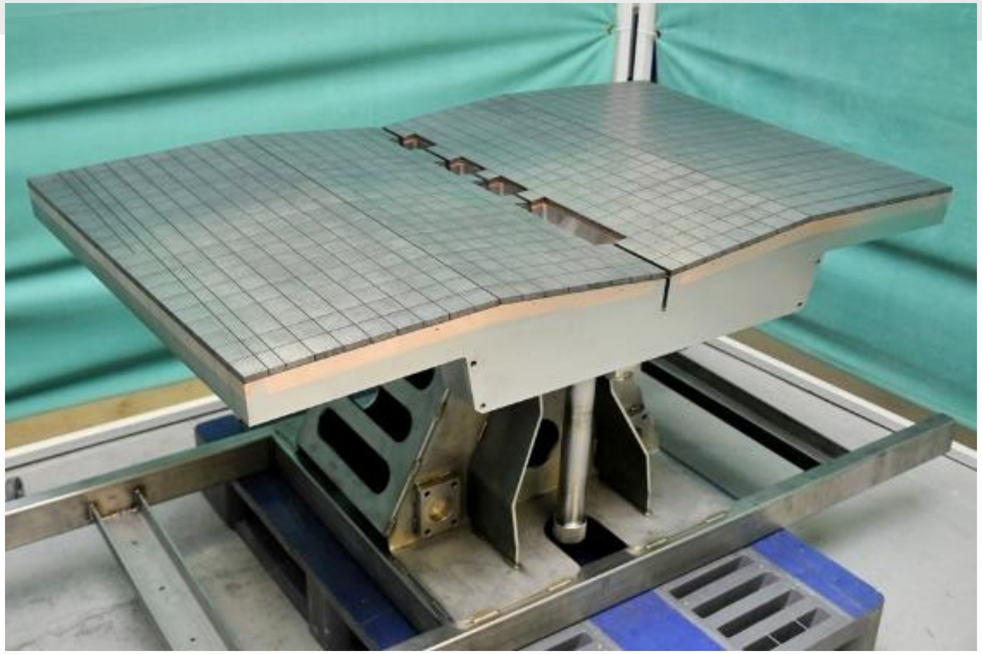
- Enhanced heat flux panel
- Normal heat flux panel



To “bridge the gap” between physics and engineering

- What engineers needs to know: total powers/stored energies (MW, MJ), maximum peak in MJ/m^2 or MW/m^2, 3D distributions on surfaces, etc.
  → Field Line Tracing (FLT) analysis: SMITER code package in use at IO





Normal Heat Flux (NHF) full-scale prototype for the final First Wall (Be armor here) produced by Atmostat-Alsyom for Fusion for Energy (F4E)

G. Simic, 30th IEEE Symposium on Fusion Engineering, 2023

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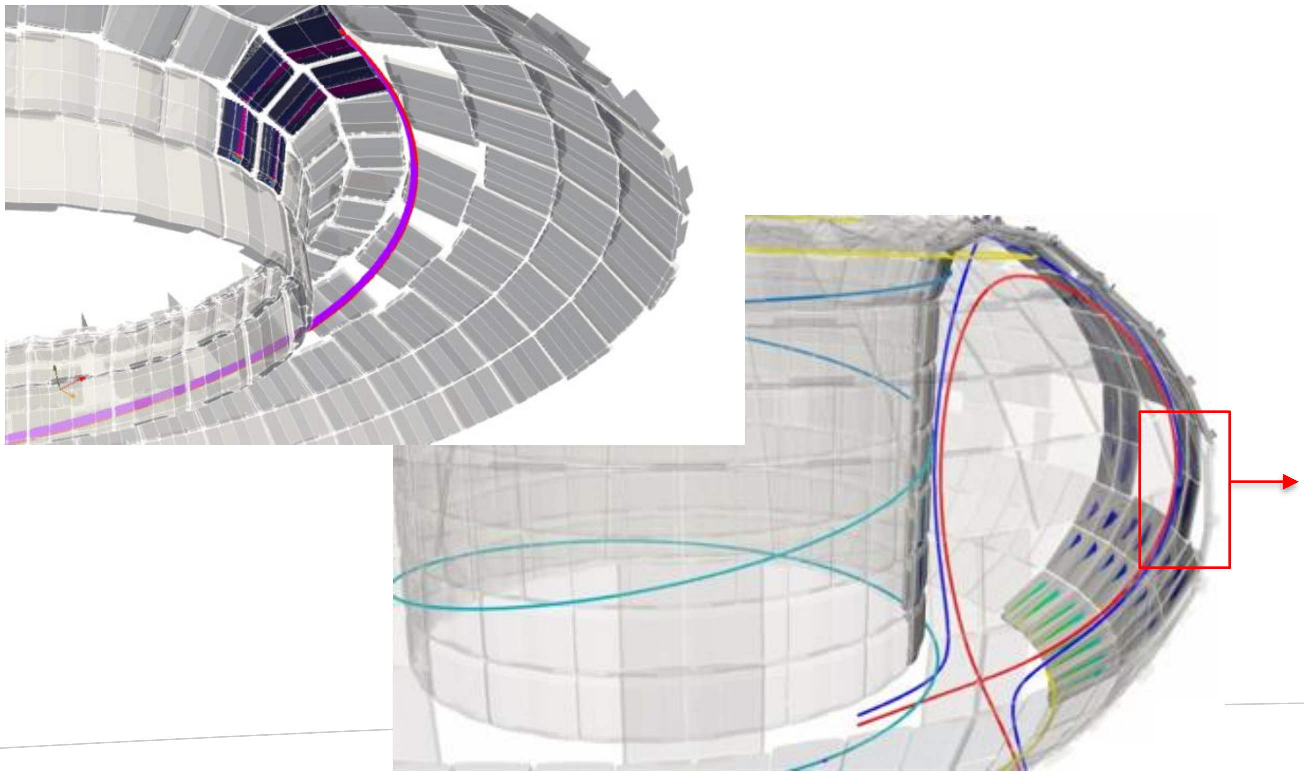
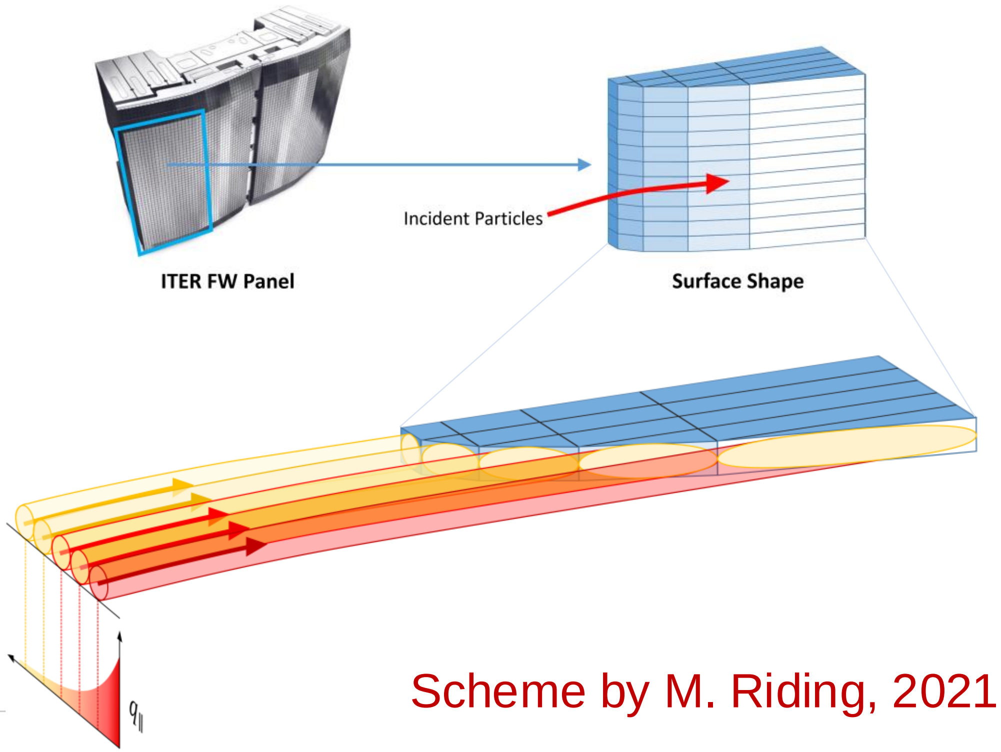


G. Simic, 30th IEEE Symposium on Fusion Engineering, 2023



Scheme by M. Riding, 2021

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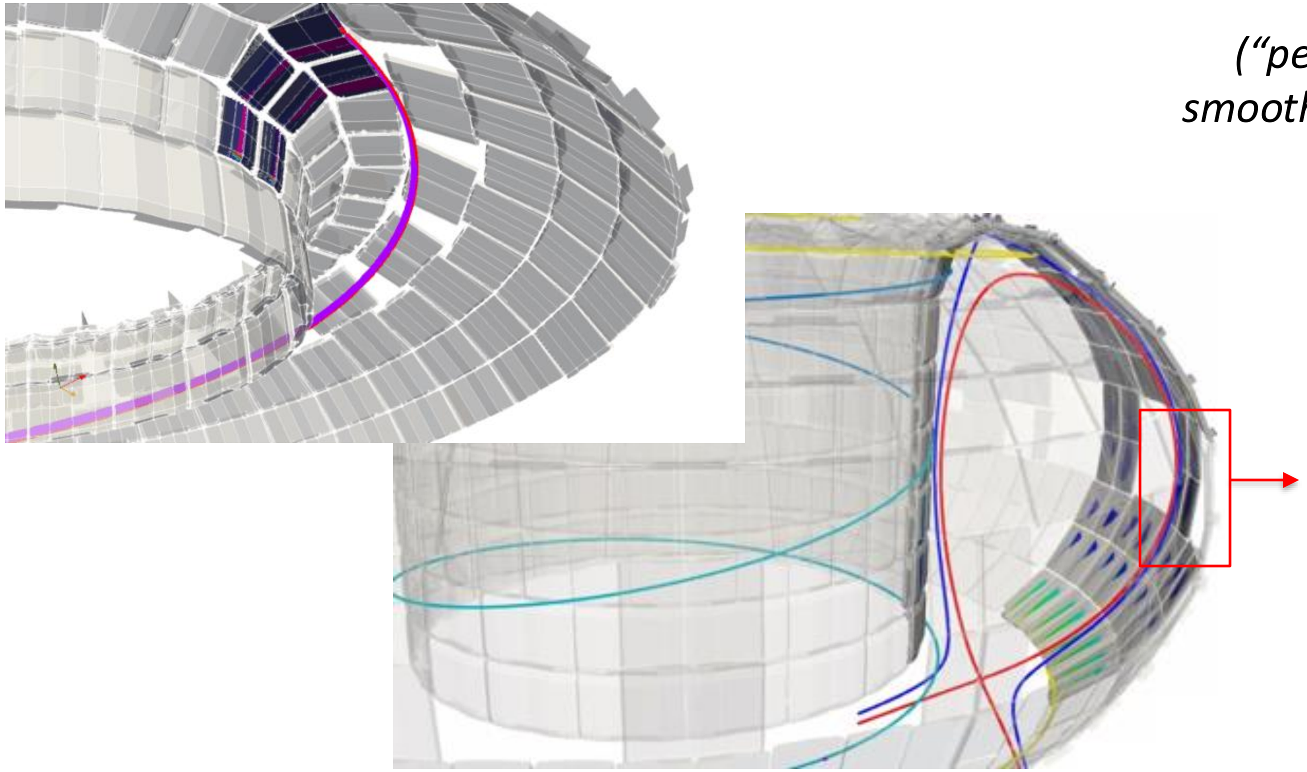
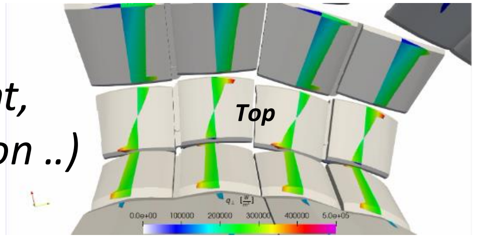
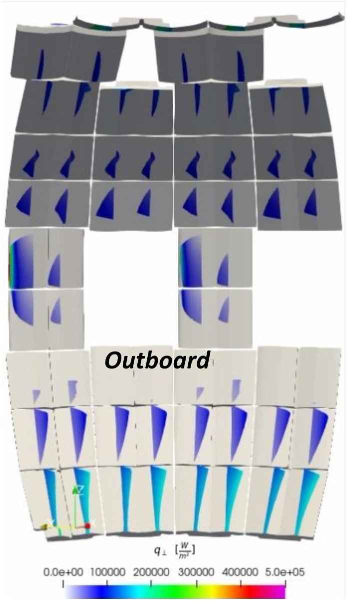


G. Simic, 30th IEEE Symposium on Fusion Engineering, 2023

Example of FLT results
(“perfect” situation: no misalignment, smooth shape - no radiation contribution ..)

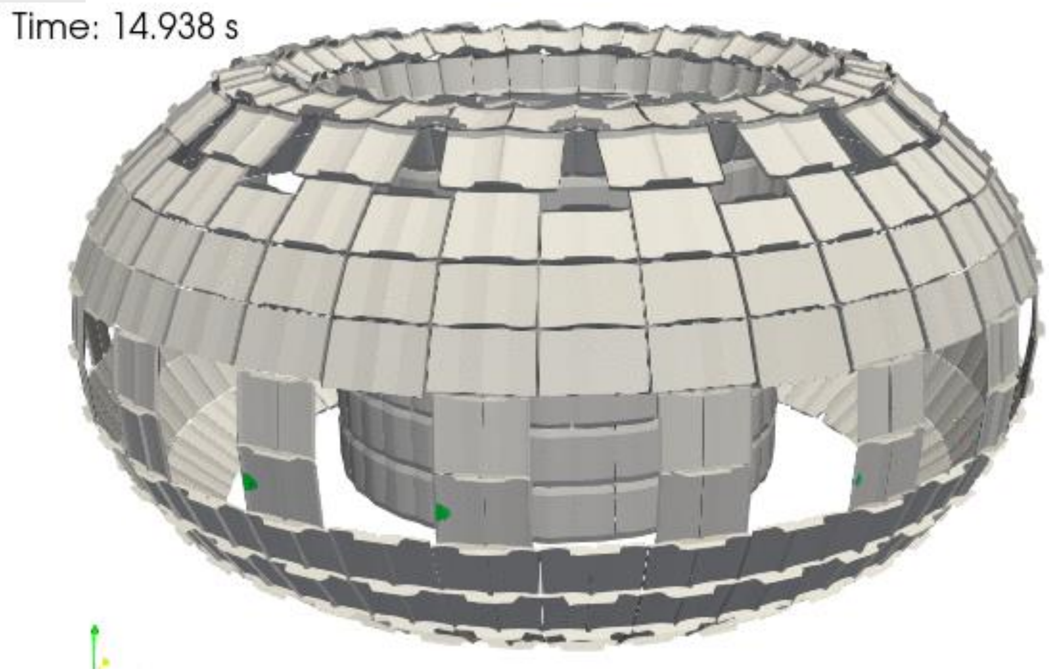




G. Simic, 2024

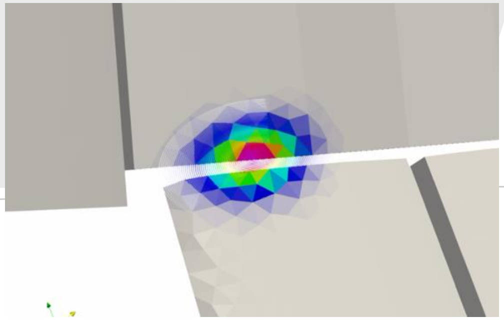
ECRH losses to FWs as design driver too?

- Upgrade EC heating systems for SRO and DT phases:
  - Diffused stray radiation generally lower than $P_{radiation\text{-}W}$ → neglected
  - EC losses from reflections due to cross-polarization, or Shinethrough with multiple reflections → detailed assessment on-going:
    - Workflow: DINA → TORBEAM → SMITER
    - ECRH loading during S-Up assistance (shinethrough at lower plasma density)
    - EC to non protected areas



EC heat loads mapping to ITER FW loads using SMITER (for illustration: W absorption coefficient or multiple reflections not yet allowed for)

G. Simic, 2024 (see also M. Schneider and M. Preynas, contributions to EC Workshop 2024)



Meshing of CAD model

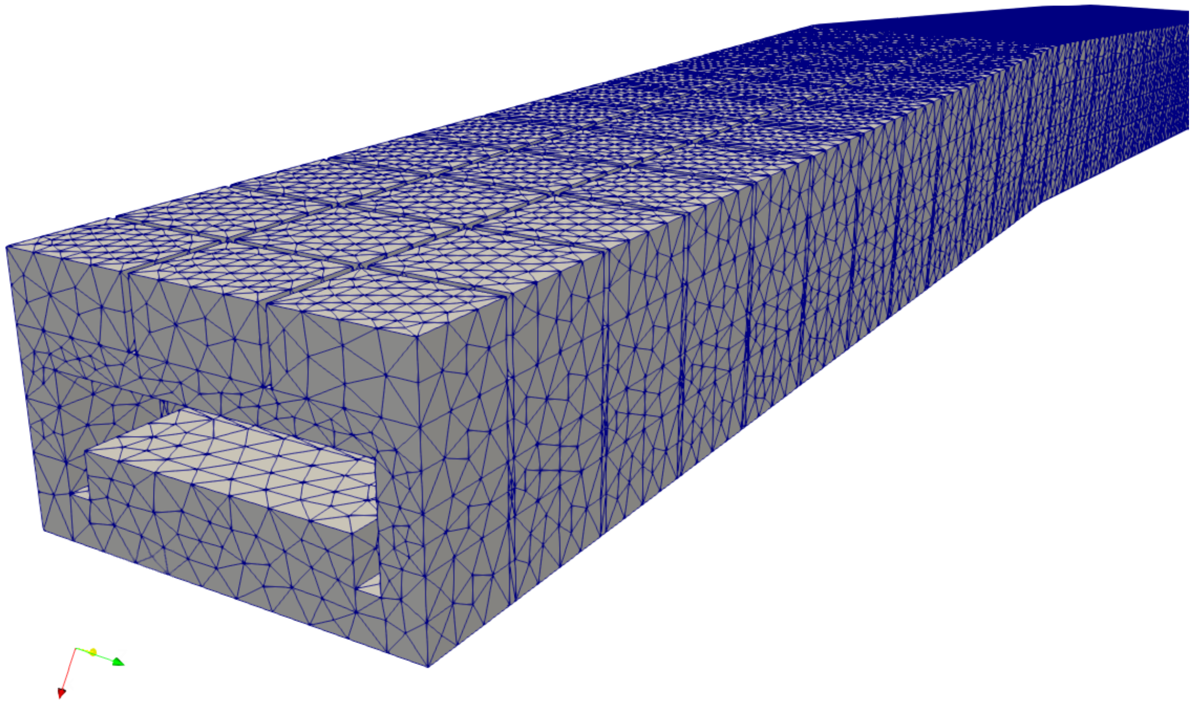
Meshing is done in Mesh module of SMITER environment. Meshes are created from geometrical models or imported CAD models, using mesh edition operations, especially extrusion and revolution and by generation of the 3D mesh from the 2D mesh.

Features:

- Creation of mesh groups, used for material property or boundary condition definition
- Export to other formats

Difficulties:

- Increased mesh density due to
- CAD model complexity -> longer
- computational time
- Unstructured grid



Mapping of Power Deposition

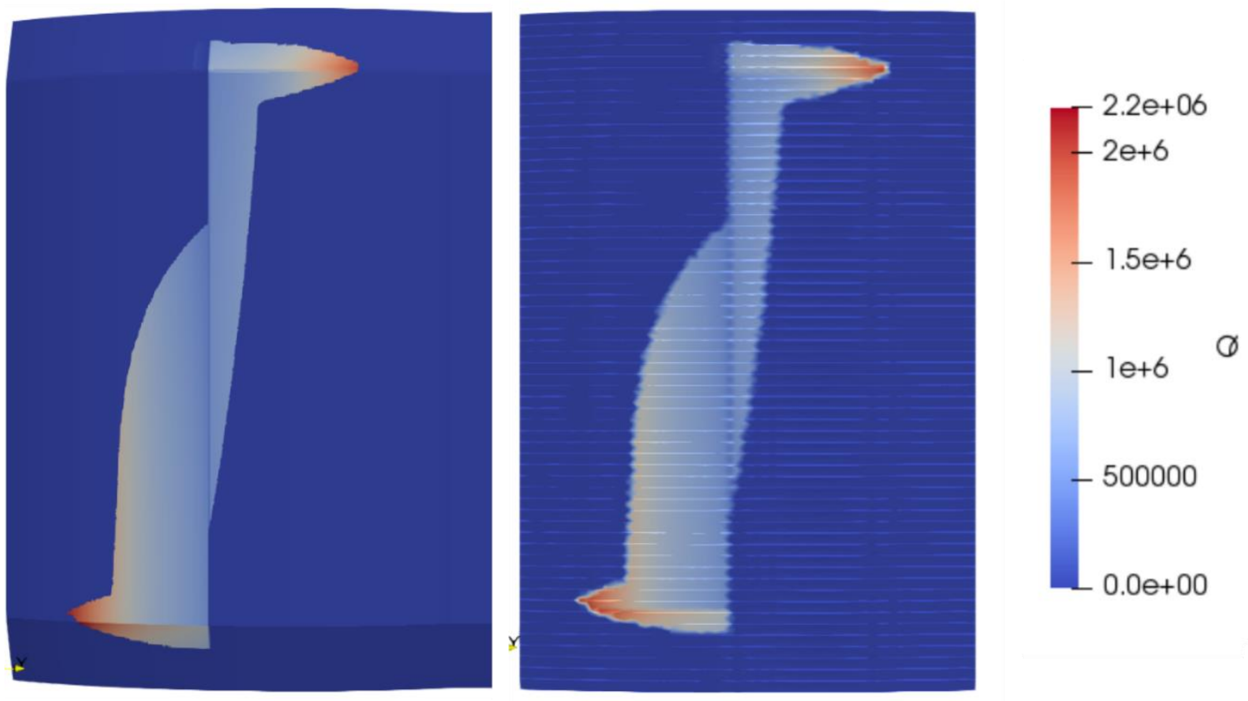
The mapping function used is based on radial basis function. Mapping is done on point cloud of heat fluxes, computed by SMITER.

Features:

- Accurate representation of heat fluxes
- Mapping is done separately fo every finger instead of applying mapping function to the whole panel

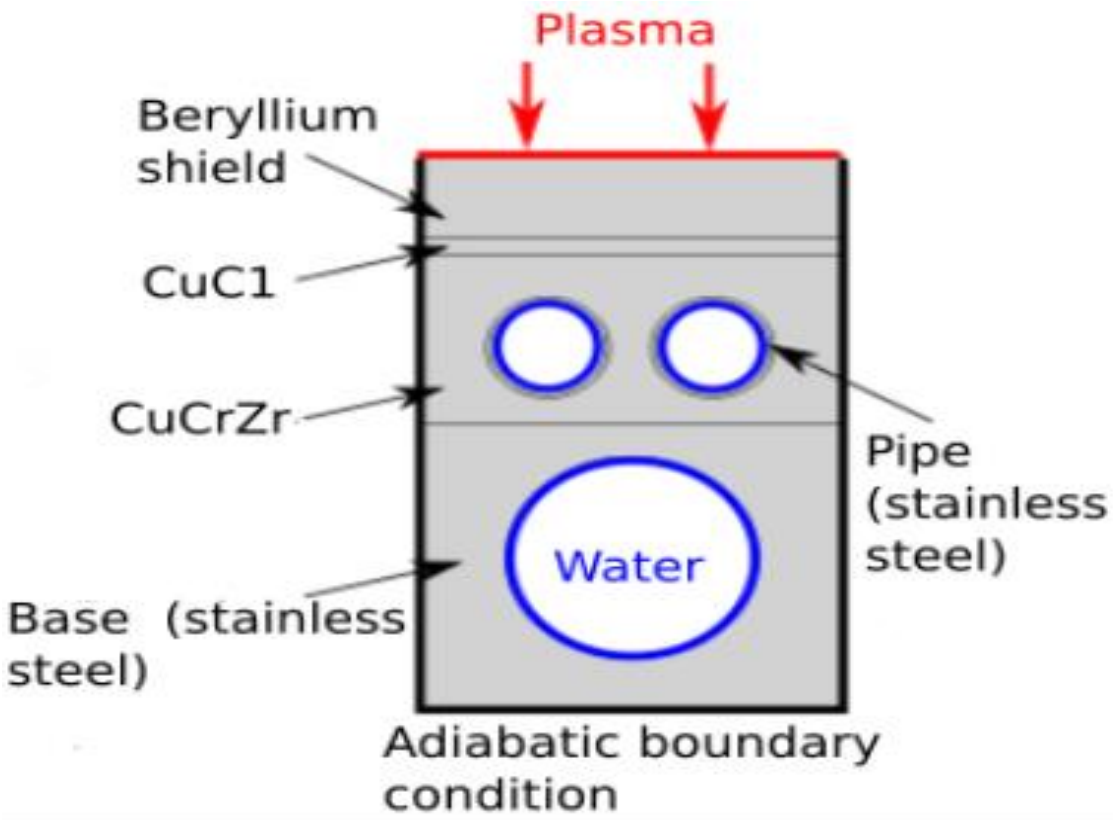
Difficulties:

- Memory consuming method



Thermal Model

Fourier's law is used to model the heat conduction. The differential form of Fourier's law of thermal conduction shows that the local heat flux density is equal to the product of thermal conductivity and the negative local temperature gradient.



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SMITER workflow

- Inputs
  - Magnetic equilibrium from simulation or experiment
  - CAD surfaces (STEP) or 3D triangular meshes (NASTRAN)
  - Heat flux profile
- Shadowing and heat flux calculations on 3D surfaces
  - Particles are following magnetic field lines
  - Shadowing by neighboring structures
- Outputs
  - Shadowing and wetted areas
  - Heat flux and incident angles
  - Thermal model (in development)

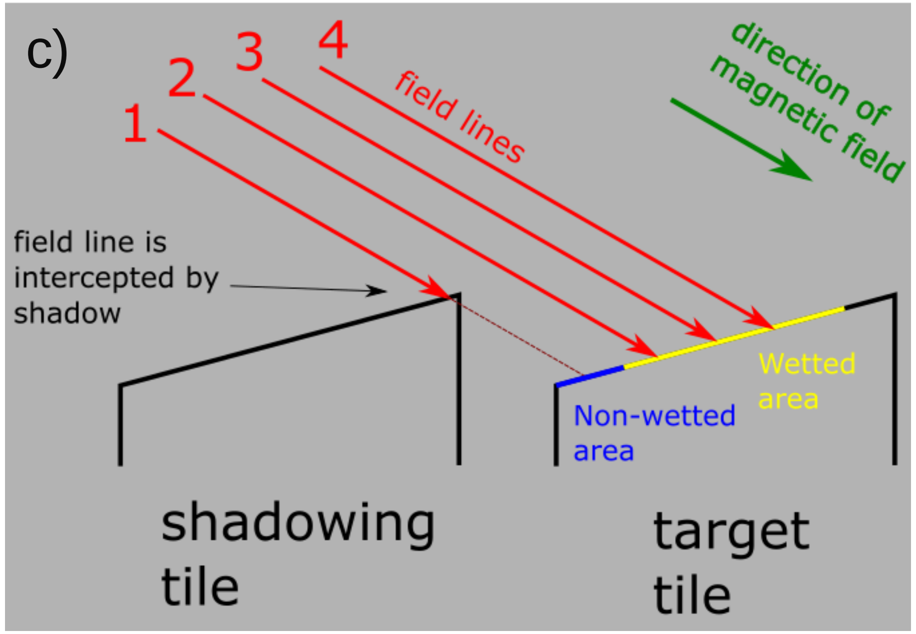
LeCAD

FLT procedure

Based on particle tracing through magnetic field

- For a given magnetic equilibrium, movement of particles is traced through magnetic field
- The result of such trace is a **field line**:
  - A line that represents particle path through magnetic field inside tokamak
- Main goal is to determine whether a field line intersects individual sections of plasma facing components
- Due to shaping of PFC tiles, field lines intersect some PFC surfaces but not all:
  - Wetted area -> area hit by field lines
  - Non-wetted area -> area not hit by field lines

Figure 1: (a) Basic presentation of field line interception. Note that field line 1 is intercepted by neighbouring shadowing tile, thus the corresponding blue area on target tile is non wetted. Meanwhile yellow area receives field lines and is thus considered wetted.



FLT procedure

Based on particle tracing through magnetic field

In terms of magnetic flux Ψ, the magnetic field components in cylindrical polars are

$$B_R = -\frac{1}{R}\frac{\partial\Psi}{\partial Z}$$
$$B_T = -\frac{I}{R}$$
$$B_Z = \frac{1}{R}\frac{\partial\Psi}{\partial R}$$

The standard field-line equation is given as

$$\dot{x} = \frac{dx}{dt} = B(x)$$

Here dot denotes differentiation with respect to pseudo-time t measured along the field line. The equation is solved using Runge-Kutta schemes (RK2 or RK-Fehlberg scheme) with step adaptation by the Cash-Karp algorithms [1].

[1] L. Shampine and H. Watts, "The art of writing a Runge-Kutta code. II." Applied Mathematics and Computation, vol. 5, no. 2, pp. 93–121, 1979.
[2] L. Kos et al, SMITER: A field-line tracing environment for ITER, Fusion Engineering and Design, Volume 146, Part B, 2019,

Stationary profile

- The calculation of parallel heat flux comes from the knowledge of the power partition in SOL which is the problem of physics and is an ongoing field of research. Multiple models exist, such as Eich model, double exponential and single exponential decay. Assuming single exponential decay loss across the SOL, starting from the first separatrix (diverted configuration) or last closed flux surface (limiter configuration), the parallel heat flux is defined as [2]

$$q_{||s}(r) = q_{||,omp} \exp\left(-\frac{R - R_m}{\lambda_m}\right) \qquad (1)$$

- Parameters in eq. 1 are:
  - SOL decay length $\lambda_m [m]$
  - Parallel heat flux at midplane $q_{||,omp} [W/m^2]$

Radial distance from the separatrix can be expressed as

$$R - R_m = \frac{\Psi - \Psi_m}{R_m B_{pm}} \qquad (2)$$

Thermal modelling of FWPs

$$q = -k\nabla T$$

Where
- q … heat flux $[W/m^2]$
- k … heat conductivity $[W/mK]$
- ∇T … temperature gradient $[K/m]$

Use of finite element method to solve the problem.

The goal is to obtain surface temperatures to be used in modelling the reflectivity for all PFCs:
- Divertor targets (monoblocks)
- Enhanced heat flux panel (4.7 MW/m^2)
- Normal heat flux panel (2 MW/m^2)

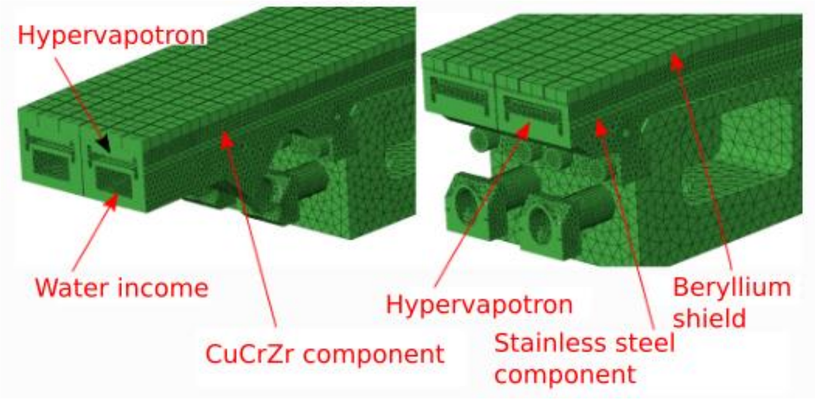


Figure 1: EHF panel: hypervapotron cross-section.

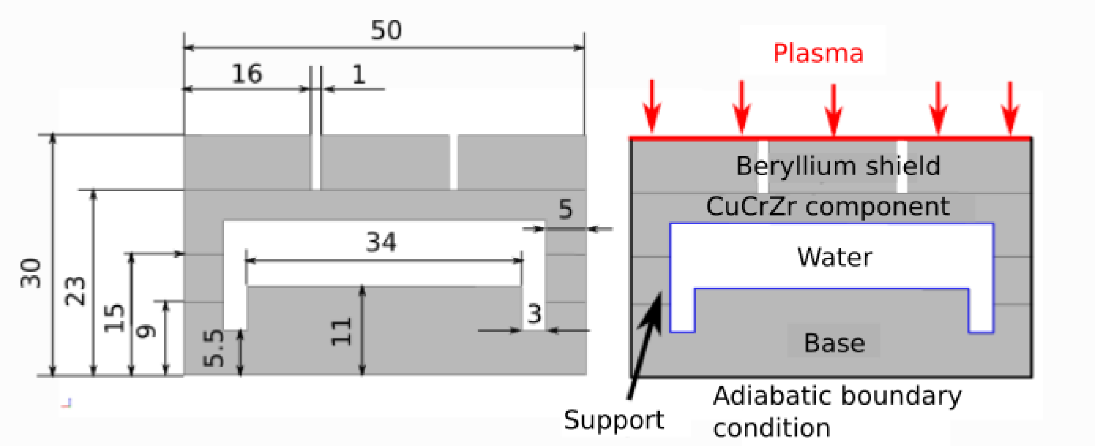


Figure 2: Simplified thermal model of hypervapotron.

Raysect interface

Calculation of radiative heat loads on target based on JINTRAC simulation profiles

- Definition of geometry
- Definition of material properties
- Plasma profile definition

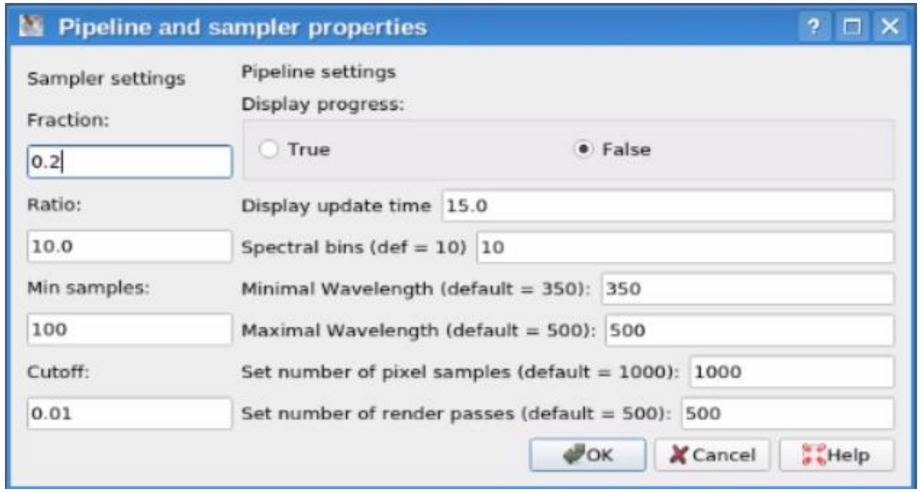


Figure 1: Interface for pipeline definition.

Ray tracing governing equation

$$P_i = \int_{A_i} \int_{\Omega} L_i\,(r,\omega) \cos\theta \; d\omega dr$$

P_i… total power measured by observing surface

$L_i(r,\omega)$… incident radiance measured at a point r and angle ω on the surface

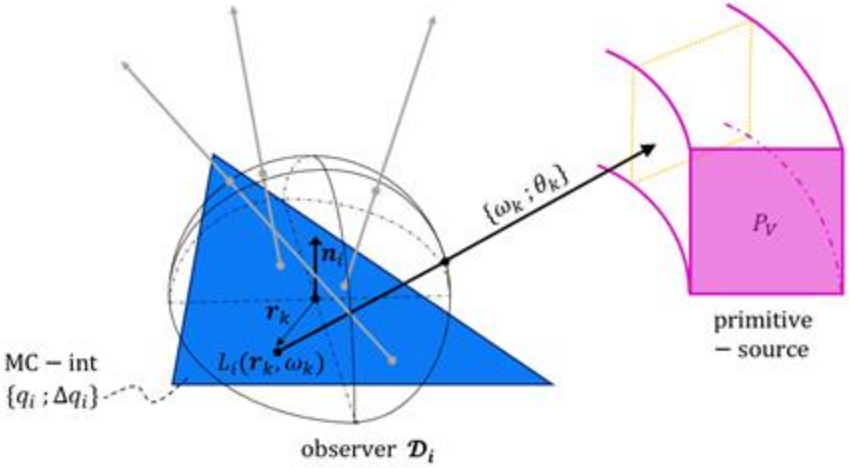
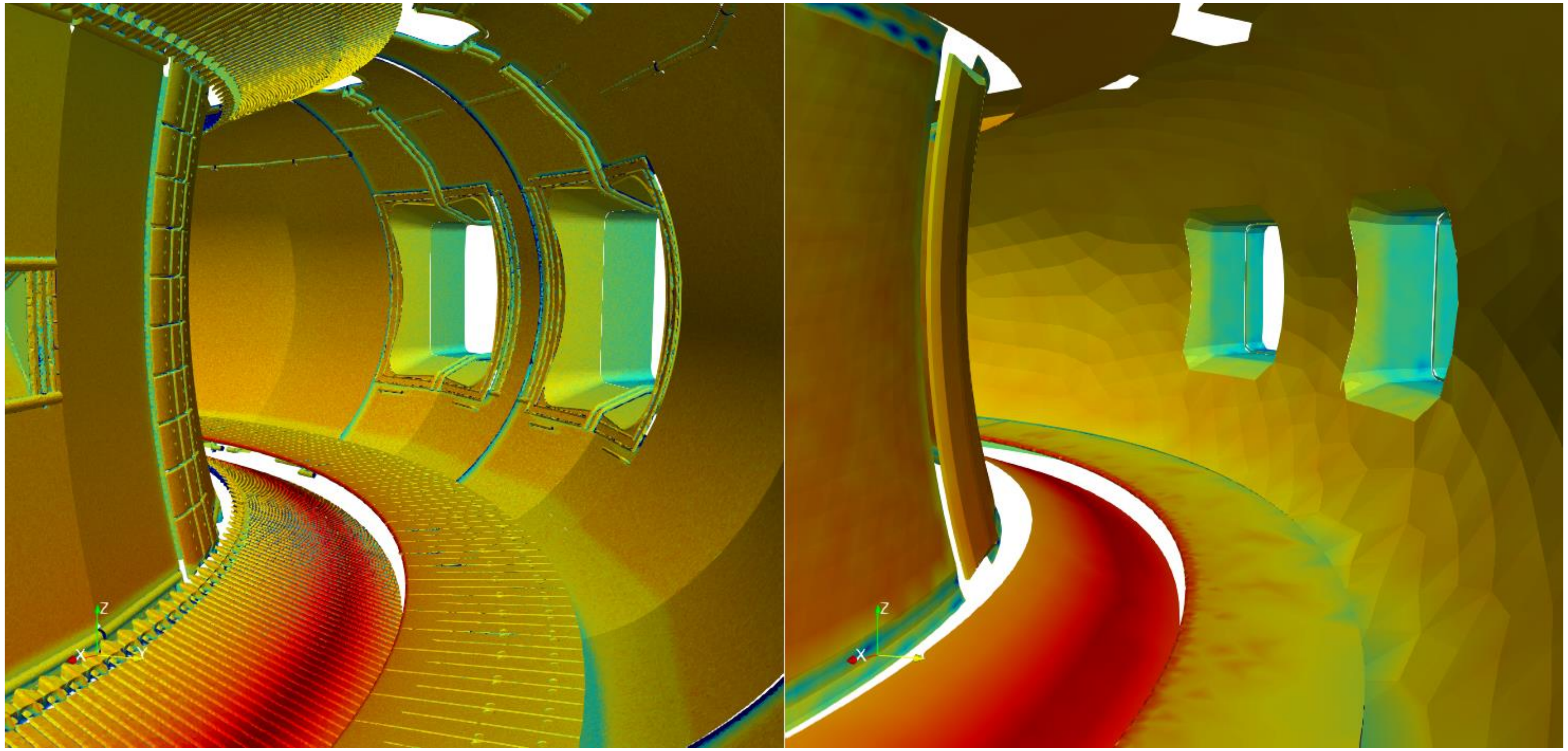
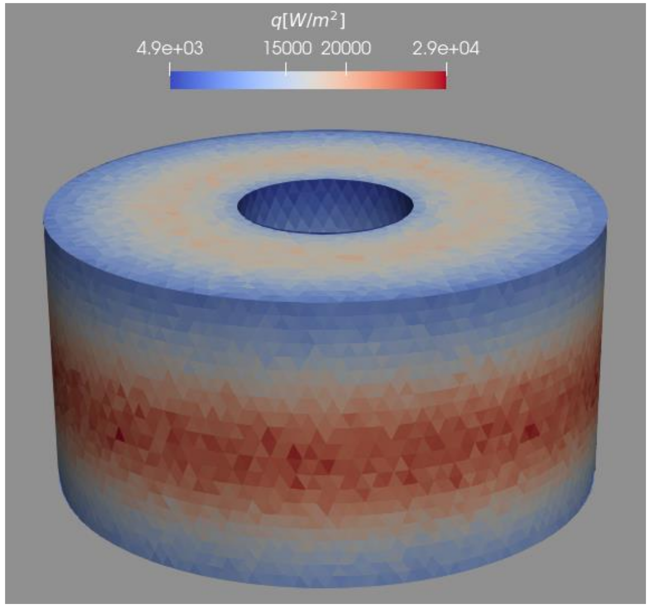


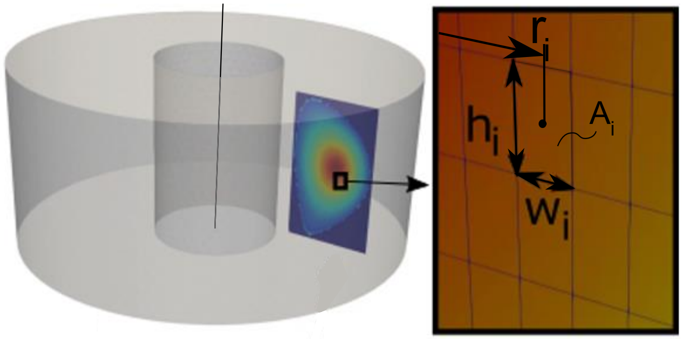
Figure 1: Basic scheme of ray-tracing [1].

[1] M. Moscheni et al., Radiative heat load distribution on the EU-DEMO first wall due to mitigated disruptions, Nuclear Materials and Energy, Volume 25, 2020,

SPEOS vs Raysect







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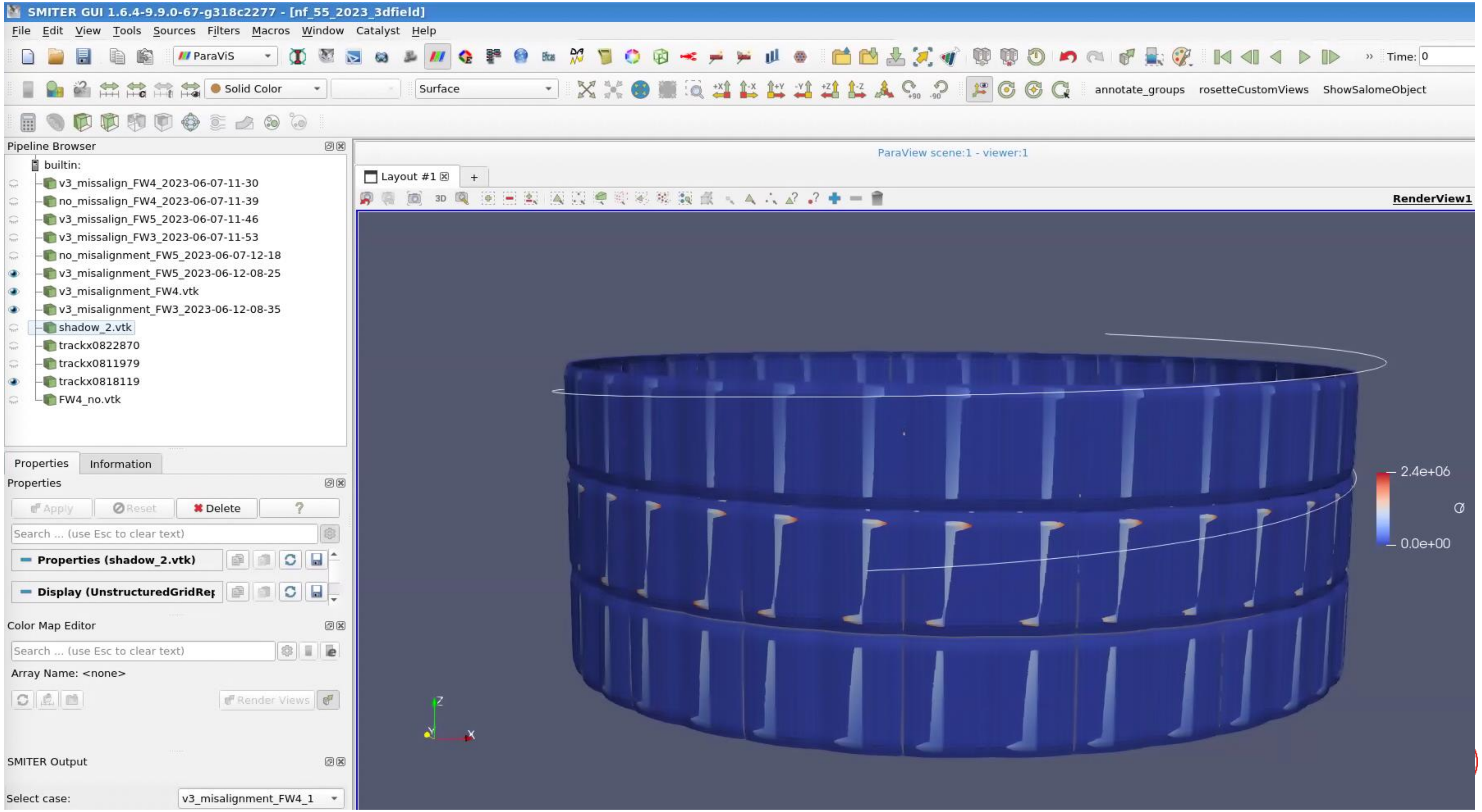
Misalignment ITER based on data from DINA simulations



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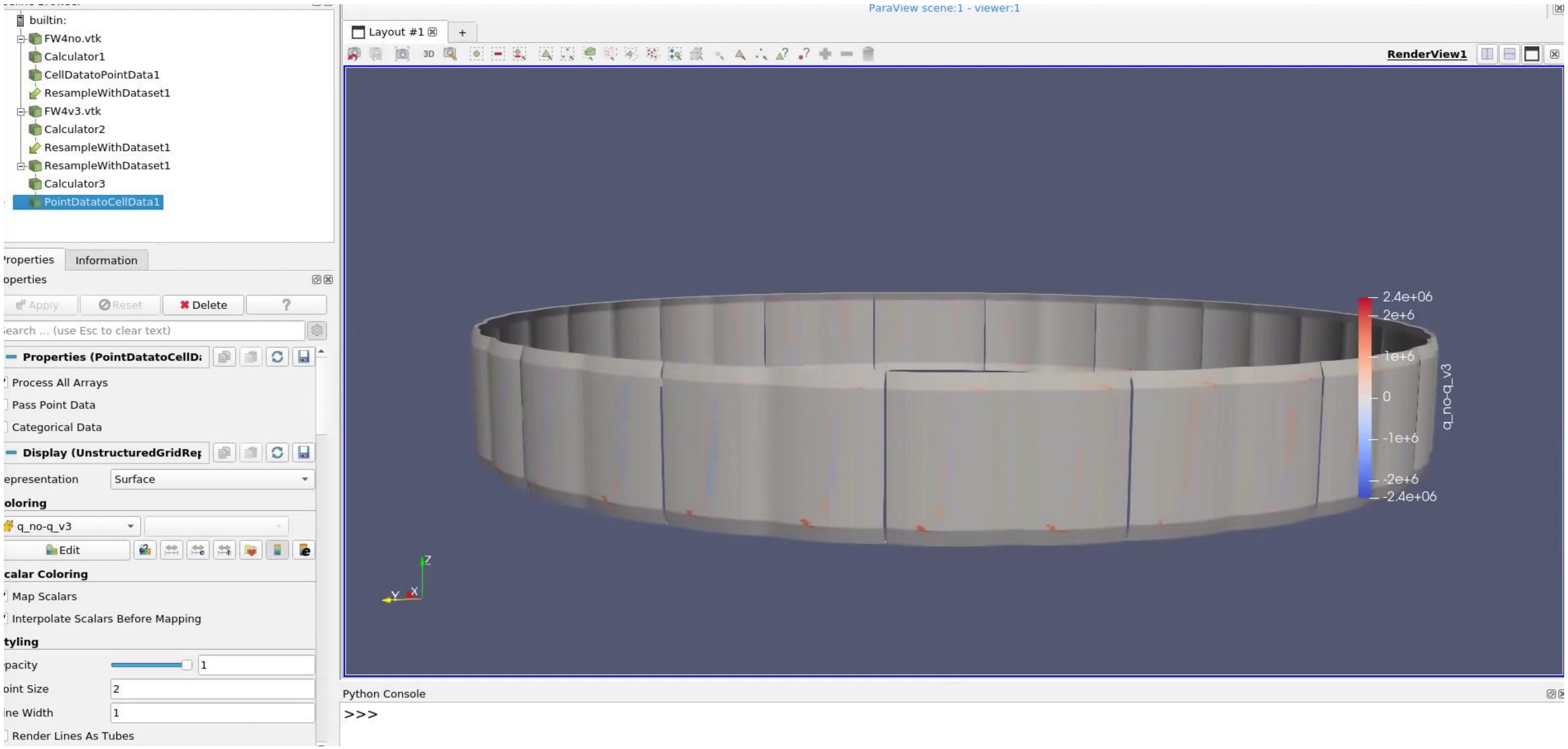
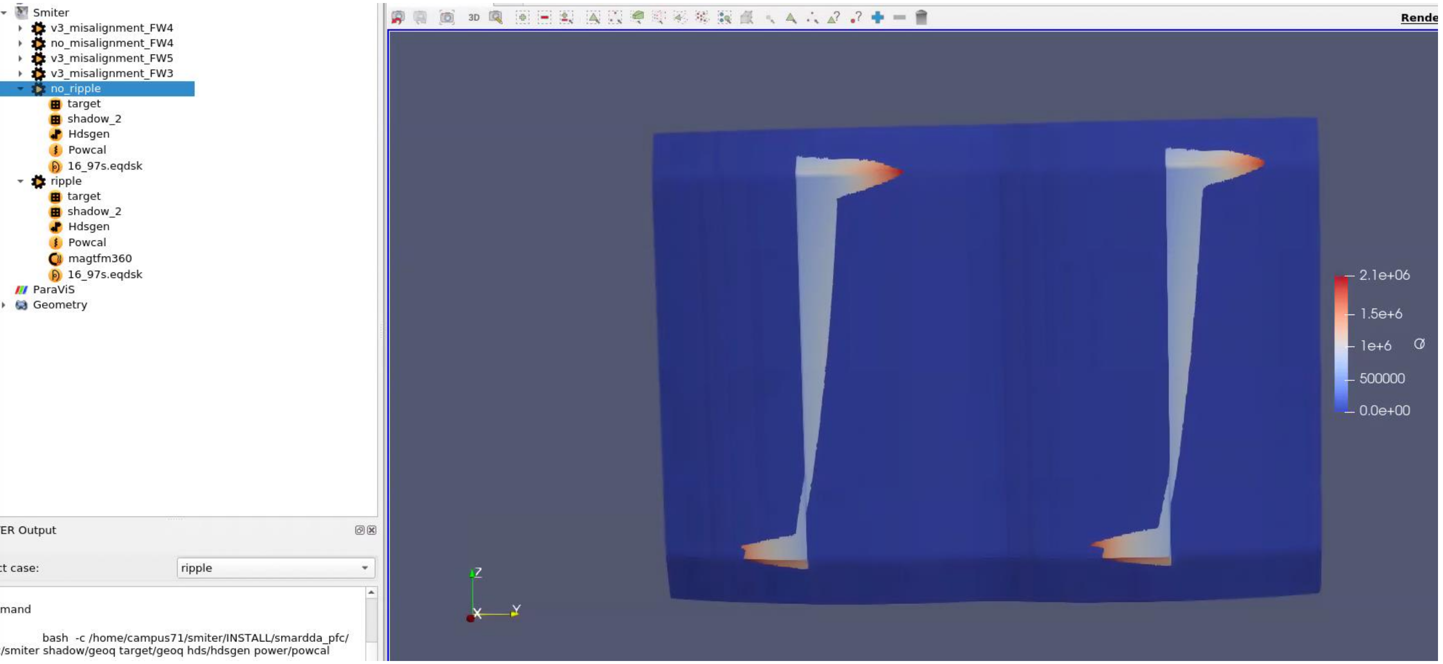
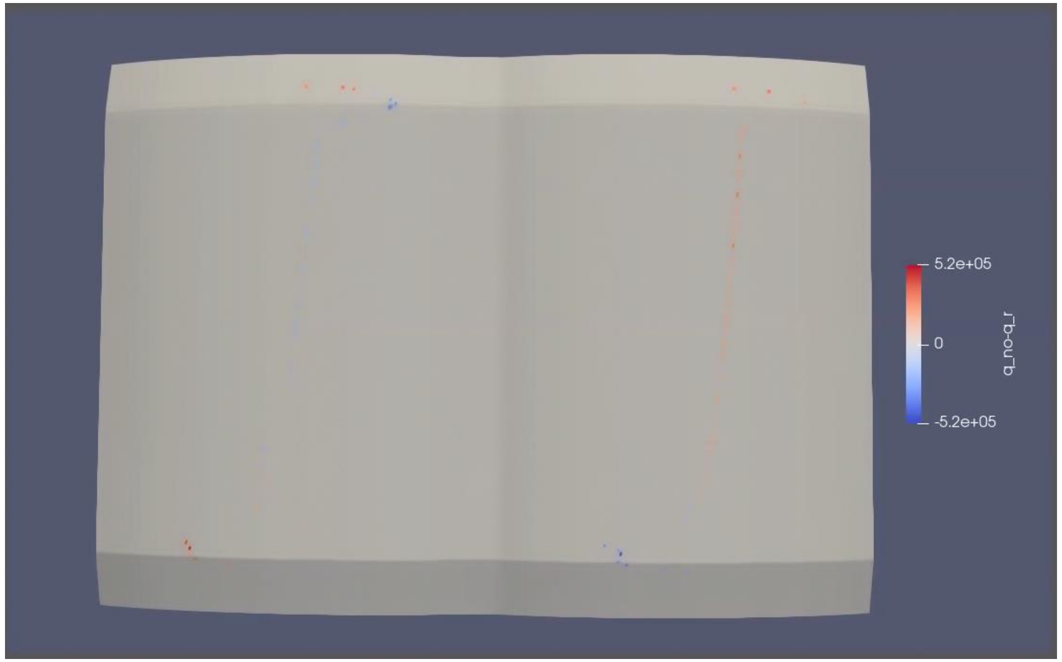
Difference with V3 misalignment



Comparing ripple and without ripple (NF55 axisymmetric case)

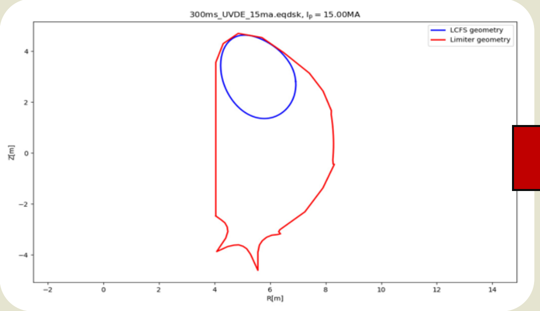


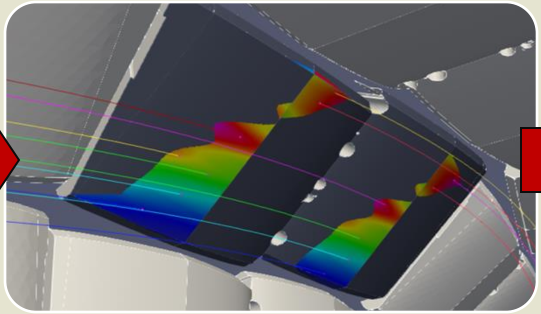


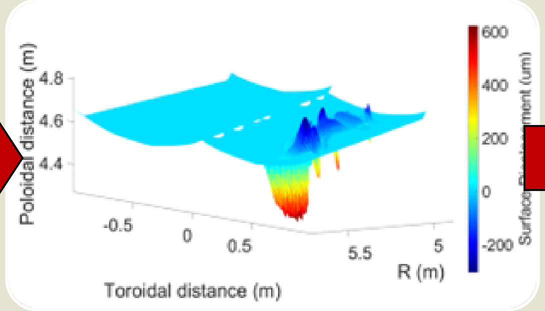
- Ripple field effect with 1/18 symmetry compared to axisymmetric case is negligible different on a limiter case (NF55 study). Only few triangles on the edge are different. See right figure where difference at nodes between ripple and non-ripple is shown.
- Conclusion: 3D case setup for misalignment is correct

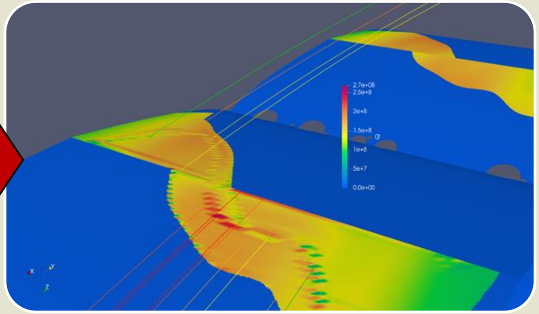
SMITER/MEMOS Workflow

1) Vapor Shielding Model
2) Deformed Panel Meshes
3) Heat Flux on Deformed Mesh









DINA

- Time- dependent Plasma Equilibrium
- Various Disruption Scenarios

SMITER

- 3D Heat Flux Distribution on PFC Surfaces
  - B-field
  - Impact Angle
  - Surface Normal
- Single time-step

MEMOS

- Time-dependent melt formation and motion
  - Temperature
  - Melt thickness
  - Vapor Shielding
  - Surface Displacement

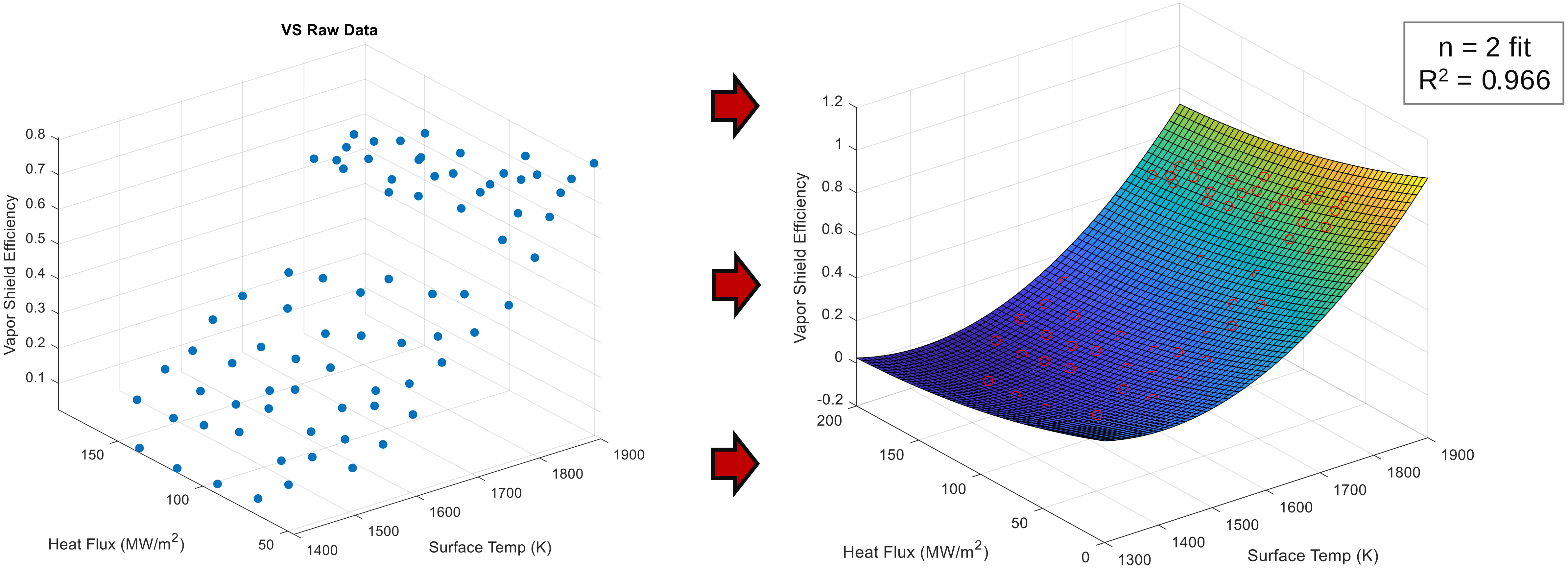
SMITER

- 3D Heat Flux Distribution on DAMAGED PFC Surfaces

Vapor Shielding Implementation into MEMOS

- MATLAB script developed for fitting n-order polynomial function to K. Ibano VS dataset (n = 2 example below)

$$\varepsilon_{VS} = A\left(T_{surf}\right)^2 + B\left(T_{surf}\right)(q_\perp) + C\left(T_{surf}\right) + D(q_\perp)^2 + E(q_\perp) + F$$



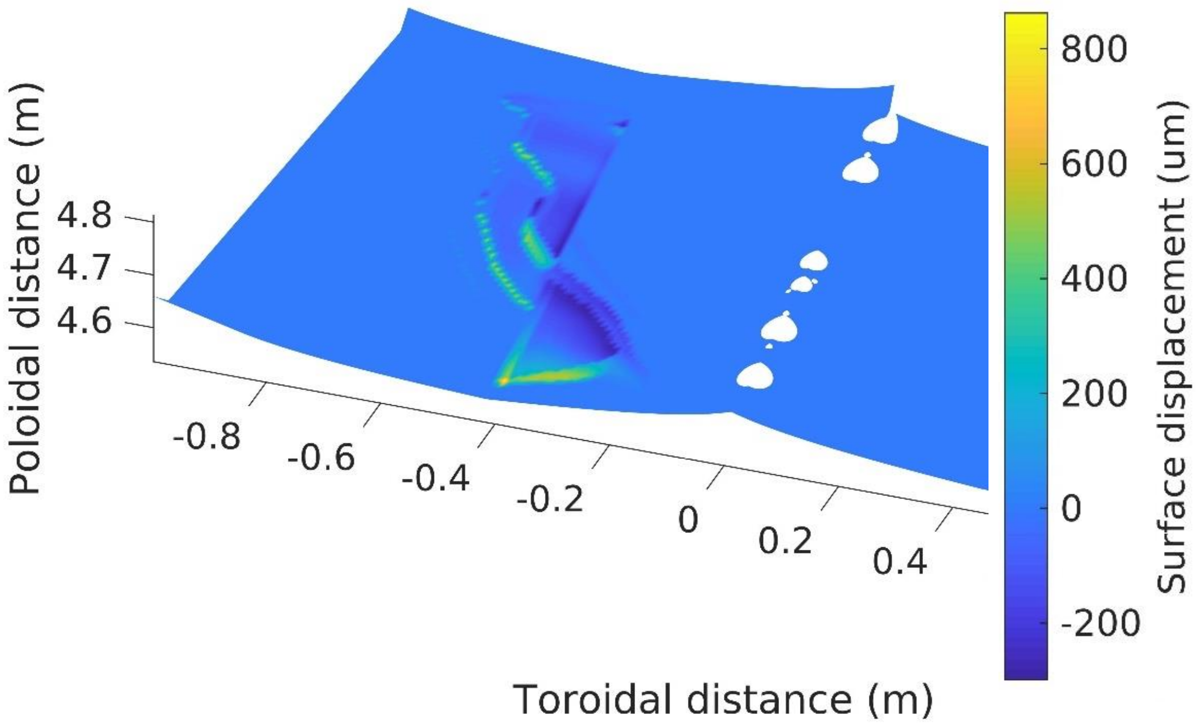
Example Vapor Shield Comparison

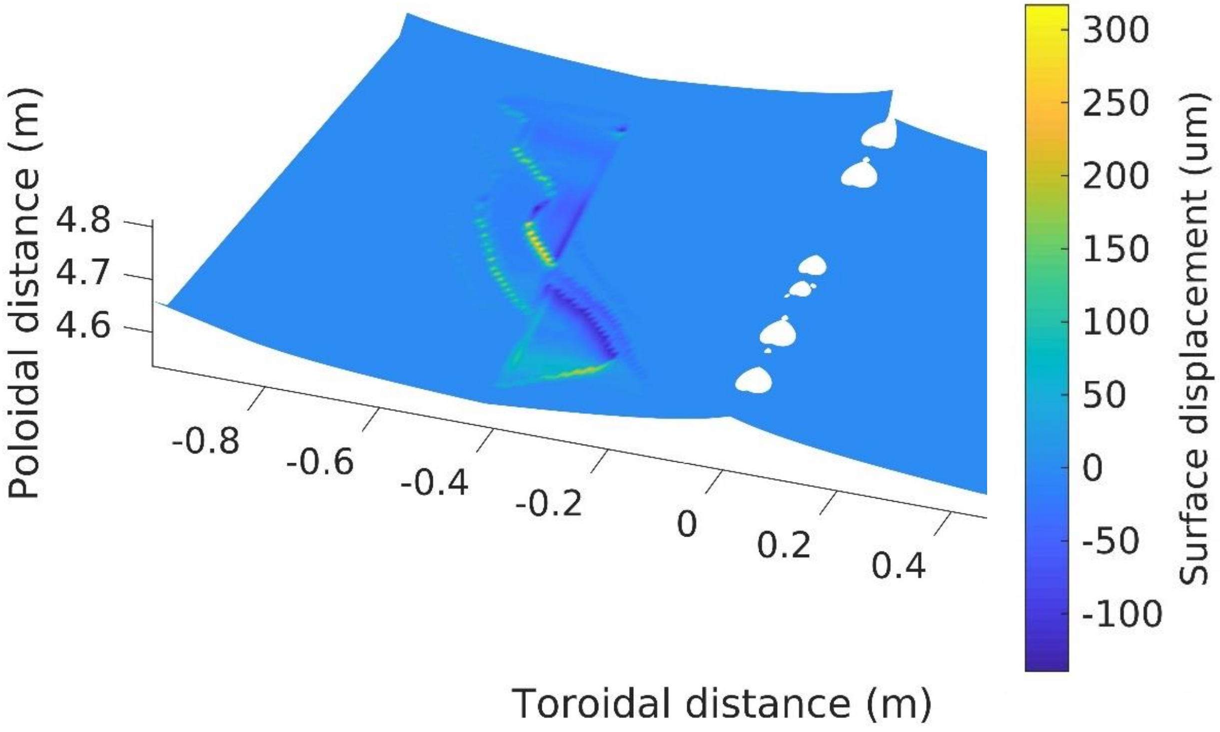
- No Vapor Shield
  - Surface Excavation: -302 um
  - Surface Buildup: 891 um

Vapor Shielding

Surface Excavation: -144 um

Surface Buildup: 338 um

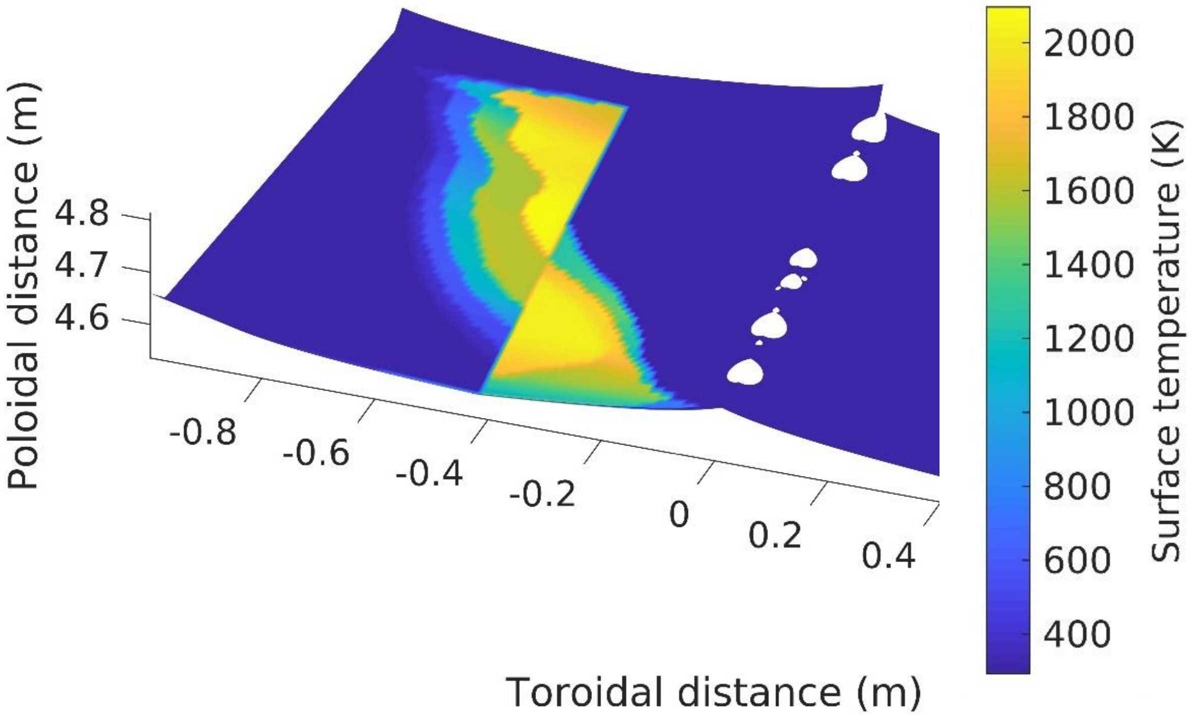




Time: 250 ms (50ms after VDE HF ends)

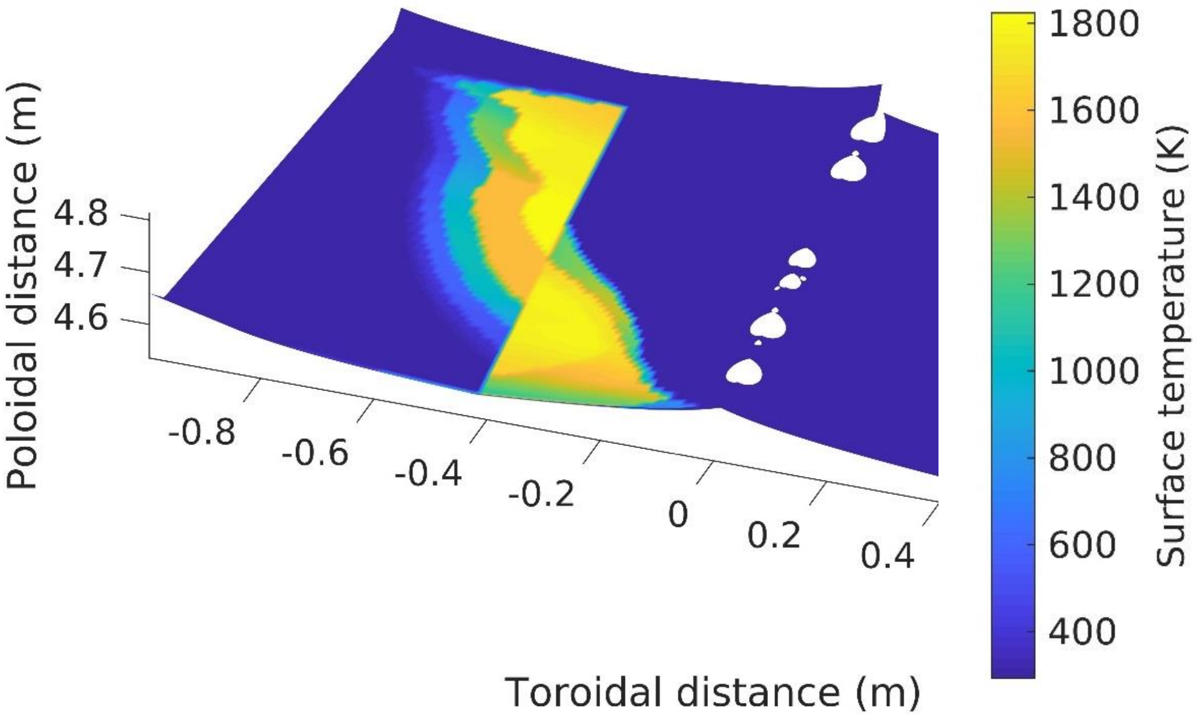
Example Vapor Shield Comparison

- No Vapor Shield
  - Max Surf Temperature: 2100 K



Vapor Shielding

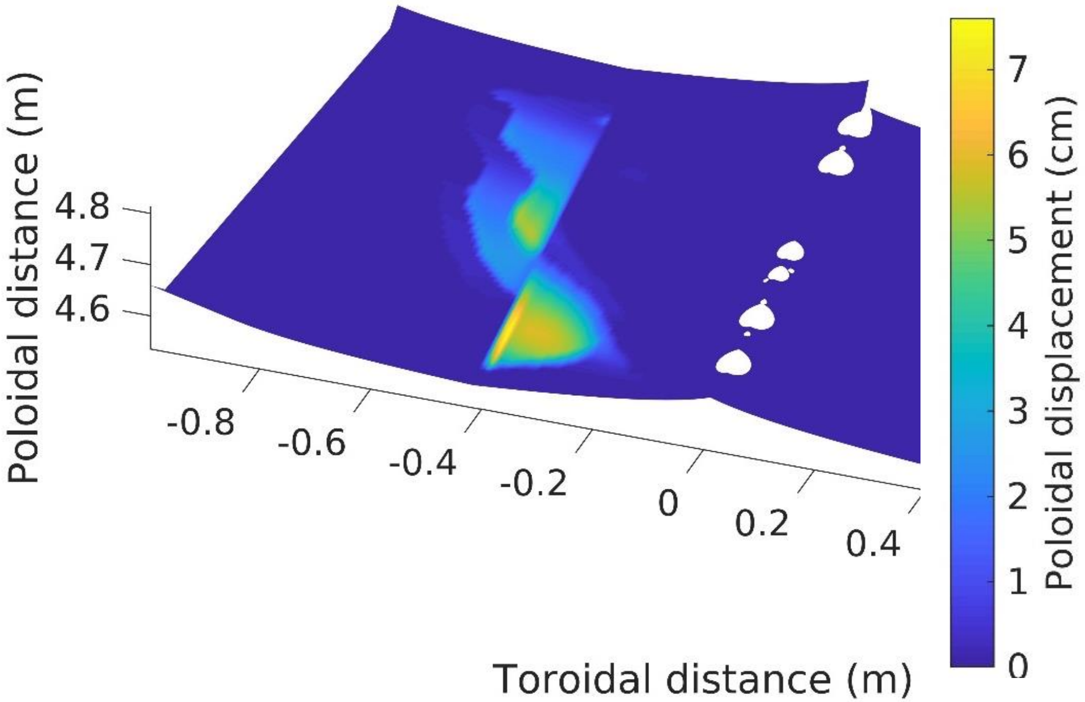
Max Surf Temperature: 1827 K



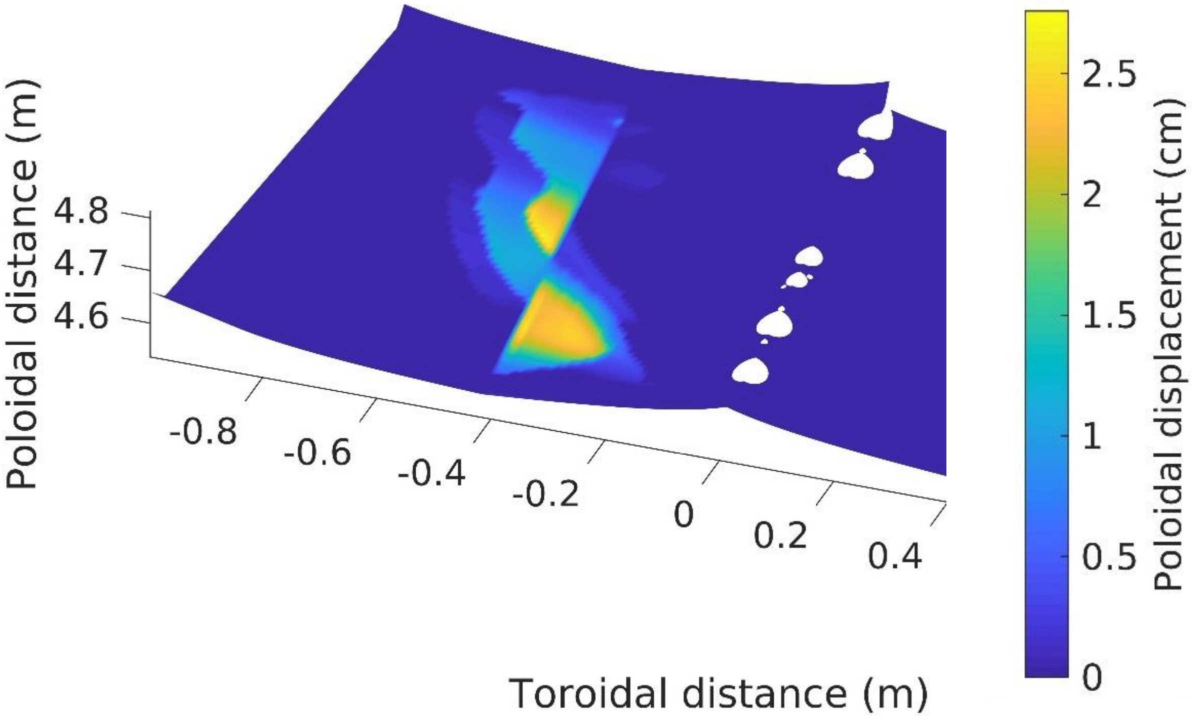
Time: 150 ms

Example Vapor Shield Comparison

- No Vapor Shield



Vapor Shielding



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Example Vapor Shield Comparison

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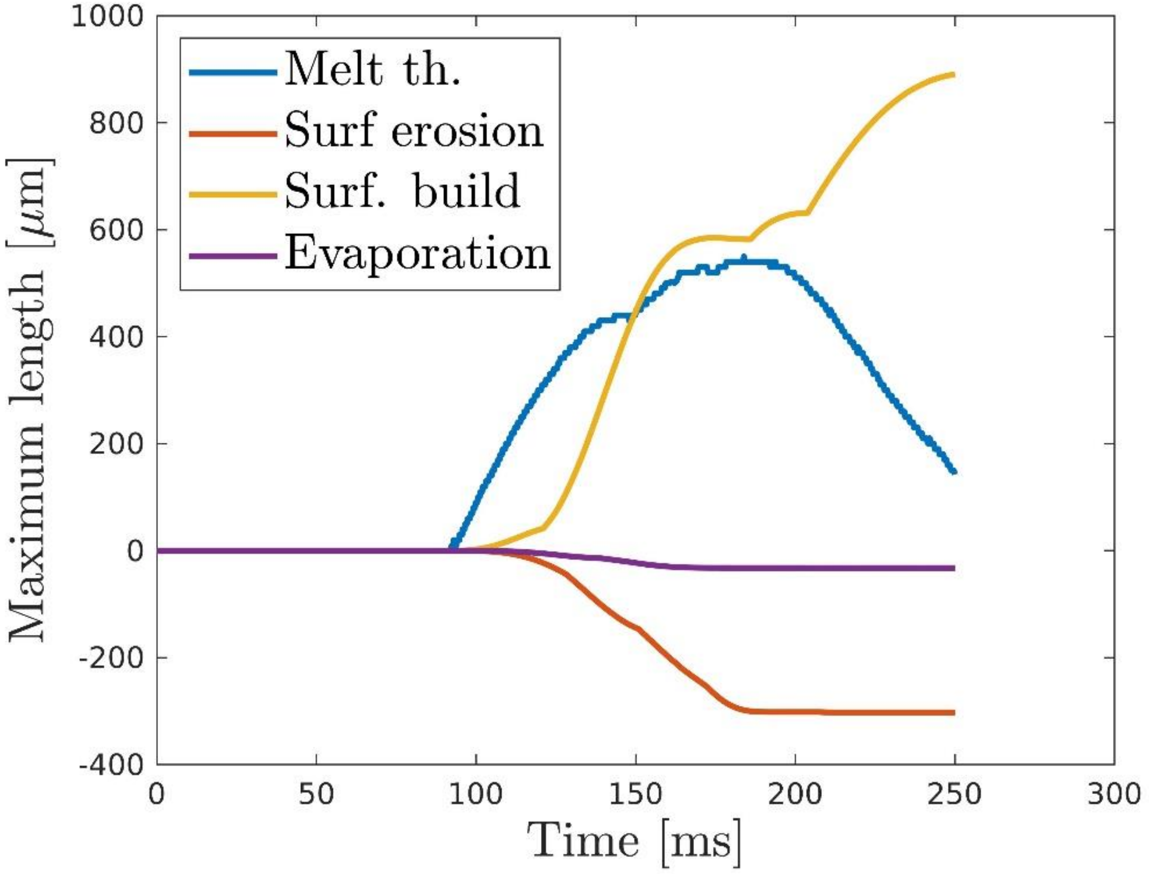
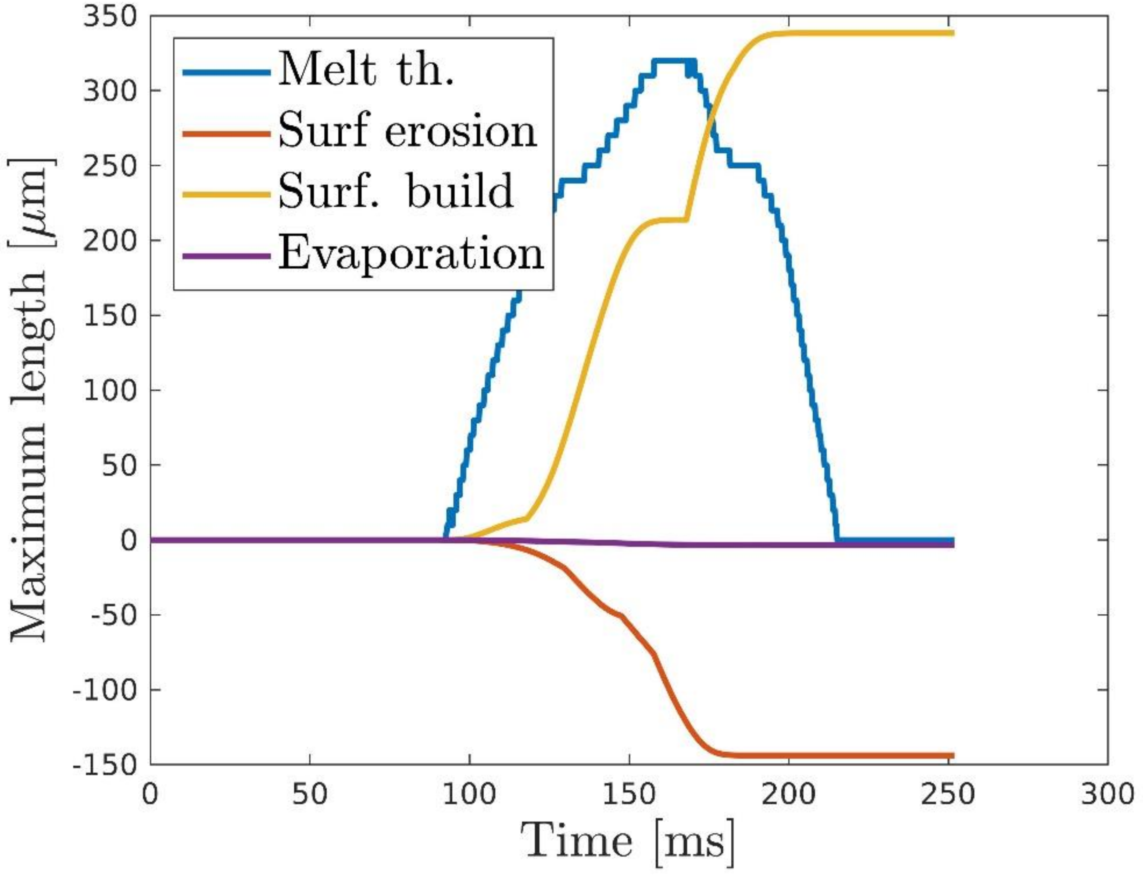


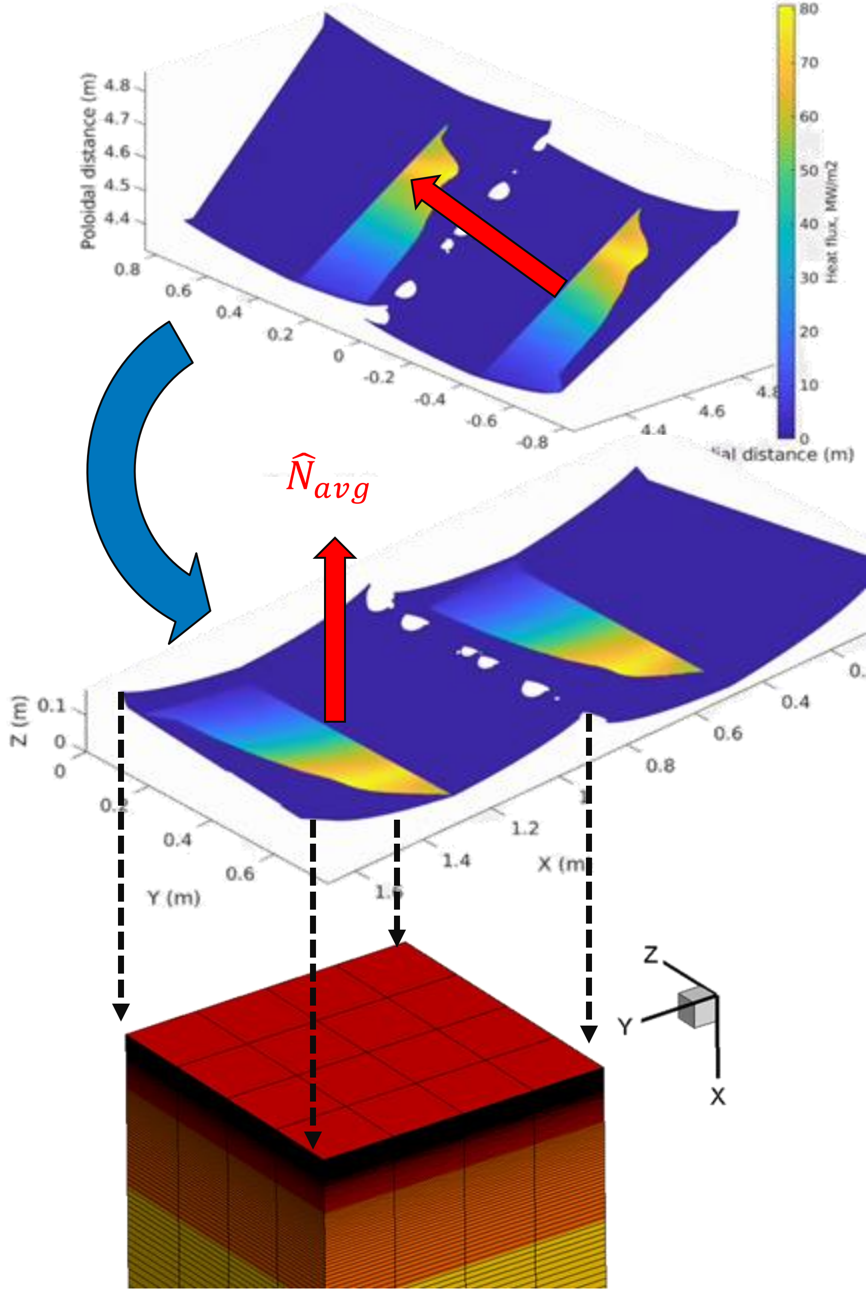
Vapor Shielding



FW Panel Mesh Deformation

Methodology

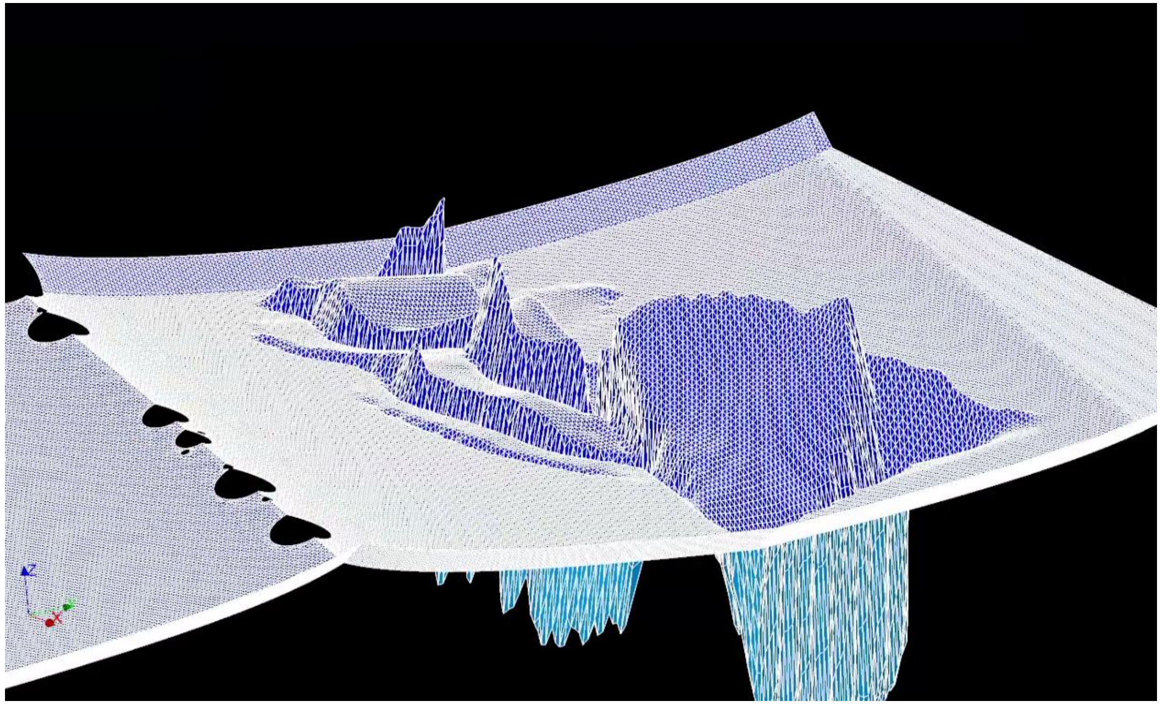
- SMITER coordinate modifications required for MEMOS:
    - Rotate FWP mesh so that average surface normal aligns with 2D (x,y) plane for MEMOS simulations
    - Height variable (Z) for SMITER mesh is ignored for MEMOS input, effectively projecting the 3D SMITER mesh onto the 2D MEMOS grid
- MEMOS surface displacement data and surface normal data recorded for each mesh face
    - However, mesh modification requires updating vertex points of each mesh face



FW Panel Mesh Deformation

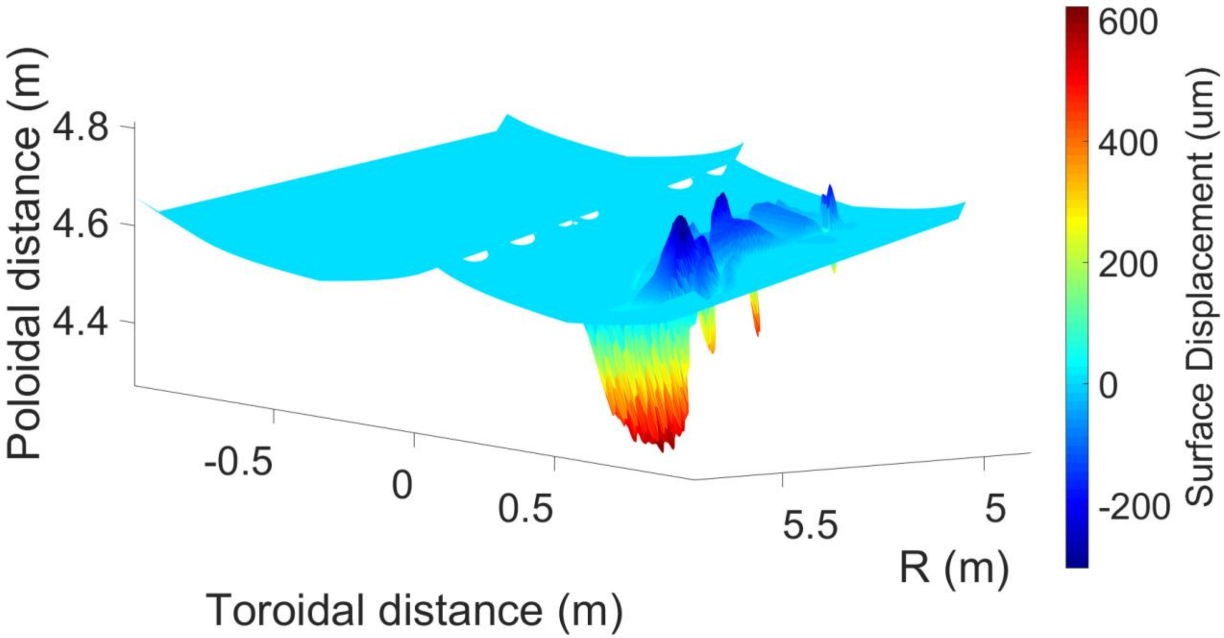
FWP 9: 525ms, 0mm Shift

Deformed Mesh imported into SMITER



(500x Displacement Magnitude)

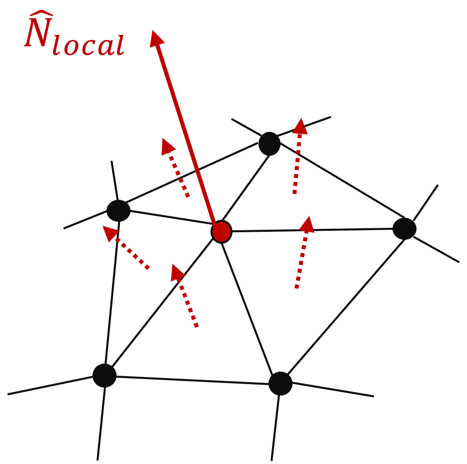
Data Layered onto Deformed Mesh

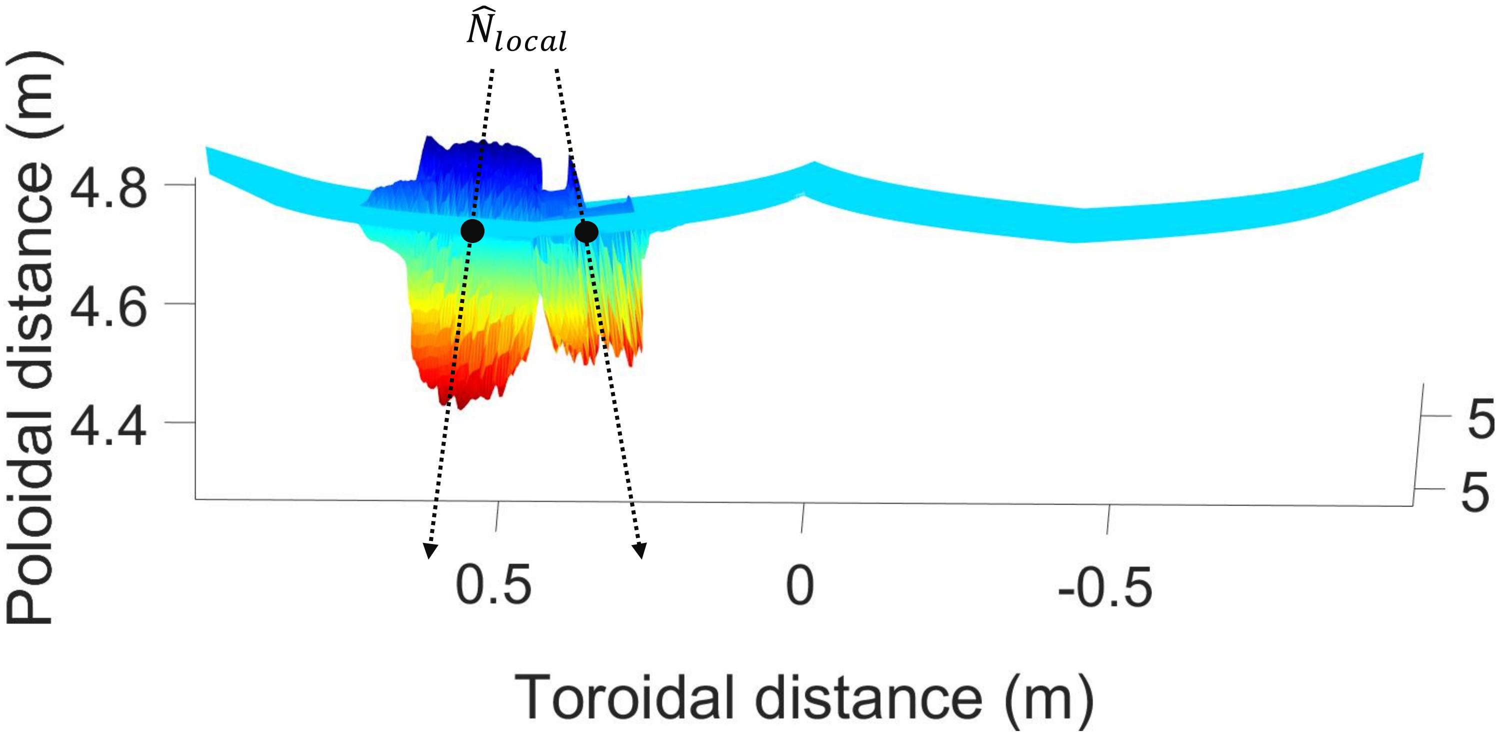


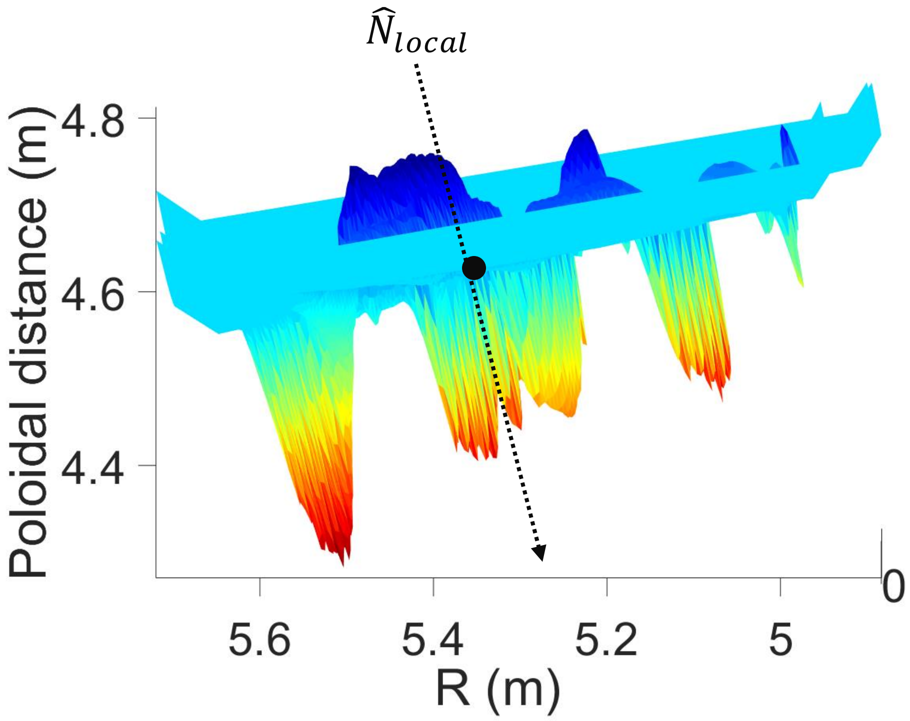
(500x Displacement Magnitude)

FW Panel Mesh Deformation

- Surface displacement magnitude Δh shifts mesh vertices along local surface normal vector $\widehat{N}_{local}$
  - $\widehat{N}_{local}$ at each vertex is an area-weighted average of each $\widehat{N}_{face}$ connected to that vertex
  - Same for Δh

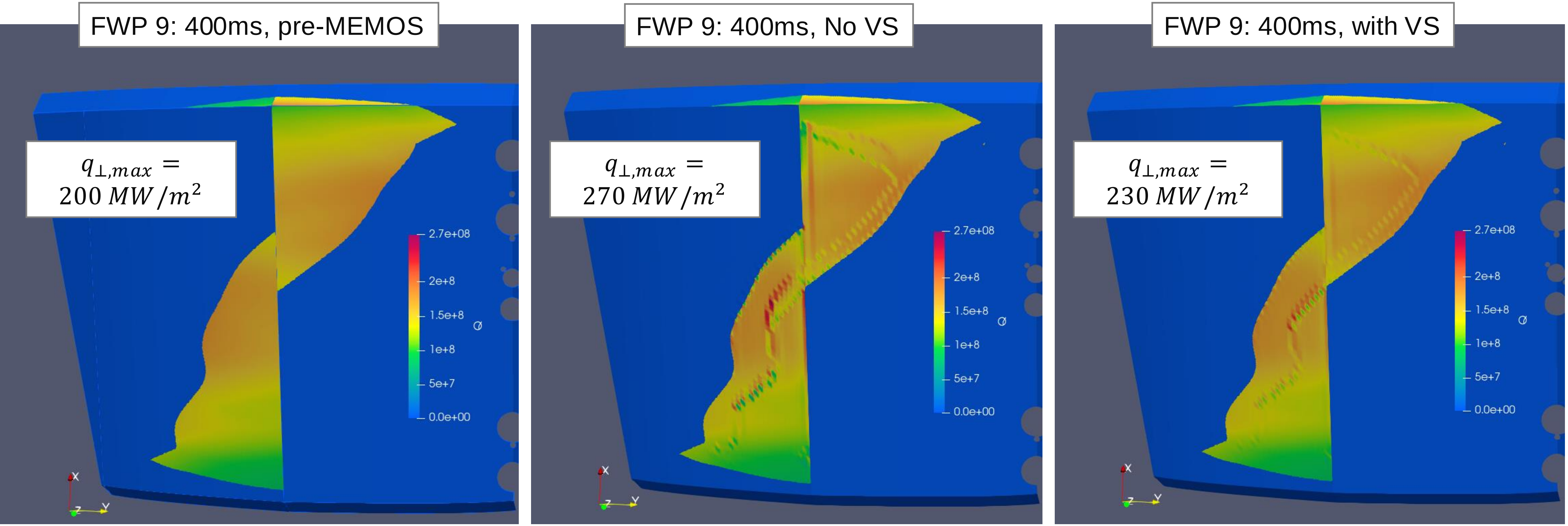






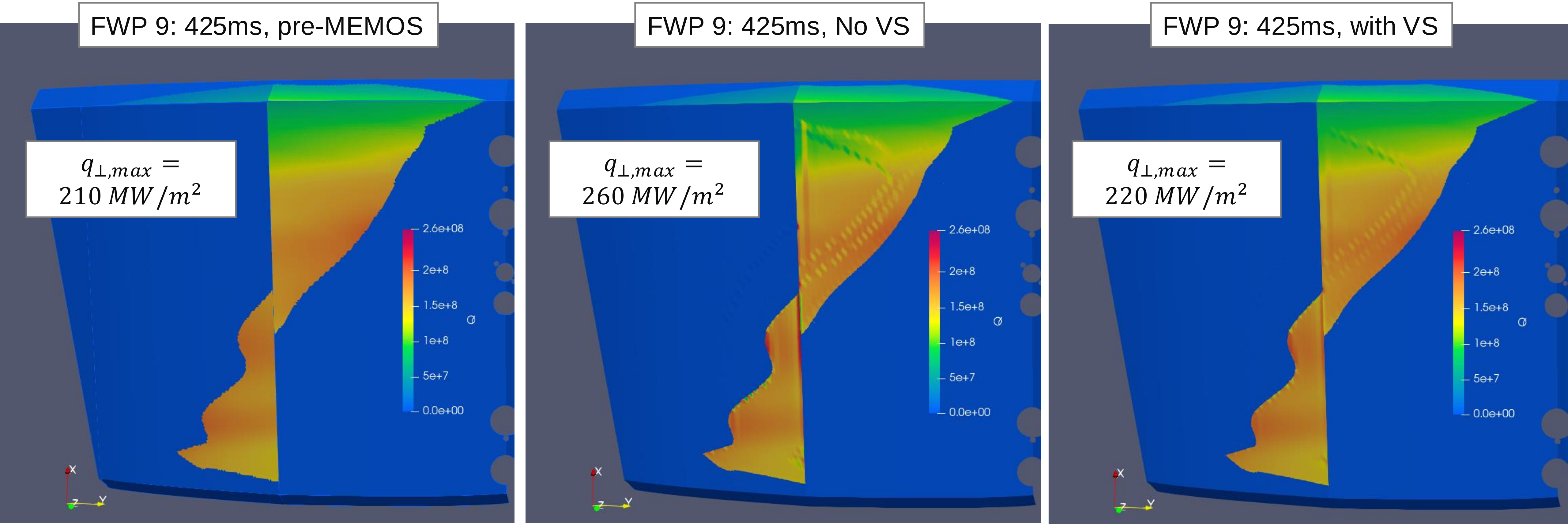
Successive VDE Heat Flux on Deformed FWP 9

- There is a ~ 15 – 35% increase in local $q_{\perp,max}$ due to melt ridges & excavated pits during subsequent VDE
  - Location (ridge vs pit) depends on field line direction



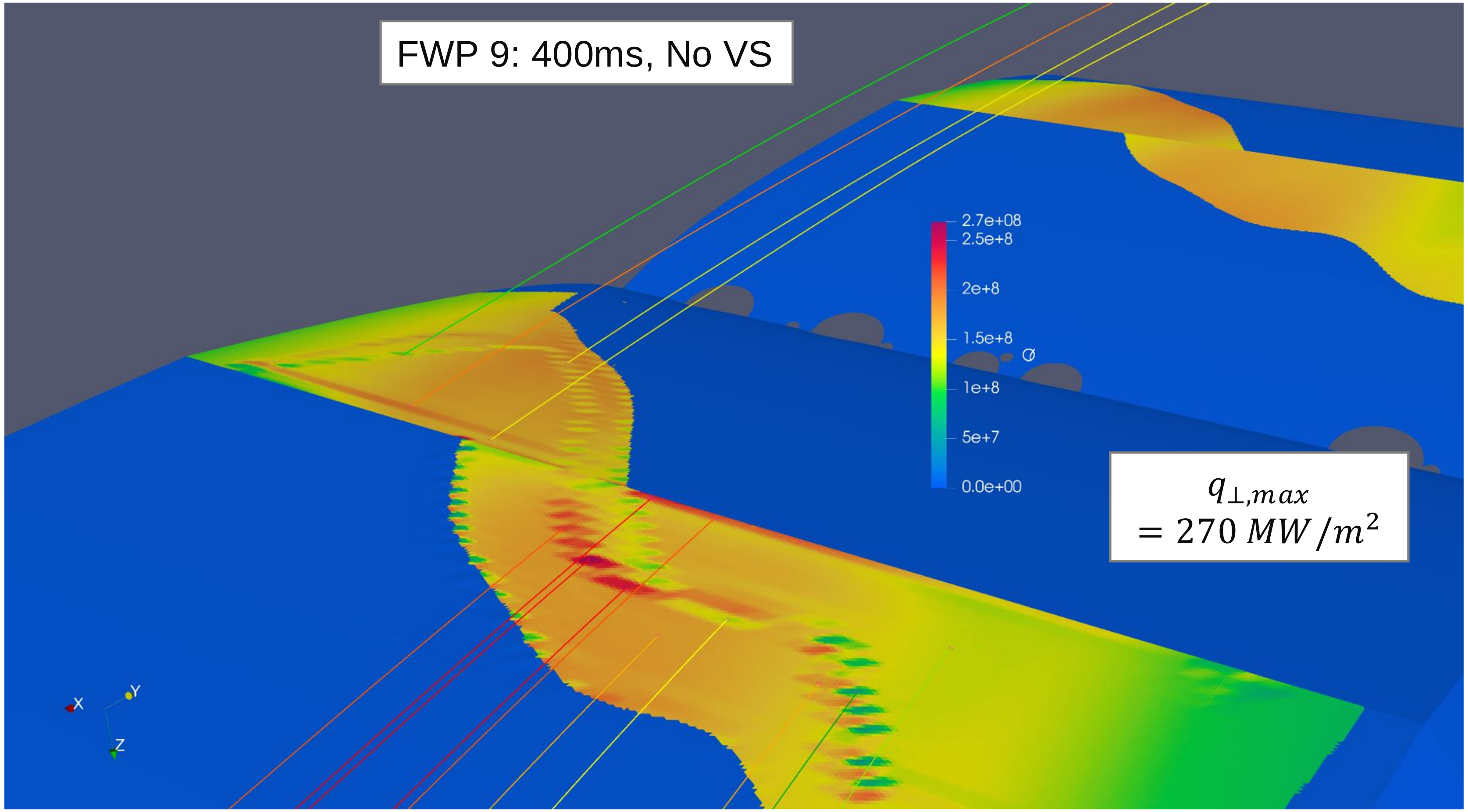
Successive VDE Heat Flux on Deformed FWP 9

- There is a ~ 15 – 35% increase in local $q_{\perp,max}$ due to melt ridges & excavated pits during subsequent VDE
  - Location (ridge vs pit) depends on field line direction



Successive VDE Heat Flux on Deformed FWP 9

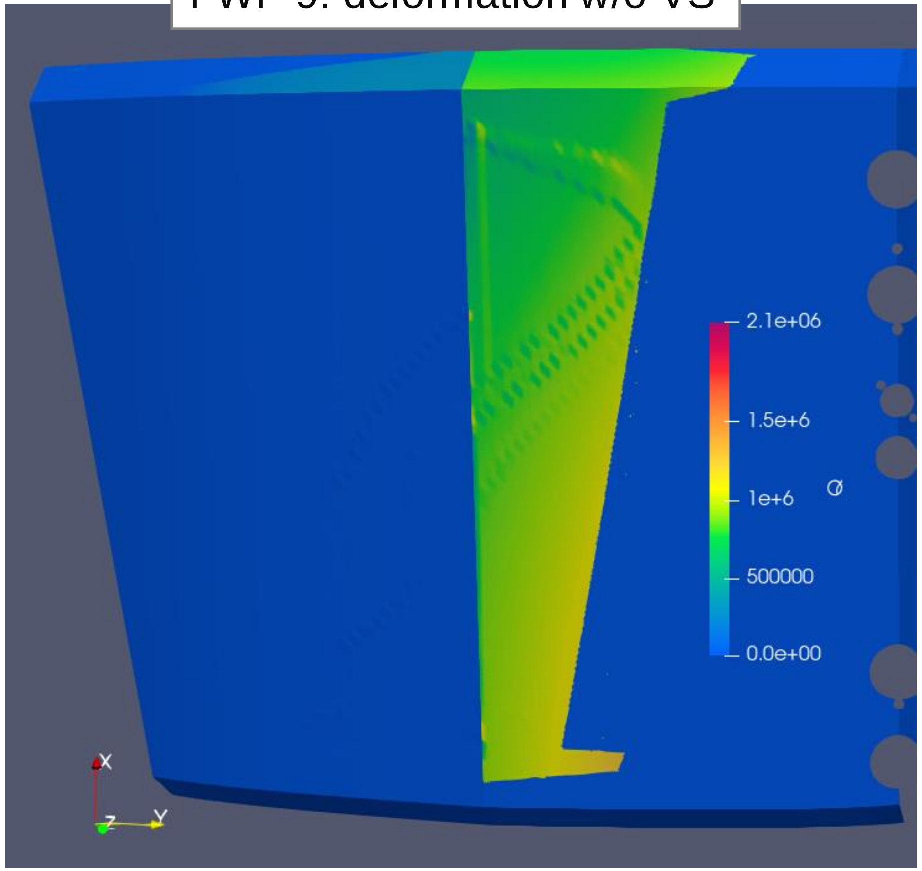
- There is a ~ 15 – 35% increase in local $q_{\perp,max}$ due to melt ridges & excavated pits during subsequent VDE
  - Location (ridge vs pit) depends on field line direction



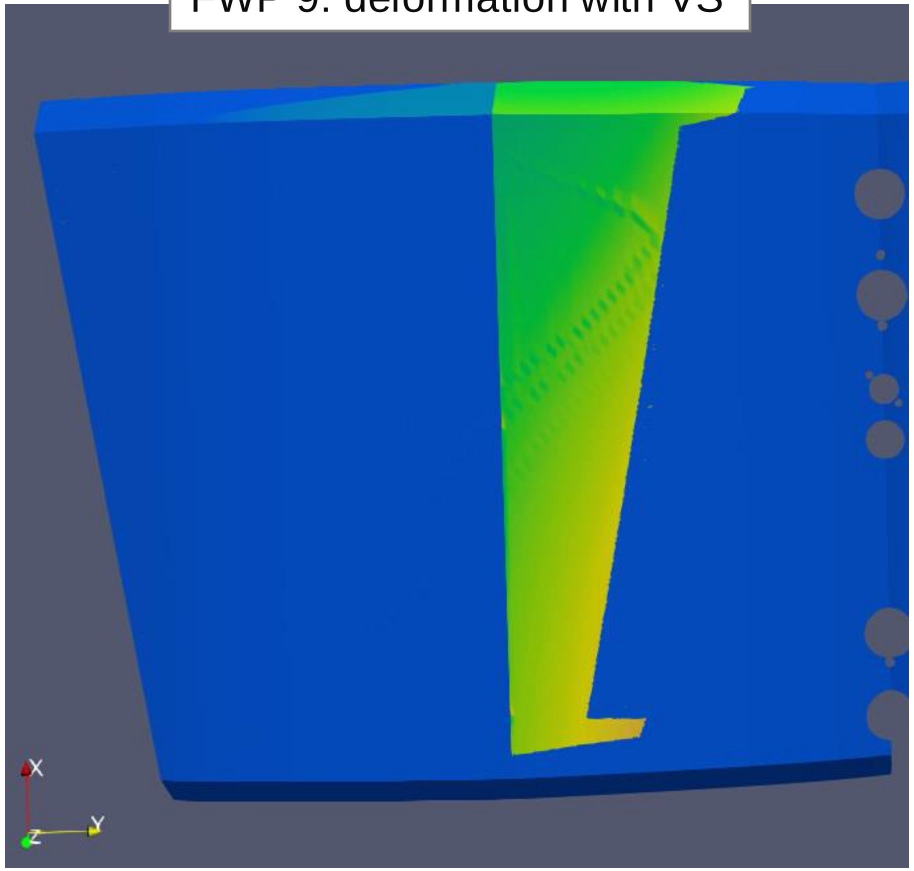
Steady-State Heat Flux on Deformed FWP 9

- No discernable increase in local $q_{\perp,max}$ due to melt ridges during SS operation scenario w/ ELMs
  - No overlap on FWP 8

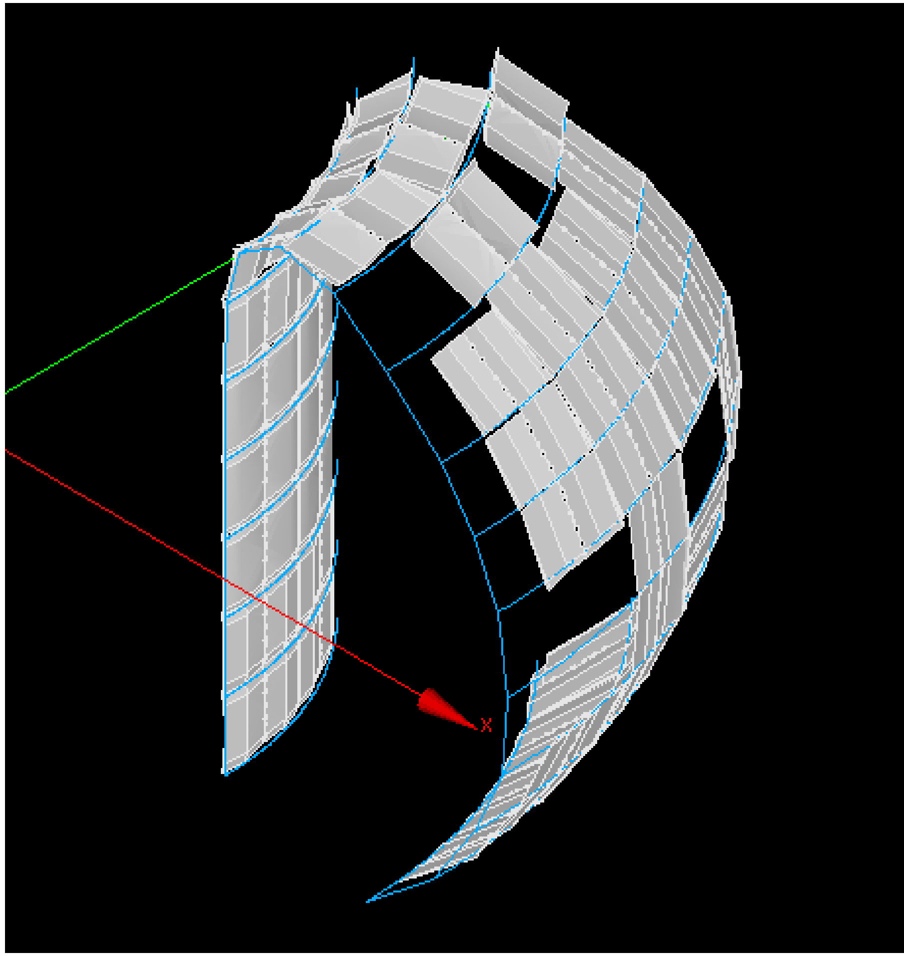
FWP 9: deformation w/o VS



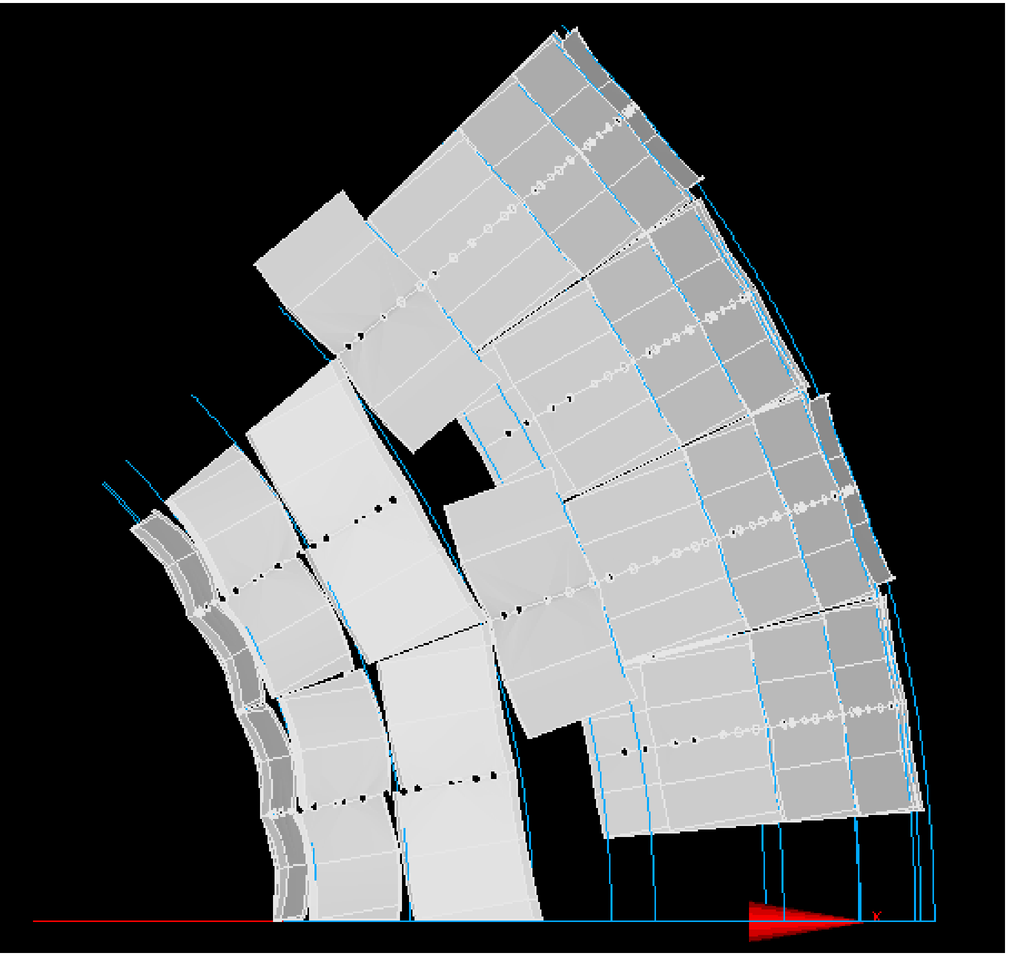
FWP 9: deformation with VS



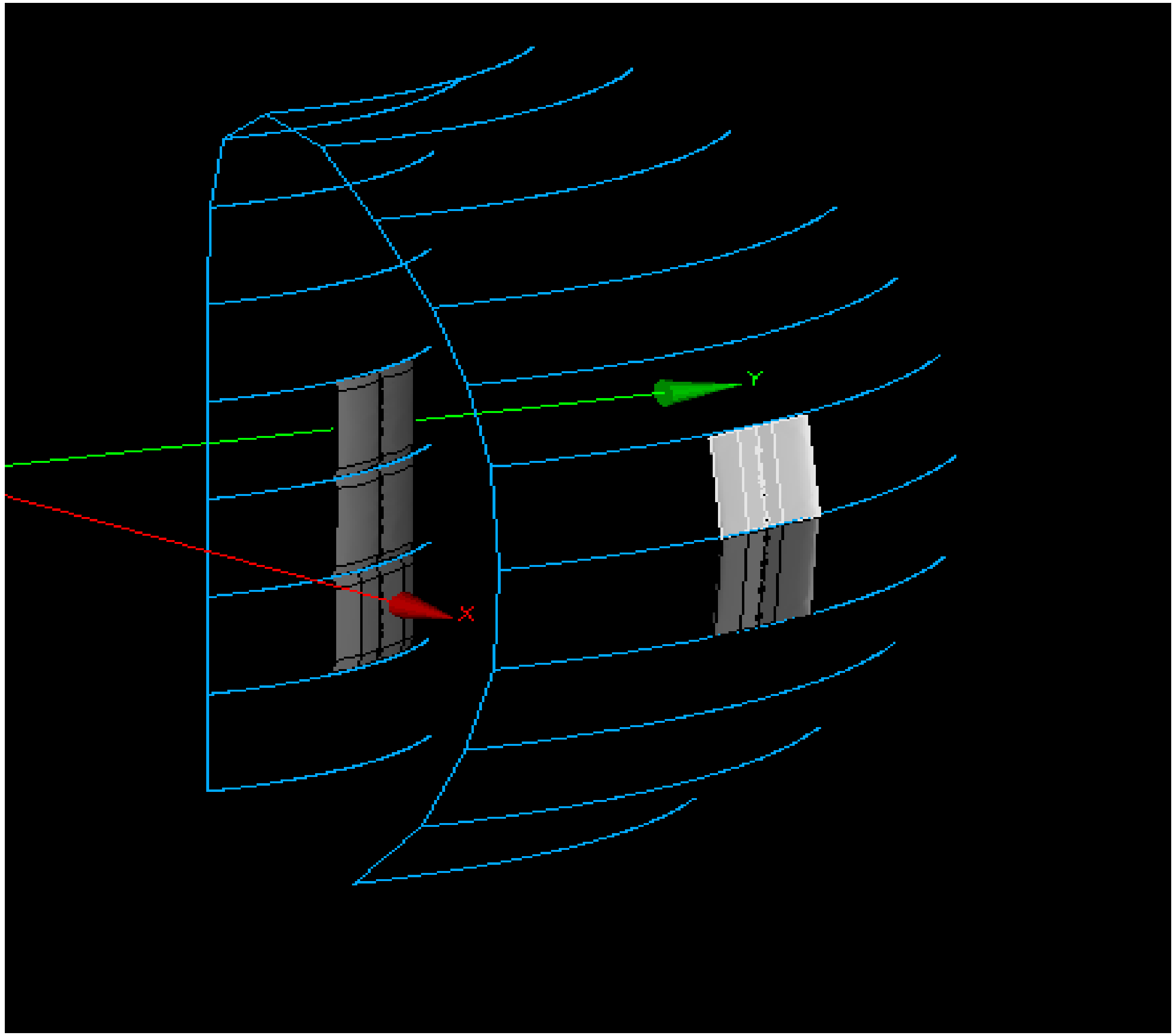
Wall mesh vs. new CAD module



Whole sector - Mario

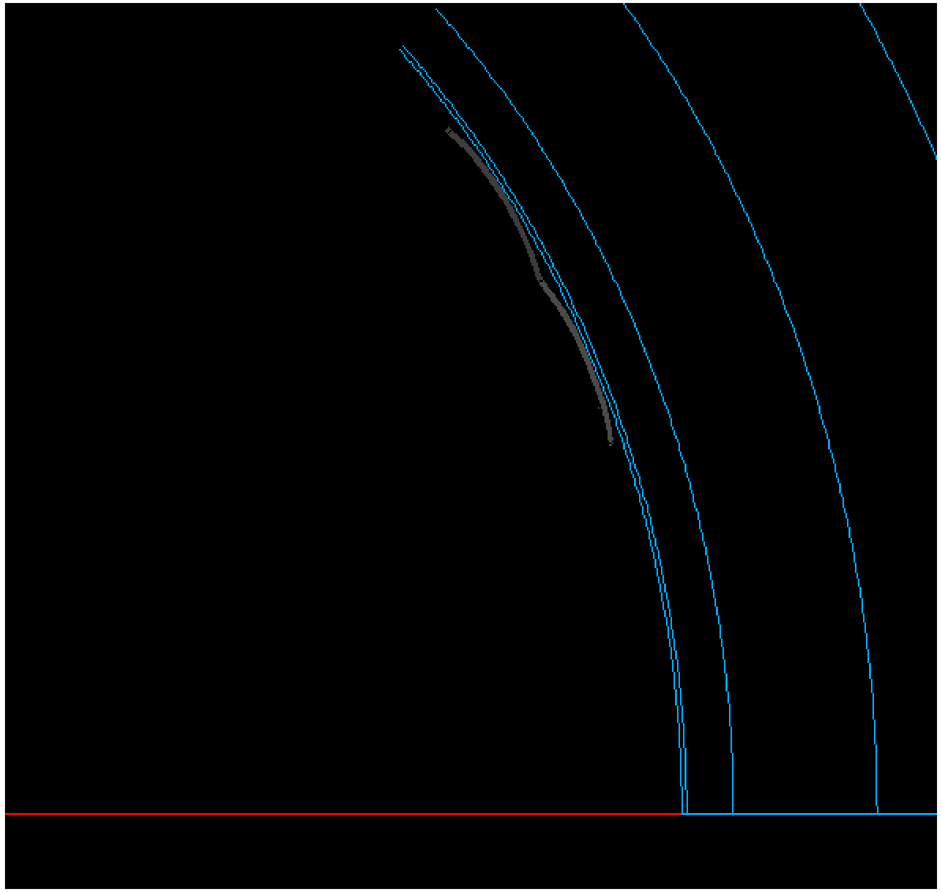


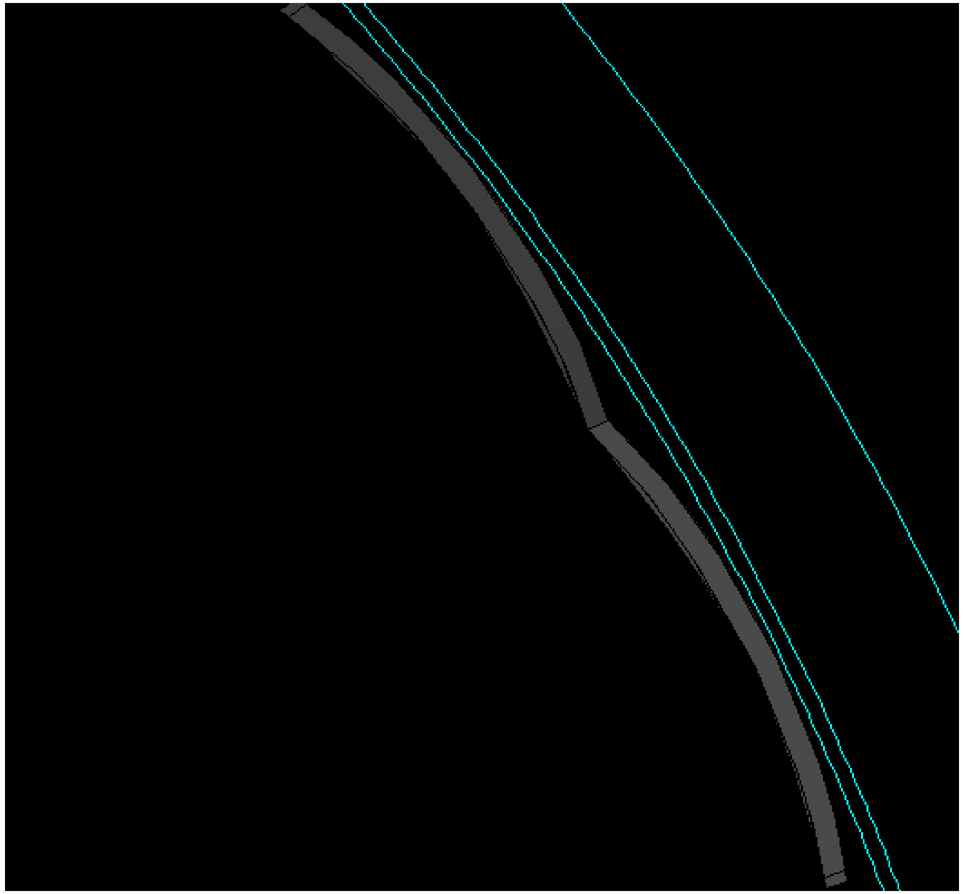
Whole sector – top view



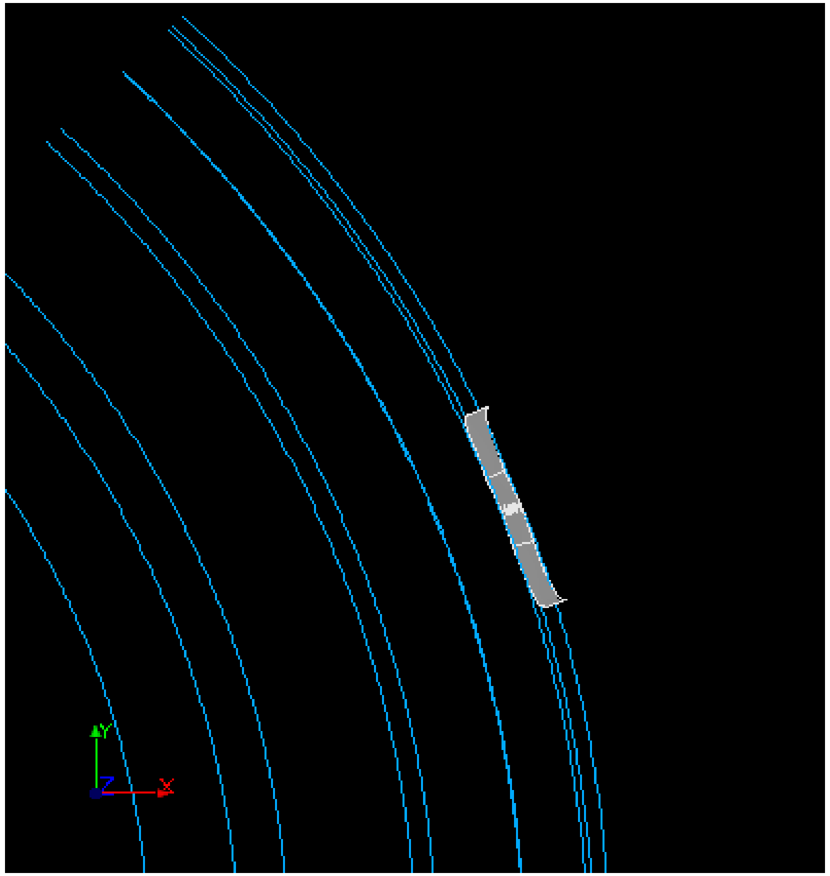
- Inner tiles (FW2, FW and FW4)
- Outer tiles (FW14 and FW15)

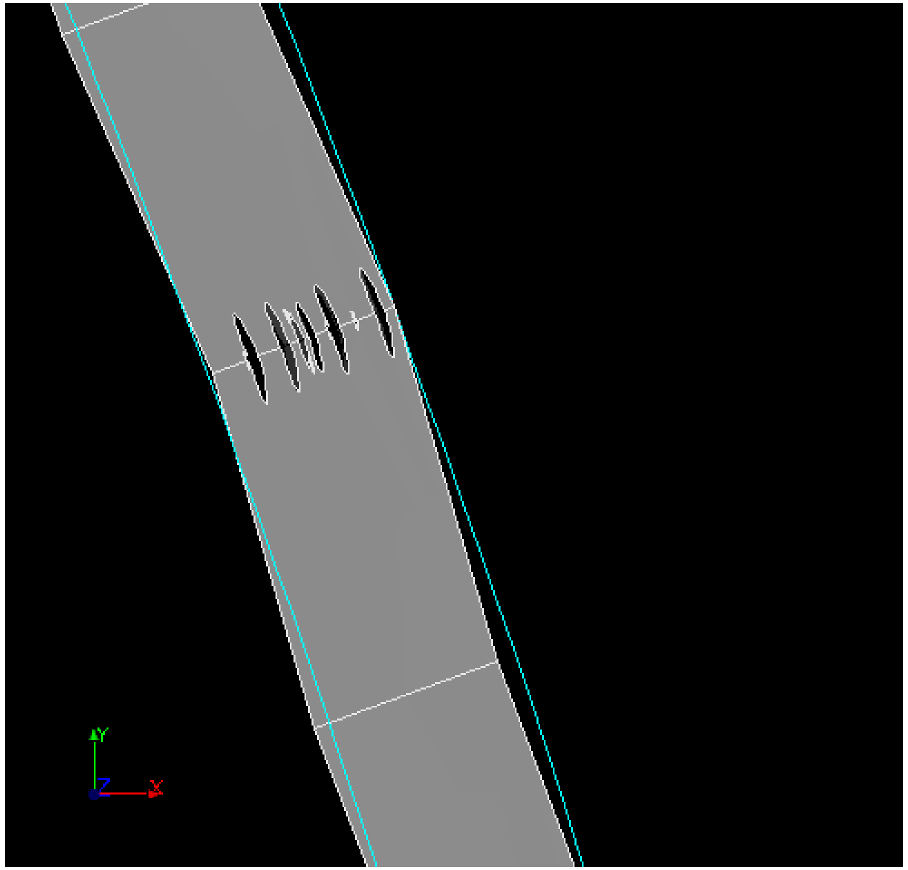
Inner tiles – top view



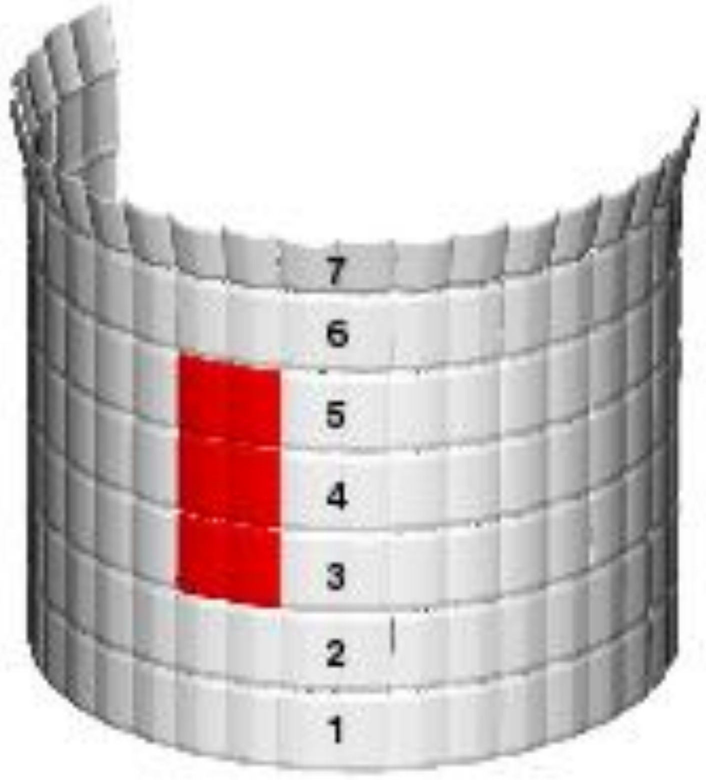


Outer tiles - top view



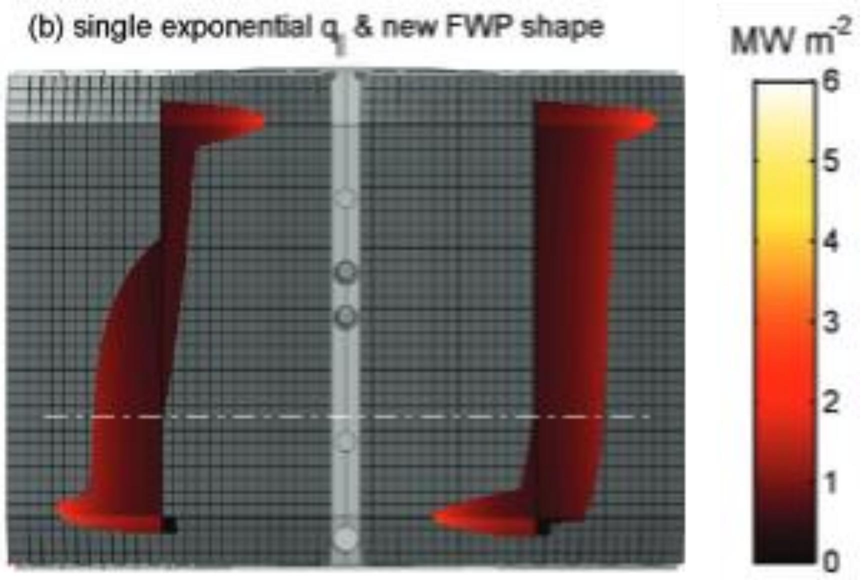


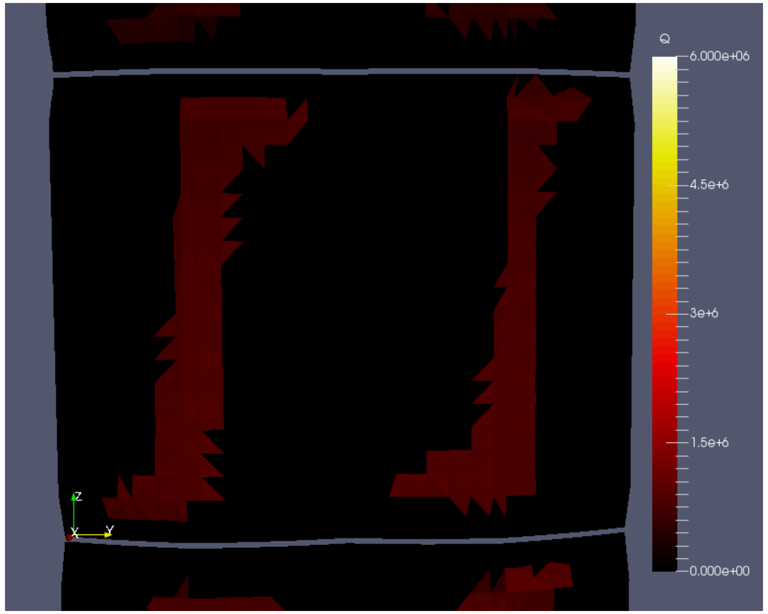
M. Kocan Nucl.Fus.55 report study

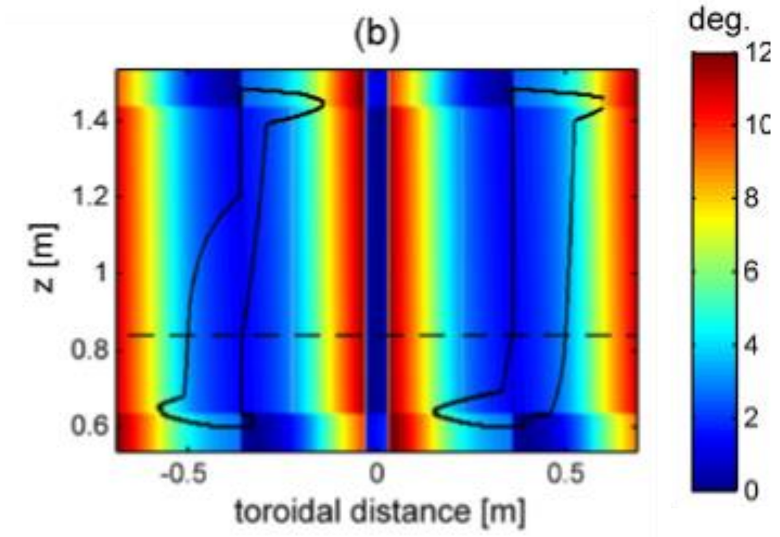


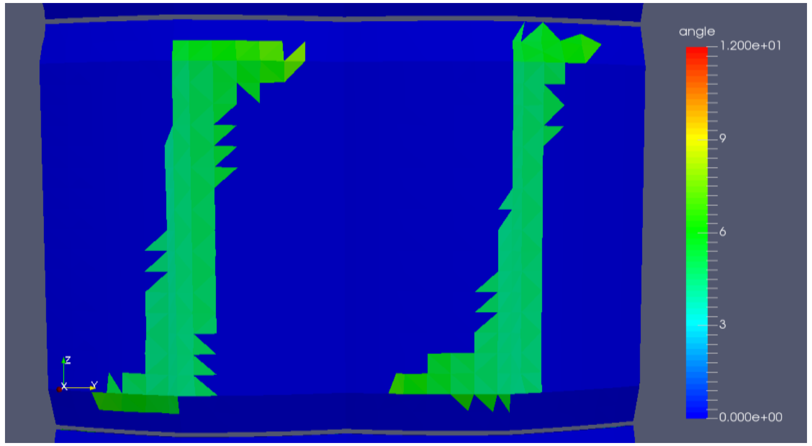
- Target (red) shifted towards the plasma for 5 mm (because of estimated FWP radial alignment tolerance)
- Decay length is 50 mm
- Power deposition is 5 MW
- Shadow (half of sector or surrounding panel around the target) ?

Kocan benchmark mesh - Results









CAD module - Results