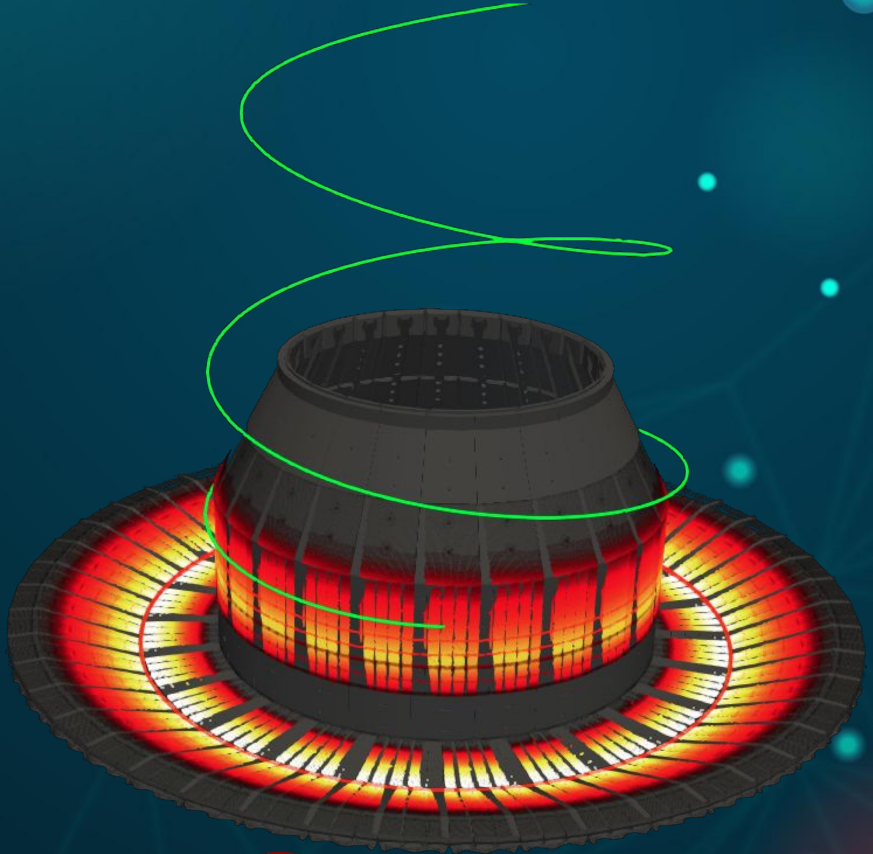
H.E.A.T. UPDATE



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08/31/2020

Oak Ridge National Laboratory

NSTX-U

01 **Demonstration**

Introduction to HEAT capabilities

02 **HEAT Overview**

HEAT architecture and module descriptions

03 **NSTX-U PFC Analysis**

Determination of NSTX-U operational space w/ respect to PFCs

04 **HEAT Roadmap**

Upcoming modules

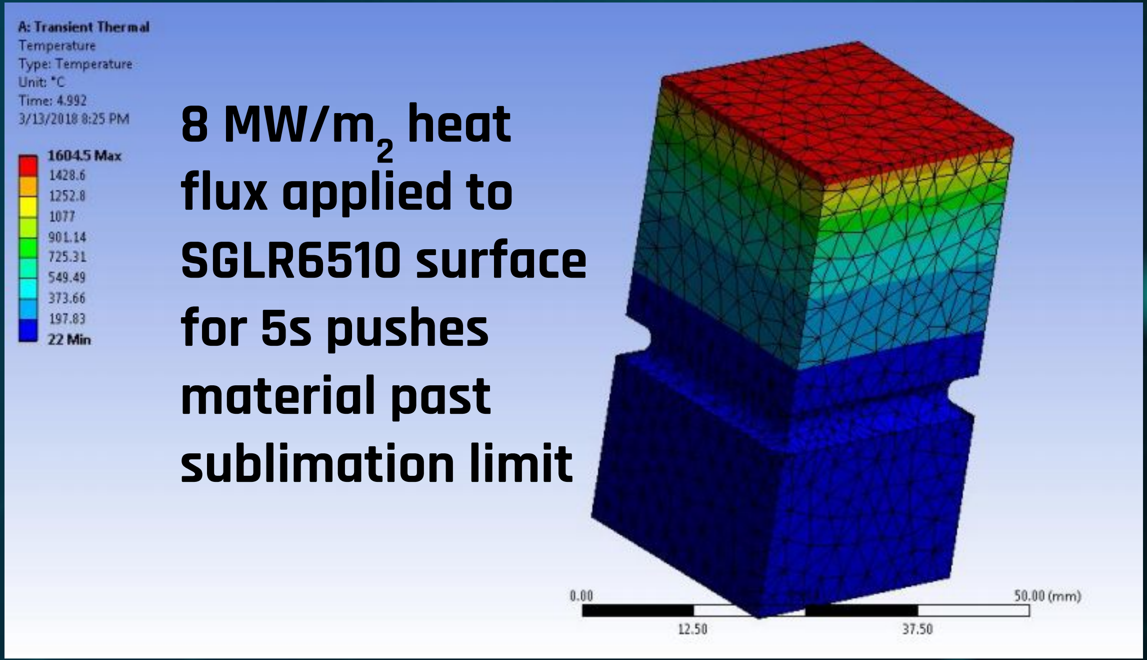
Demonstration 01

NSTX-U graphite Plasma Facing Components (PFCs) are thermally limited at 1600˚C

Graphite has a sublimation limit of ~ 1600˚C

NSTX-U Recovery PFC working group understood this limit, but lacked the tools to check physics scenarios against PFC sublimation

PFC temperature can constrain physics scenarios

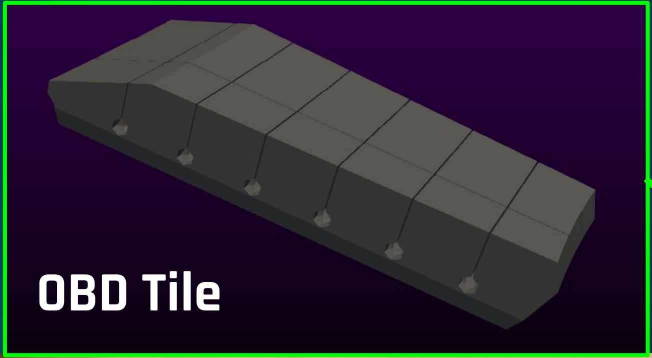


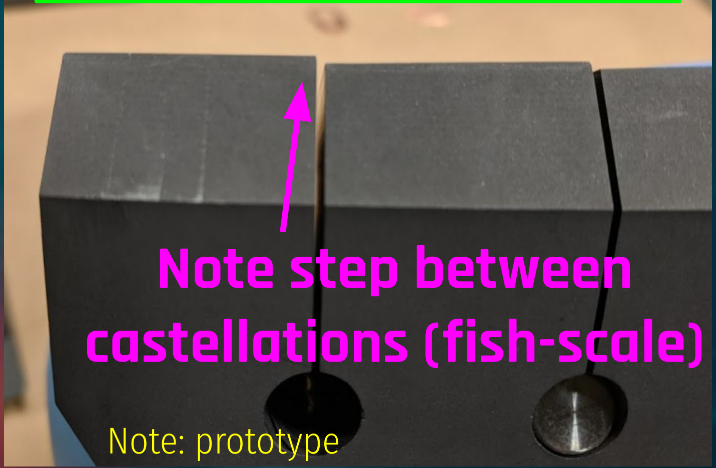
8 MW/m_2 heat flux applied to SGLR6510 surface for 5s pushes material past sublimation limit

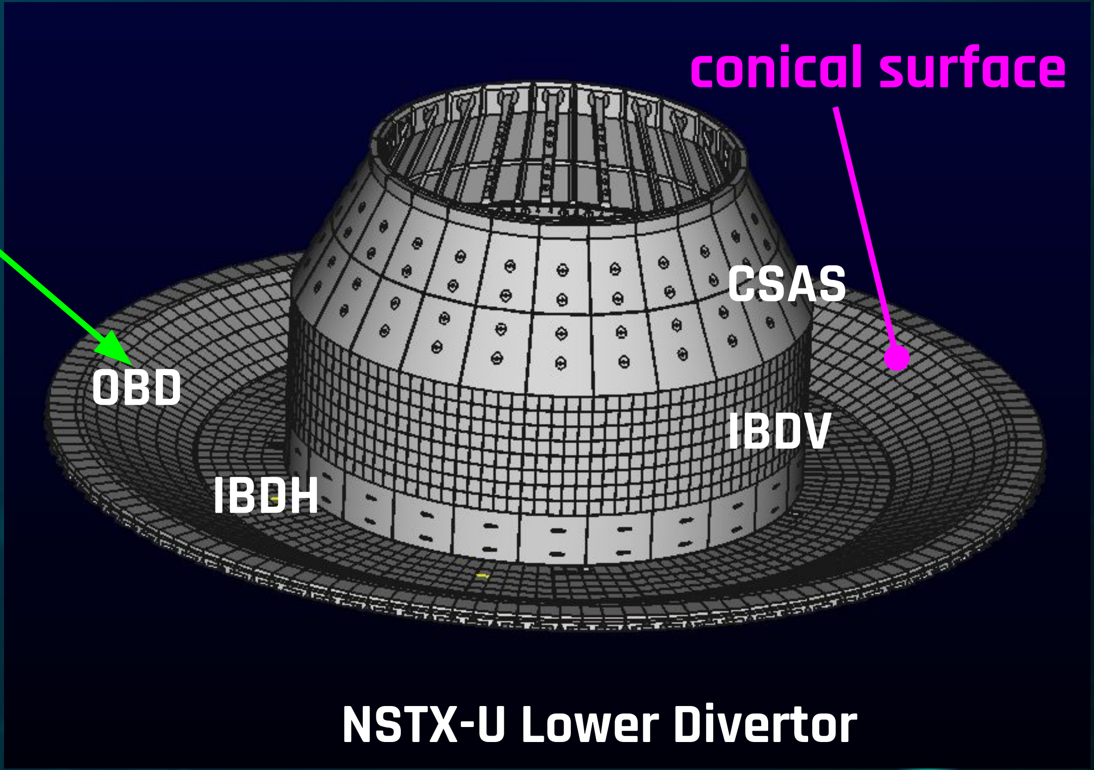
Result above from PFC WG Memo 016 pg. 4:
https://nstx.pppl.gov/DragNDrop/Working_Groups/PFCR/memos/PFCR-MEMO-016-00.pdf

First, an example from recent events at NSTX-U...

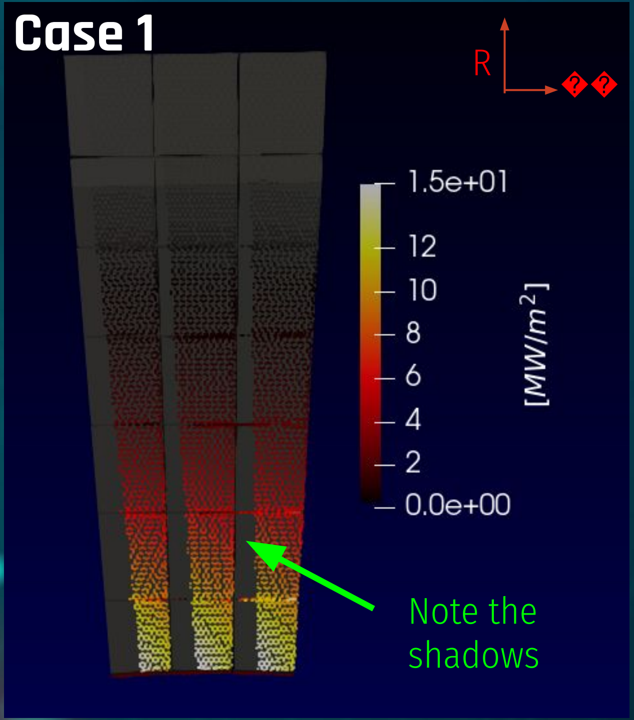
OutBoard Divertor (OBD) tile has complicated 3D geometry and is aligned to conical plane





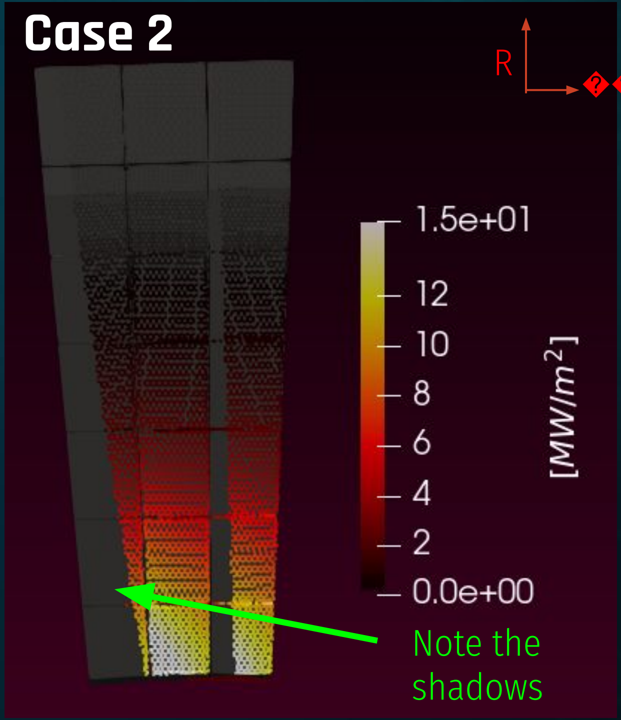


Stark contrasts in heat footprint can arise from discharges with identical plasmas



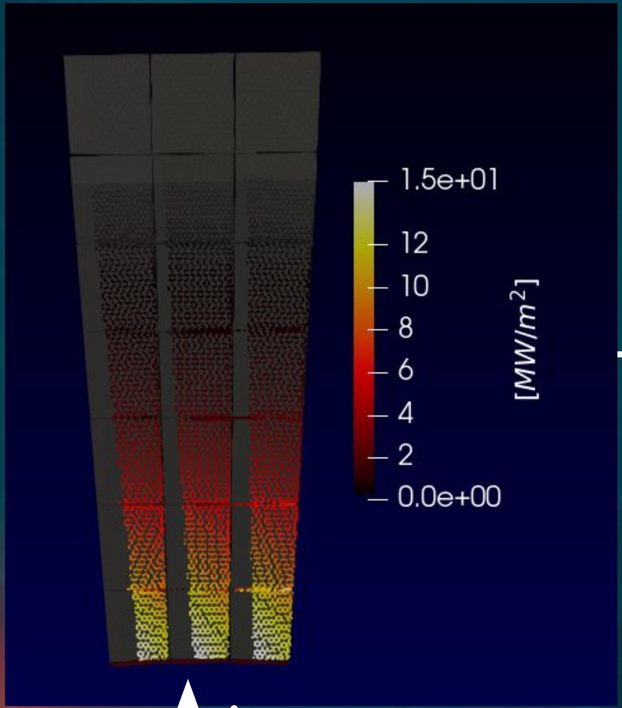
Identical:

- Equilibrium
- Input Variables
- Physics models
- Divertor Location

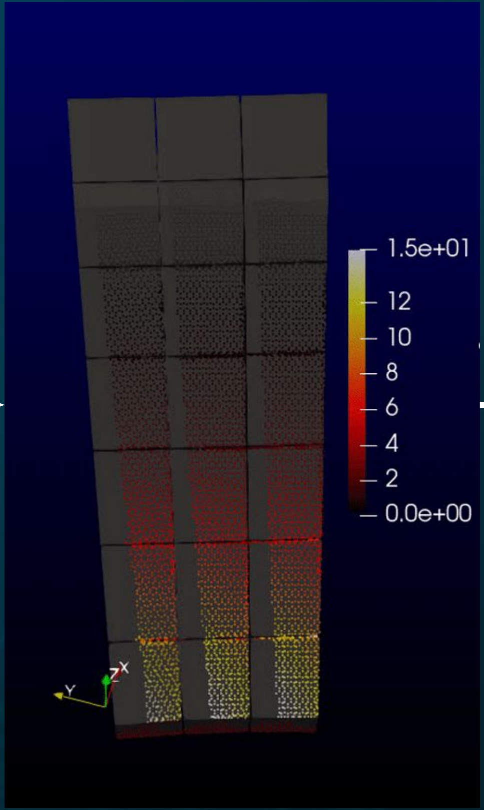


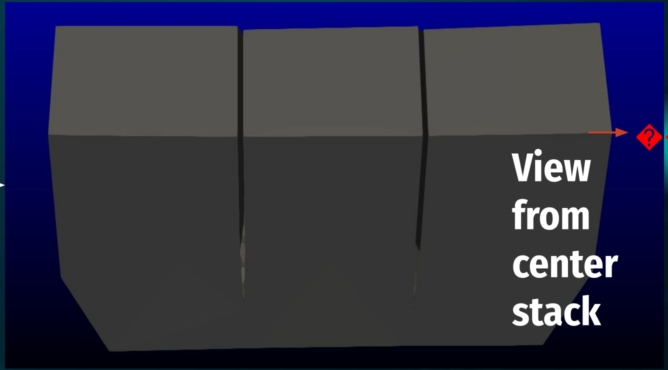
What is the source of the difference in heat loads between these two cases?

Change of perspective to find the difference…

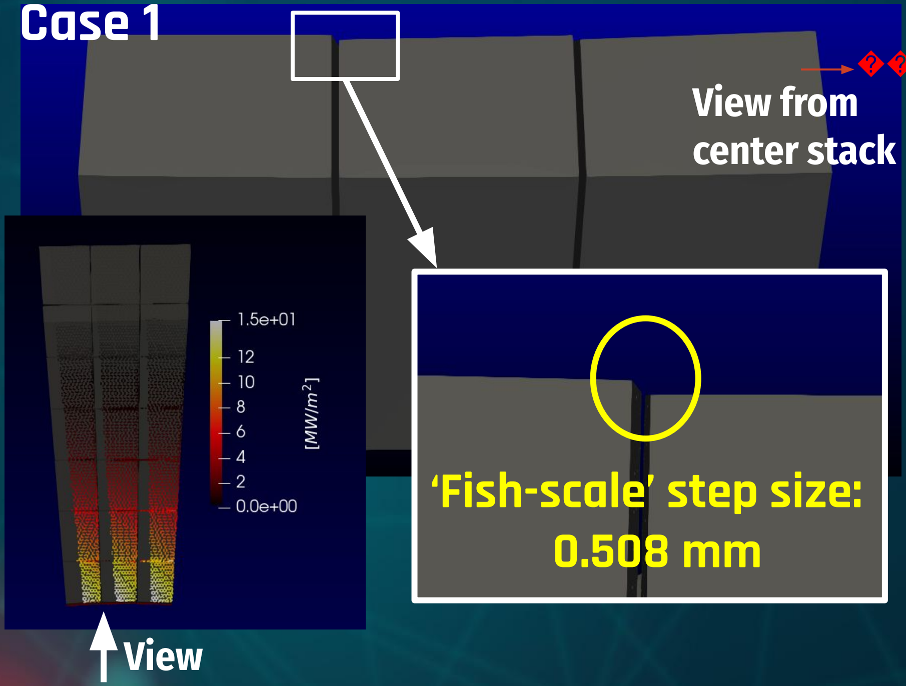


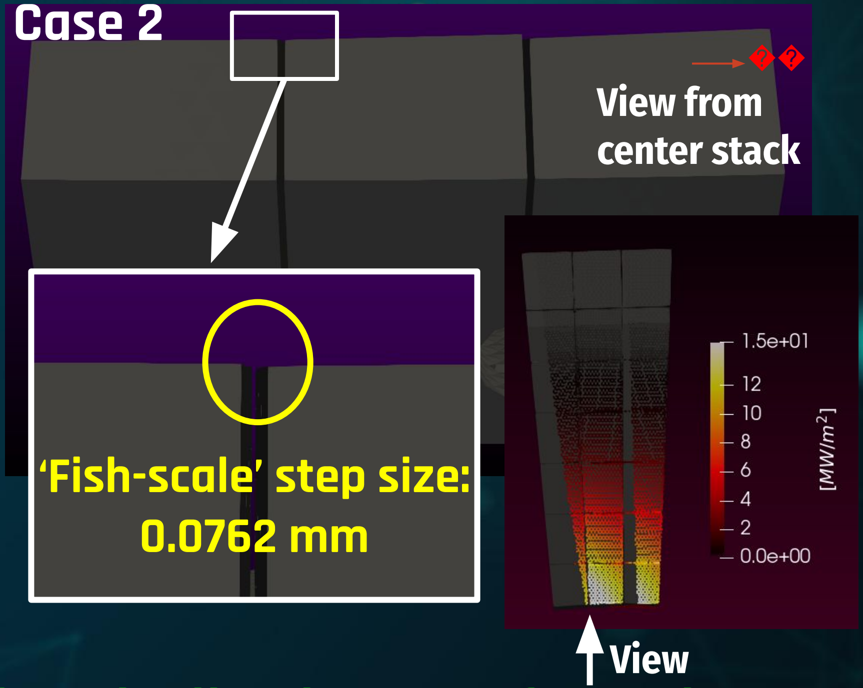
View





Small changes to PFC geometry can have a significant impact on heat flux footprint

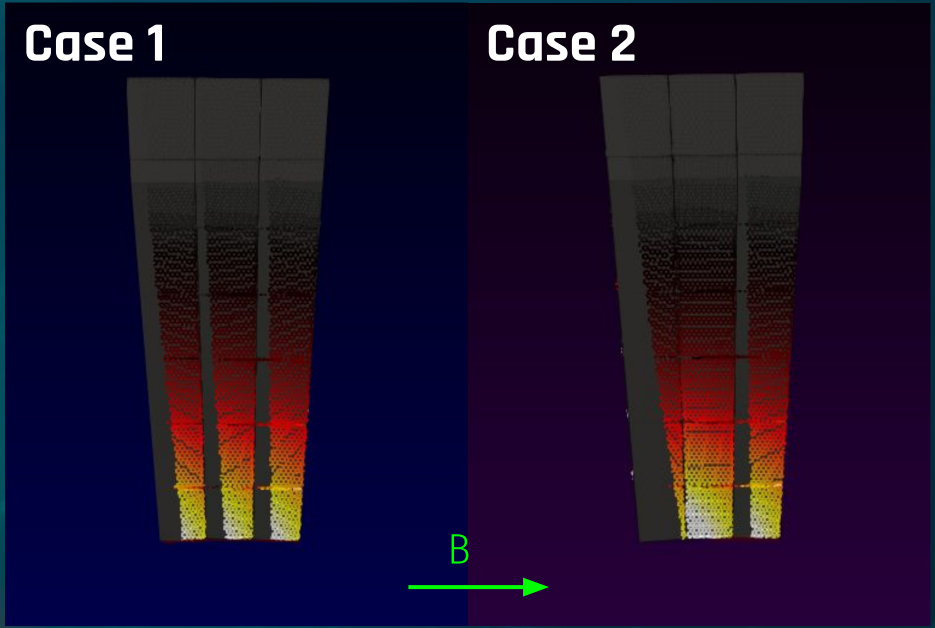


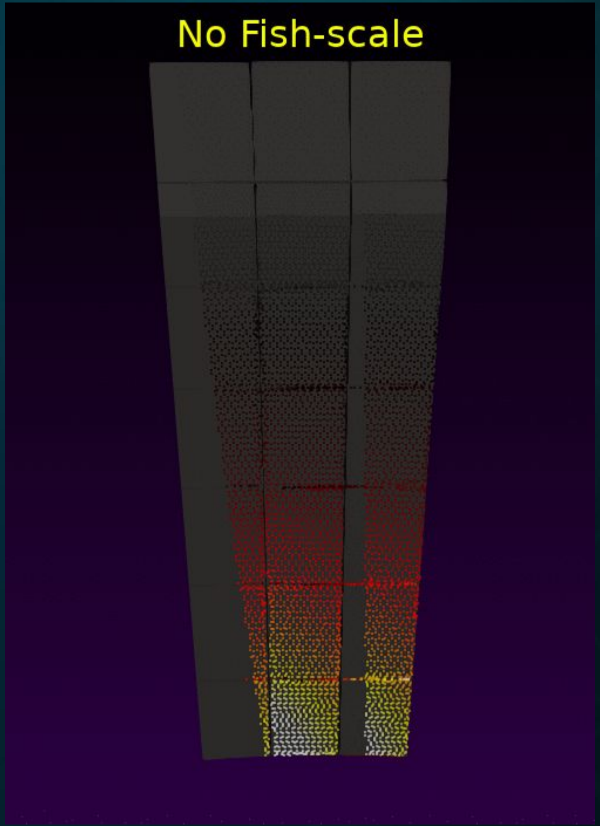


Change of 0.4318 mm in step size drastically alters HF footprint!

This corresponds to a mass Δ of ~5g carbon per tile!

Fish-scales create magnetic shadows and ‘reassign’ power to new locations





Case 1 uses fish scale to redeposit power more uniformly

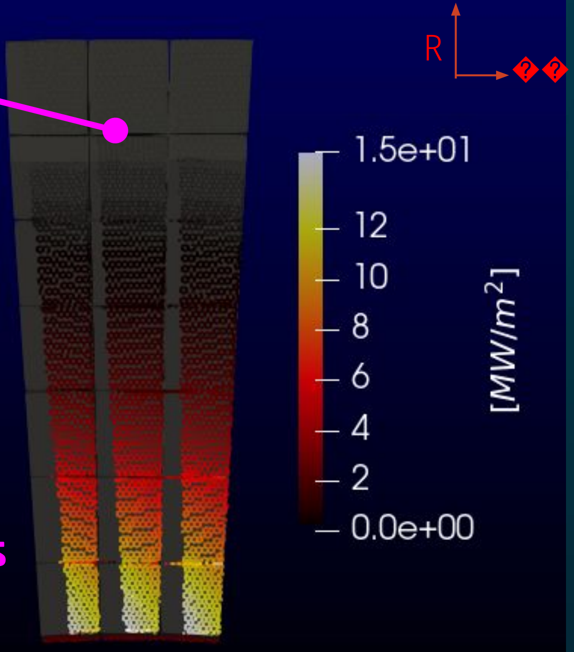
Changing heat flux footprints on PFCs has thermal consequences…

Case 1

Fish-scale size: 0.508 mm

Peak Heat Flux: 15.6 MW/m^2

Sublimation T reached @ ~1.25s

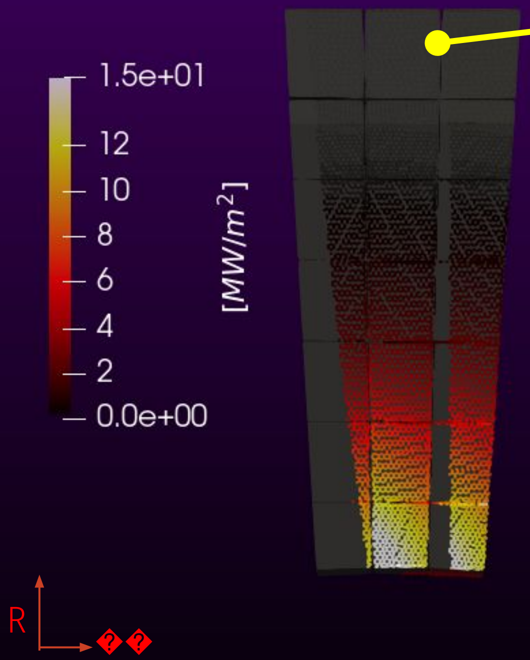


Case 2

Fish-scale size: 0.0762 mm

Peak Heat Flux: 17.5 MW/m^2

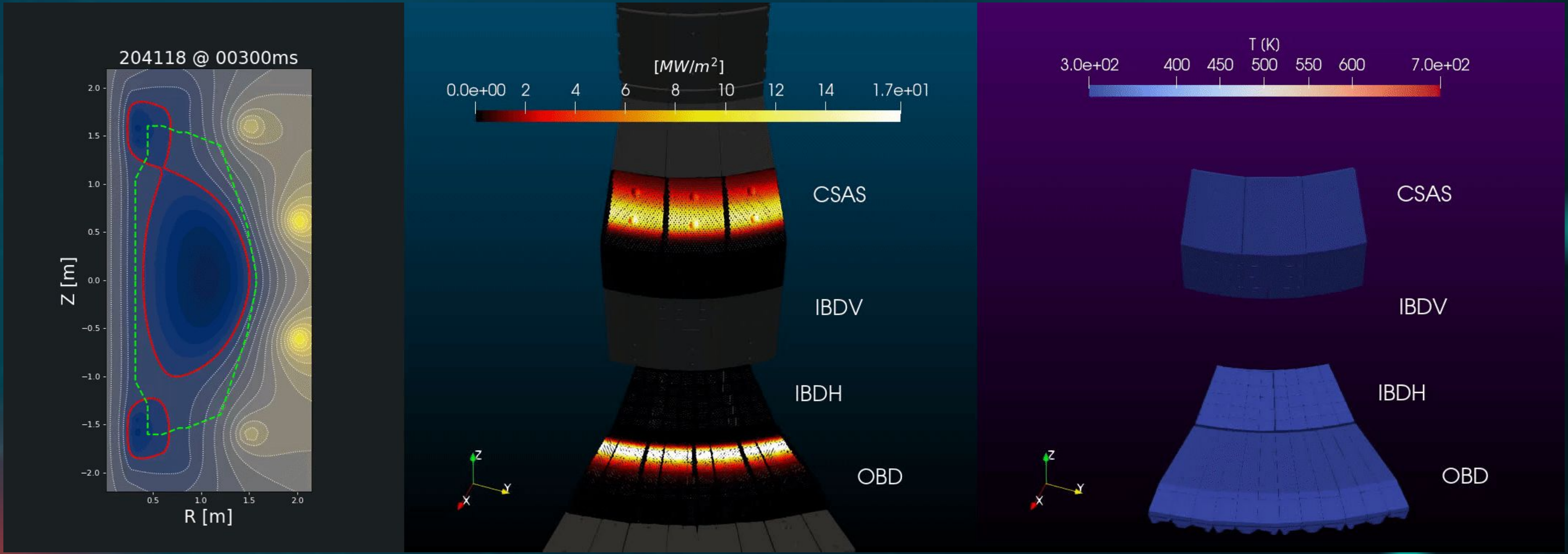
Sublimation T reached @ ~1s



Results shown for $P_{SOL,\ LowerOuter}$ = 4 MW using PFC WG Memo 010 Case 1.1 (g116313.00850.NfHz0+_0)

Time varying output simulated with HEAT
Diverted Example: 204118@300-1000ms

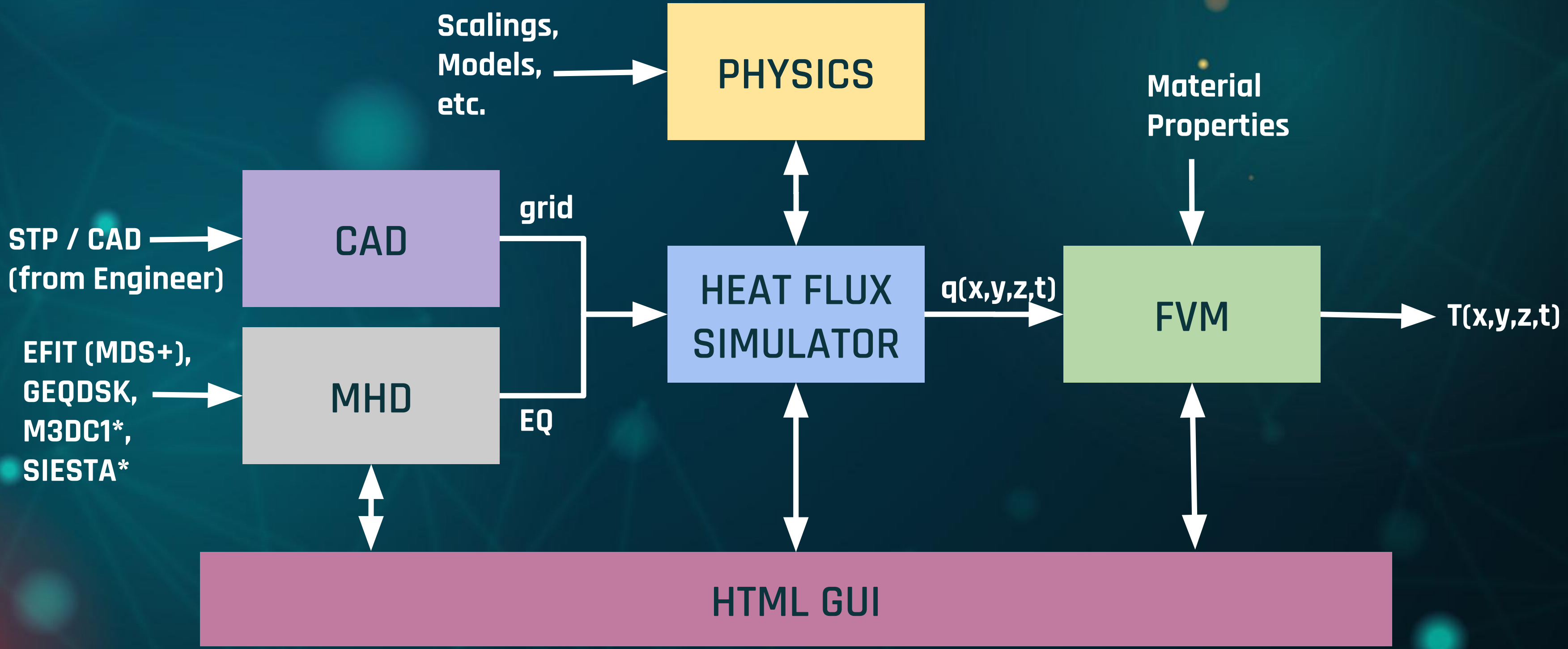
30° Section of Lower Divertor



HEAT Overview

02

HEAT couples disparate computational modules into a single integrated (open source) python suite



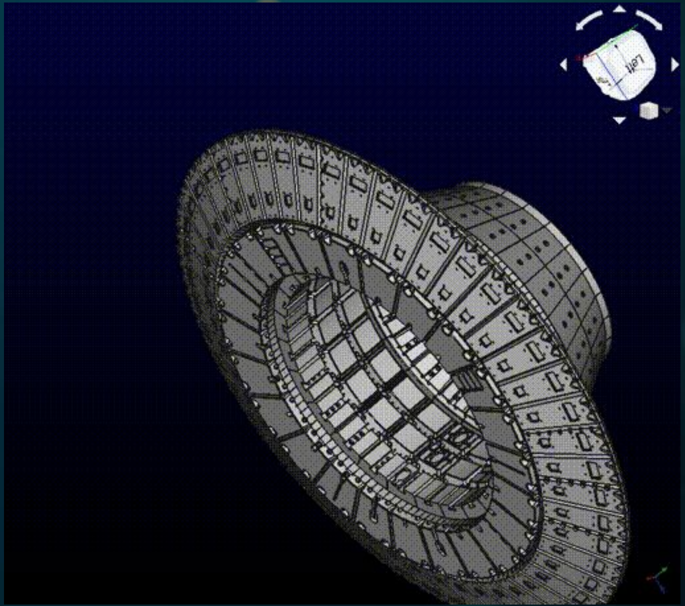
* = partially implemented

HEAT has a full-blown parametric CAD program built into the CAD python module

FreeCAD is an open source parametric CAD modeler. https://www.freecadweb.org/

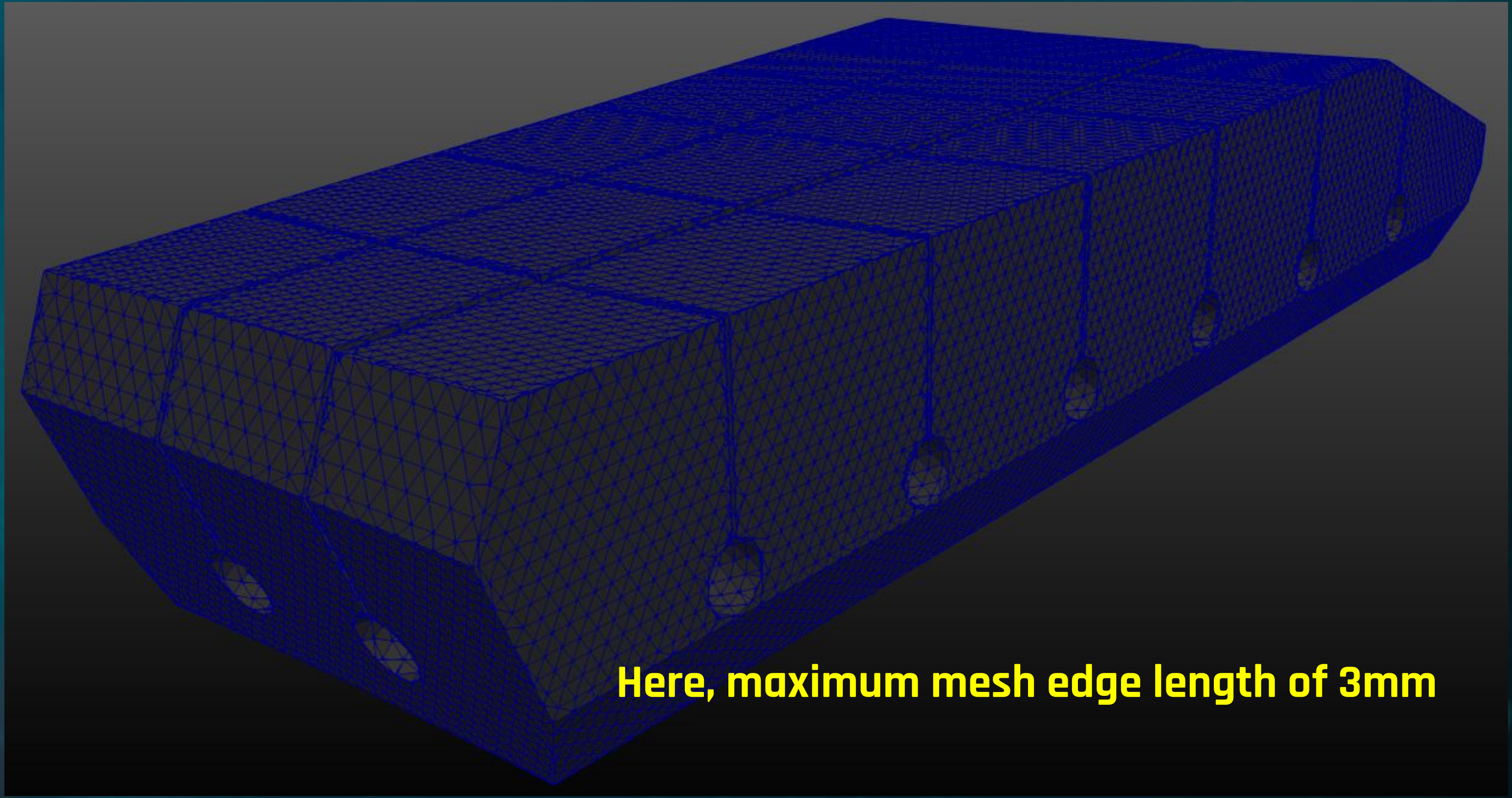
HEAT's python wrapper uses FreeCAD for:

- Interacting with STP files
- Filtering large CAD files by part #
- Meshing each PFC (STL)
- Coordinate permutations
- Digging through assemblies



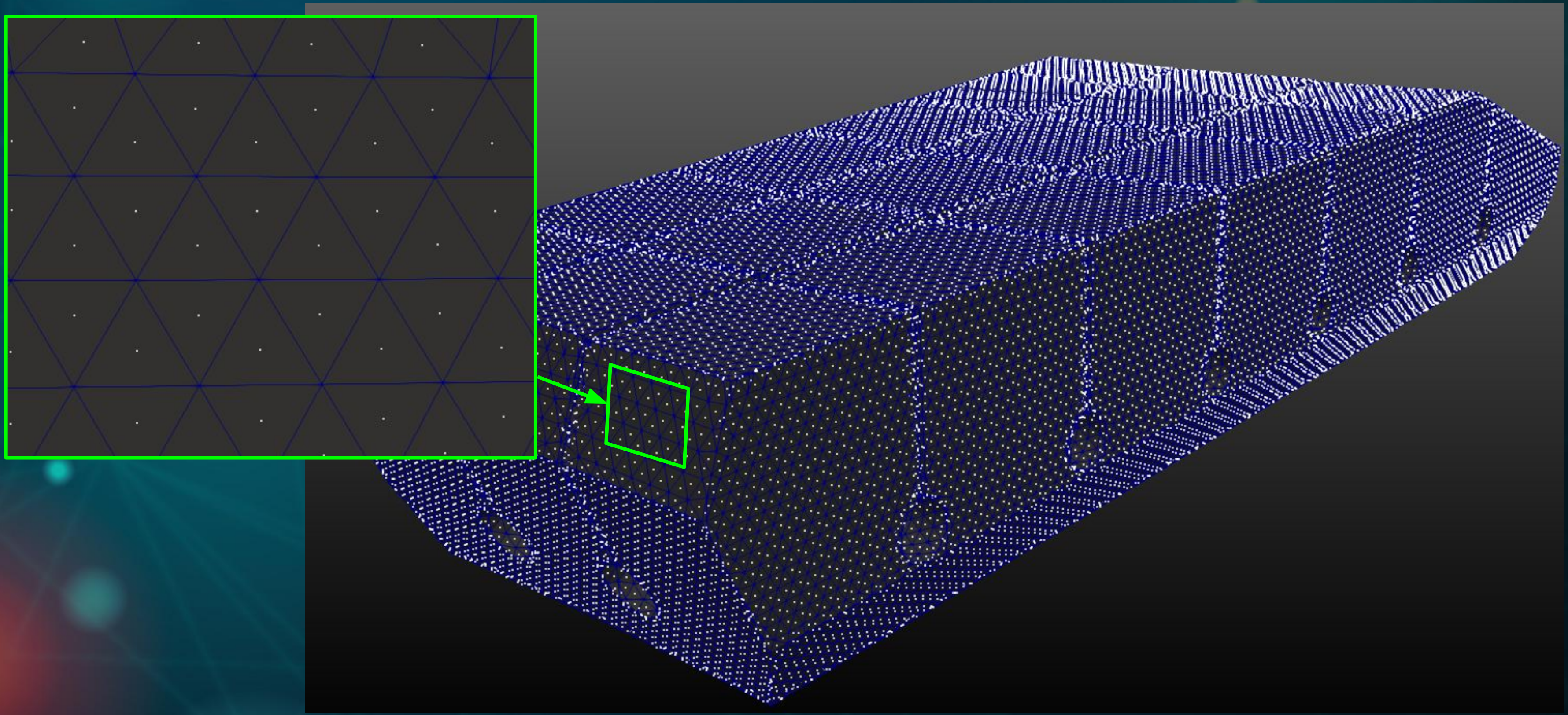
FreeCAD
Your own 3D parametric modeler

HEAT converts parametric surfaces into STL meshes in the CAD module



Here, maximum mesh edge length of 3mm

A point cloud of points is generated using each mesh center for calculations



Heat flux is calculated at divertor surface points incorporating flux expansion and incident angle

$$q_{div} = q_{||0} \cdot \hat{q}_{||}(\psi) \cdot \frac{B_{div}}{B_{omp}} \cdot (\hat{b} \cdot \hat{n})$$

Divertor heat flux

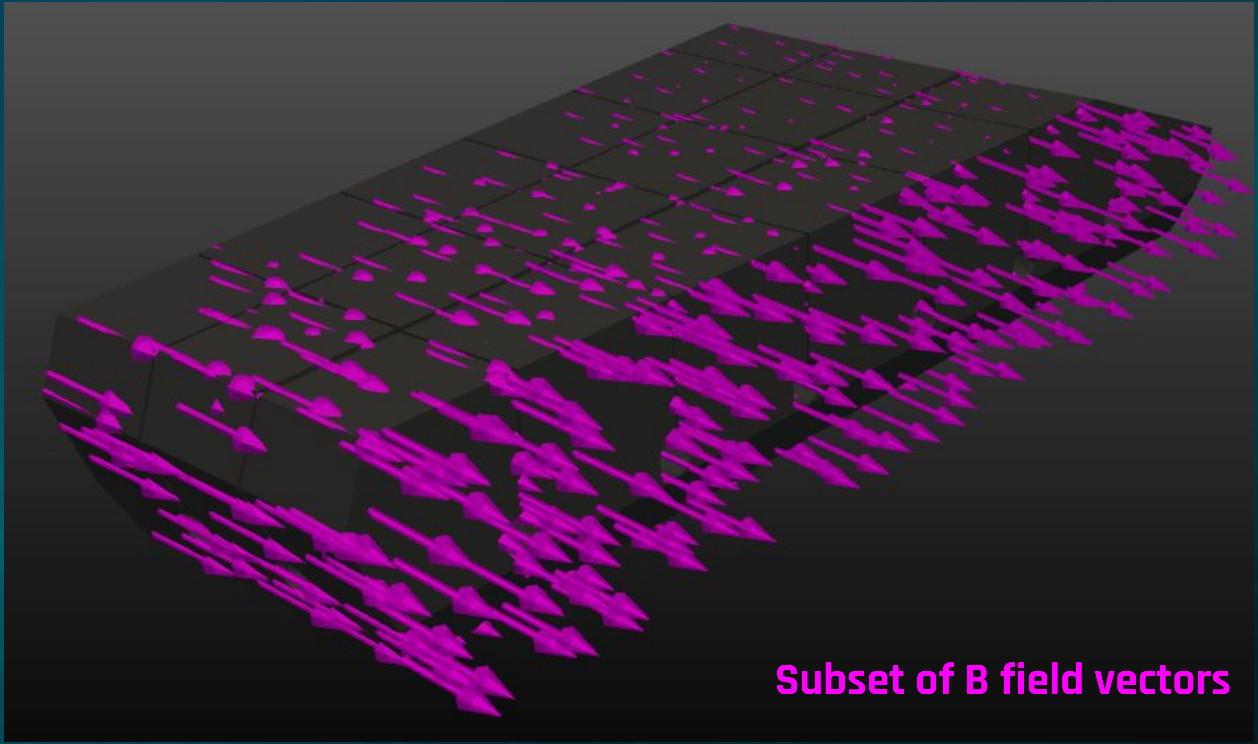
Scaling coefficient

User defined heat flux profile (here as function of poloidal flux)

Flux expansion effect

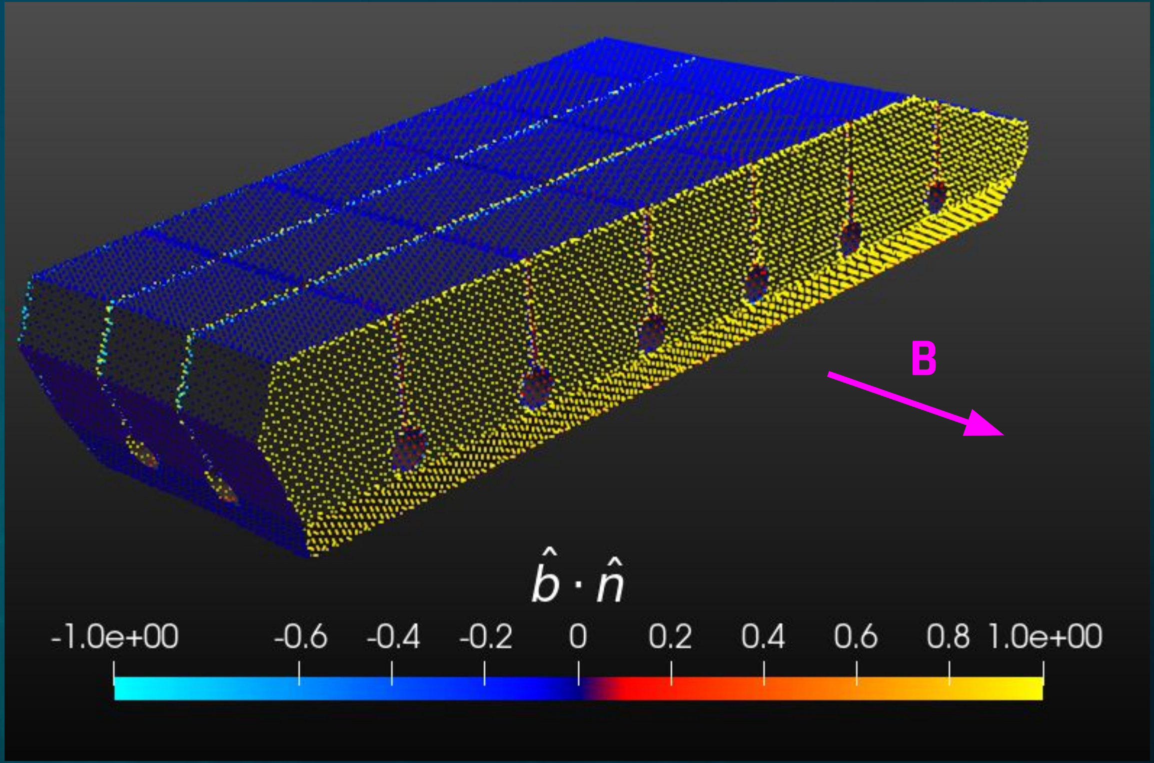
Field line incident angle effect

Magnetic field is calculated at each point



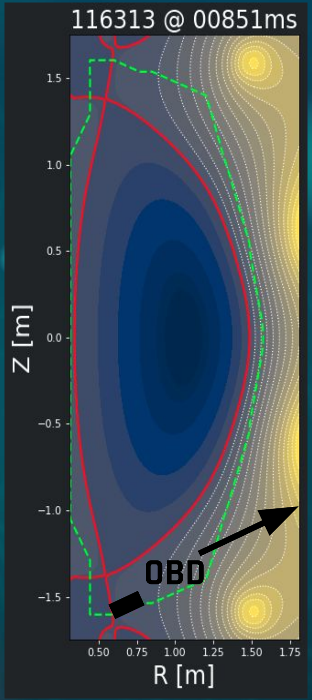
$$q_{div} = q_{||0} \cdot \hat{q}_{||}(\psi) \cdot \boxed{\frac{B_{div}}{B_{omp}}} \cdot (\hat{b} \cdot \hat{n})$$

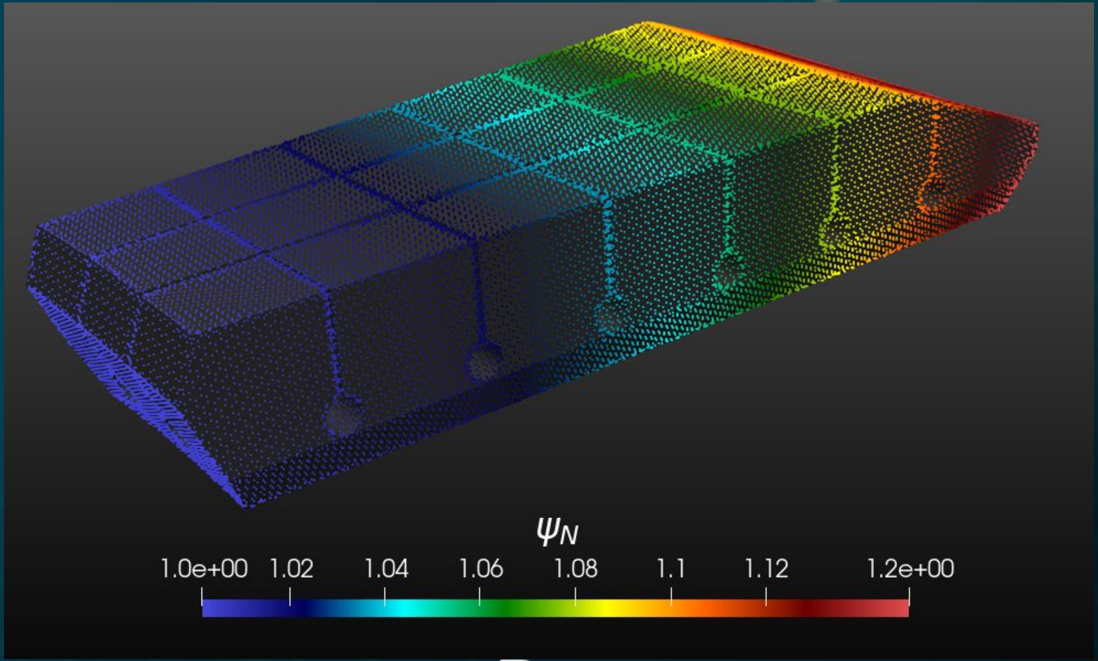
Incident angle effect is calculated at each point



$$q_{div} = q_{||0} \cdot \hat{q}_{||}(\psi) \cdot \frac{B_{div}}{B_{omp}} \cdot (\hat{b} \cdot \hat{n})$$

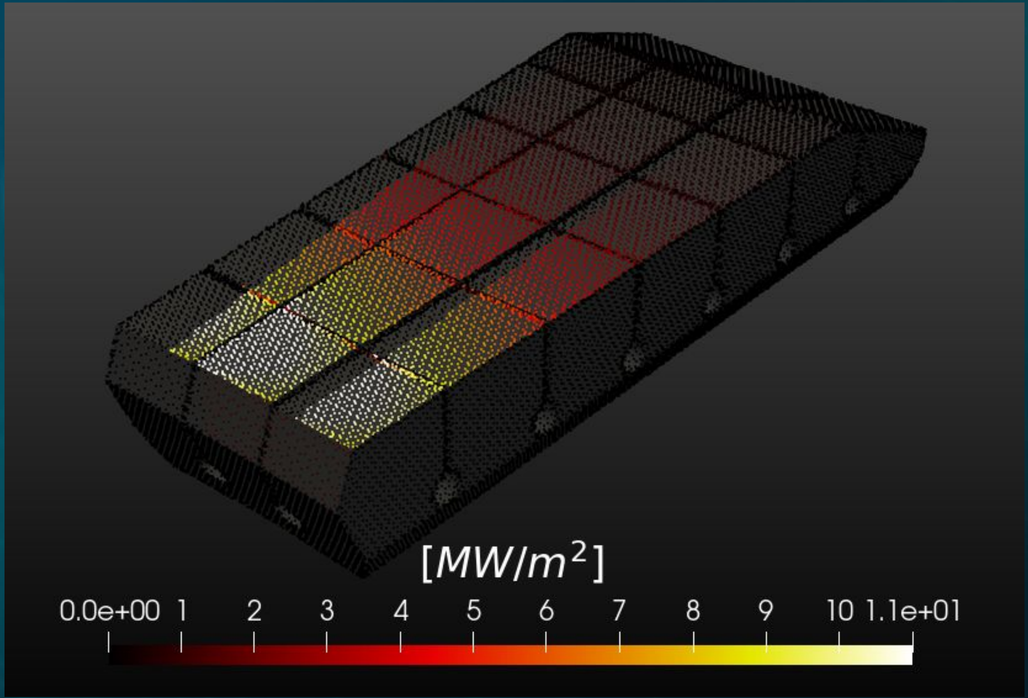
Poloidal flux (ψ) is calculated at each point, then $q_{||}$ calculated from user defined profile





$$q_{div} = \boxed{q_{||0} \cdot \hat{q}_{||}(\psi)} \cdot \frac{B_{div}}{B_{omp}} \cdot (\hat{b} \cdot \hat{n})$$

Heat flux is calculated across divertor surface by combining all terms



$$\boxed{q_{div}} = q_{||0} \cdot \hat{q}_{||}(\psi) \cdot \frac{B_{div}}{B_{omp}} \cdot (\hat{b} \cdot \hat{n})$$

Easy to identify shadowed points are determined using backface culling

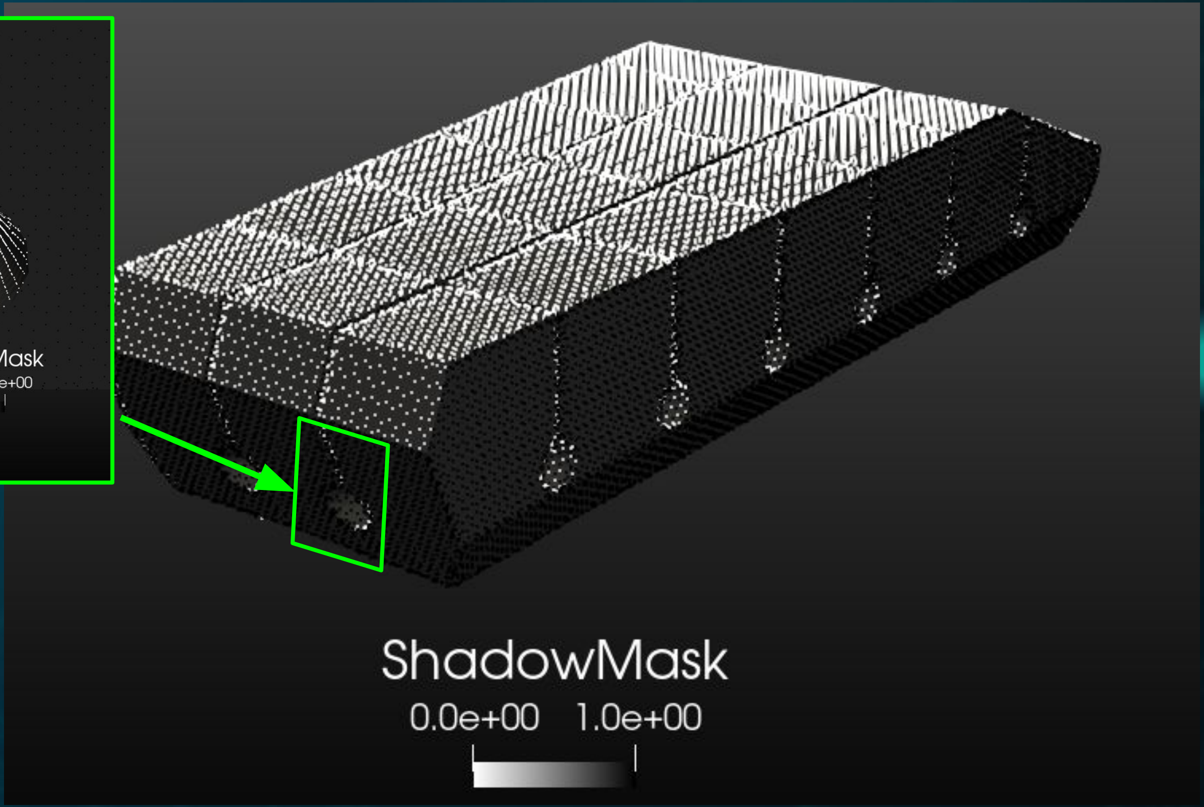
Backface culling (BC) is a technique from computer graphics and rendering

BC used in HEAT to identify potential loaded faces for further checking

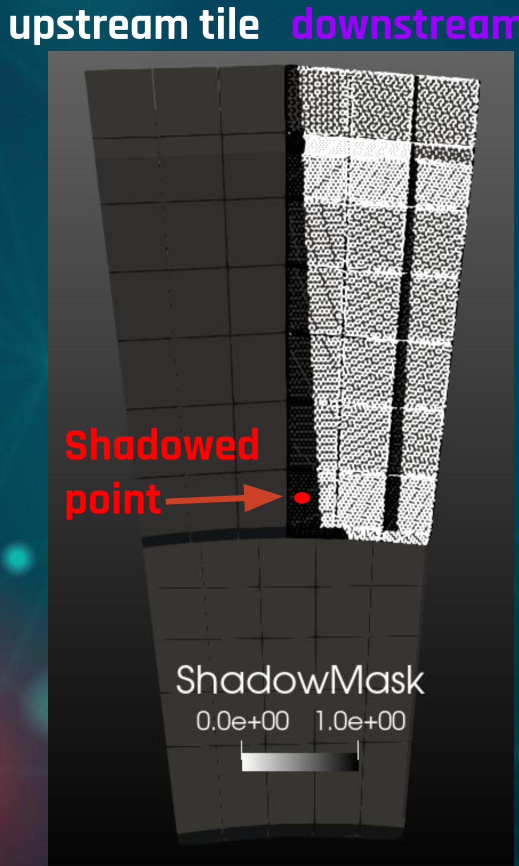
Face is culled when:

$$(\hat{b} \cdot \hat{n}) \cdot \text{mapDir} > 0$$

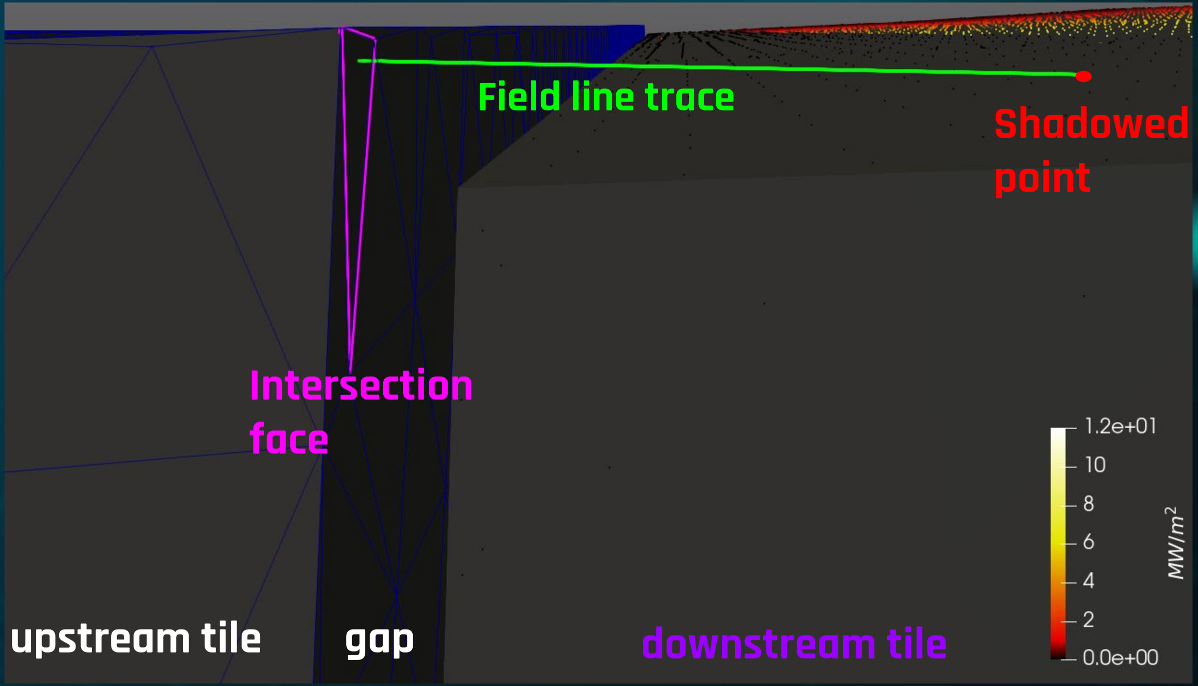
User defined +/- 1.0 for each PFC



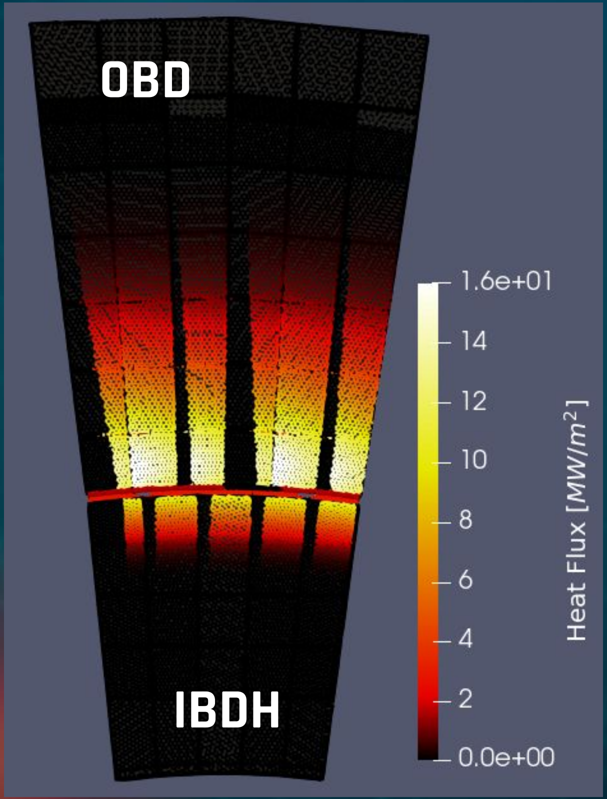
A. Wingen's MAFOT code traces field lines from mesh points to identify shadowed faces

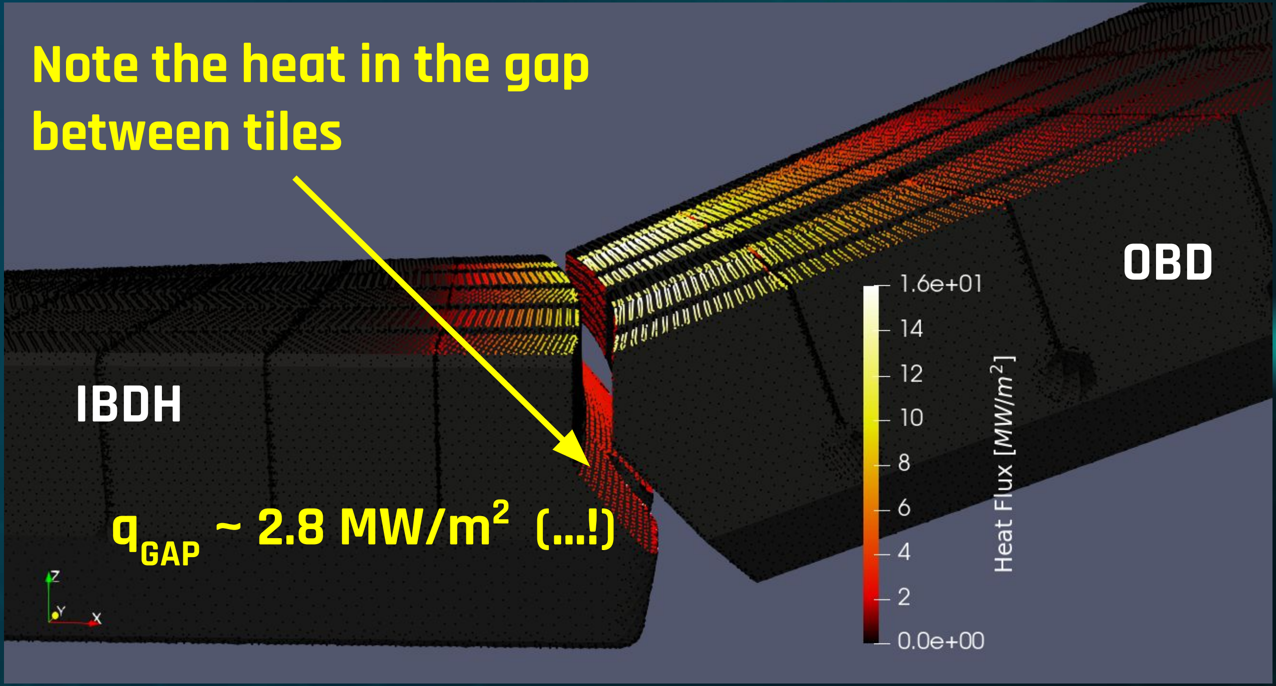


Shadowed points identified by checking for intersections with other mesh elements



A. Wingen's (ORNL) MAFOT code can also be used to illustrate heat loading in toroidal gaps



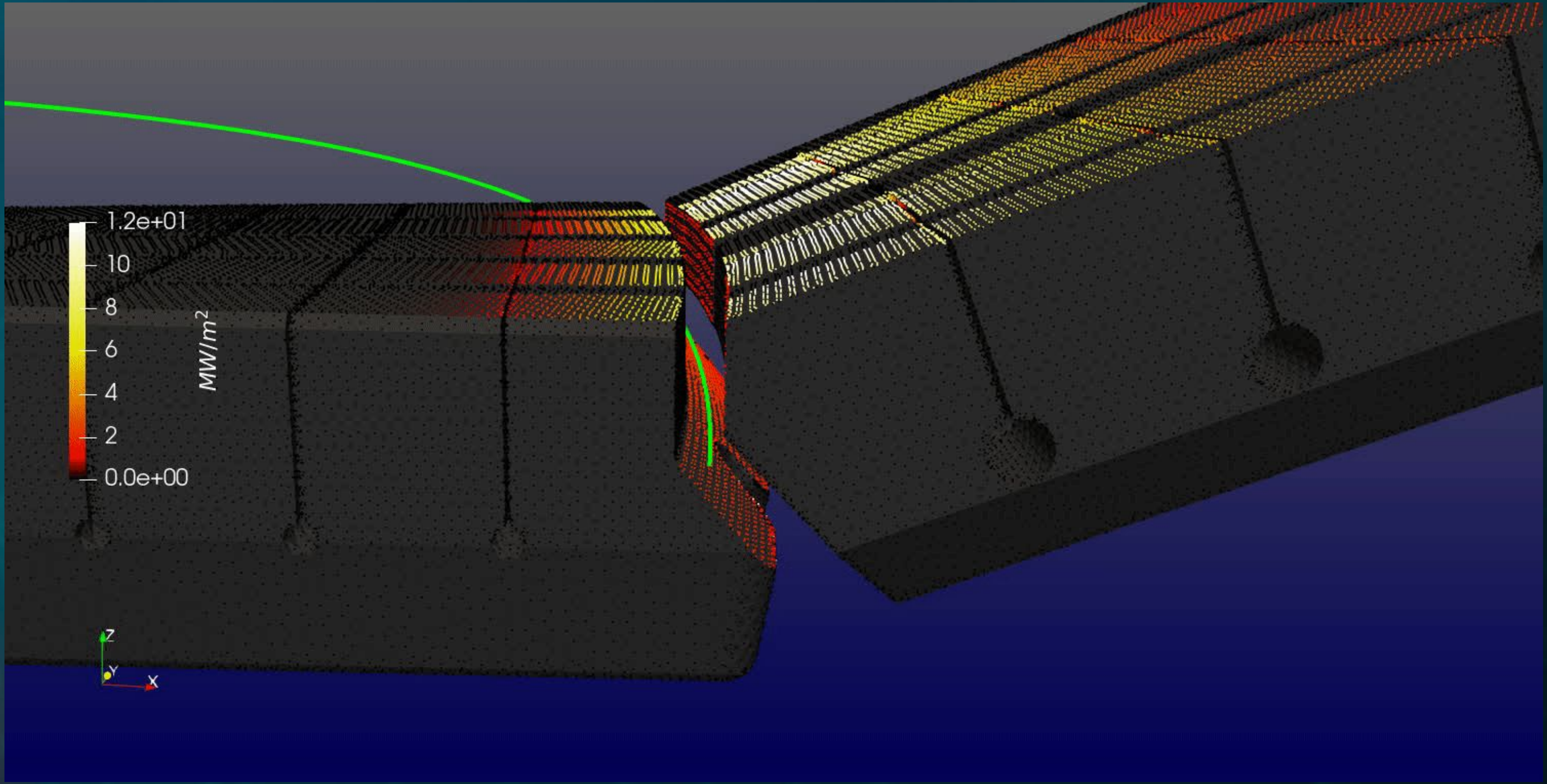


HF Resolution = 3 mm, Wall Clock Time = 483 s

P_{in} = 2.8 MW, P_{out} = 2.903 MW

Memo 010 Case 1.21 (g116313.00851.NfHz0+_k)

A. Wingen's (ORNL) MAFOT code can also be used to illustrate heat loading in toroidal gaps



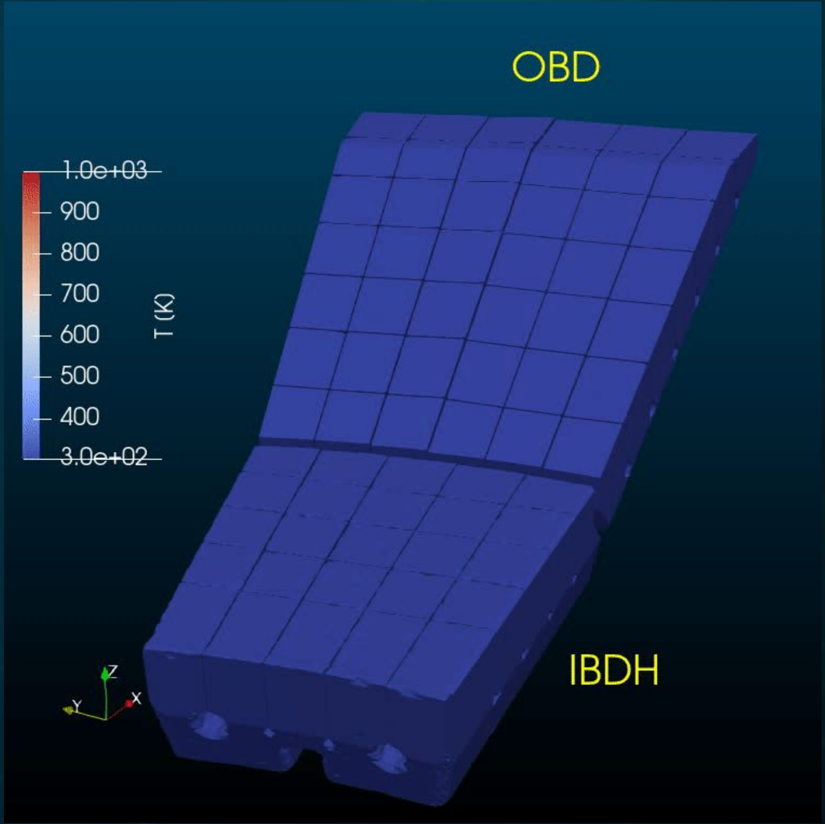
HEAT uses openFOAM for Finite Volume Methods (FVM) and Computational Fluid Dynamics (CFD)

openFOAM is an open source package for:

- Continuum Mechanics
- Finite Volume Methods
- Developing PDE solvers
- Creating FV meshes
  https://www.openfoam.com/releases/openfoam-v1712/

HEAT uses openFOAM to:

- Create volume meshes from STLs
- Map heat flux to surfaces
- Solve heat diffusion equation
- Use material dependent T properties

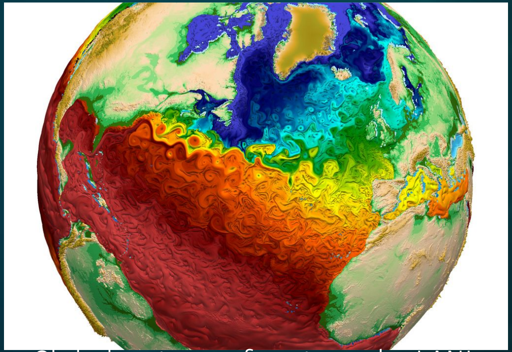


ParaVIEW is under the hood of HEAT's powerful visualization algorithms

ParaVIEW is an open source package (originally from LANL) for:

- Visualization
- Data probing, Interaction, Virtual Reality
- Rendering movies
- Parallel / cluster rendering (terascale)

https://www.paraview.org/



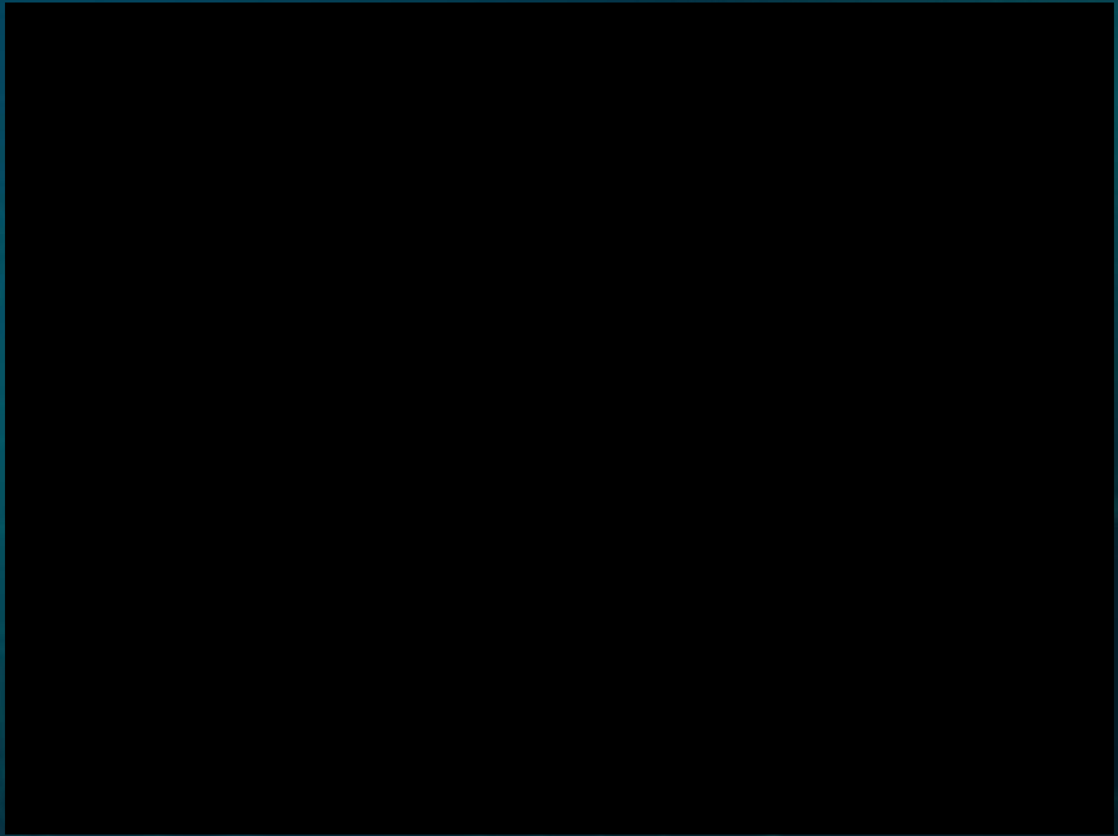
Global water surface temp by LANL

HEAT uses ParaView to:

- Visualize all data
- Serve HTML clients via iFrames
- Render movies

Images from ParaVIEW website gallery

HEAT is accessible to anyone on the LAN via it's HTML5 GUI built with DASH / plotly



HEAT has a wide domain of tokamak physics modules in the requirements

Completed:

- Time varying heat fluxes
- Axisymmetric
- Nonaxisymmetric
- 3D PFCs
- Optical Approximation
- Sweeping
- Limiters
- Attached Divertor

In Progress:

- 3D Fields
- Power Sharing with d_{Rsep}

Not Yet Completed:

- Gyro Orbits
- Detached Divertor
- ELMs
- Disruptions*
- Energetic particle losses*

* = outside PhD scope

NSTX-U PFC Analysis

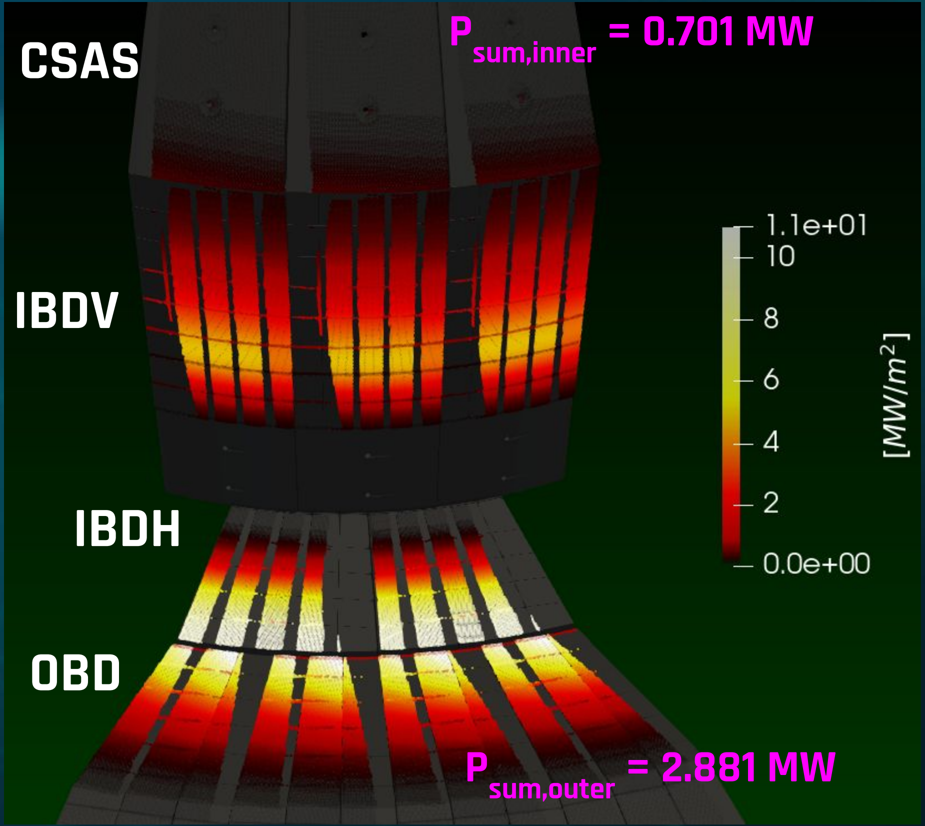
03

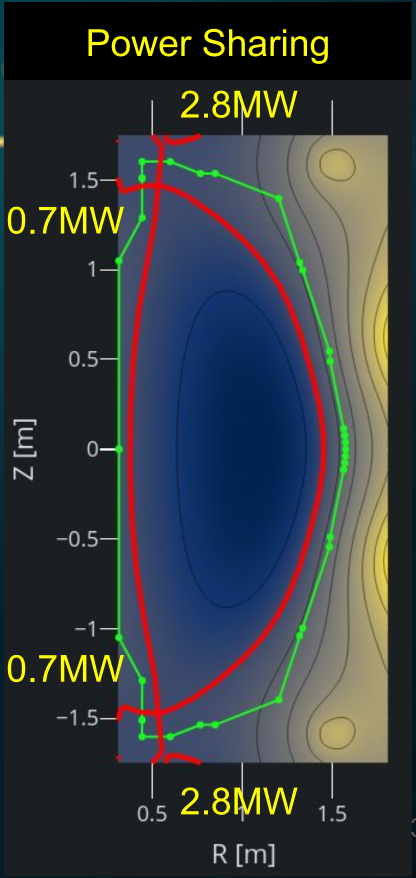
Memo 010 Case 1.1 is a static discharge with desired pulse length of 5s

P_{inj} = 10.0 MW
f_{rad} = 0.3
B_T = 1T
I_p = 2MA
∠ @ peak = 0.86°

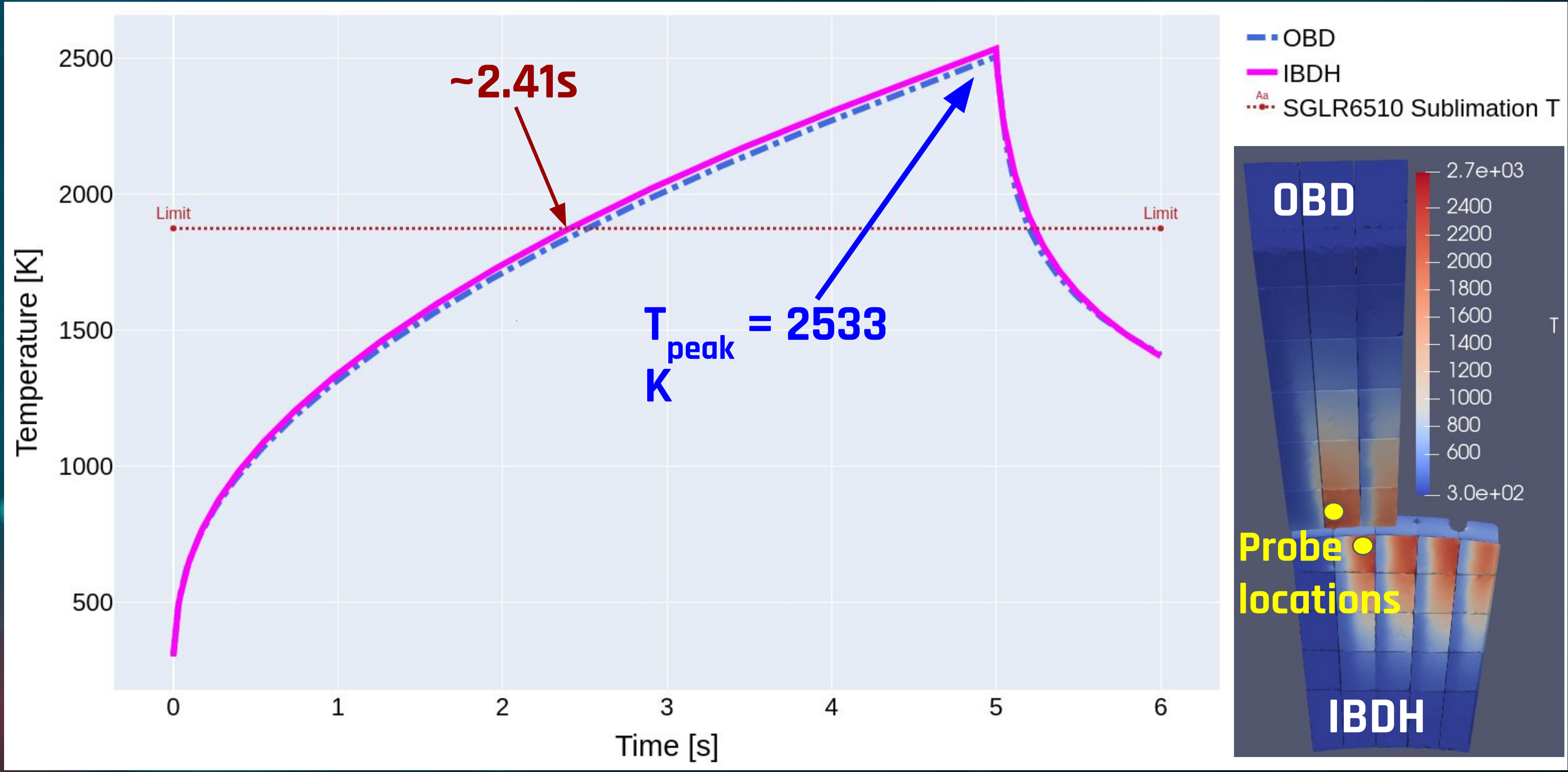
Profile:
Gaussian Spreading
λ_q = 1.903mm (Eich)
S = 0.914 mm (Makowski)

Max Mesh Edge Length:
3 mm

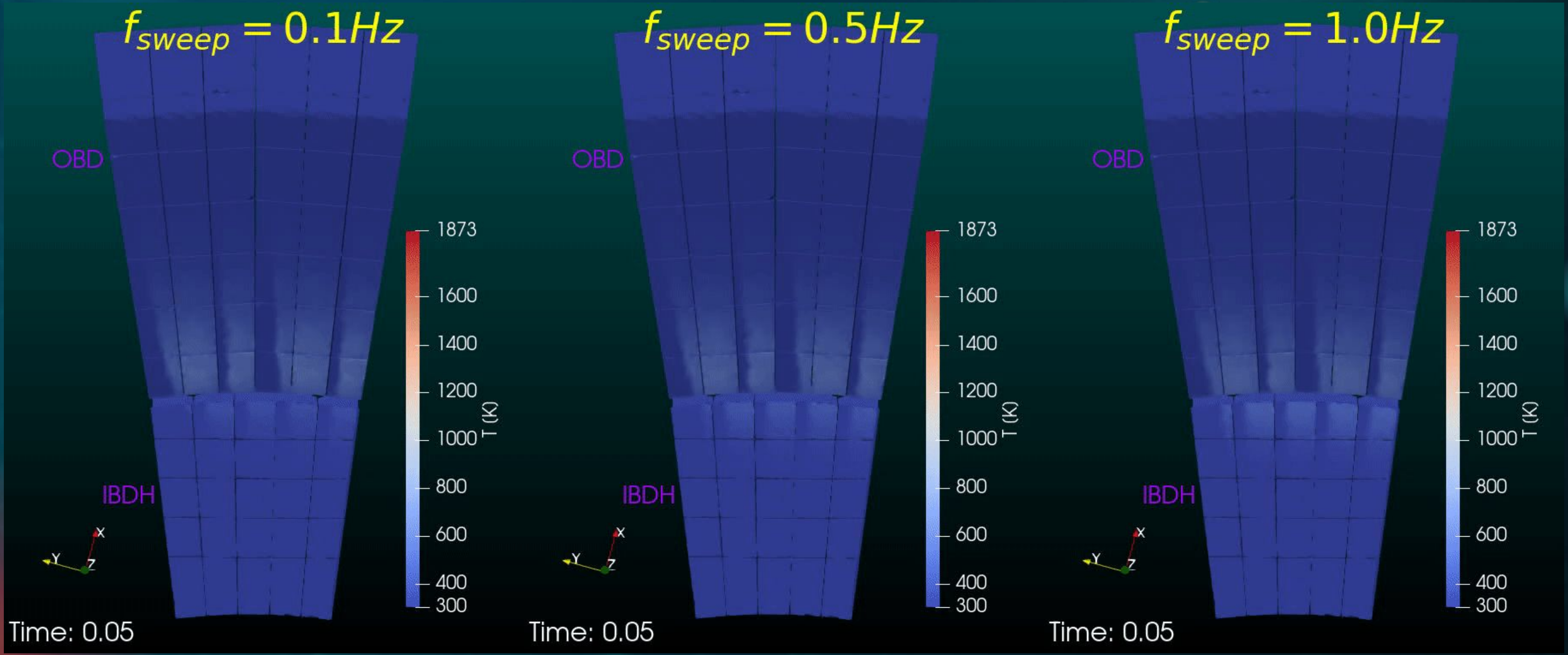




Memo 010 Case 1.1 can NOT be run for the 5s desired steady state duration!

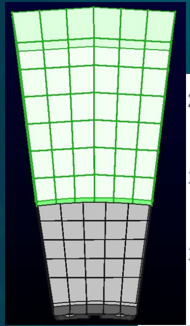


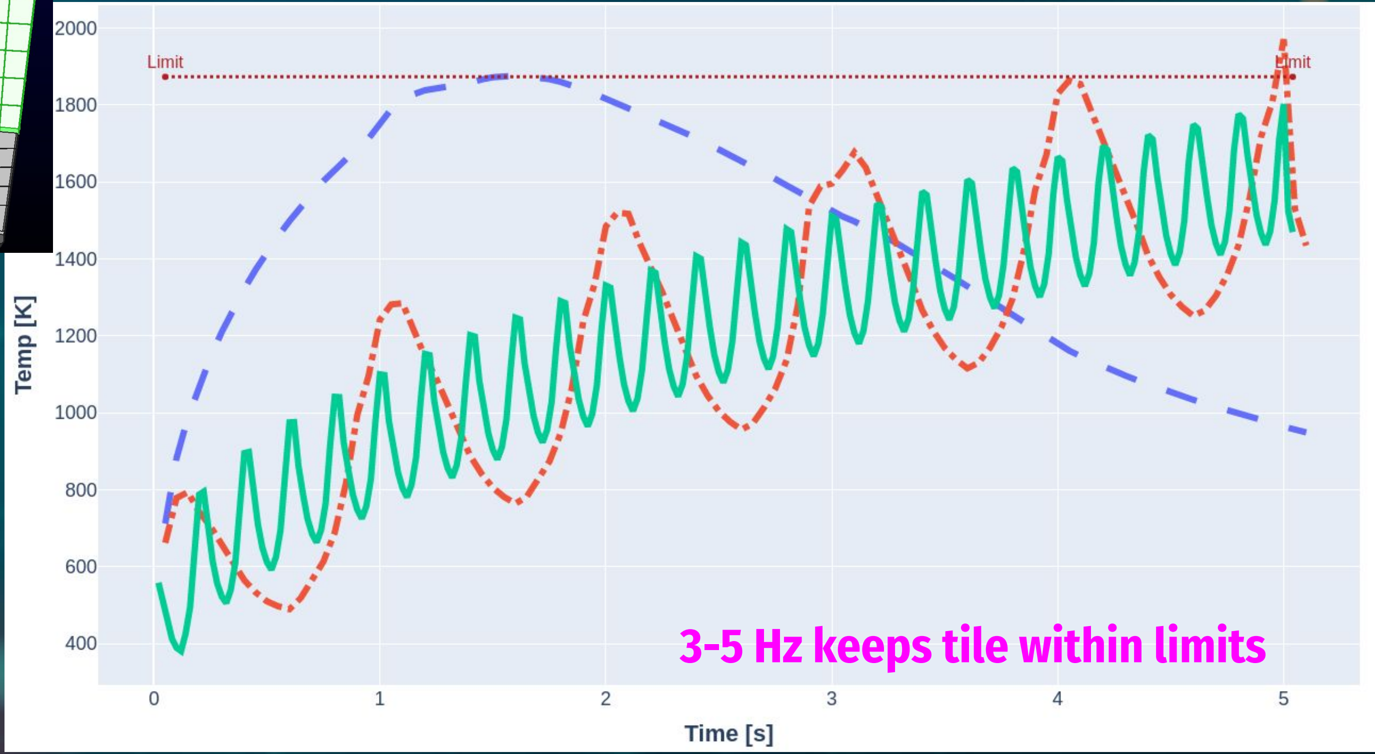
Strike point sweep frequency (f_{sweep}) can be used to reduce T_{peak} on outer divertor tiles



Memo 010 Case 2 Scan 4 (g135111.00500_k2.<#>), P_{inj} = 10MW, f_{rad} = 0.3, B_T = 1T, I_p=2MA, DN, Res_{HF} = 2.5mm

Strike point sweep frequency (f_{sweep}) can be used to reduce T_{peak} on Outboard Divertor (OBD)





Δt until limit:

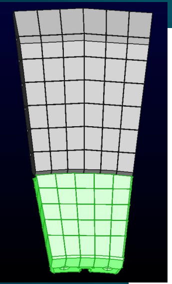
0.1Hz@1.55s

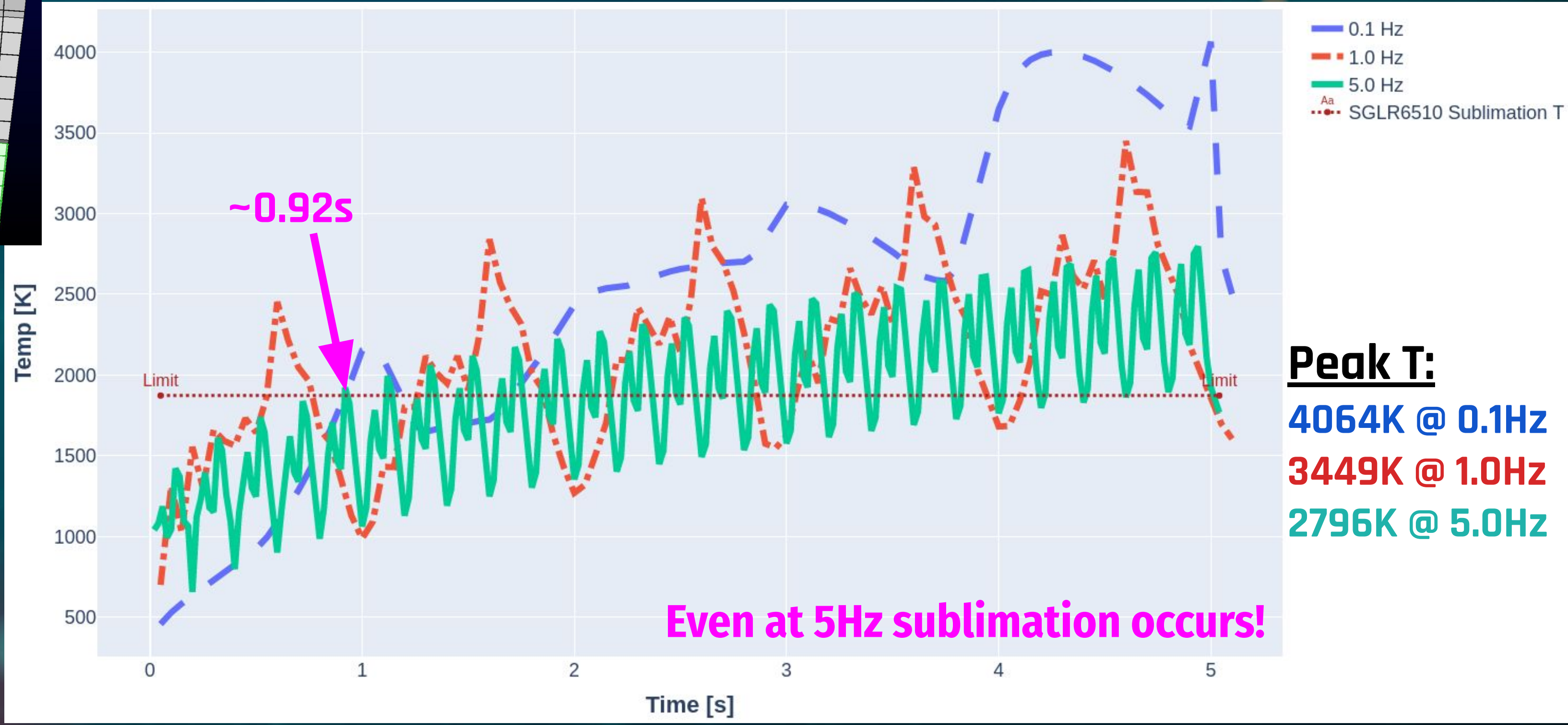
1.0Hz@4.95s

5.0Hz@>5s

Memo 010 Case 2 Scan 4 (g135111.00500_k2.<#>), P_{inj} = 10MW, f_{rad} = 0.3, B_T = 1T, I_p=2MA, DN, Res_{HF} = 2.5mm

Strike point sweep frequency (f_{sweep}) can be used to reduce T_{peak} on Inboard Divertor Horizontal (IBDH)





Peak T:

4064K @ 0.1Hz

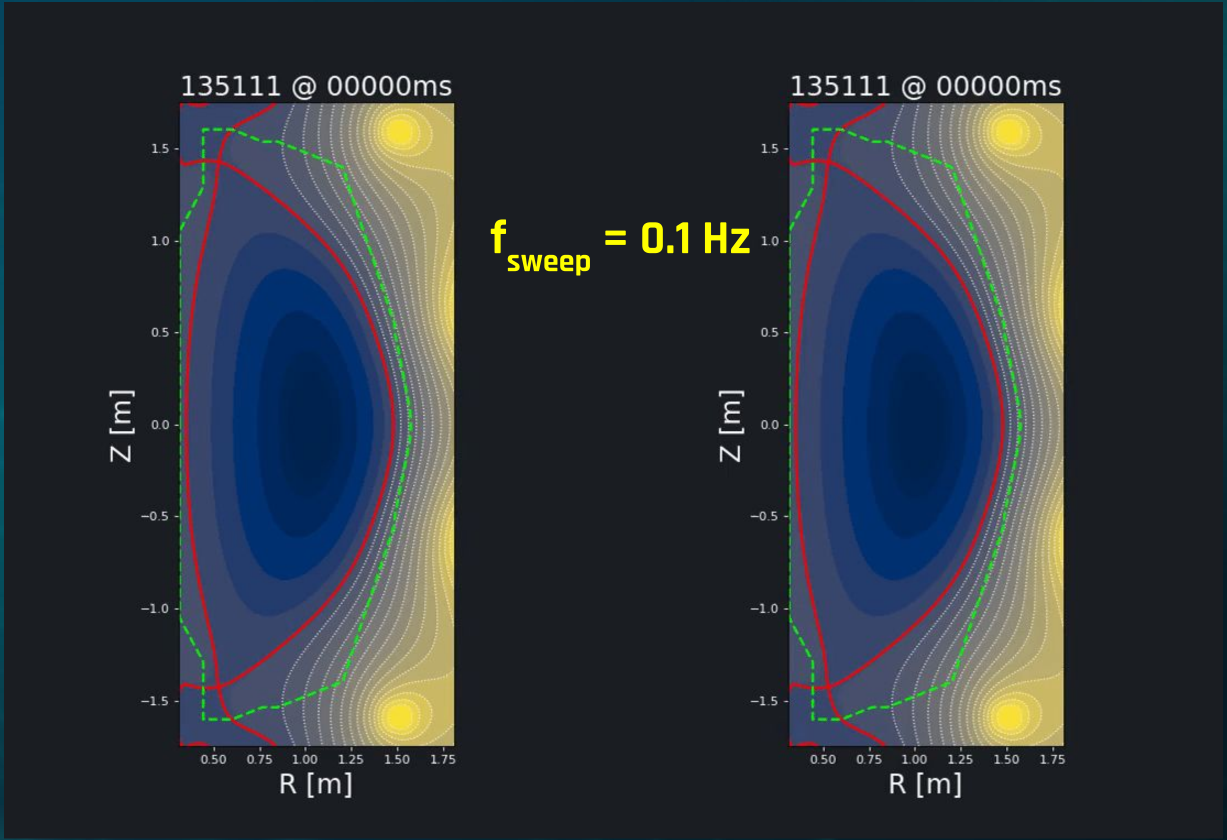
3449K @ 1.0Hz

2796K @ 5.0Hz

Memo 010 Case 2 Scan 4 (g135111.00500_k2.<#>), P_{inj} = 10MW, f_{rad} = 0.3, B_T = 1T, I_p=2MA, DN, Res_{HF} = 2.5mm

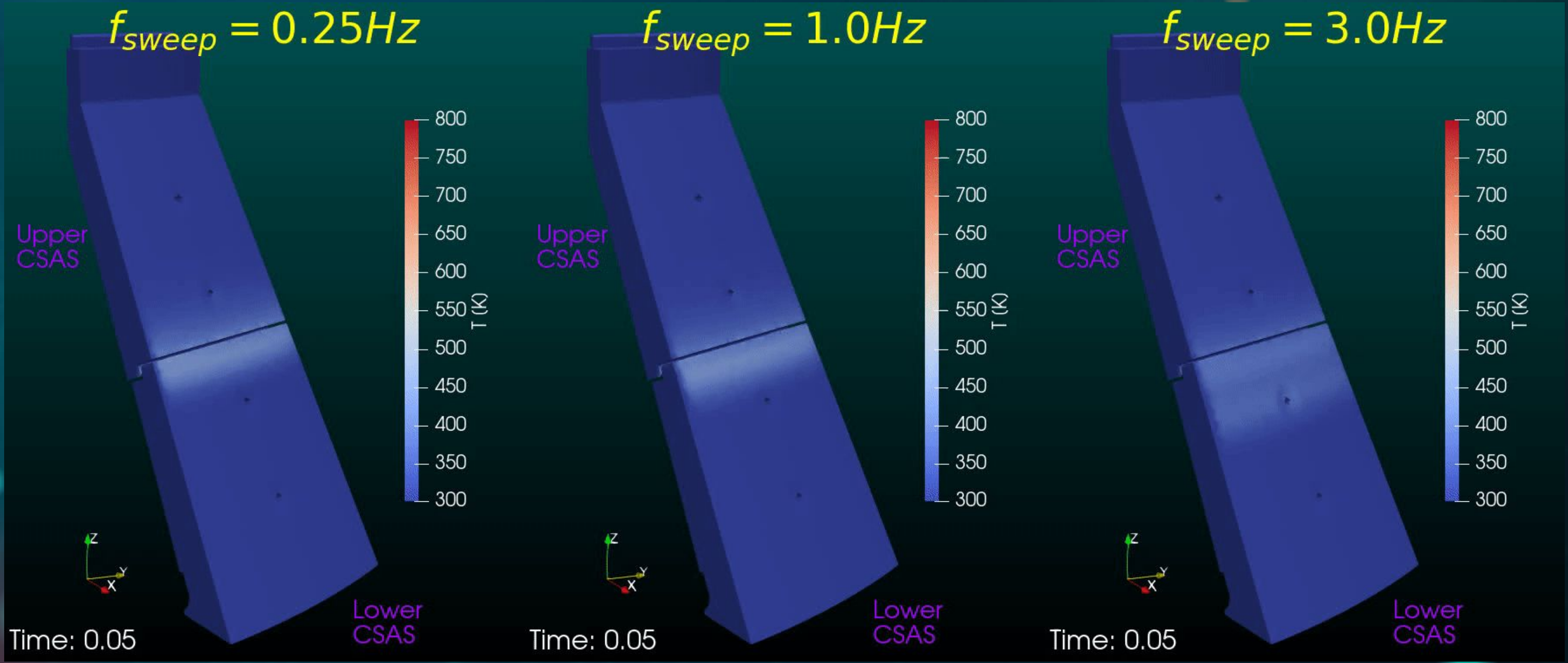
HEAT has a built in gFile interpolator / stitcher that can be used to generate strike point sweeps

Originally only 5 geqdsk steps



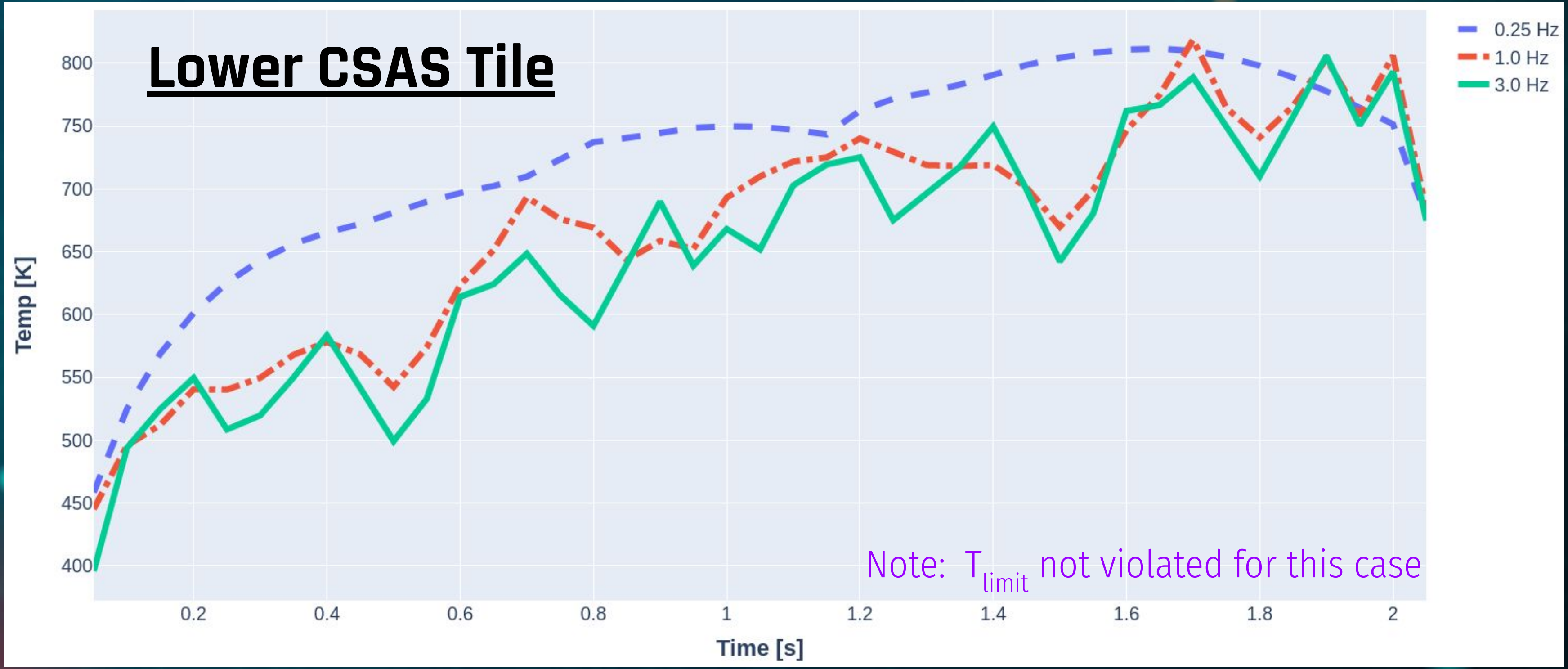
HEAT tool interpolates geqdsk to 50 steps

Strike point sweep frequency (f_{sweep}) can be used to reduce T_{peak} on Center Stack Angled Surface (CSAS)



Memo 008 TSGTT 204a (g204062.01250_TT_2-04_<#>), P_{inj} = 2MW, f_{rad} = 0.3, B_T= 0.75 T, I_p = 800kA, LSN, Res_{HF} = 2.5mm

Strike point sweep frequency (f_{sweep}) can be used to reduce T_{peak} on Center Stack Angled Surface (CSAS)



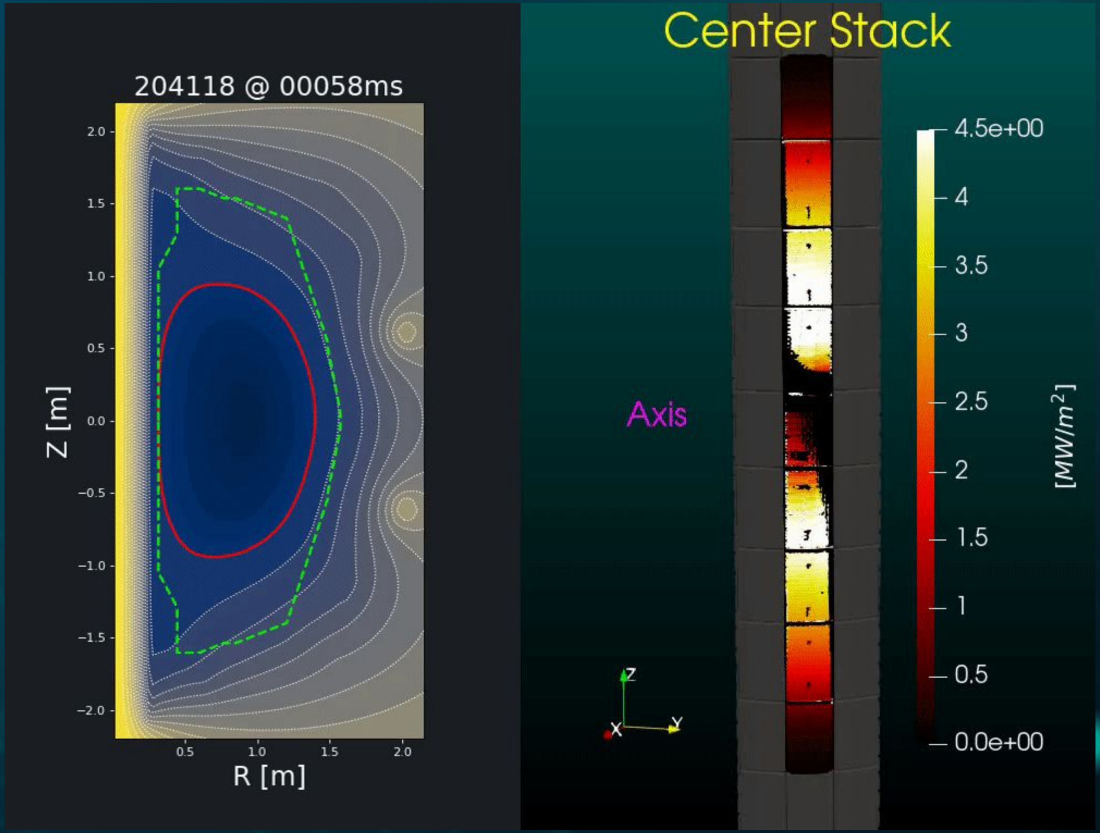
Memo 008 TSGTT 204a (g204062.01250_TT_2-04_<#>), P_{inj} = 2MW, f_{rad} = 0.3, B_T= 0.75 T, I_p = 800kA, LSN, Res_{HF} = 2.5mm

Time varying output simulated with HEAT
Limited Example: 204118@50-250ms

P_{SOL} = 3.0 MW

Profile Type: Limiter
λq_N=3mm
λq_F=5mm

Max Mesh Edge Length: 5 mm



Looking for more cases or discharges to run through HEAT

Cases that demonstrate:
Was the 'intent' of the PFC requirements captured by the tiles?

HEAT Roadmap

04

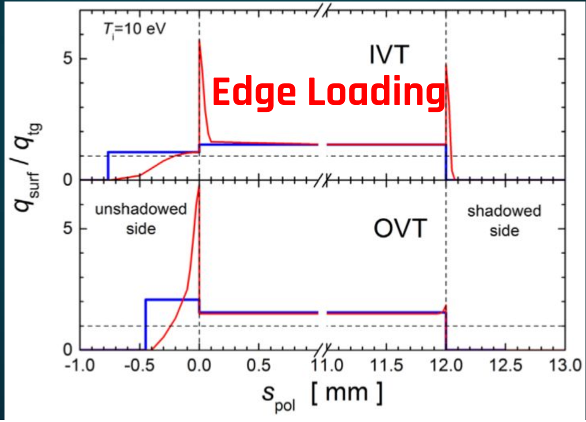
ROAD MAP (NEAR TERM)

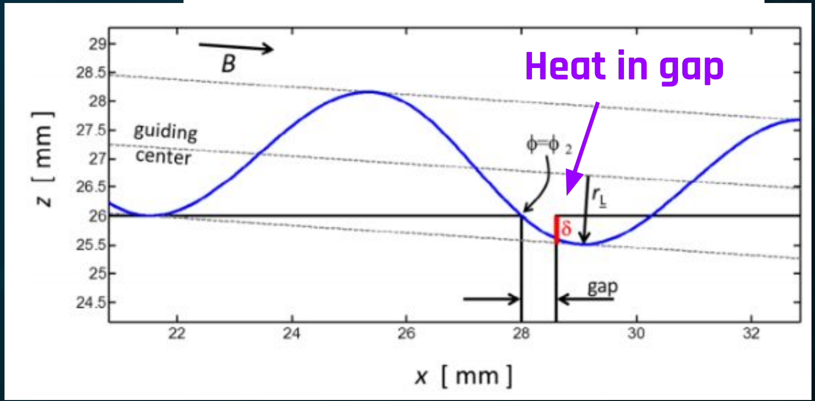
- **Aug 2020** — Version 1.0 pushed to github
- **Nov 2020** — Ion orbits physics module complete
- **Jan 2021** — Detachment physics module complete
- **May 2021** — 3D Plasmas, M3DC1, ELMs, module complete

Next module under development is ion gyro orbits

- Typically we use the 'optical' approximation to describe heat loads
  - Heat flows along field lines
- The truth is, particles carry heat and they precess about the magnetic field lines
- Sometimes particles can 'dip' into a gap and load shadowed faces because of their gyro-orbits
- 3D PFC geometry causes 3D heat loading effects because of cyclotron resonance
- <u>High field machines see narrower edge loading!</u>

$$r_g = \frac{m v_\perp}{|q|B}$$





J. P. Gunn et al., "Surface heat loads on the ITER divertor vertical targets," Nucl. Fusion, vol. 57, no. 4, p. 046025, Apr. 2017.

Questions?

If you think HEAT could benefit your research, reach out!
We are seeking collaborators and contributors.

tlooby@vols.utk.edu

https://github.com/plasmapotential/HEAT