A PRELIMINARY FIRST WALL DESIGN PROCEDURE AND RELEVANT HEAT FLUX ESTIMATION

AUTHOR:
Dario Vaccaro
AFFILIATION:
United Kingdom Atomic Energy Authority

OUTLINE

Introduction

Heat load modeling for the engineering systems code Bluemira [8,9]

- Charged Particle model
- Radiation source model

Wall load specification and wall shape design

Referral project

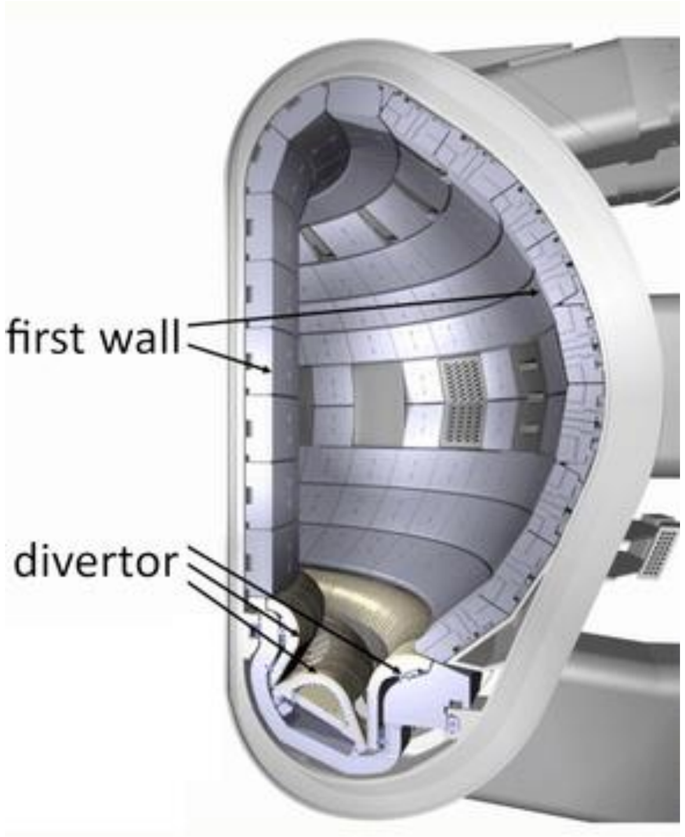
FIRST WALL HEAT LOADS

Engineering constraints

- Large electricity production
- **Heat loads on the first wall**
- Superconducting magnets
- Maximum allowable stress on the support structure

Plasma-wall interaction challenge

- No perfect core plasma confinement
- Power crossing separatrix
- Flux lines intersecting wall
- Power loads restricted to a small wetted area
- If all SOL power strikes the divertor plates, peak loads might be intolerable



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HEAT LOAD MODELING FOR THE ENGINEERING SYSTEMS CODE BLUEMIRA

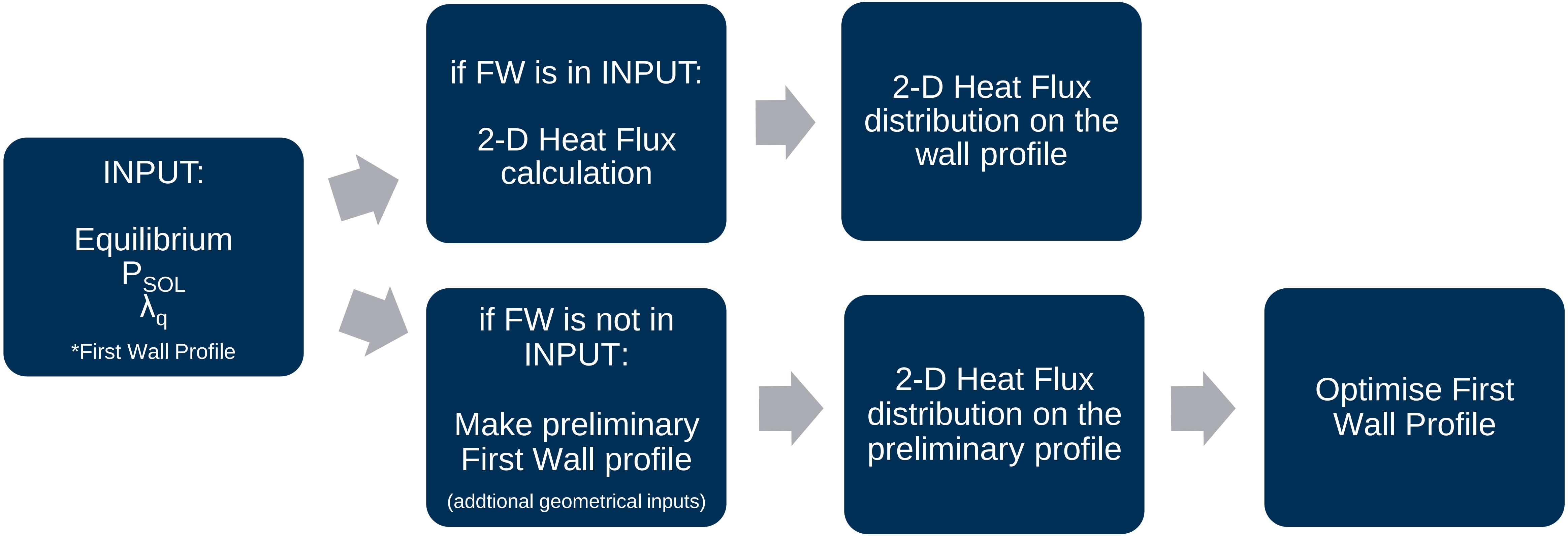
Goal: defining a procedure to design a preliminary first wall profile and estimate expected heat loads as support of the *engineering phase*

Main requirement: quick and sufficiently reliable

Current state:

- First wall shape design
- First wall heat flux calculation due to charged particles
- First wall heat flux calculation due to radiation

FIRST WALL SHAPE DESIGN & HF CALCULATION DUE TO CHARGED PARTICLES



INPUT:

Equilibrium
P_{SOL}
λ_q
*First Wall Profile

if FW is in INPUT:

2-D Heat Flux calculation

2-D Heat Flux distribution on the wall profile

if FW is not in INPUT:

Make preliminary First Wall profile

(addtional geometrical inputs)

2-D Heat Flux distribution on the preliminary profile

Optimise First Wall Profile

FIRST WALL SHAPE DESIGN & HF CALCULATION DUE TO CHARGED PARTICLES

INPUT:

Equilibrium
P_{SOL}
λ_q
*First Wall Profile

if FW is not in INPUT:

Make preliminary First Wall profile
(addtional geometrical inputs)

2-D Heat Flux distribution on the preliminary profile

Optimise First Wall Profile

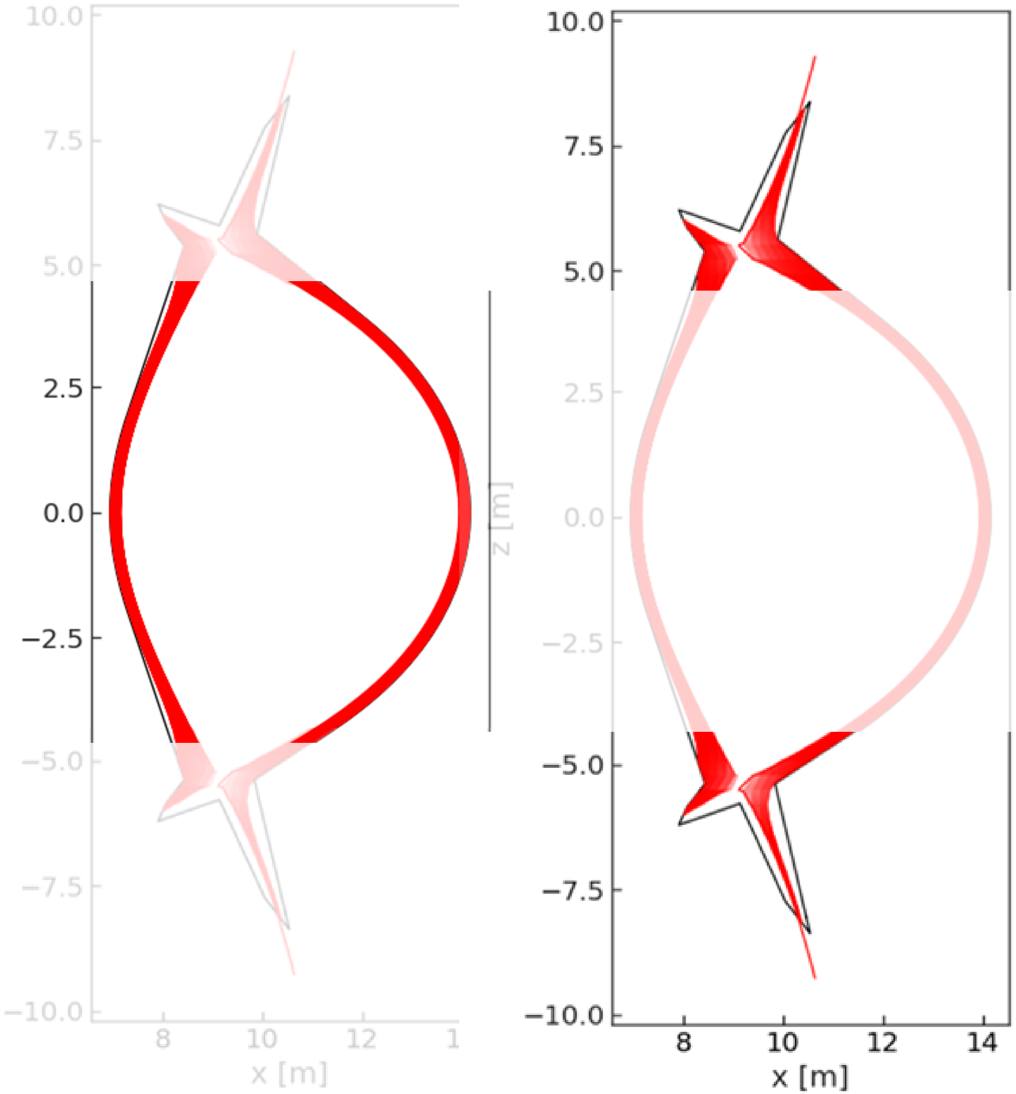
FIRST WALL SHAPE DESIGN & HF CALCULATION DUE TO CHARGED PARTICLES

if FW is not in INPUT:

Make preliminary First Wall profile

(addtional geometrical inputs)

- ➢ Main chamber shaping
- ➢ Divertor parametrization



FIRST WALL SHAPE DESIGN & HF CALCULATION DUE TO CHARGED PARTICLES

2-D Heat Flux distribution on the preliminary profile

- Double exponential decay [10]

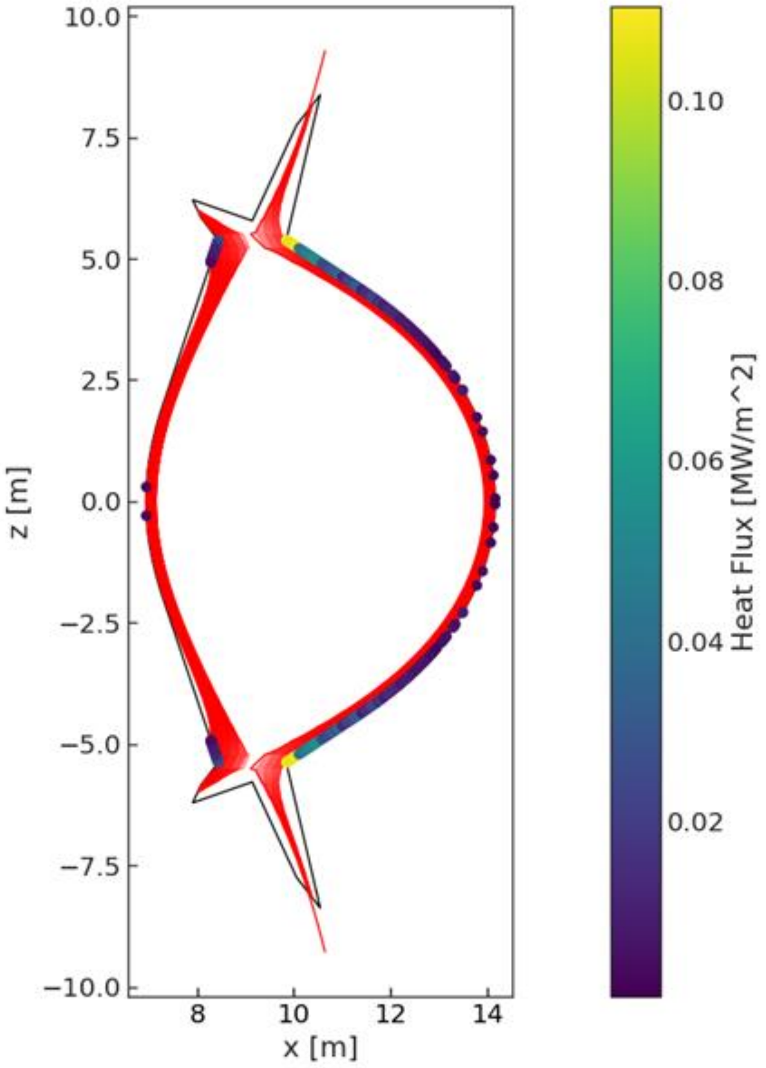
$$q_{p,u}(r_u) = \frac{P_{SOL,n} e^{\left(-r_u/\lambda_n\right)}}{2\pi R(r_u)\lambda_n} + \frac{P_{SOL,f} e^{\left(-r_u/\lambda_f\right)}}{2\pi R(r_u)\lambda_f}$$

- Flux expantion

$$f_{x,t} = \frac{dr_t}{dr_u} = \frac{R_u B_{p,u}}{R_t B_{p,t}}$$

- Angle between flux surface and first wall

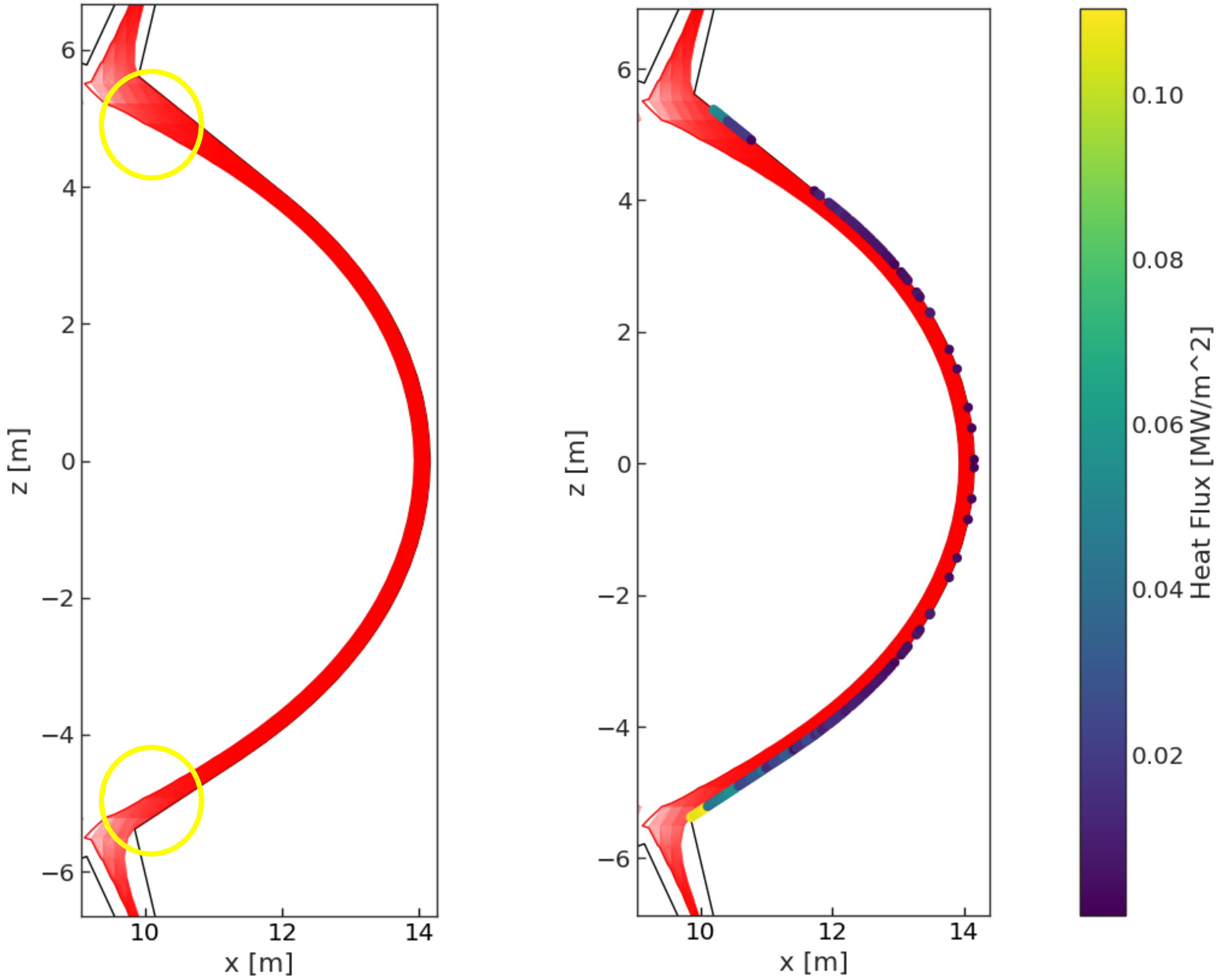
$$q_{\perp,t} = q_{p,t} sin\beta_t$$



FIRST WALL SHAPE DESIGN & HF CALCULATION DUE TO CHARGED PARTICLES

Optimise First Wall Profile

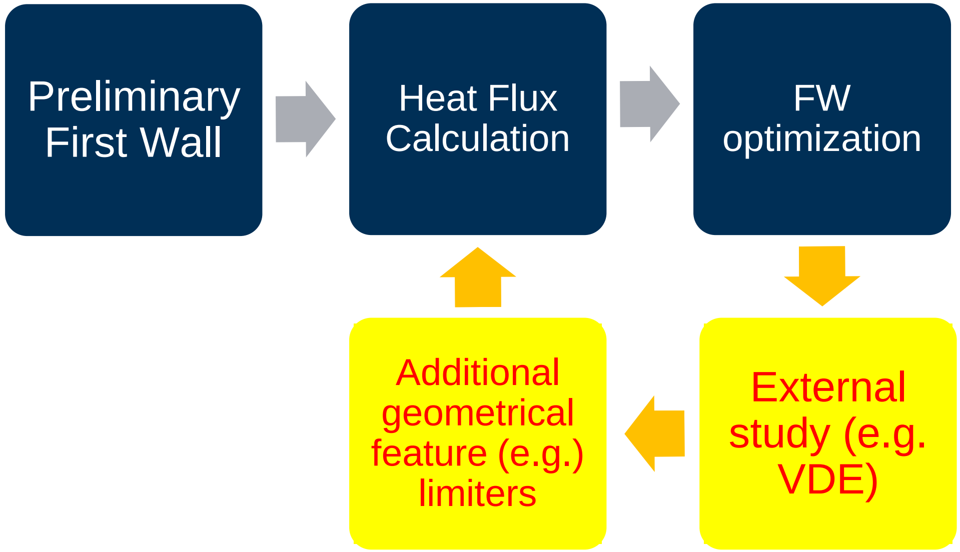
- Heat Flux limit (user input)
- Local first wall reshaping



FIRST WALL SHAPE DESIGN & HF CALCULATION DUE TO CHARGED PARTICLES

Outcome:

- Results benchmarked against SMARDDA[11]
- t < 1’
- Flexible set of input params
- The module has been widely appreciated and used outside bluemira
- Suitable for a sensitivity analysis/robust design
- Suitable for cross functional team work



Preliminary First Wall

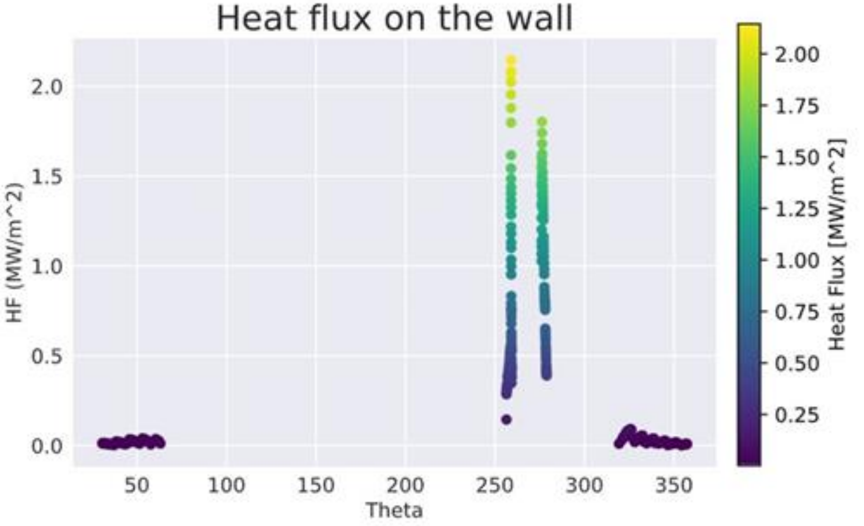
Heat Flux Calculation

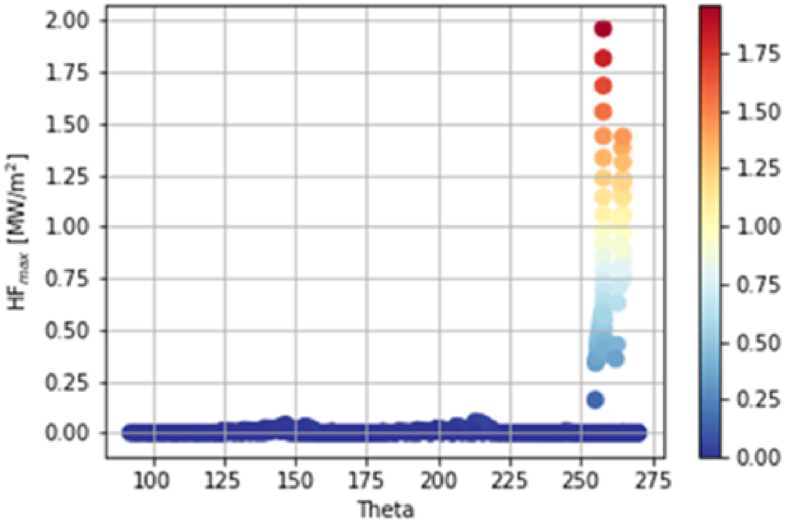
FW optimization

External study (e.g. VDE)

Additional geometrical feature (e.g.) limiters

2D CODE

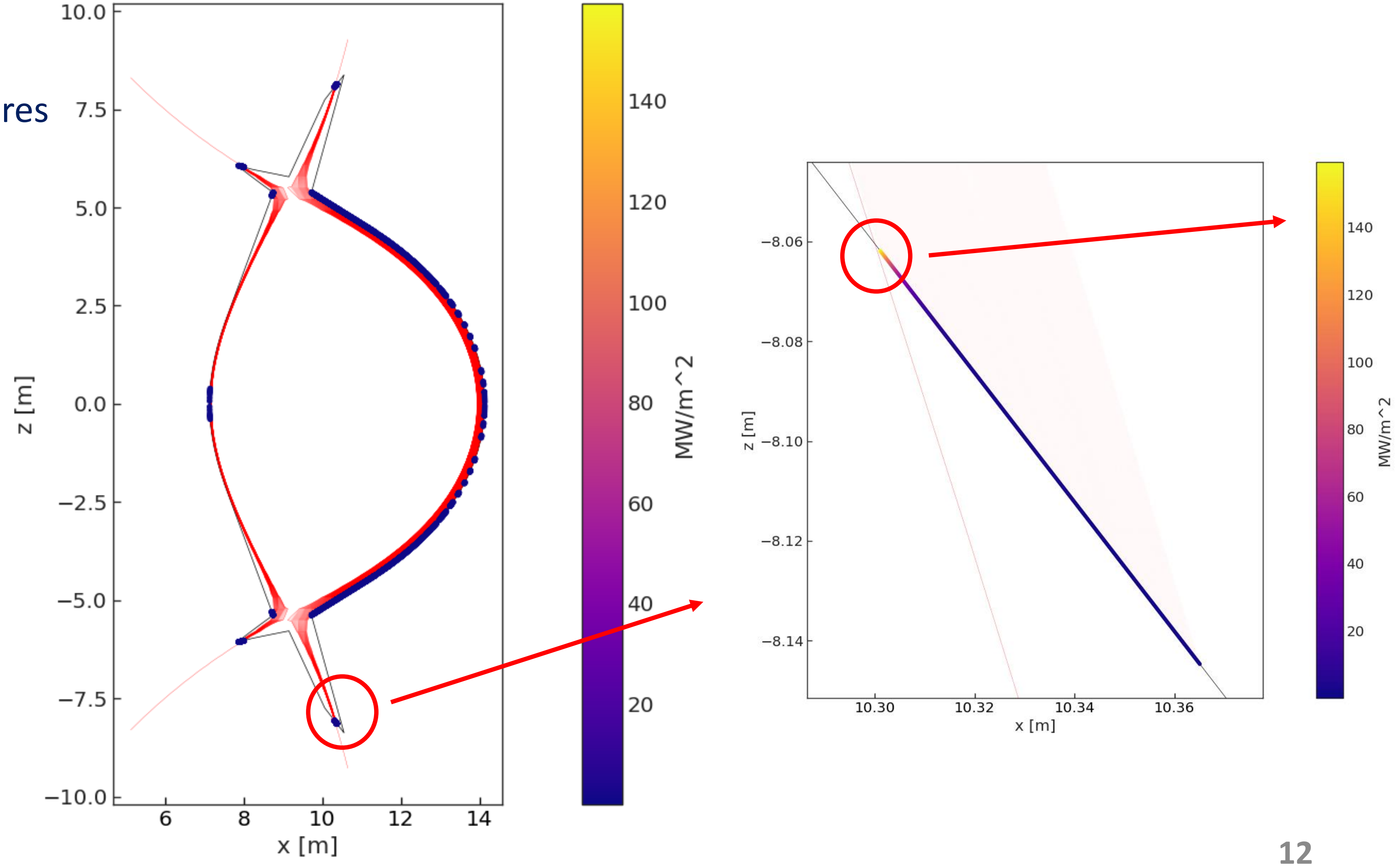




FIRST WALL SHAPE DESIGN & HF CALCULATION DUE TO CHARGED PARTICLES

Limit:

- Non-axisymmetric scenario
  ⟶ tile gaps, edges, apertures
- Divertor loads
  ⟶ power to be exhausted by radiation



FIRST WALL HEAT FLUX CALCULATION DUE TO RADIATION

Potential steady-state scenario:

- Fusion power ~ 2GW
- Alpha + auxiliary heating to be exhausted ~ 500MW
  - Core ~ 350MW
  - SoL ~ 150MW

➢ Detailed calculation of radiation distribution requires high-fidelity modelling

  * Time

  * Uncertainty ⟶ need of full understanding on transport processes

Simple assessment:

➢ Core radiation source

➢ SoL radiation source

➢ Coupling with CHERAB

⟶ First wall heat flux

FIRST WALL HEAT FLUX CALCULATION DUE TO RADIATION

- ➢ Core radiation source
- ➢ SoL radiation source
- ➢ Coupling with CHERAB

$$\frac{dP_{line,\,Imp}}{dV} = f_{Imp}\, n_e^2\, P_{line\text{-}LF,\,Imp}(n_e, T_e) \longrightarrow \left\{ \begin{array}{l} \text{T, n} \\ \text{Impurity data} \\ \text{Atomic database[6]} \end{array} \right.$$

Core:

- Te > 300eV
  - ⟶ low-Z impurities fully stripped ⟶ main contribution from bremsstrahlung
- Synchrotron radiation currently not included
  - ⟶ less Xe in the core to radiate same amount of power
  - ⟶ Radiation distribution may slightly change ⟶ peak in the core
  - ⟶ No significant impact on the first wall heat flux

FIRST WALL HEAT FLUX CALCULATION DUE TO RADIATION

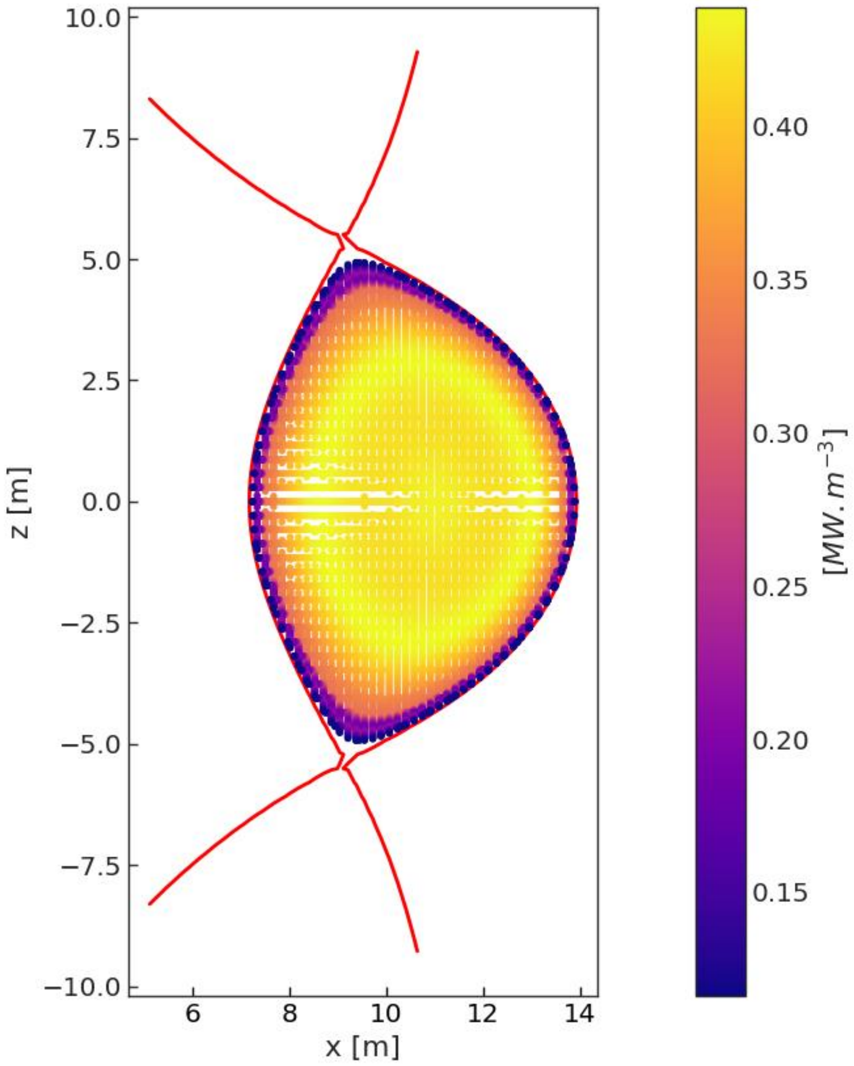
- ➢ Core radiation source
- ➢ SoL radiation source
- ➢ Coupling with CHERAB

* [Jean, FST (2011)]

$$n(\rho) = \begin{cases} n_{ped} + (n_0 - n_{ped})\left(1 - \dfrac{\rho^2}{\rho_{ped}^2}\right)^{\alpha_n} \\ \qquad \text{for } 0 \le \rho \le \rho_{ped} \\ n_{sep} + (n_{ped} - n_{sep})\dfrac{1-\rho}{1-\rho_{ped}} \\ \qquad \text{for } \rho_{ped} \le \rho \le 1 \end{cases}$$

and

$$T(\rho) = \begin{cases} T_{ped} + (T_0 - T_{ped})\left(1 - \dfrac{\rho^{\beta_T}}{\rho_{ped}^{\beta_T}}\right)^{\alpha_T} \\ \qquad \text{for } 0 \le \rho \le \rho_{ped} \\ T_{sep} + (T_{ped} - T_{sep})\dfrac{1-\rho}{1-\rho_{ped}} \\ \qquad \text{for } \rho_{ped} \le \rho \le 1 \ . \end{cases}$$



FIRST WALL HEAT FLUX CALCULATION DUE TO RADIATION

- ➢ Core radiation source
- ➢ SoL radiation source
- ➢ Coupling with CHERAB

- Two-Point model

$$2n_t T_t = n_u T_u$$

$$T_u^{7/2} = T_t^{7/2} + \frac{7}{2}\frac{q_\parallel L}{\kappa_{0e}}$$

$$q_\parallel = \gamma n_t k T_t c_{st}$$

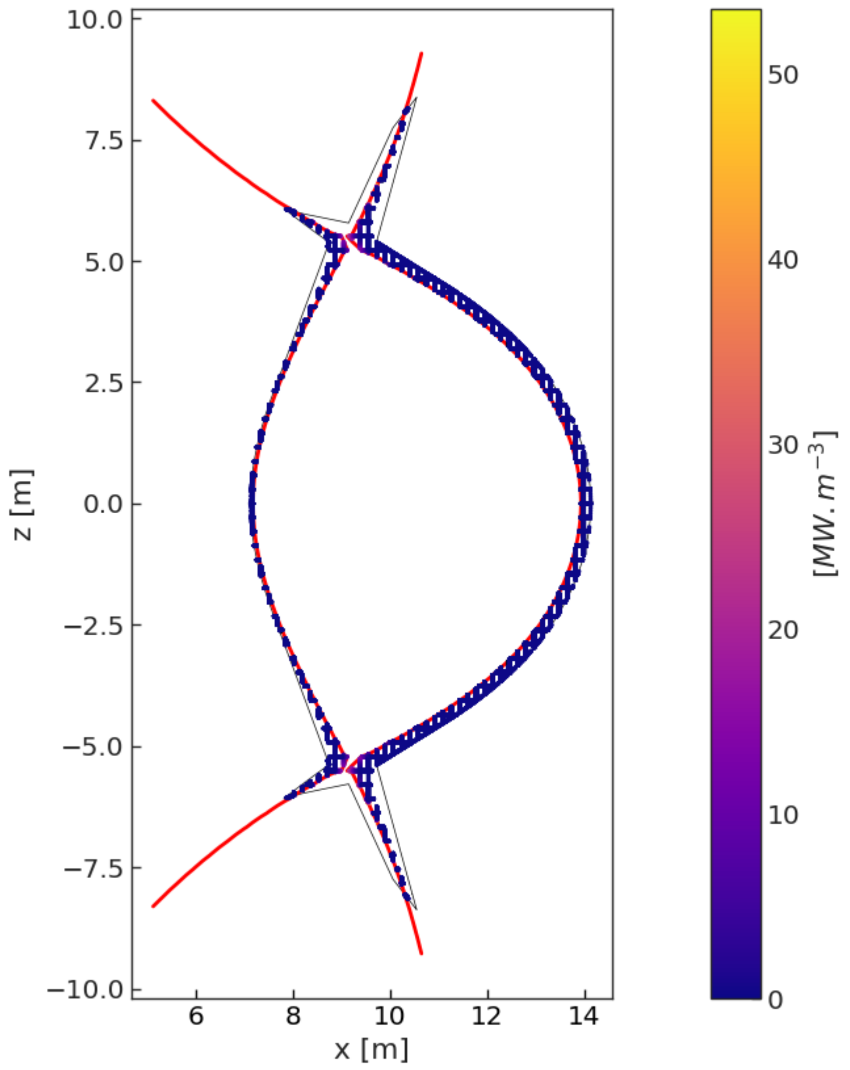
$$T_t = F_u \left(1 + \frac{\varepsilon/\gamma}{T_t}\right)^{-2}$$

- Exponential decay

$$n(r) = n_{\mathrm{LCFS}} \exp(-r/\lambda_n)$$

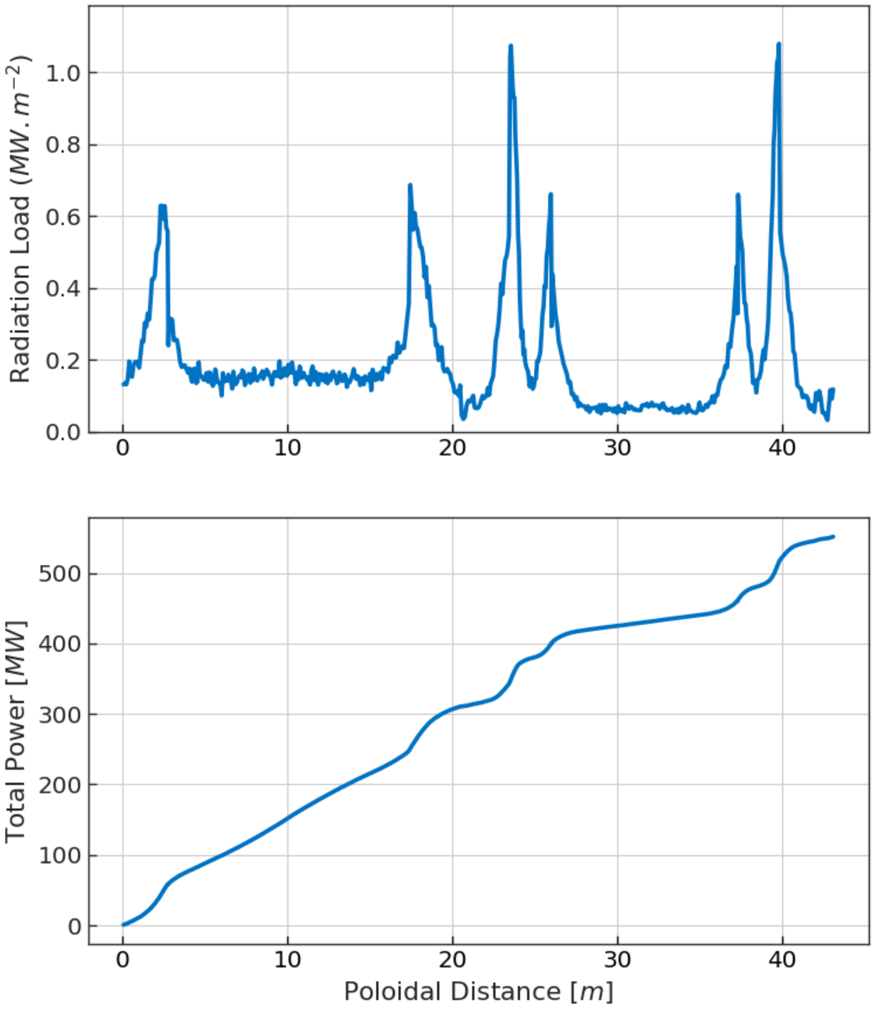
$$T_e(r) = T_{e,\mathrm{LCFS}} \exp(-r/\lambda_{T_e})$$

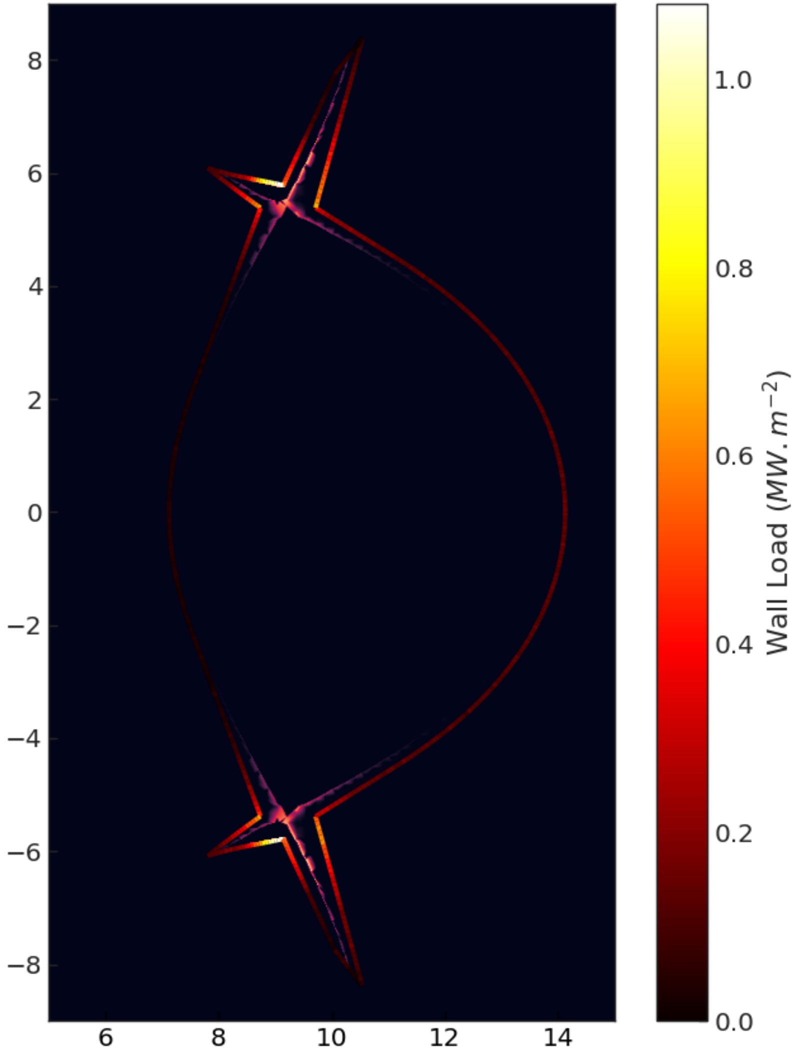
* [Pitcher, PPCF (1997)]
* [Stangeby, IPP (2000)]



FIRST WALL HEAT FLUX CALCULATION DUE TO RADIATION

- Core radiation source
- SoL radiation source
- Coupling with CHERAB



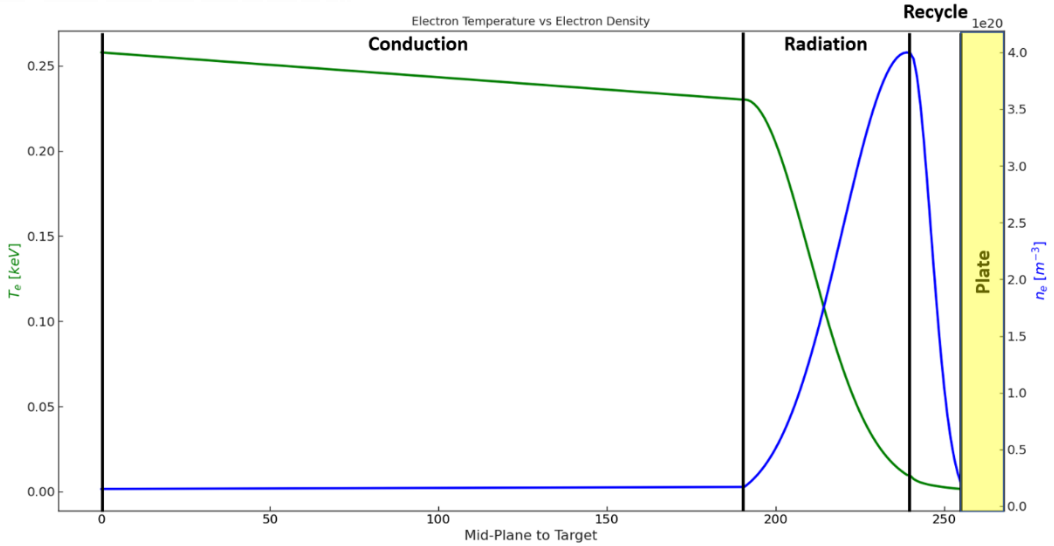


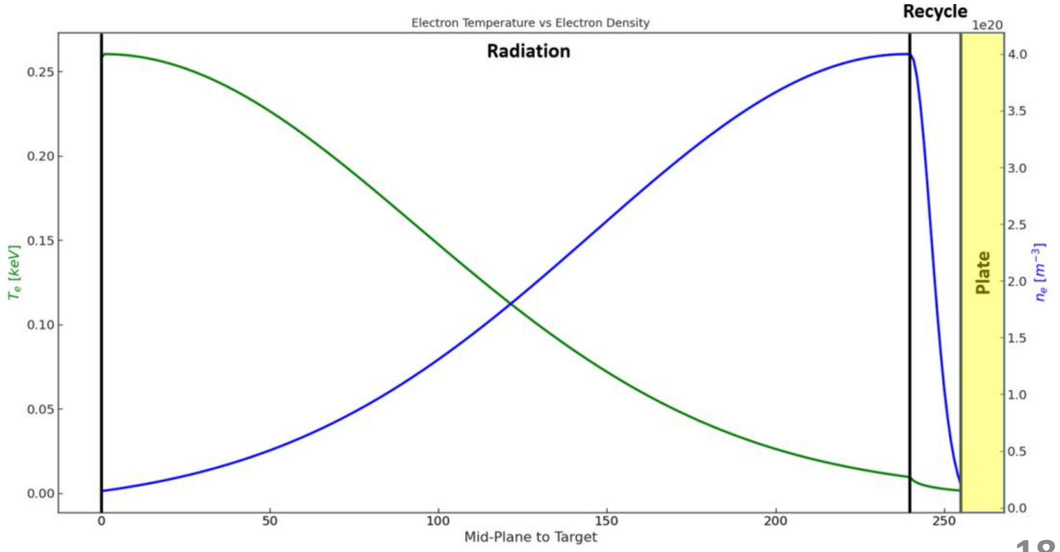
FIRST WALL HEAT FLUX CALCULATION DUE TO RADIATION

Outcome:

- t source ~ 3’
- t tracing ~ 30’
- The module has been widely appreciated and used outside bluemira

⟶ Going to benchmark against MAST-U experimental results





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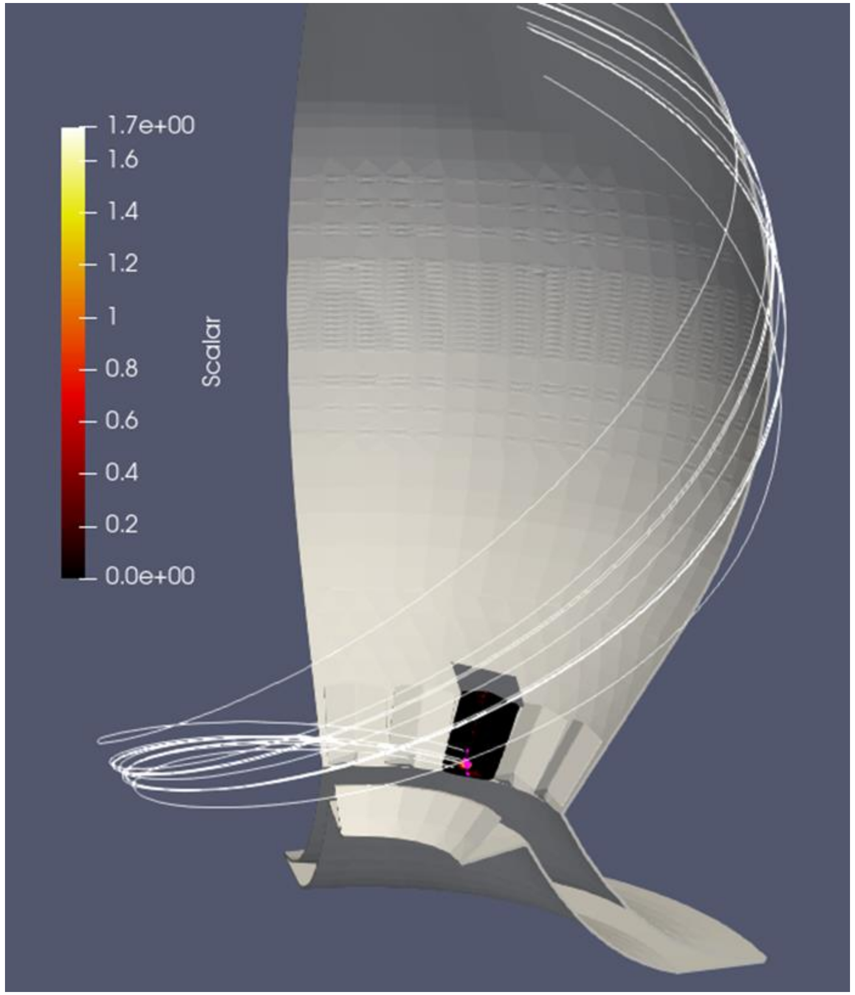
WALL LOAD SPECIFICATION AND WALL SHAPE DESIGN

- From 2D to 3D analysis
- Providing inputs for PFC design
- Found out about H.E.A.T. [6]
- Made contact with Tom Looby
- Promoting the use



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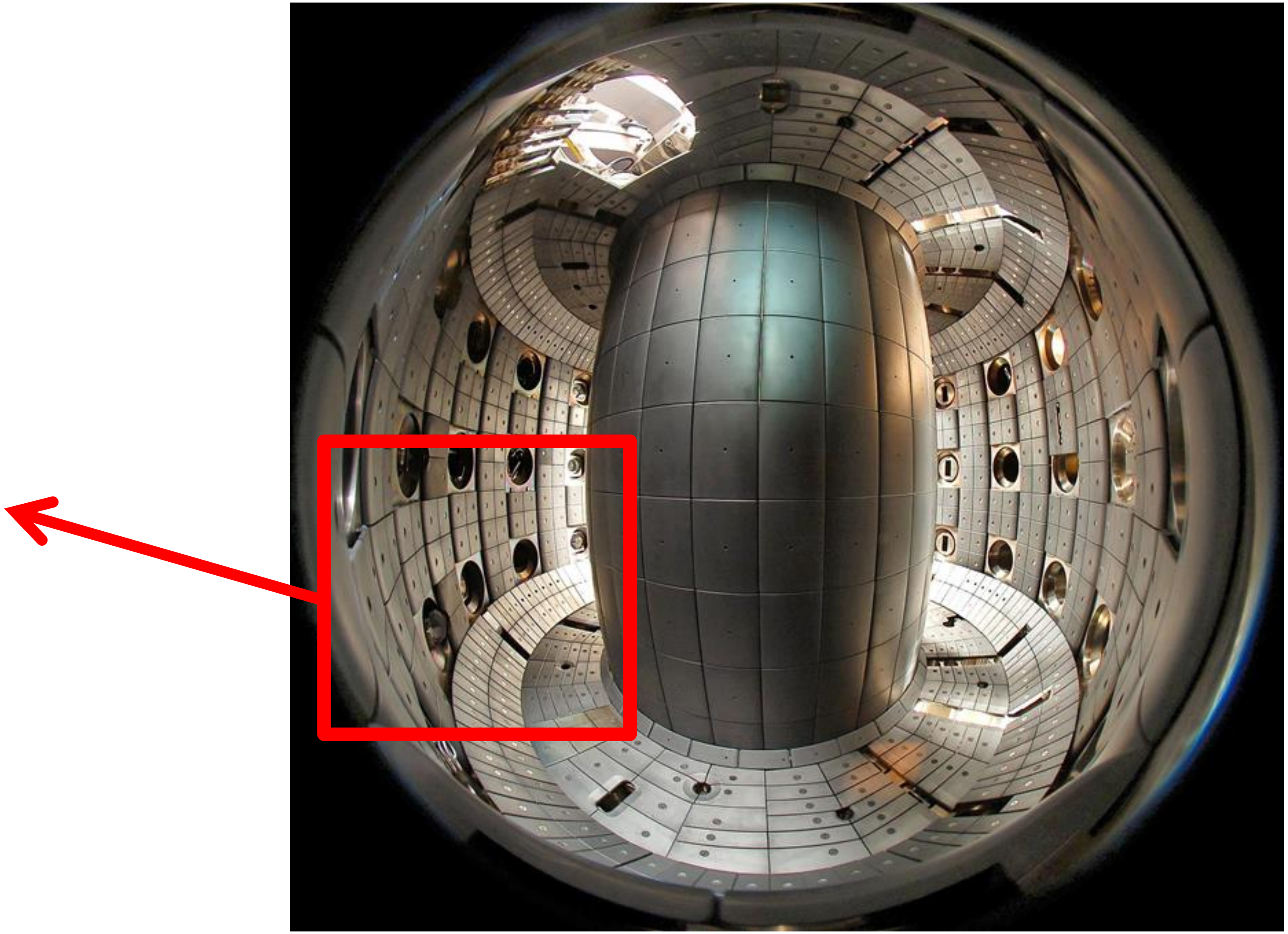
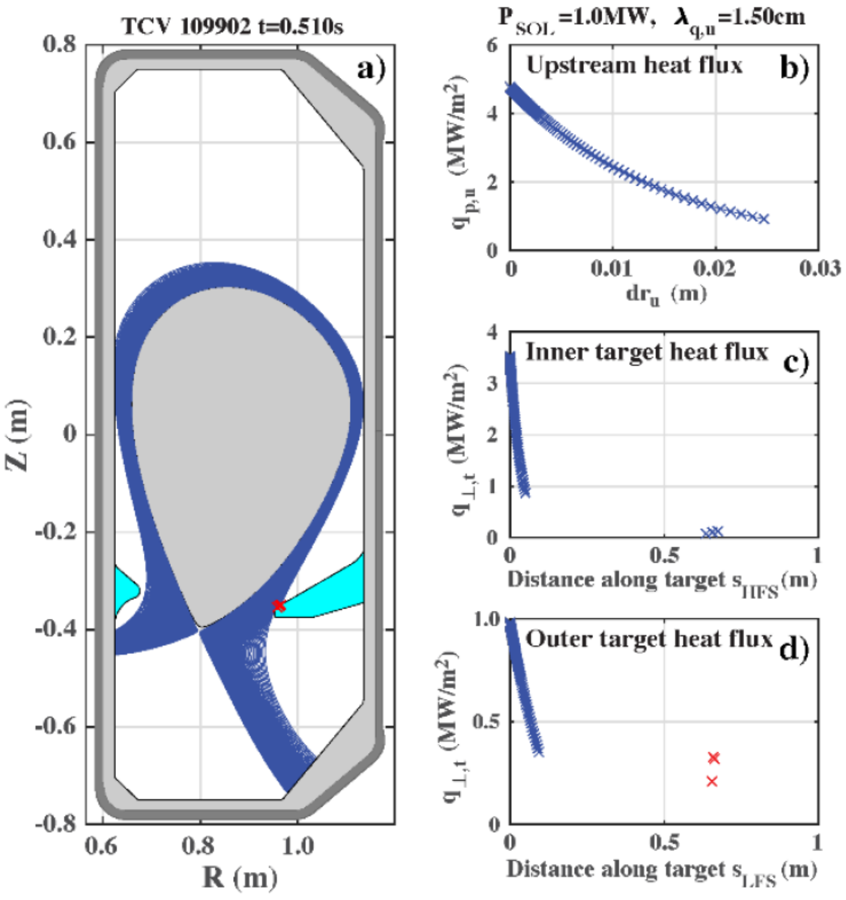
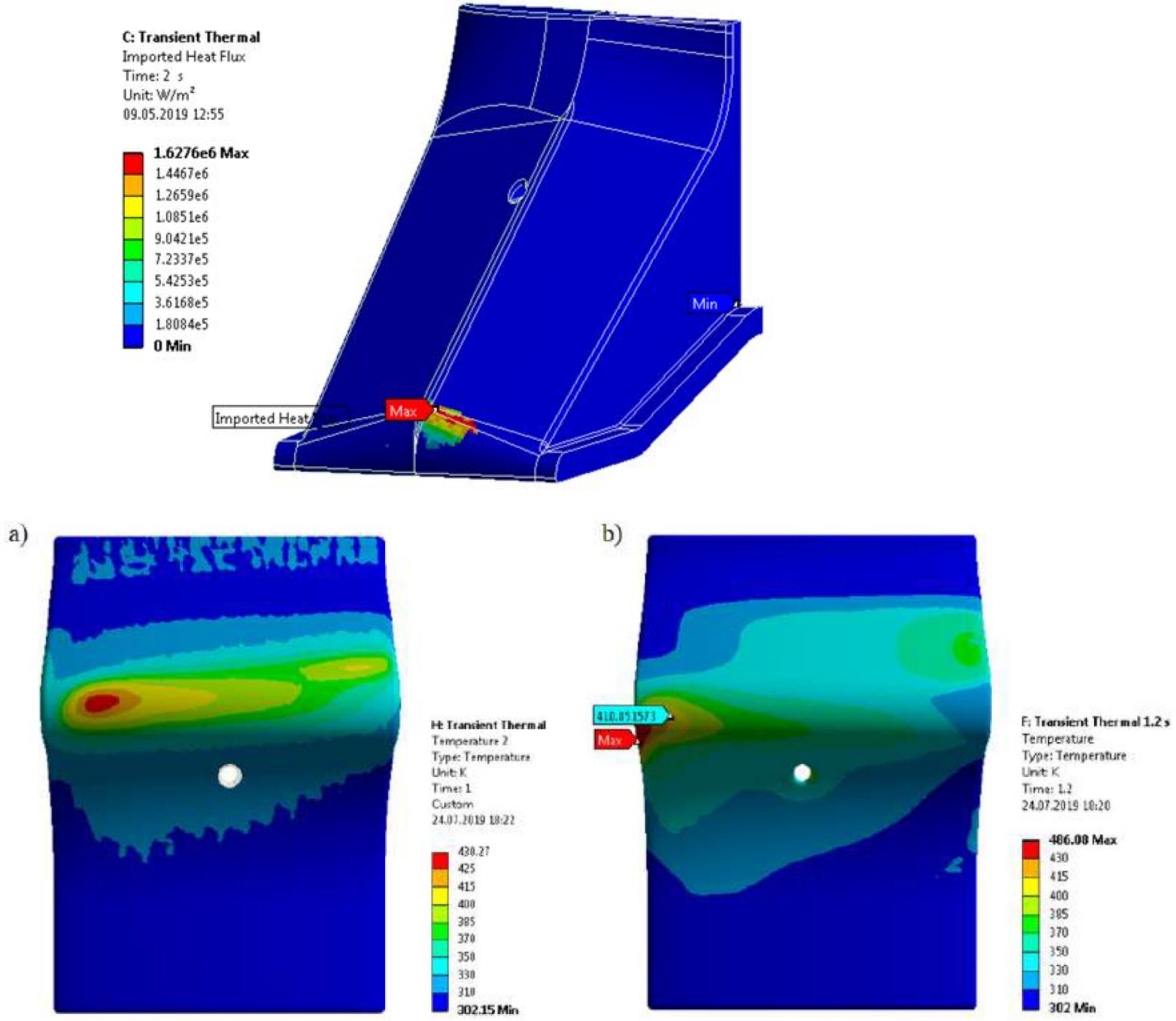
TCV DIVERTOR UPGRADE



TCV DIVERTOR UPGRADE





* **Vaccaro, D.**, Elaian, H., Reimerdes, H., et al., *Thermal, electromagnetic and structural analysis of gas baffles for the TCV divertor upgrade*, Fusion Engineering and Design

Thank you!

References:

1. **STANGEBY, Peter C.** The plasma boundary of magnetic fusion devices. Vol. 224. Philadelphia, Pennsylvania: Institute of Physics Pub., 2000.
2. **PITCHER**, Charles Spencer, and P. C. **STANGEBY**. “Experimental divertor physics.” Plasma Physics and Controlled Fusion 39.6 (1997): 779.
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4. **VERHAEGH**, Kevin. Spectroscopic investigations of detachment on TCV: Investigating the role of atomic physics on the ion current roll-over and the dynamics of detachment in TCV. Diss. University of York, 2018.
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6. **LOOBY**, Thomas, "Tokamak 3D Heat Load Investigations using an Integrated Simulation Framework. " PhD diss., University of Tennessee, 2022.
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8. **COLEMAN, M. and MCINTOSH, S.** *The design and optimisation of tokamak poloidal field systems in the BLUEPRINT framework.* s.l. : Fusion Engineering and Design, 2020. 154: 111544.
9. **COLEMAN, M. and MCINTOSH, S.** *BLUEPRINT: A novel approach to fusion reactor design.* s.l. : Fusion Engineering and Design, 2019. 139: 26-38.
10. **MAURIZIO, Roberto.** *Investigating Scrape-Off Layer transport in alternative divertor geometries on the TCV tokamak.* s.l. : EPFL, 2020.
11. **ARTER, Wayne, SURREY, Elizabeth and KING, Damian B.** *The SMARDDA Approach to Ray Tracing and Particle Tracking.* IEEE : Transactions on Plasma Science, 2015. 43.9: 3323-3331.
12. **BRUNNER, D., et al.** *he dependence of divertor power sharing on magnetic flux balance in near double-null configurations on Alcator C-Mod.* s.l. : Nuclear Fusion, 2018. 58.7: 076010.

EXTRA SLIDES

TCV DIVERTOR UPGRADE

Goal:

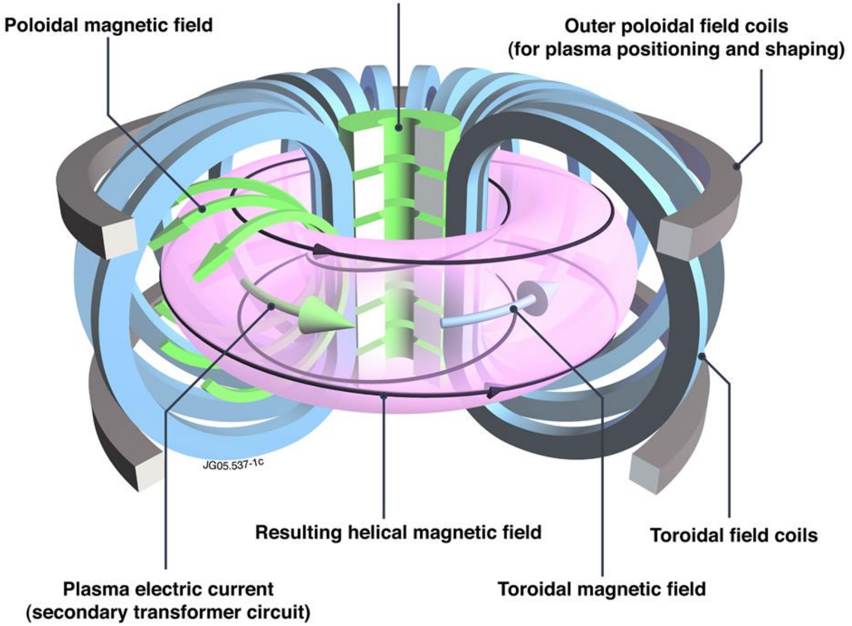
- **Avoiding neutrals generated by recycling at the divertor targets to escape into the main chamber**

Design consideration:

- **Thermal loads**
- **Electromagnetic loads**

Design solution:

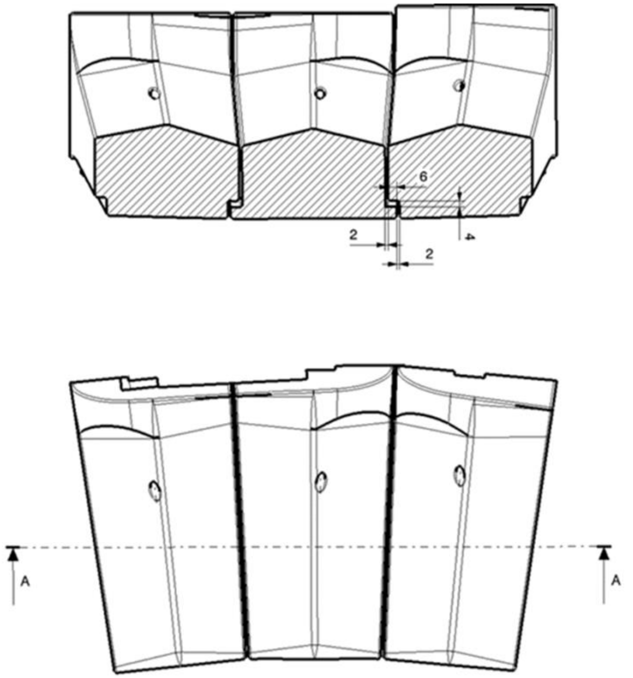
- **Polycrystalline graphite (SGL R6650)**
    - **32 tiles mounted on the HFS**
    - **64 tiles mounted on the LFS**

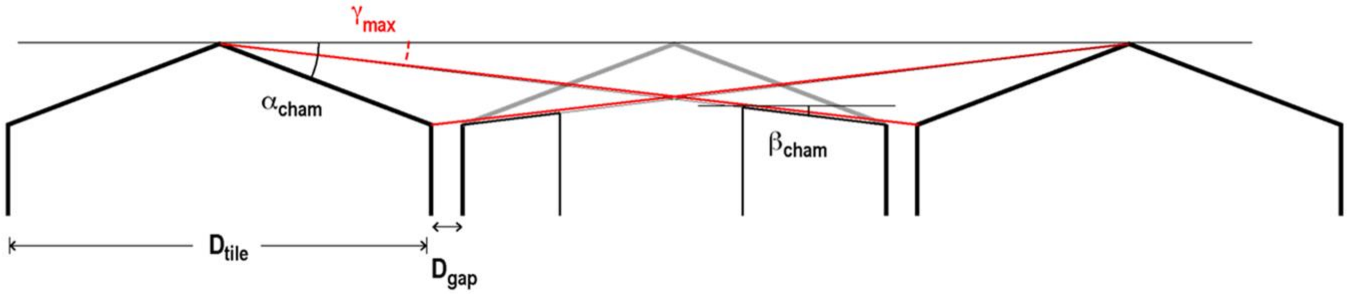


TCV DIVERTOR UPGRADE

Guidelines

- Avoid exposure of leading edges → set-back
- Holes for diagnostics impose most severe constraints → ad hoc baffle
- Maintain compatibility with both magnetic field helicities →symmetric design

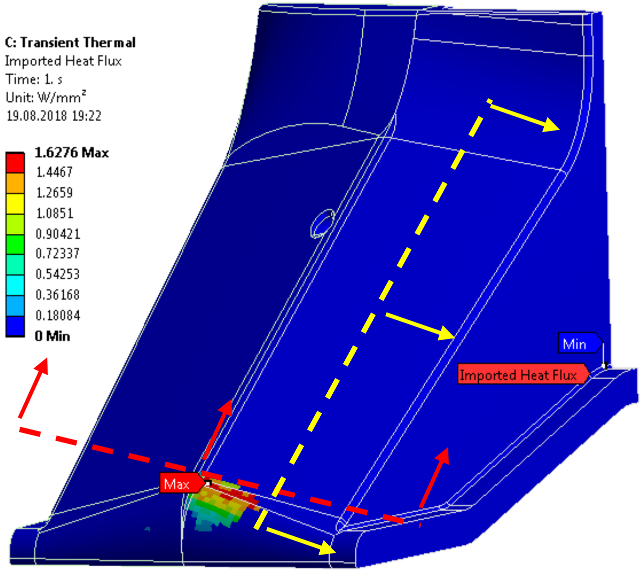




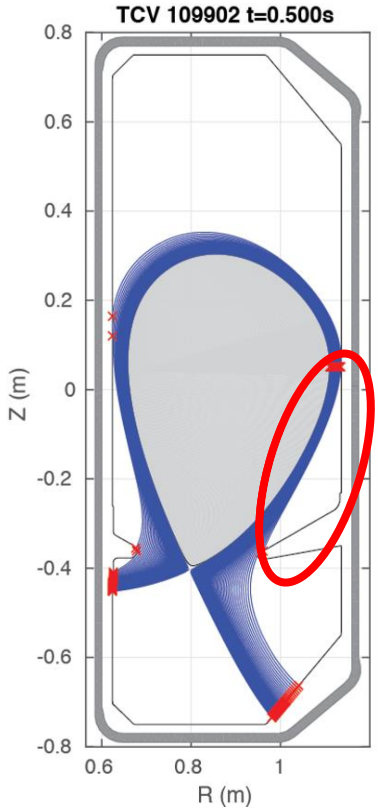
TCV DIVERTOR UPGRADE

Shielded effect is provided by two shadow zone

- Upper part of the baffle surface is in the shadow of the wall
- Laterally baffle surface is in the shadow of the adjacent baffle



$$P_{max} = 1.63 \frac{MW}{m^2}$$



➢ **The surface temperature**

- T^{2s}_{Surf}: $435\ K < 2200\ K$

TCV DIVERTOR UPGRADE

Fraction of the plasma current is conducted through the baffle

Typical values expected in TCV

- $I_{h,max}$ =250kA

Input

- Magnetic field: 1.43 T
- Current: 4kA

Output

- Volumetric force

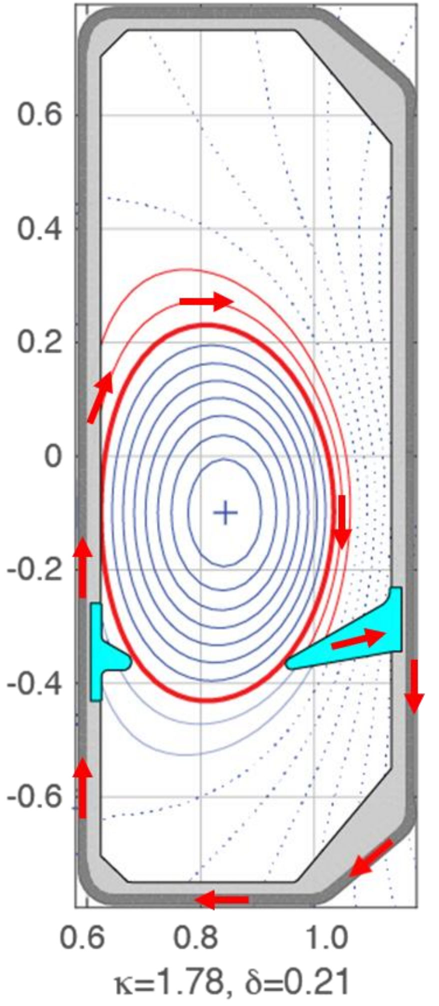
TOTAL FORCE

$$F_x = 425\ N$$

$$F_y = -0.5\ N$$

$$F_z(vertical) = 1090\ N$$

FBTE 109907 t=0.750s

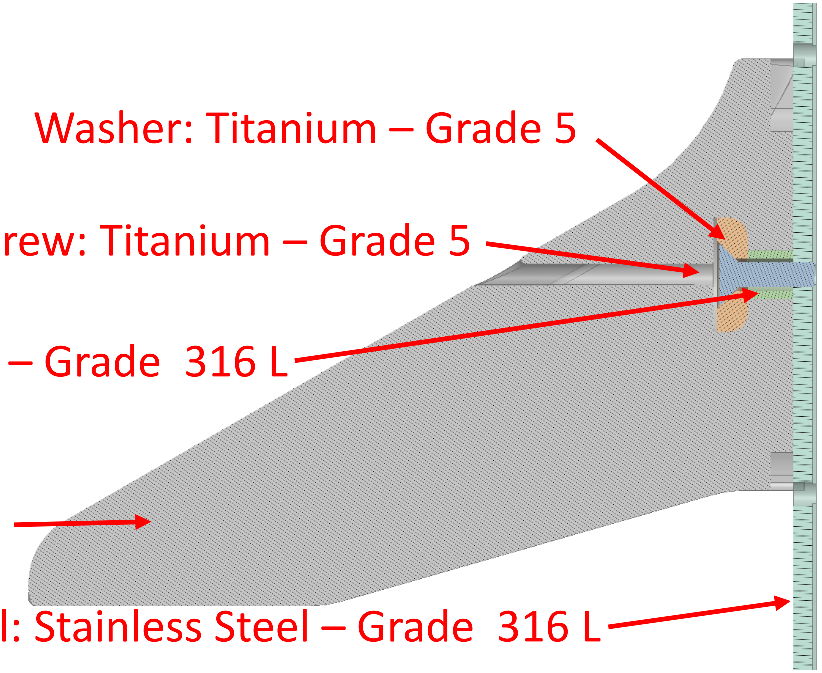


κ=1.78, δ=0.21

TCV DIVERTOR UPGRADE

The geometry at the screw is optimised to limit baffle deformation, displacement and stresses (mainly in the graphite) to tolerable values

- Stresses lower than graphite limits
- Deformations and displacements between baffles to be avoided
- Movement in vertical and toroidal directions limited by 4mm and 2mm spacing, respectively


Washer: Titanium – Grade 5

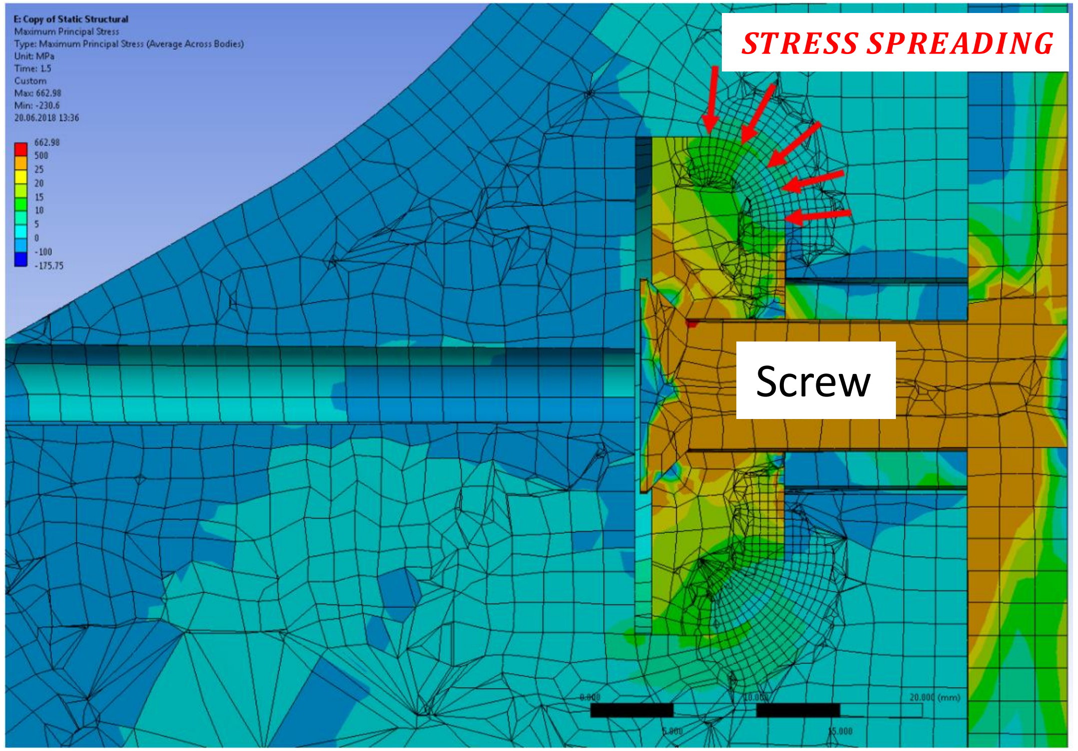
Screw: Titanium – Grade 5

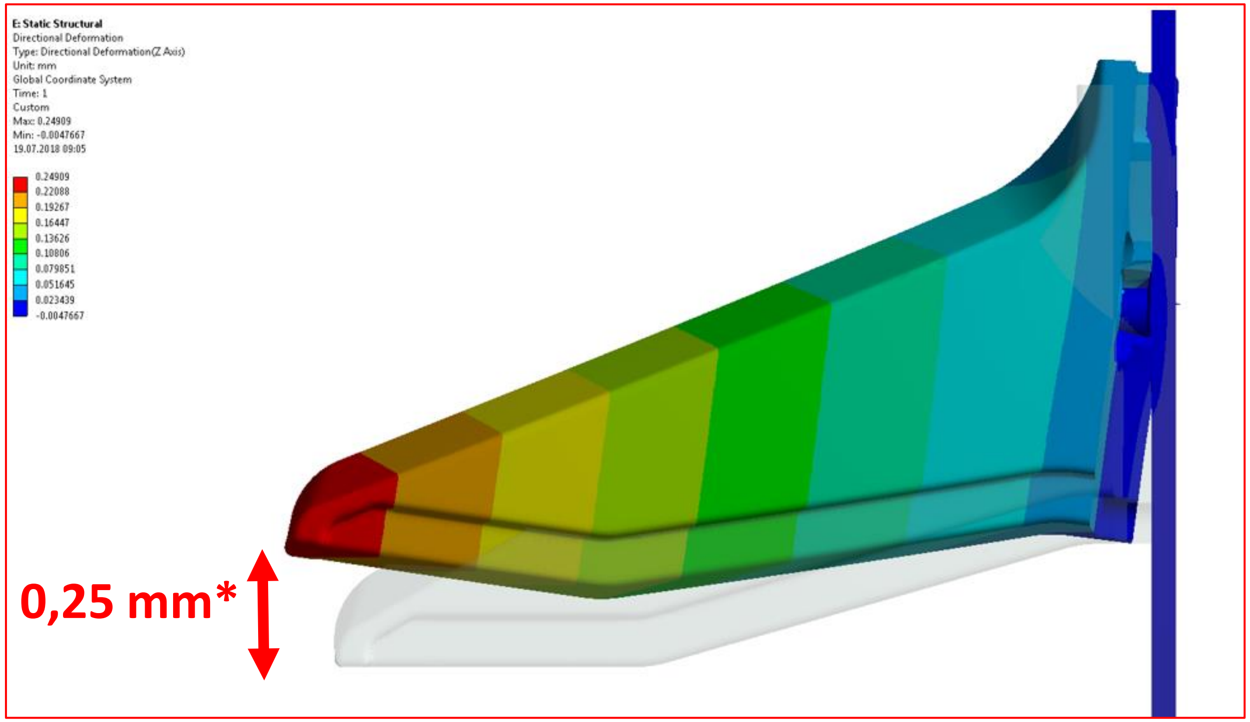
Tube: Stainless Steel – Grade 316 L

Baffle: Graphite SGL R6650

Rail: Stainless Steel – Grade 316 L

The force calculated by the ANSYS Maxwell Module generates a deformation that is highest at the baffle tip



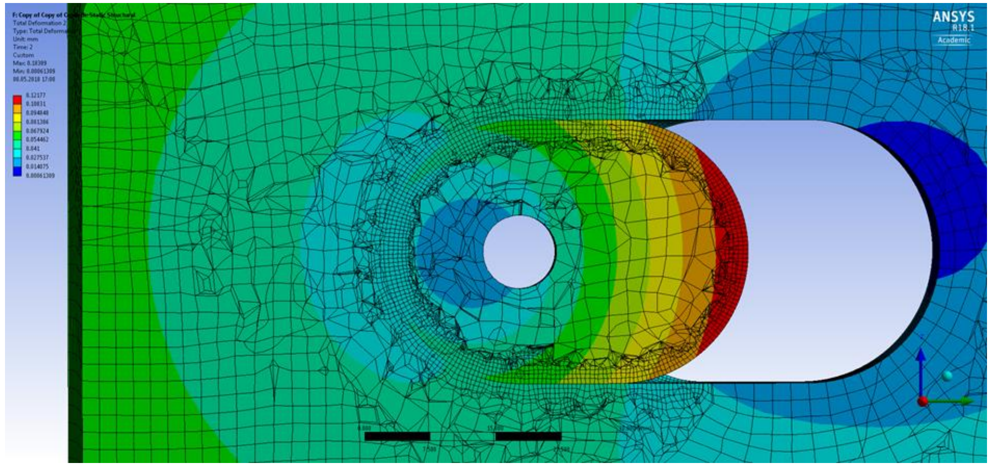


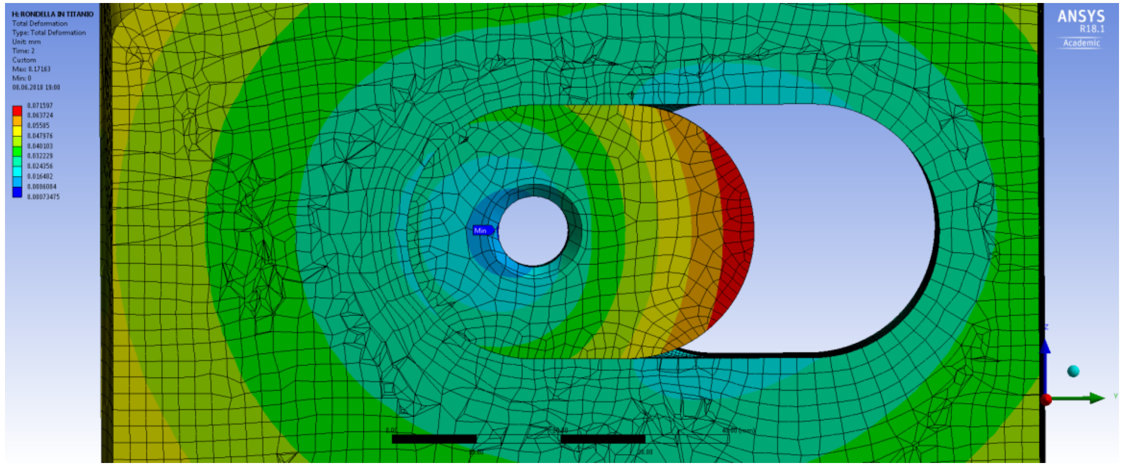
Maximum tensile stress 32 MPa
Maximum compressive stress 80 MPa
} Both 2x lower than limit

TOTAL DEFORMATION

$$D_x = 0.09\ mm$$
$$D_y = 0.04\ mm \ll 2\text{mm}$$
$$D_z = 0.25\ mm \ll 4\text{mm}$$

- **Graphite and titanium coefficient of thermal expansion are characterized by close magnitude**
- **The thermal analysis which simulates baking operations shows that stresses due to thermal expansion do not give cause for concern**





- *BAKING SIMULATION*
  - $T_{Start} = 22°$
  - $T_{Finish} = 250°$
- Thermal Expansion
  - Graphite: 3.5 x10^{-6} C^{-1}
  - Titanium: 9.2 x10^{-6} C^{-1}

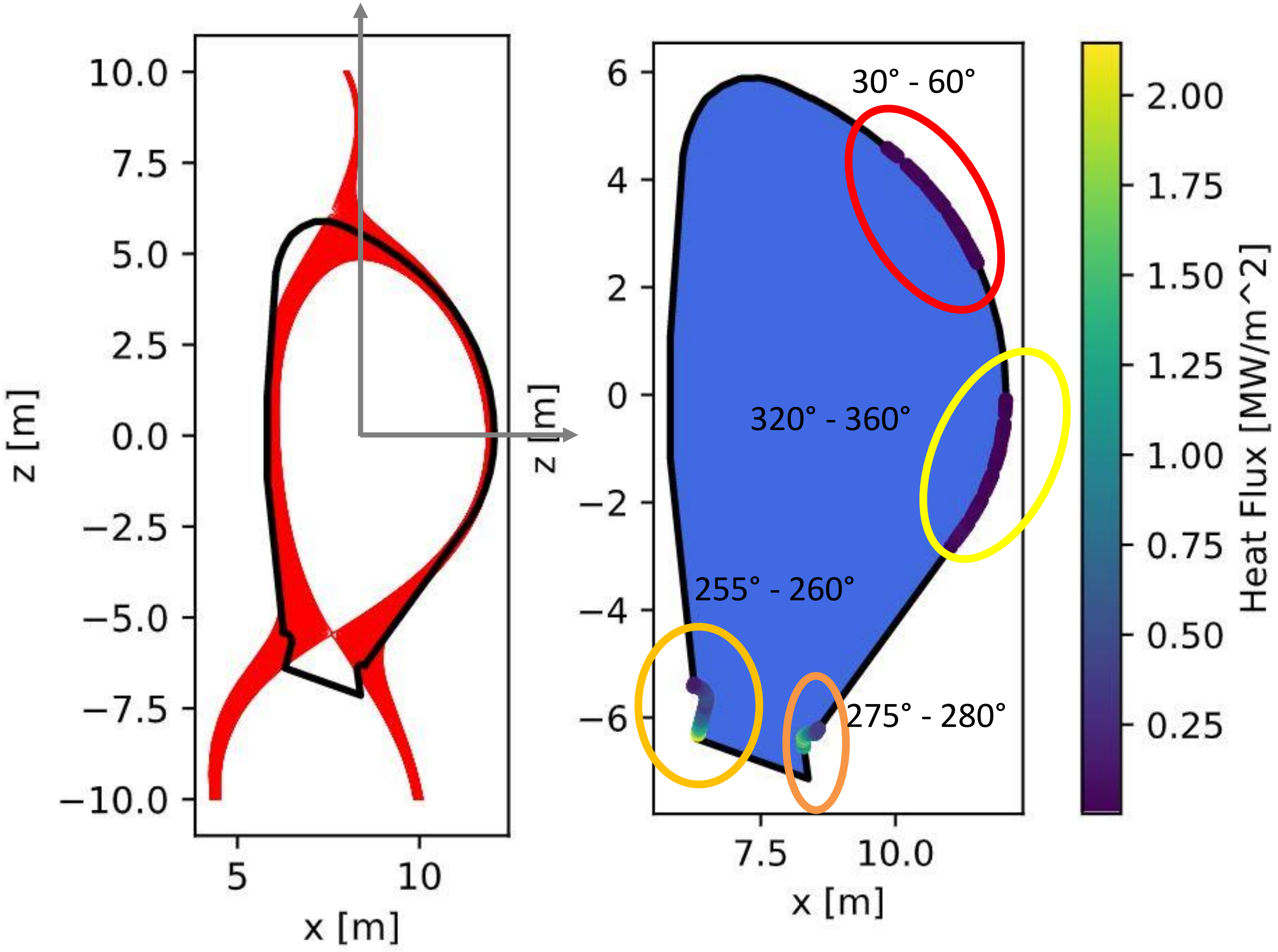
PRELOAD AND THERMAL CONDITION	
Maximum obtained tensile stress	**Maximum obtained compressive stress**
10.76 MPa	67.85 MPa

$$SF_{Tensile\ Stress} = \frac{65}{10.8} = 6$$

$$SF_{Compressive\ Stress} = \frac{150}{67.9} = 2.2$$

HF CALCULATION – BENCHMARK DETAILS

Test on DEMO baseline 2017 and benchmark against SMARDDA(4) (Psol = 69MW, Pinner = 50%, Pouter = 50%)

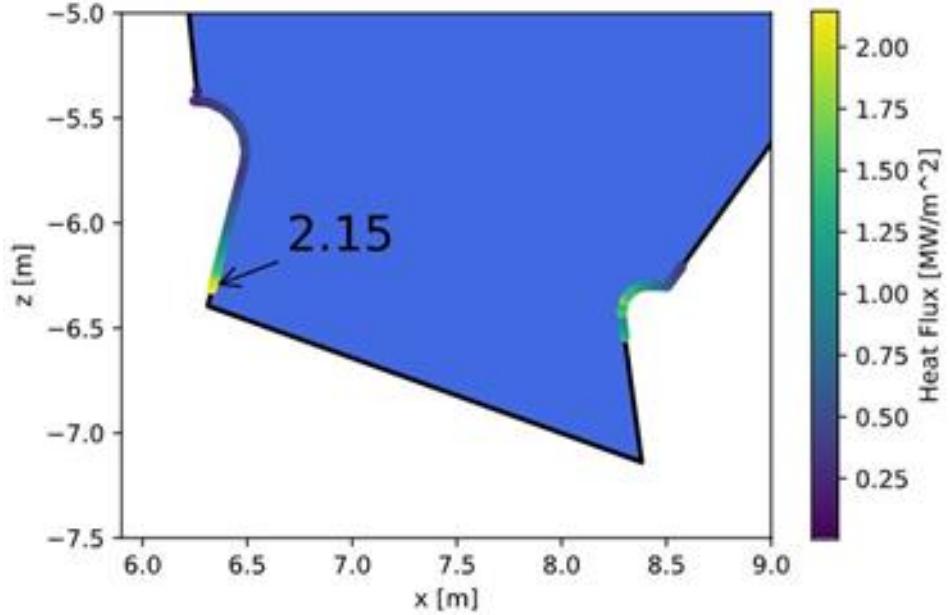


30° - 60°

320° - 360°

255° - 260°

275° - 280°



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