MAX-PLANCK-INSTITUT FÜR PLASMAPHYSIK

Divertor concept development for the W7-X stellarator experiment

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*The full list of W7-X team members is given in T. Sunn Pedersen et al 2022 Nucl. Fusion 62 042022

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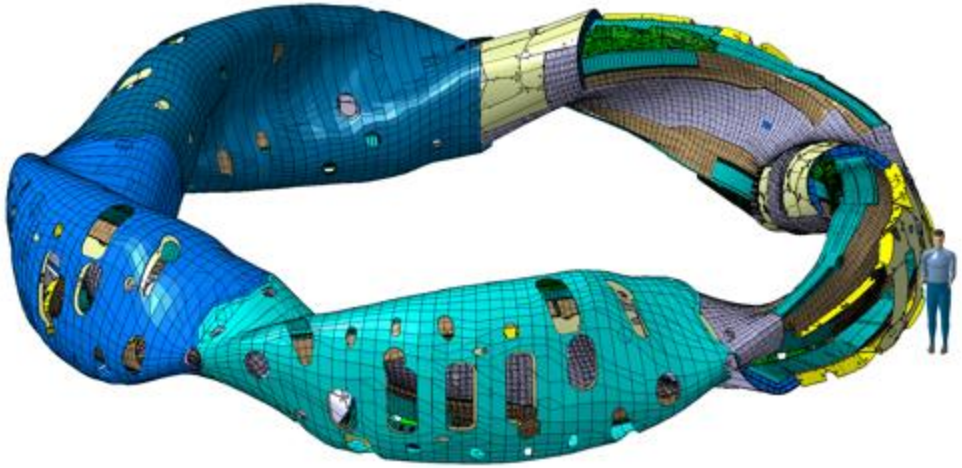
Content



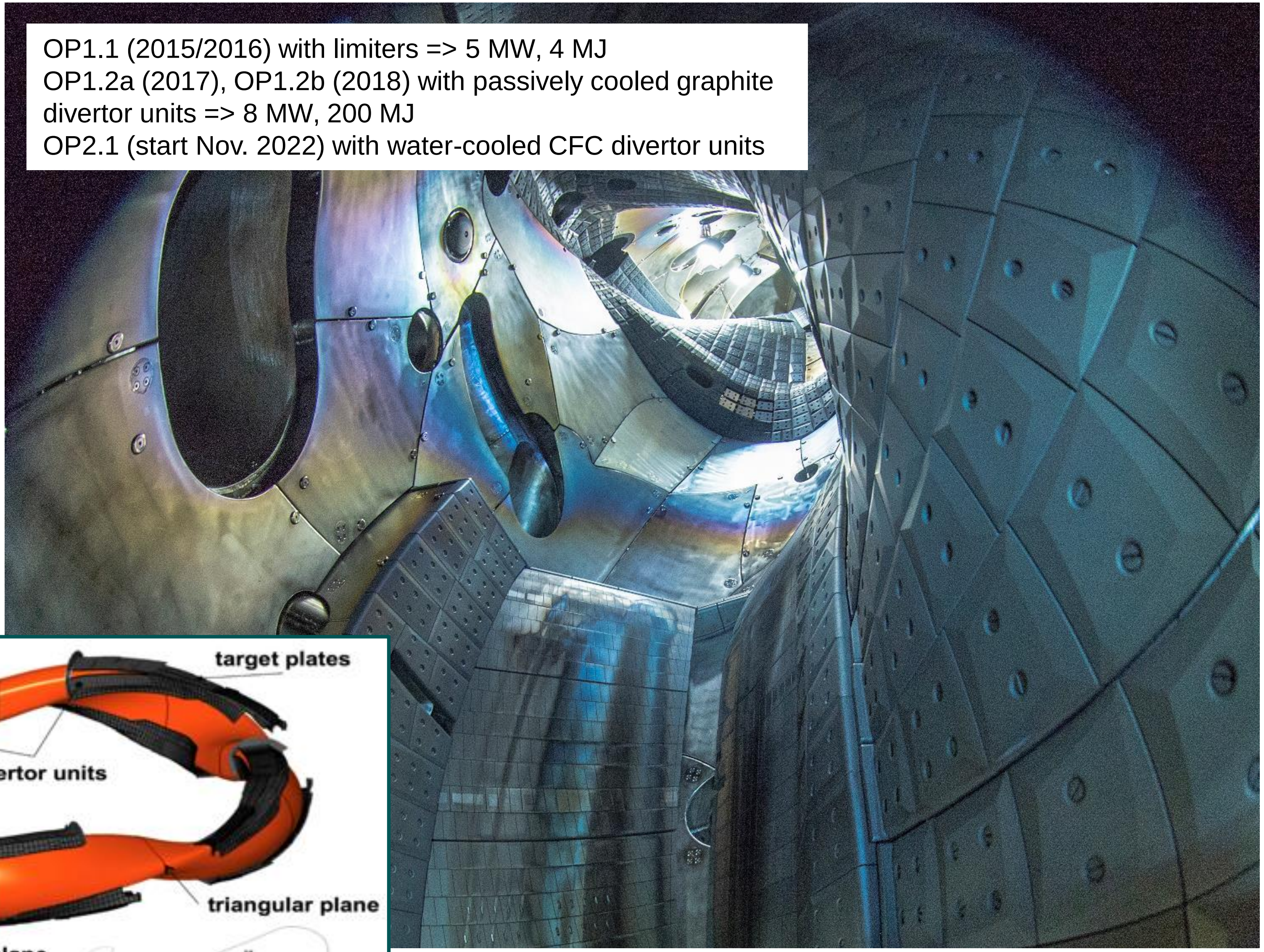
- Motivation – new tungsten divertor for W7-X
- Optimization criteria, goals and constraints
- Steps of concept development
- Tools for physics simulation/optimization:
  - heat load calculations (EMC3-Lite, EMC3/Eirene)
  - neutral gas modeling (ANSYS, DIVGAS)
  - design tools (CATIA)
- Experimental verification of the concept ideas
- Summary

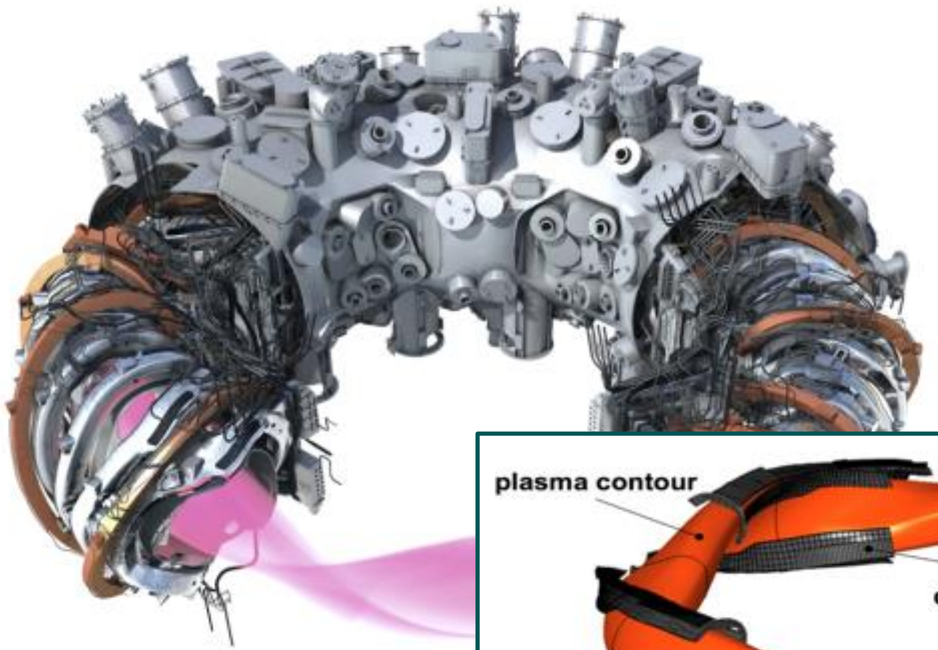
W7-X stellarator experiment – Greifswald (Germany)

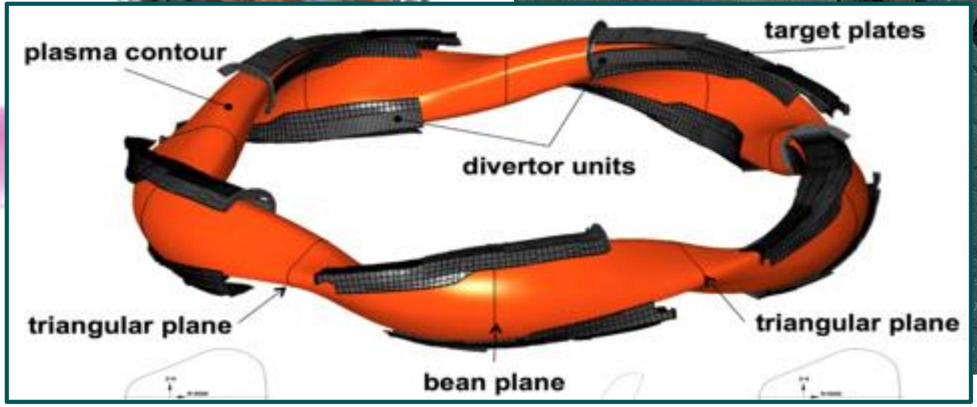
plasma pulses up to 100 s were successfully sustained at 2 MW of heating, and also plasmas exceeding 30 s duration at 5 MW of heating, of which more than 26 s were with divertor detachment

=> on the path to 30 min 18 GJ operation

OP1.1 (2015/2016) with limiters => 5 MW, 4 MJ
OP1.2a (2017), OP1.2b (2018) with passively cooled graphite divertor units => 8 MW, 200 MJ
OP2.1 (start Nov. 2022) with water-cooled CFC divertor units







plasma axis:
average major radius: 5.5 m
average minor radius: 0.5 m

Motivation – material choice

The transition to reactor relevant materials such as tungsten PFCs **for the proof of principle** that the **stellarator concept** can meet the requirements of a future fusion reactor.

heat load control (limiting heat flux density to 10 MW/m^2) to protect vessel and ports from overload by energy and particles

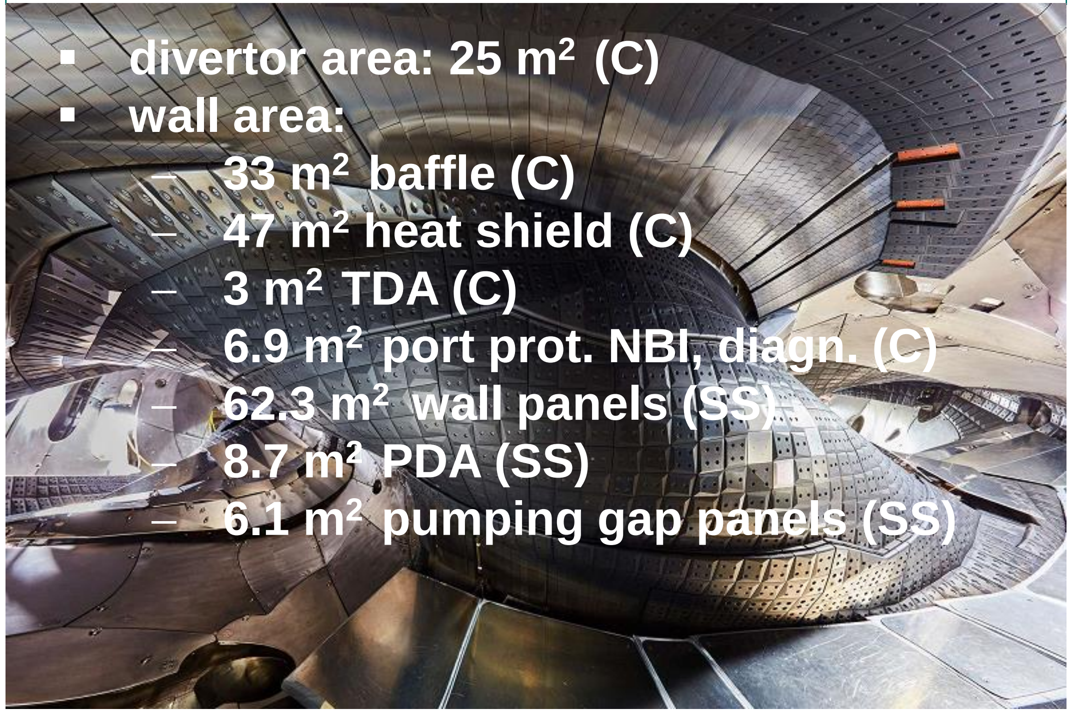
erosion control (limiting particle fluxes, reducing erosion yields)

control of particle recycling and exhaust

- active pumping
- minimum neutral gas density in main chamber (low cx flux)
- wall conditioning
- efficient impurity screening

avoidance of magnetic field perturbation by PFC materials
low activation of materials

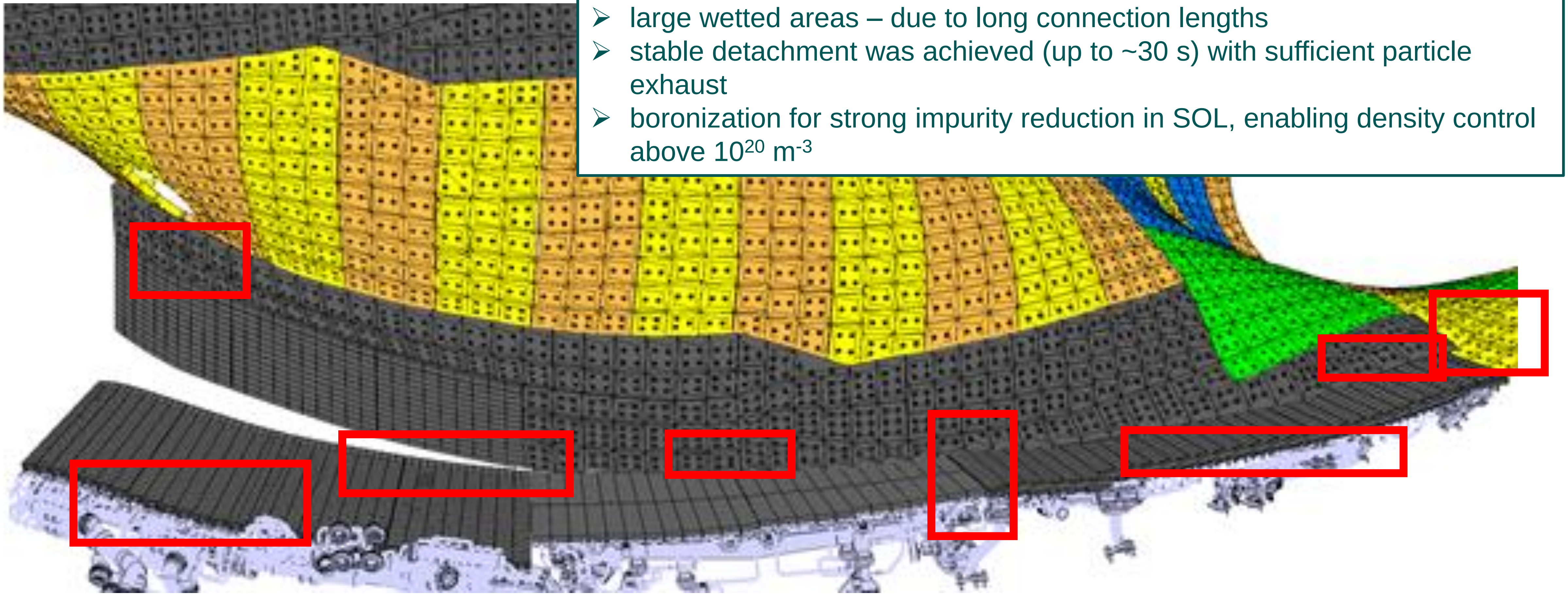
component	recommended thickness
divertor	~1-2 mm solid tungsten/tungsten based materials
baffle	> 10-20 µm -> coating with tungsten
wall	> 5 µm -> coating with tungsten



Source: Photo B. Kemnitz (IPP Greifswald),
Areas: C P Dhard et al 2021 Phys. Scr. 96 124059

Motivation – loads higher than expected in different locations

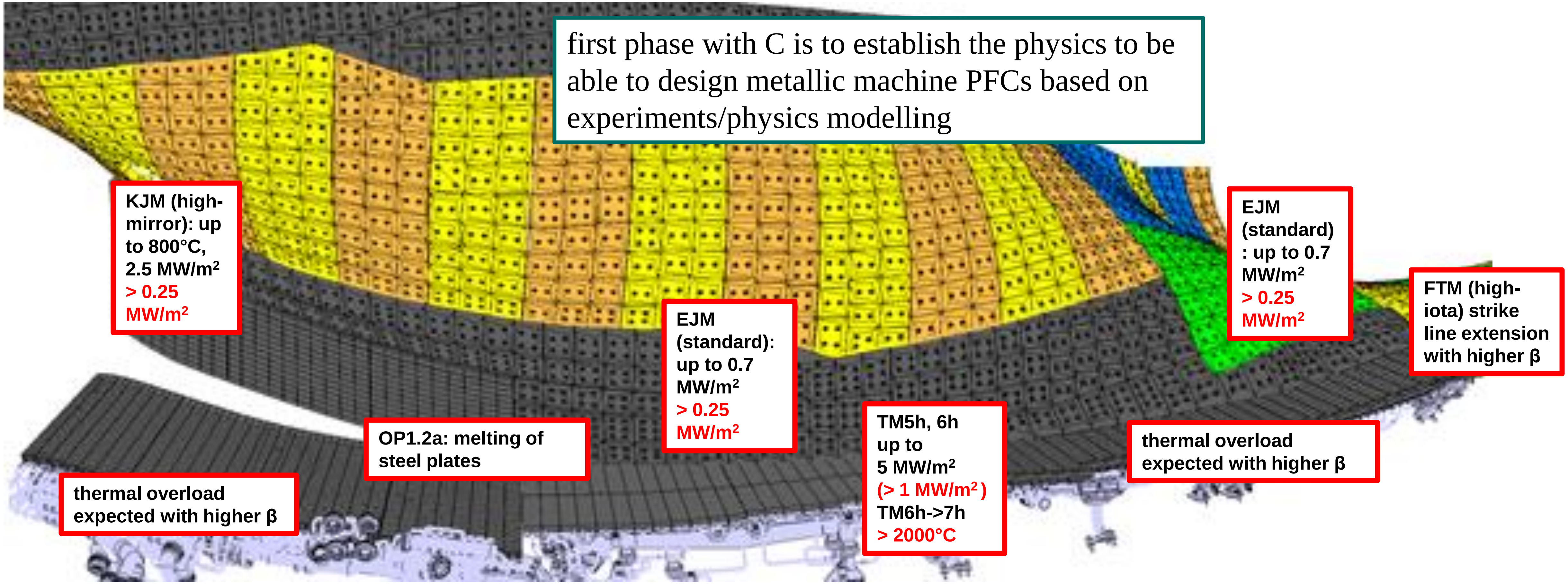
- divertor heat load patterns were generally as expected
- large wetted areas – due to long connection lengths
- stable detachment was achieved (up to ~30 s) with sufficient particle exhaust
- boronization for strong impurity reduction in SOL, enabling density control above 10^{20} m^{-3}



first lessons learned: definition of Plasma Facing Surface (PFS) meets the general requirements, but …

Motivation – heat load problems during plasma operation

first phase with C is to establish the physics to be able to design metallic machine PFCs based on experiments/physics modelling



excess heat loads are observed at several positions for different magnetic field configurations => operation limitations

Motivation – exhaust limitation

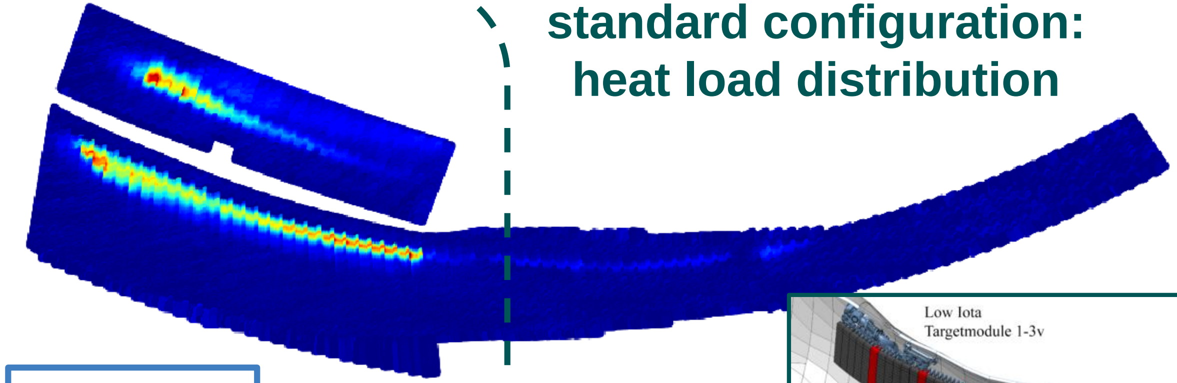
- neutral gas exhaust was sufficient for plasma density control even during long discharges (up to 100 s) – but before that wall conditioning discharges were required
- but relatively low neutral gas pressures in the sub-divertor region
- control of temperature-induced outgassing of the wall components by active pumping (TMPs, cryopumps in OP2)

standard configuration (EJM) up to P_{div} = **4*10^{-4} mbar** (AEH port)
high-iota configuration (FTM) up to P_{div}= **1*10^{-3} mbar** (AEP port)

more particle/heat load
-> more recycling
-> higher neutral gas pressure?

issue of poloidal and toroidal leakages (limited plugging by the divertor plasma) – continuous helical divertor?

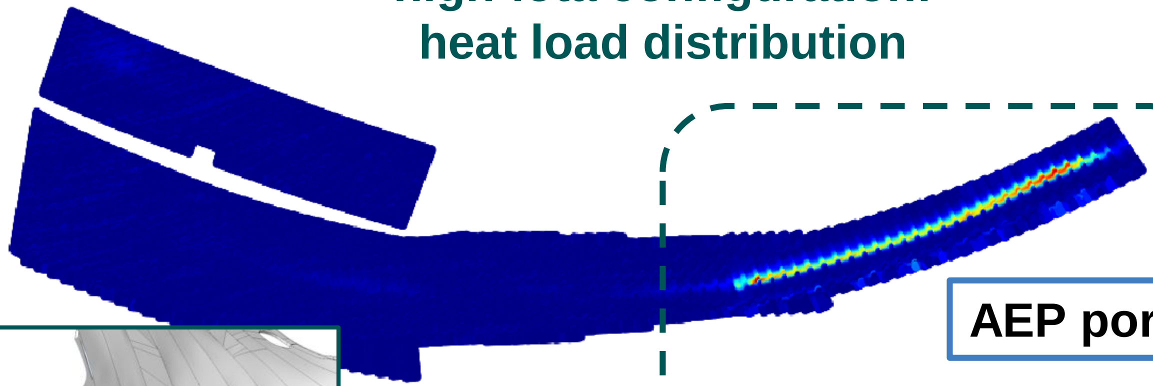
standard configuration: heat load distribution



AEH port

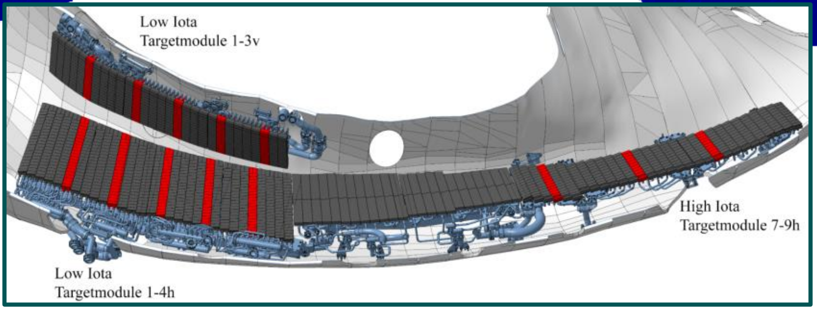
low iota divertor section

high-iota configuration: heat load distribution



AEP port

high iota divertor section



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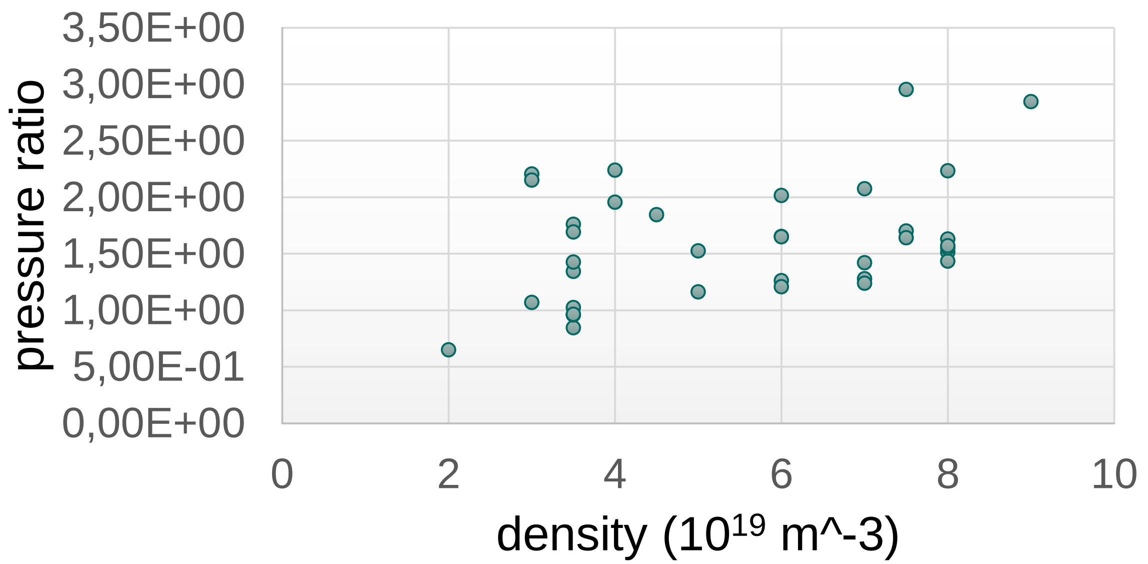
standard configuration (EJM) up to P_{div} = **$4*10^{-4}$ mbar** (AEH port)
high-iota configuration (FTM) up to P_{div}= **$1*10^{-3}$ mbar** (AEP port)

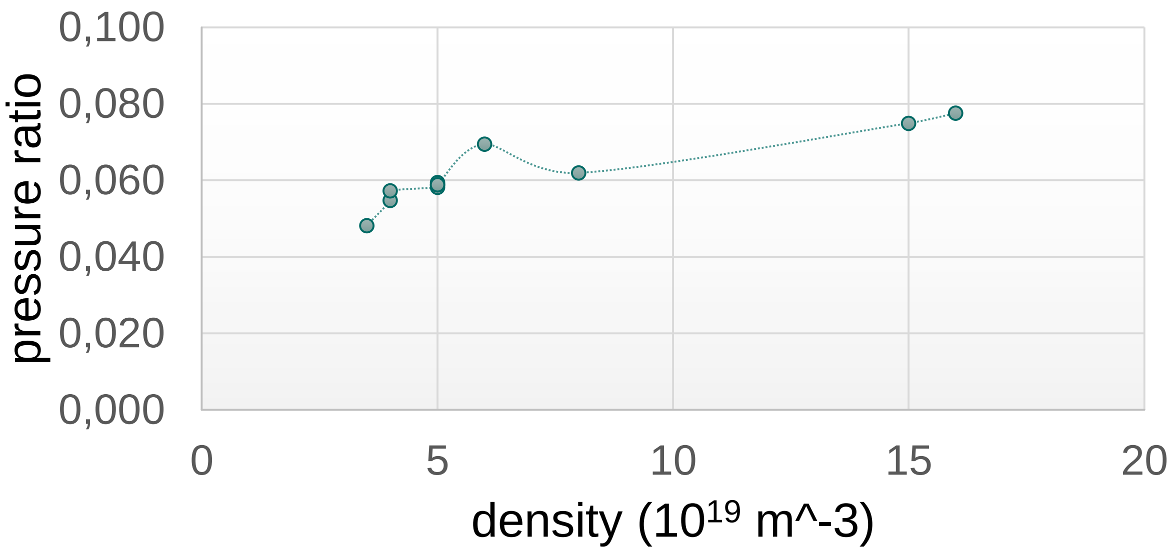
surprisingly high pressure in the high-iota section without strike line there in the standard config.

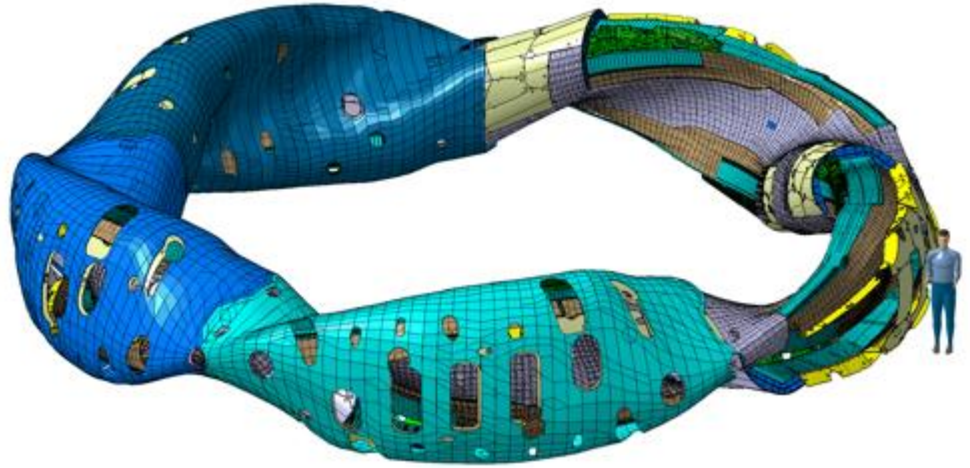
→ 105. Complete H fuel cycle with the island divertor in Wendelstein 7-X
Kremeyer Thierry (Max Planck IPP)
08/11/2022, 10:55

standard: pressure ratio AEH/AEP=2 (?)



high-iota: pressure ratio AEH/AEP=0.06 (ok)





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Optimization criteria, goals and constraints

Physics

Physics based optimization of plasma facing surface (standard, high-iota, high-mirror)

- avoiding power overload (targets, baffles, heat shield, wall, diagnostics)
- avoiding excess local erosion (e.g. at leading edges)
- improved exhaust aiming at higher neutral gas pressures in the sub-divertor space, reduce leakages, improve (toroidal & poloidal) plugging
- provide effective screening of impurities (keep them away from the core region (low Zeff)) – impact of geometry modifications?

→ 122. Impurity leakage mechanisms in the W7-X island divertor under experimentally relevant operational space
Victoria Winters (Max Planck Institut...
08/11/2022, 11:15

Technology

Development, manufacturing, high-heat load testing and installation technology qualification:

- target elements (WPDIV-W7X) for 10 MW/m^2 in steady-state (merging 3 target elements into one heat sink including parallel cooling channels and manifold), W/W-alloy bonding with Cu/CuCrZr heat sink
- reducing thermal bending of target elements
- target modules
- baffle modules

thermal-mechanical assessments, cyclic high heat flux resistance
detailed planning of series production and installation

heat removal

fuel removal

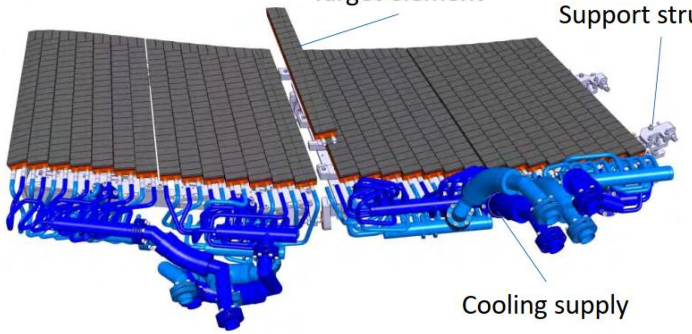
He removal

impurity control

parallel activity of the physics concept and technology development with continuous exchange of information - definition of plasma facing surface will be an essential input for the integrated design of sub-divertor components.

Optimization: technical constraints

CFC HHF divertor geometry forms the basis for a new W divertor design: 10 MW/m² design heat load, need for special tile design at the pumping gap, with increased design heat load from 2-5 to 10 MW/m² limiting target module weight ~70 kg:
cryopump operation should by ensured also with a new divertor



Using existing cooling water infrastructure:

- 5 l/s per target module, 12 modules per unit
- single phase flow at 10 MW/m²

more details →

110. Synergies in the technological developments of the W7-X and JT-60SA metallic divertor plasma facing components
Marianne Richou
08/11/2022, 14:30

simplify manufacturing

- minimize pipe work, weld seams and target element positioning issues
- minimize number of target elements per module
- preferably one target element per module without support structure
- stiff at cold side to minimize thermal curvature

simplify installation

- target modules statically determined supported
- to avoid retrained thermal expansion
- to facilitate precise positioning
- relax installation tolerances (gaps and steps)
- water connection accessible after installation

Steps of concept development: optimization via modelling

1. Construct set of representative magnetic equilibria
*include high beta effects

=> Tool: **VMEC + Extender**

2. Benchmark modelling tools (EMC3-Lite, EMC3/Eirene, etc.) against experimental observations

3. Plasma facing surface (PFS) corresponding to proposed design change

=> Tool: **CATIA + Kisslinger Format**

4. Preliminary design check using fast tools

Heat flux
- Strike line position
- Wetted area

=> Tool: **EMC3-Lite**

Neutral exhaust
- Probability to reach PG
- Neutral pressure

=> Tool**: ANSYS**, **MC**

5. Detailed design check
- validate results
- better neutral gas model

=> Tool: **HINT, EMC3/Eirene, DIVGAS**

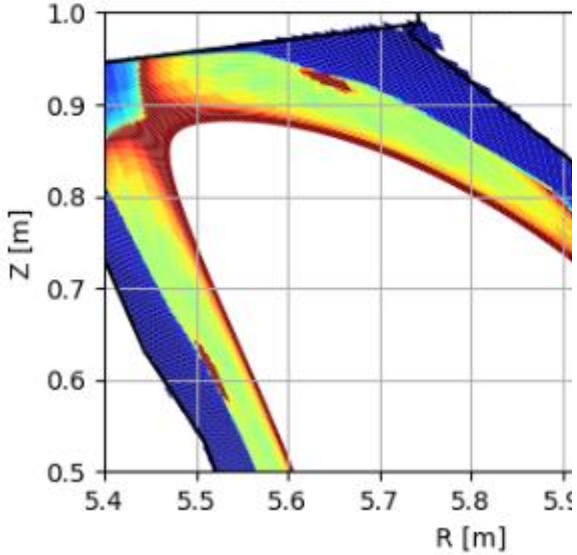
PFS definition

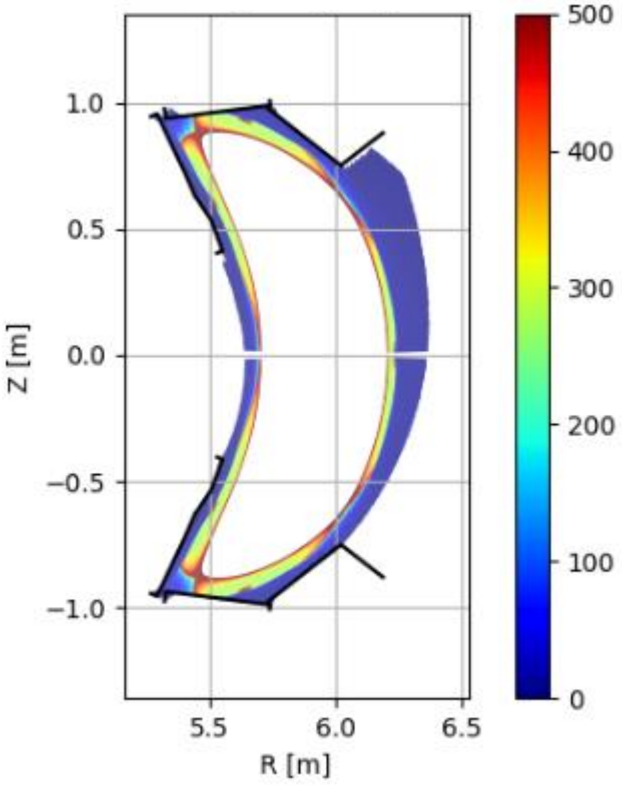
design is mainly driven by physics modeling of various complexity, which are validated against results obtained experimentally

⇨ this phase ends with an international design review and a detailed assessment of manufacturing costs, timeline and resources

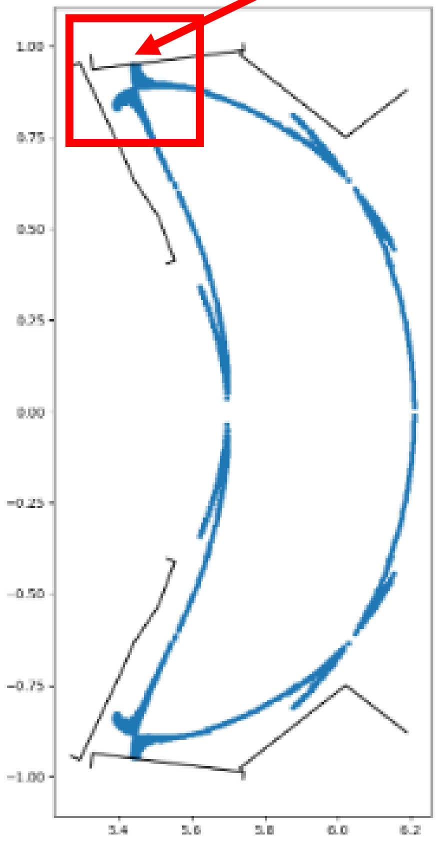
Steps of concept development – physics studies: basics

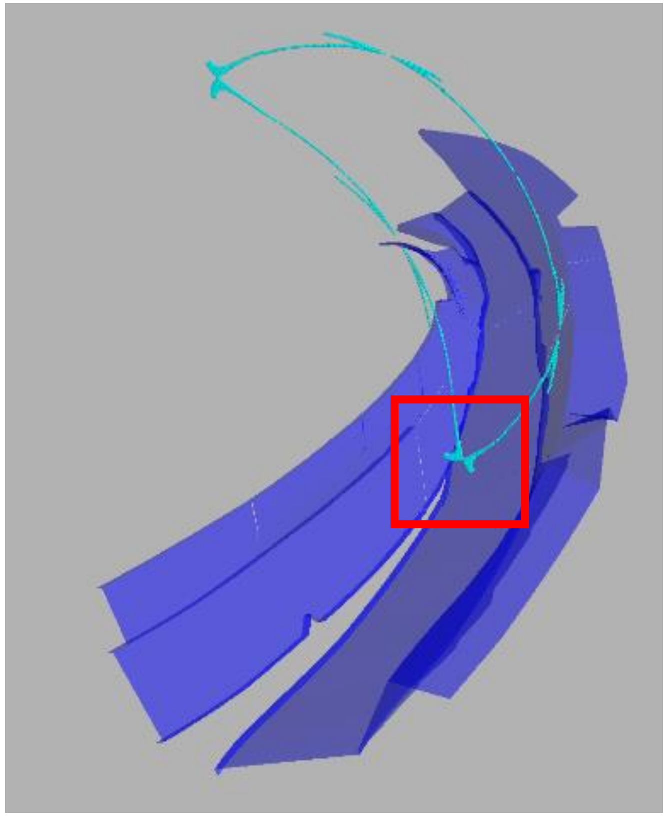
connection length
at phi=0





strike line positions

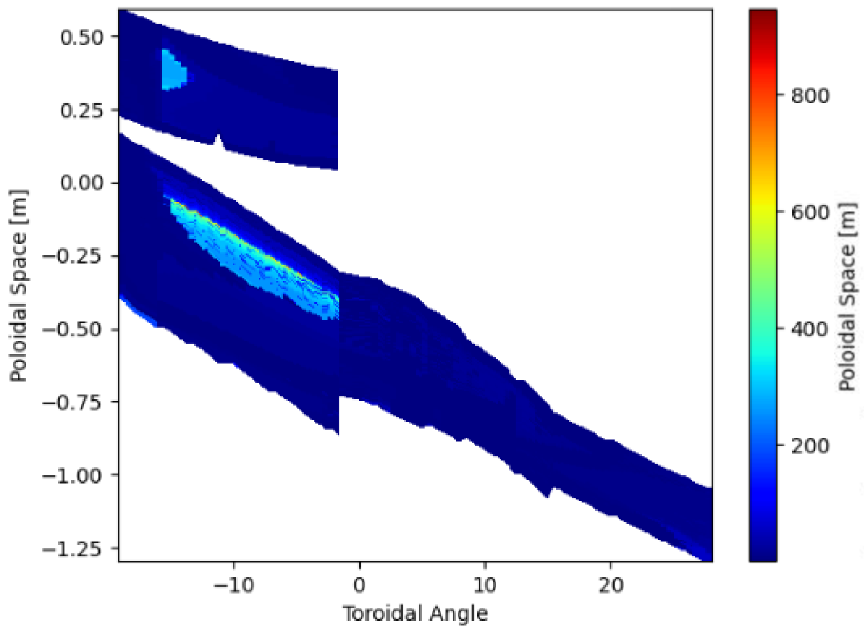




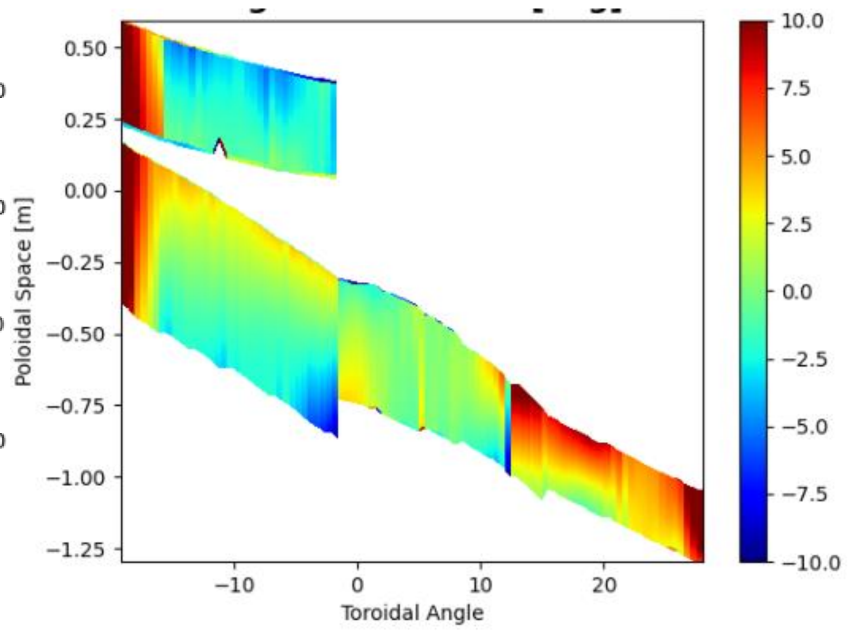
construction of a flux surface with
high parallel power fluxes = long connection length

flux tubes with long connection lengths are supplied with energy via cross-field transport from the core

Steps of concept development – physics studies: basics



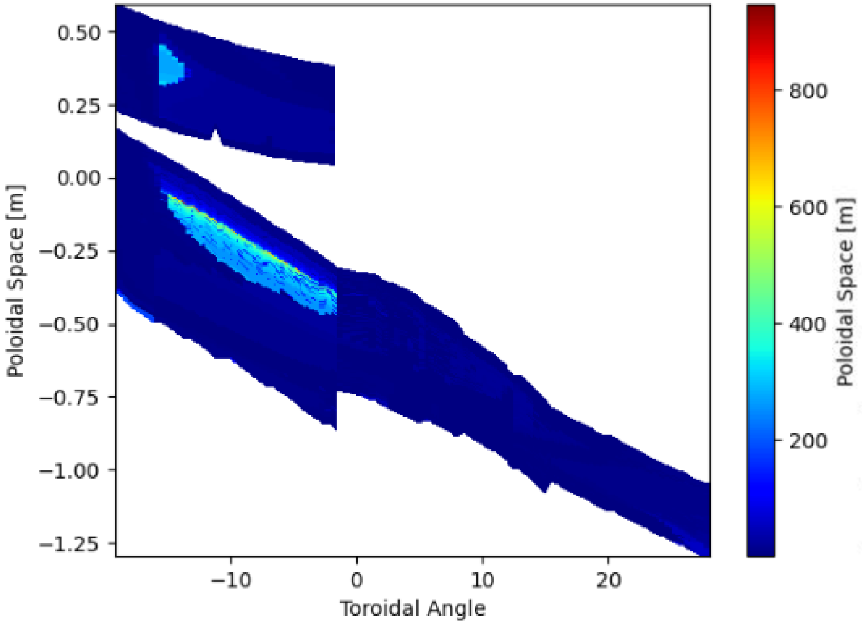
pattern of connection lengths [m]



pattern of angle of incidence

3D heat load distribution is defined by parallel/perpendicular transport of energy and by the angle of incidence: P_s [MW/m^2] = $P_{parallel}$ x sinα x exp($-\Delta/\lambda_q$)

Steps of concept development – physics studies: basics



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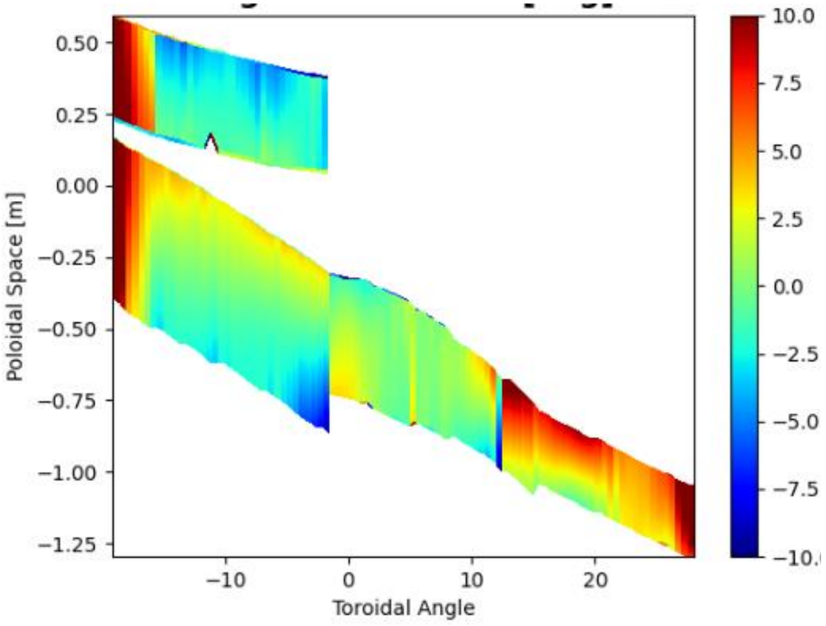

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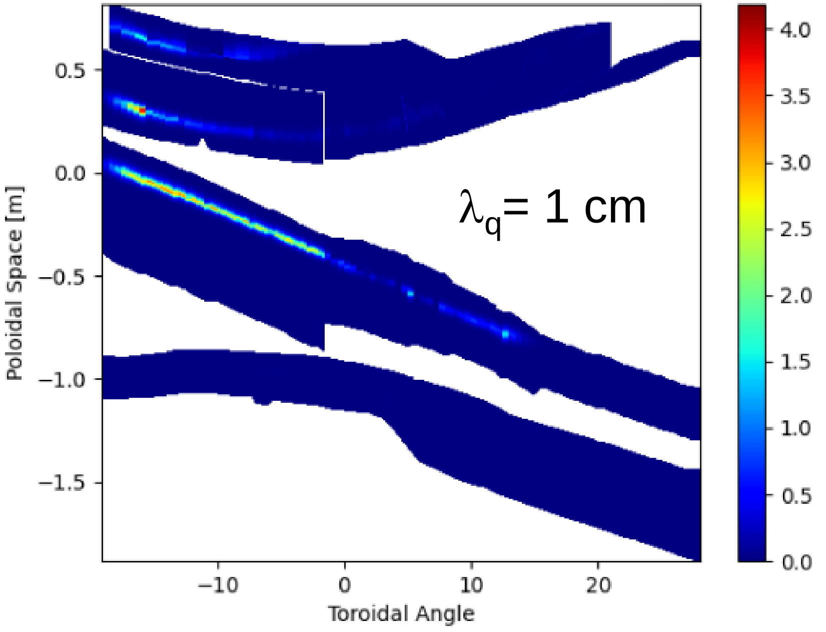
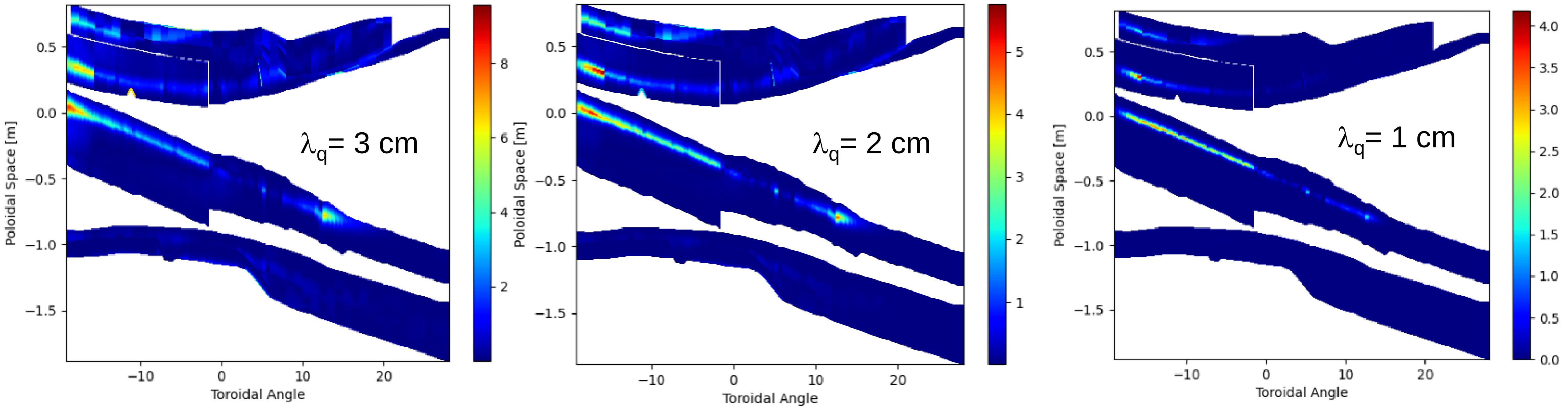


heat load distribution P_s

Δ distance from high energy flux tube to the components
λ_q power decay length in the SOL

3D heat load distribution is defined by parallel/perpendicular transport of energy and by the angle of incidence: P_s [MW/m^2] = $P_{parallel} \times \sin\alpha \times \exp(-\Delta/\lambda_q)$

Steps of concept development – physics studies: basics



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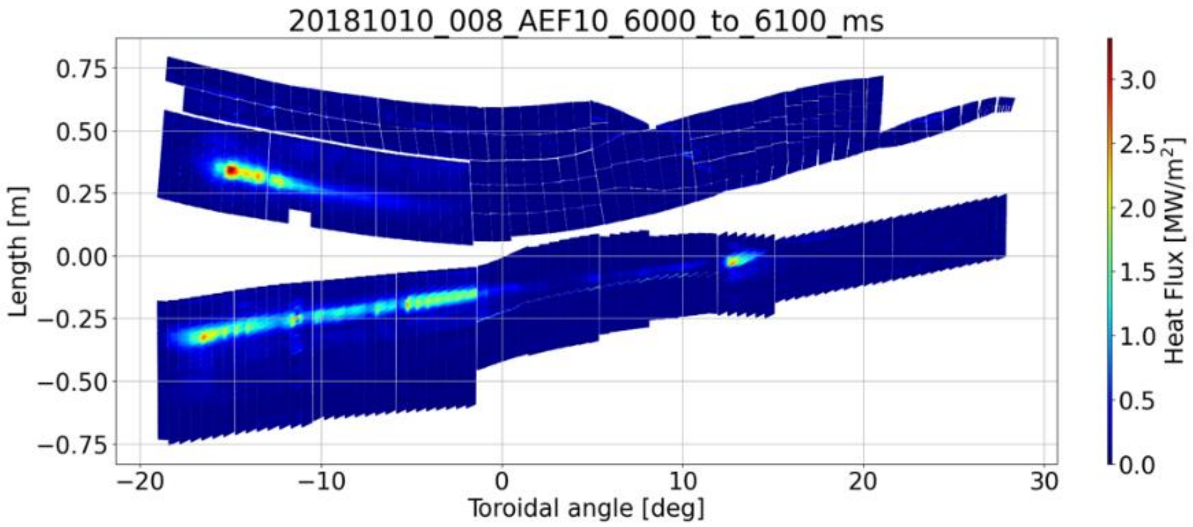
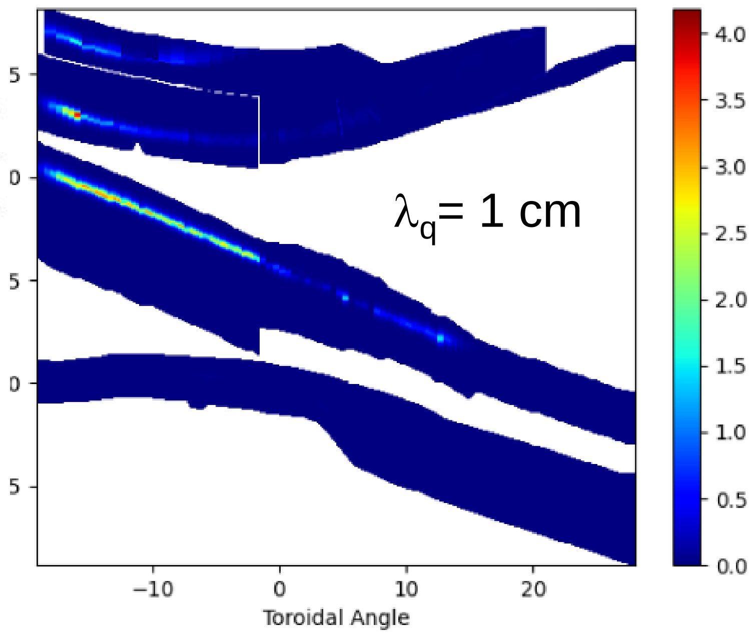


comparison with experimental results



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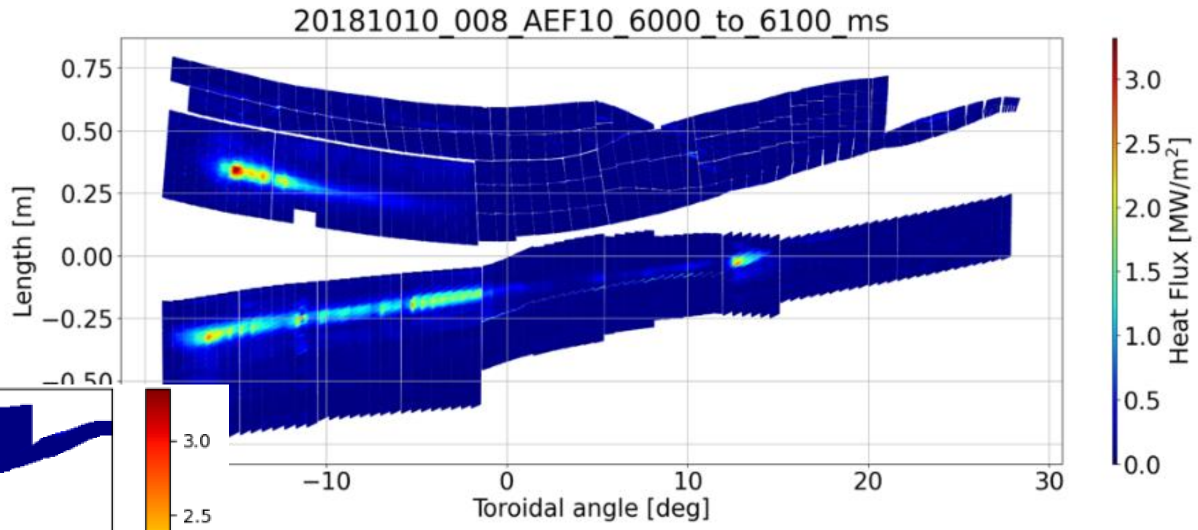

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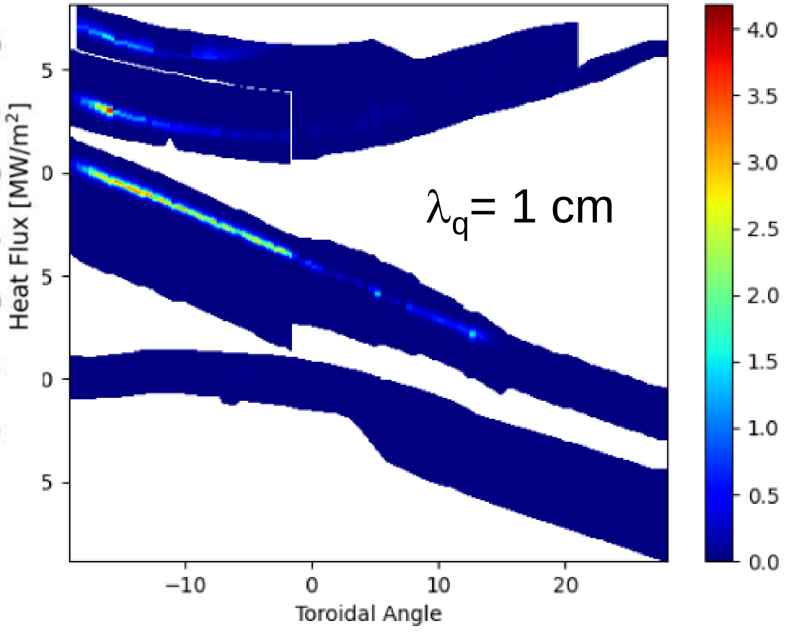

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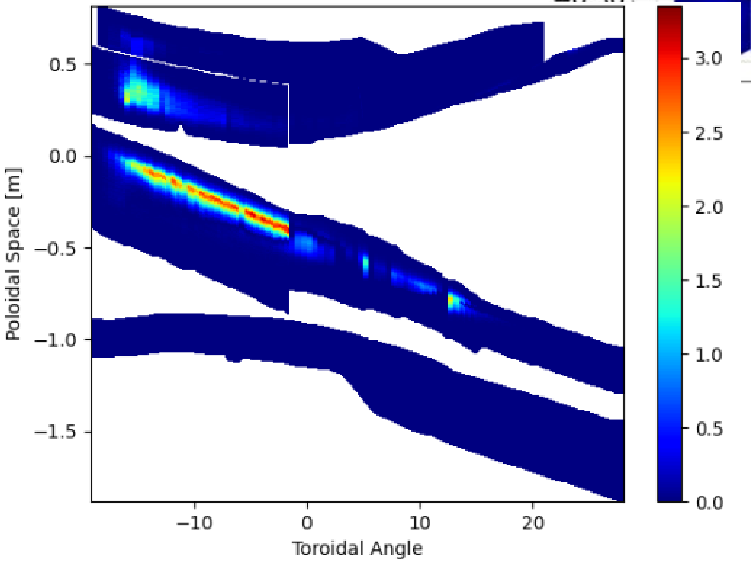

comparison
with EMC3-Lite

Δ distance from high energy flux tube to the components
λ_q power decay length in the SOL

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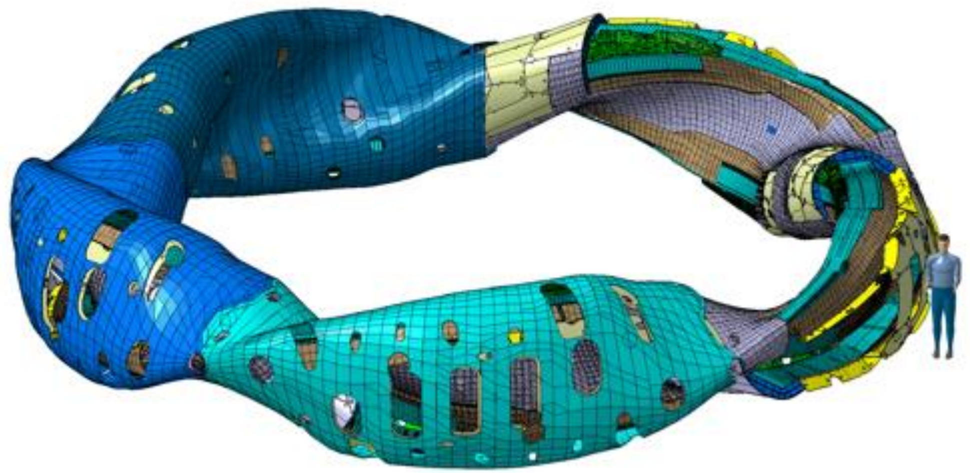

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Tools for physics simulation – heat load calculations with EMC3-Lite

Fast numerical tool -> order of magnitude estimate of heat fluxes onto arbitrary 3D PFCs ~ 100s

Heat transport equation neglecting convective energy fluxes and the parallel conduction of ions, ignoring energy source terms due to neutrals and impurities, assuming constant density:

$$\nabla \cdot \left(-\kappa_e \nabla_{\parallel} T - \chi n \nabla_{\perp} T \right) = 0$$

Bohm condition at the targets: $q_{\parallel} = -\kappa_e \nabla_{\parallel} T = n C_s \gamma T_t$

$\parallel$ transport -> electron heat conduction, $\perp$ transport -> $\chi = \chi_e + \chi_i$

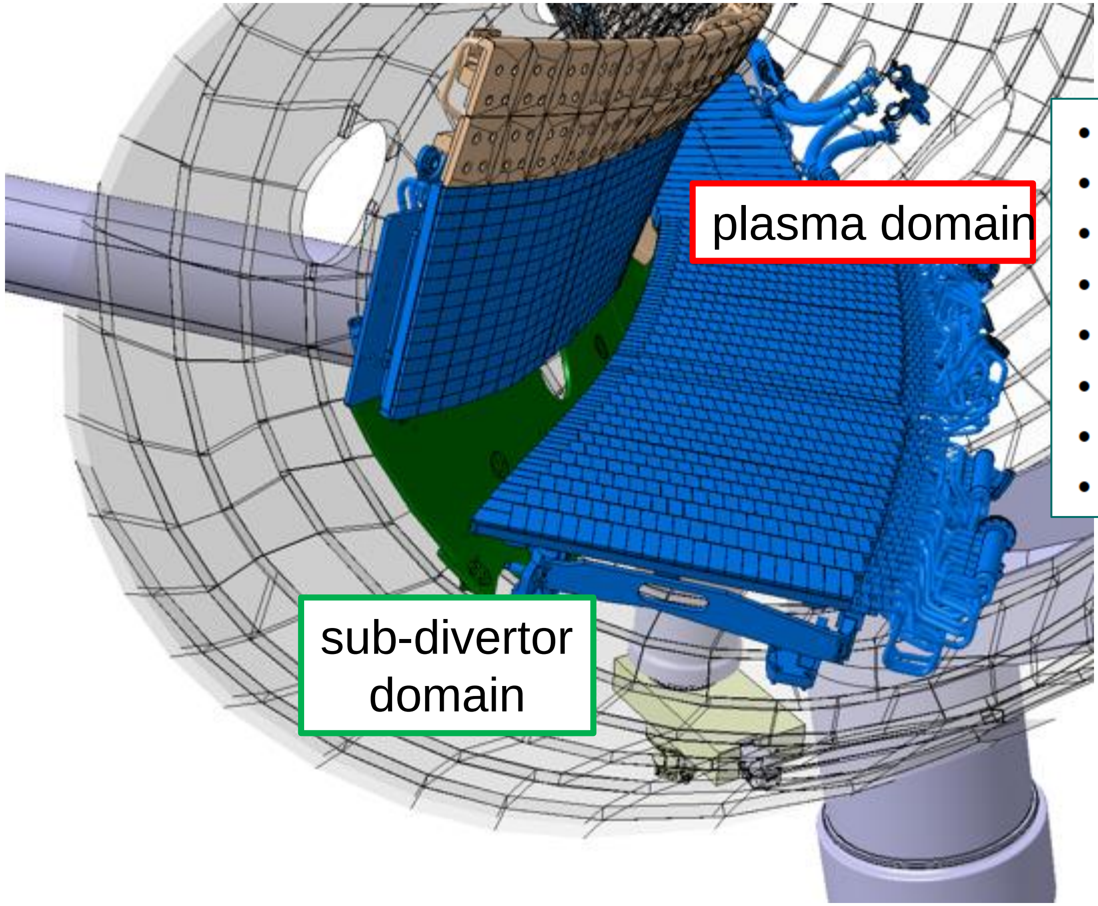
Constant parallel heat conductivity -> $\kappa_e = \kappa_{e0} T_0^{2.5}$

Constant density

EMC3-Lite includes only parallel classical electron conduction and a perpendicular anomalous conductive process, which are the dominant heat transport processes at low plasma densities.

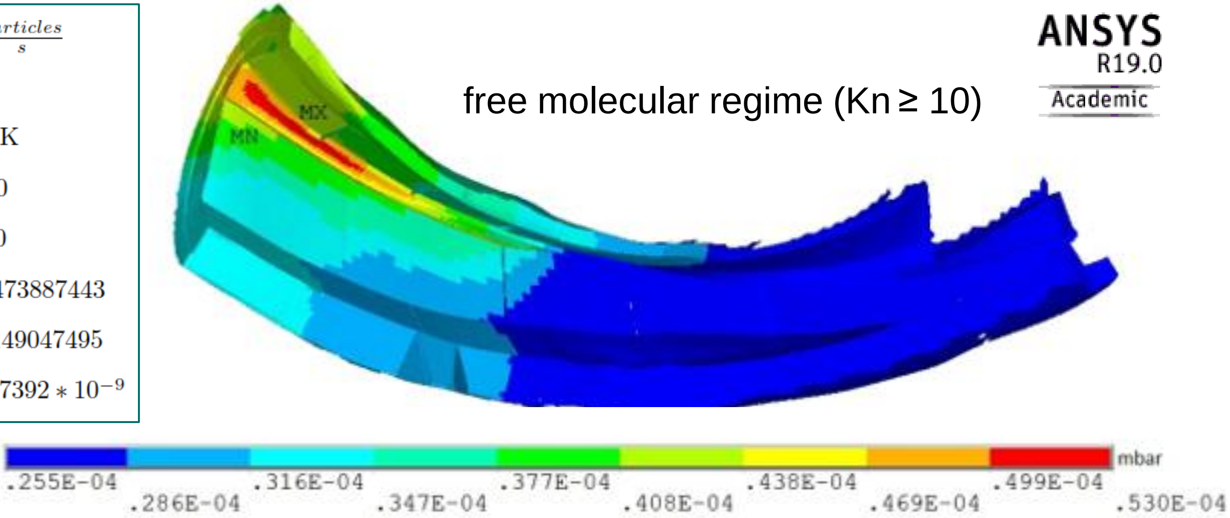
Source: Yuhe Feng 2022 Plasma Phys. Control. Fusion in press https://doi.org/10.1088/1361-6587/ac9ed9

Tools for physics simulation - neutral gas dynamics with ANSYS



- $\Phi_P = 10^{20} \frac{particles}{s}$
- $T = 600K$
- $T_n = 303.15K$
- $S_{AEH} = 2550$
- $S_{AEP} = 1300$
- $\epsilon_{AEH} = 0.0473887443$
- $\epsilon_{AEP} = 0.0149047495$
- $s_f = 8.243277392 * 10^{-9}$

3D transport of neutral molecules in the W7-X sub-divertor region calculated by using the ANSYS radiation transport code

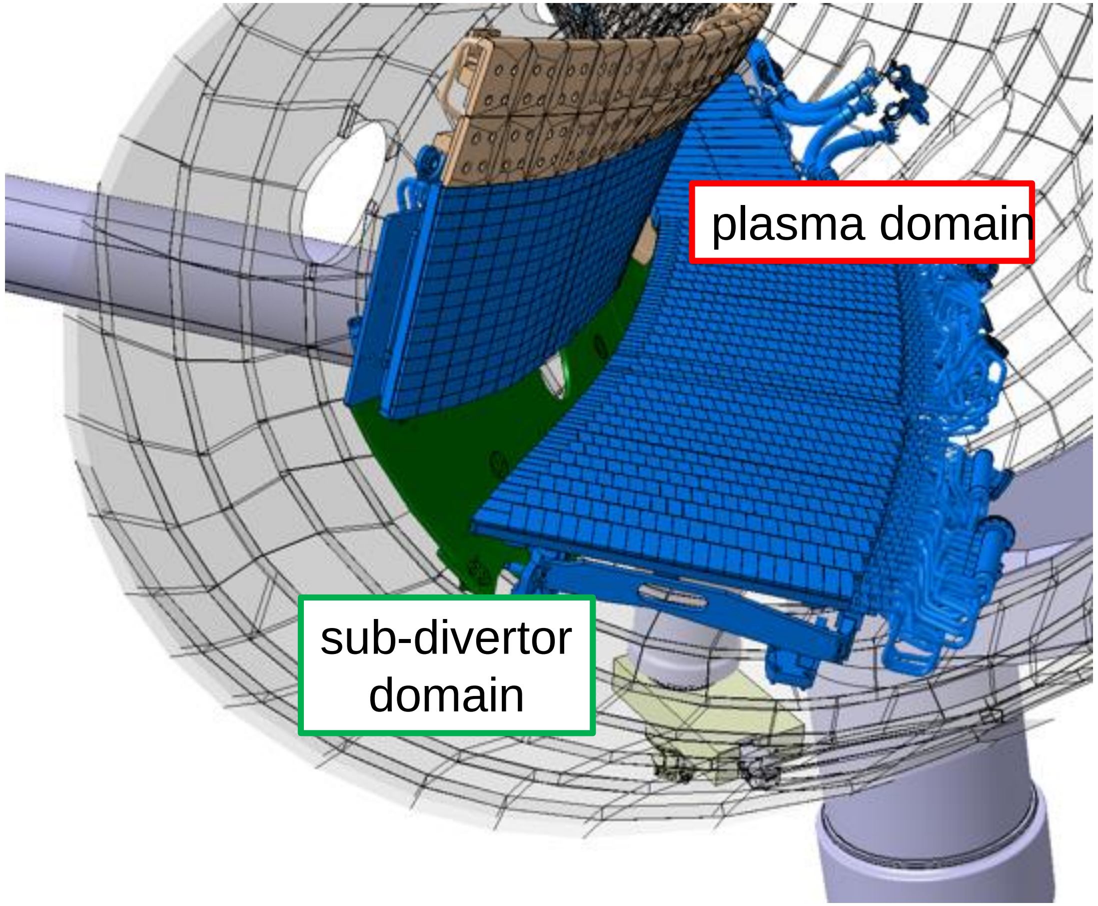


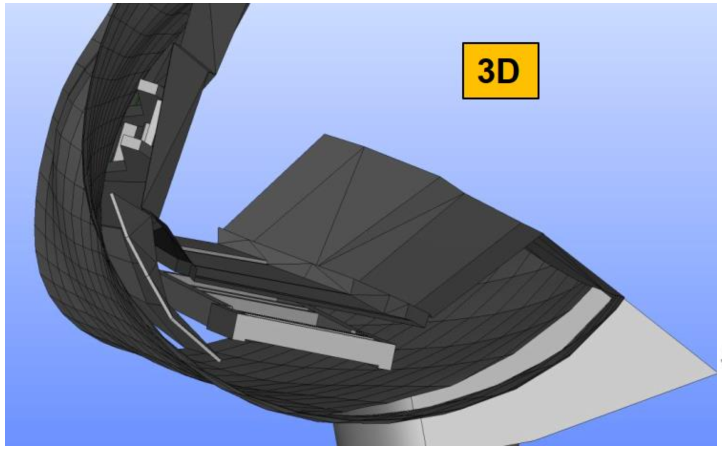
Definition of sub-divertor geometry

using neutral gas modelling

aims: efficient exhaust to the pumps (TMP, cryopumps)

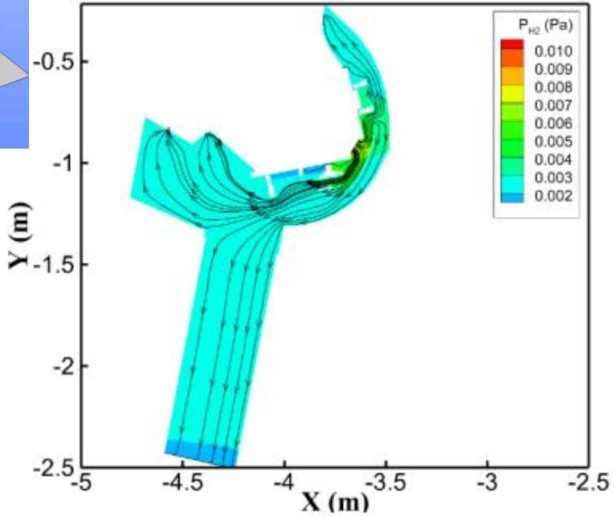
Tools for physics simulation – neutral gas dynamics with DIVGAS





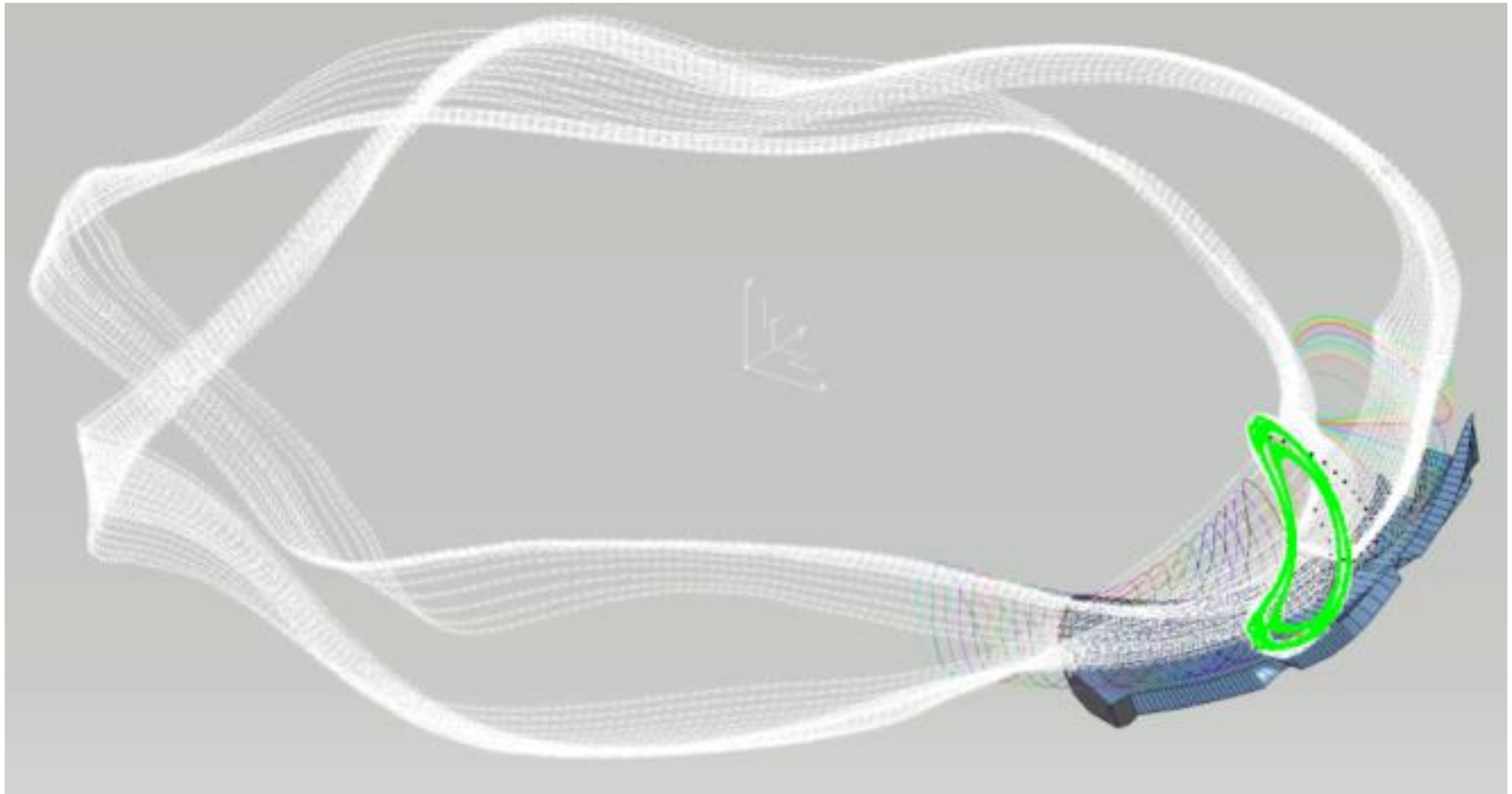
collaboration with KIT
S. Varoutis, C. Tantos, H. Strobel, Yu. Igitkhanov, Chr. Day

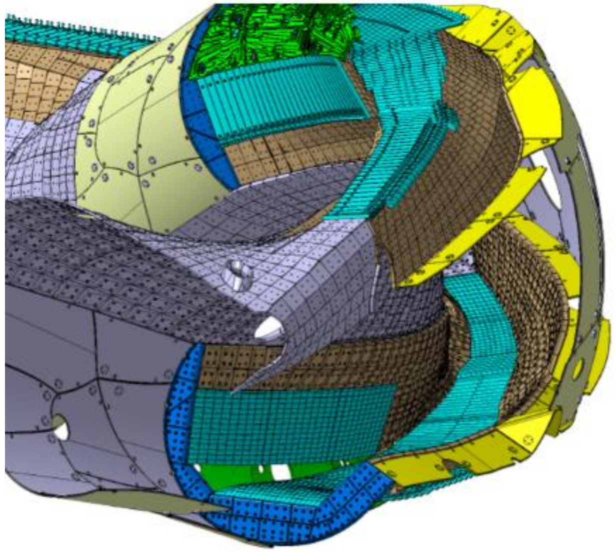
DIVGAS is based on the Direct Simulation Monte Carlo (DSMC) method including neutral-neutral collisions in the volume

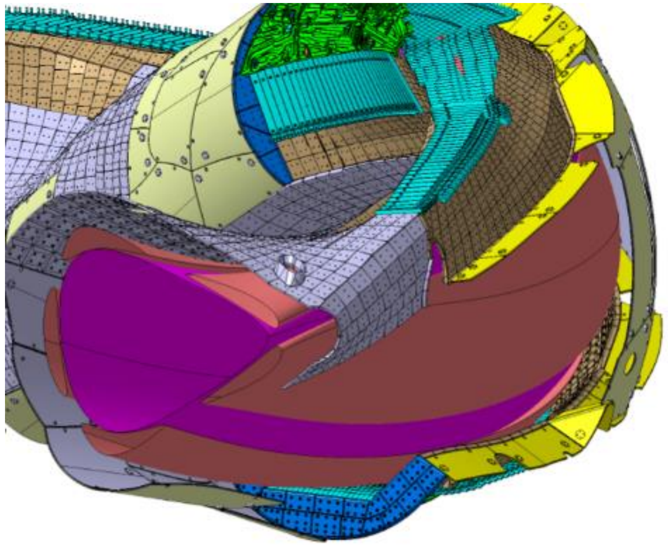


verification of the initial results by using neutral gas modelling with DIVGAS (KIT) for higher neutral gas pressure (incl. particle-particle collisions)

Design tools with CATIA

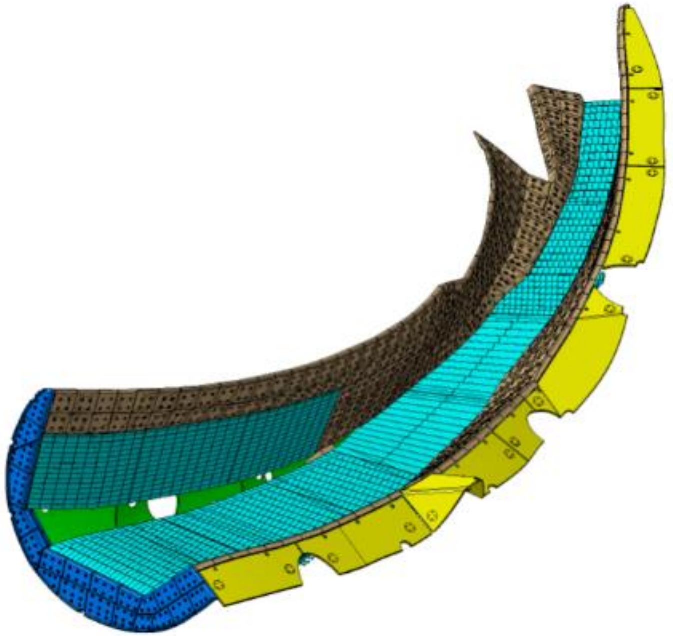






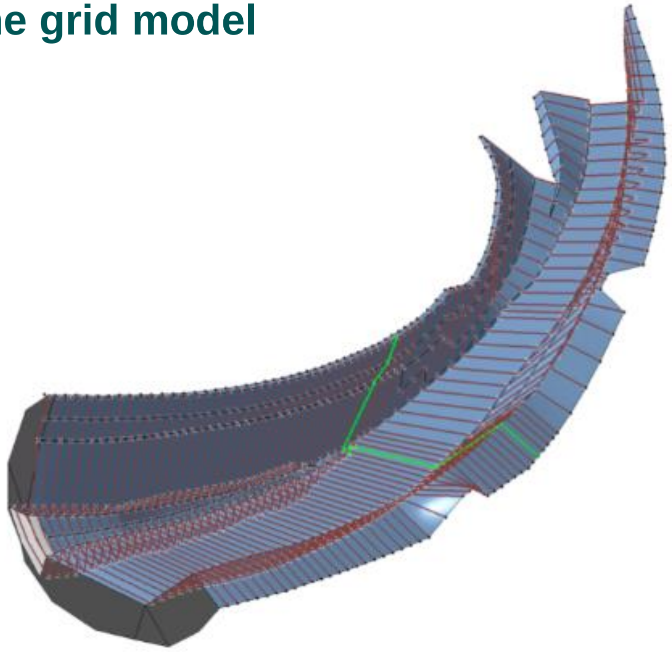
the modeling activities are supported by the development of efficient engineering tools in a CATIA environment that process the complex 3D W7-X design data at different levels of sophistication to promote an efficient interchange with the physics-based codes

Design tools with CATIA

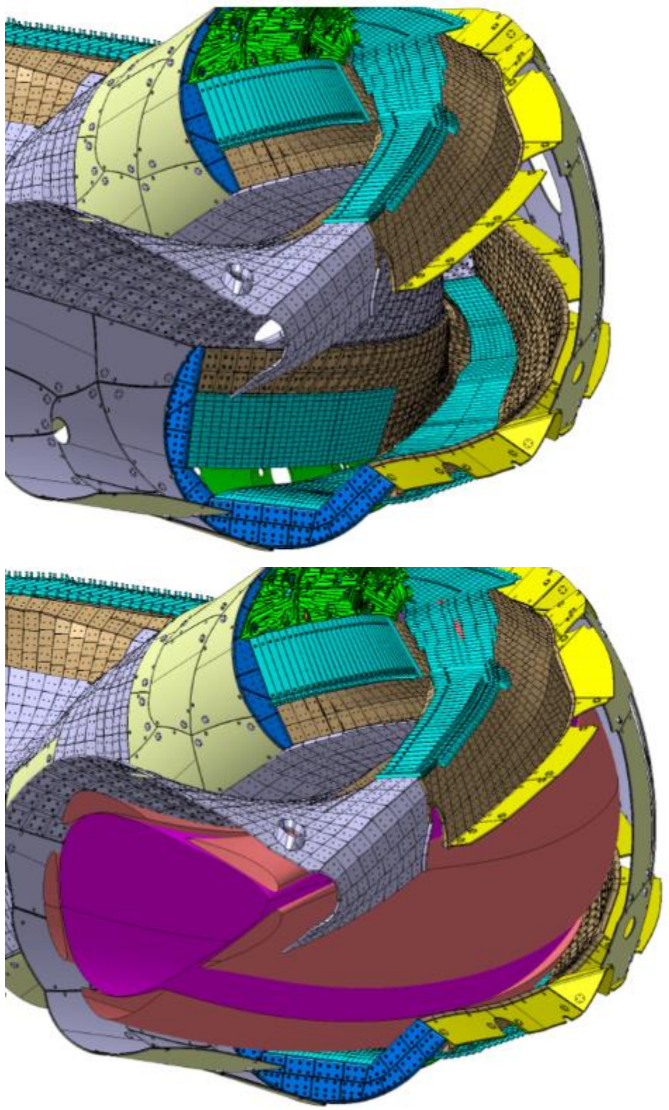


detailed CAD geometry of
one divertor unit

the grid model

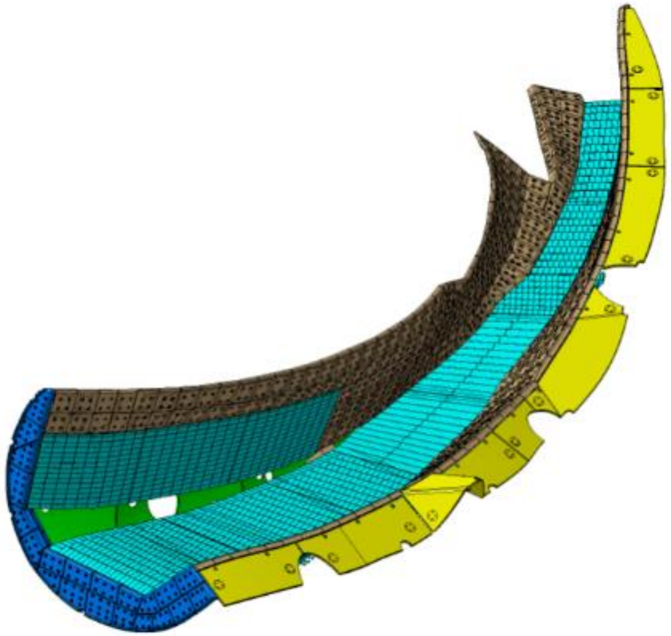


reduced grid model with
limited number of grid points

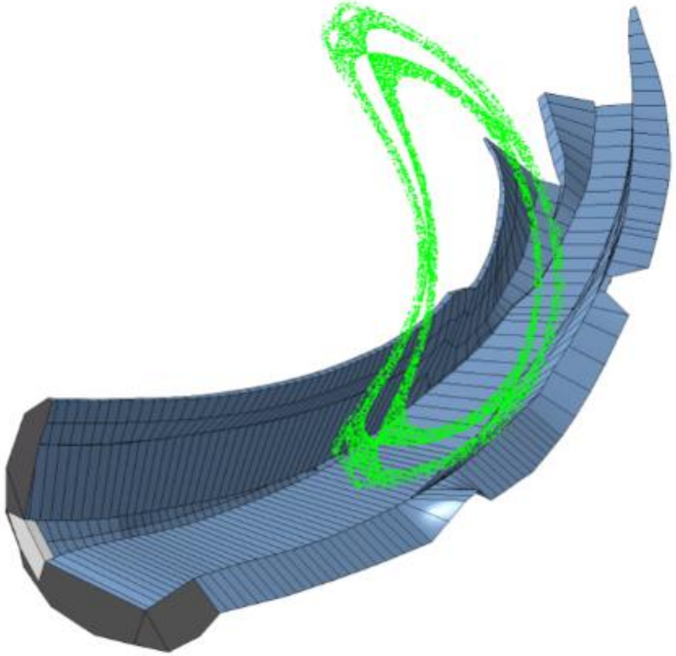


the modeling activities are supported by the development of efficient engineering tools in a CATIA environment that process the complex 3D W7-X design data at different levels of sophistication to promote an efficient interchange with the physics-based codes

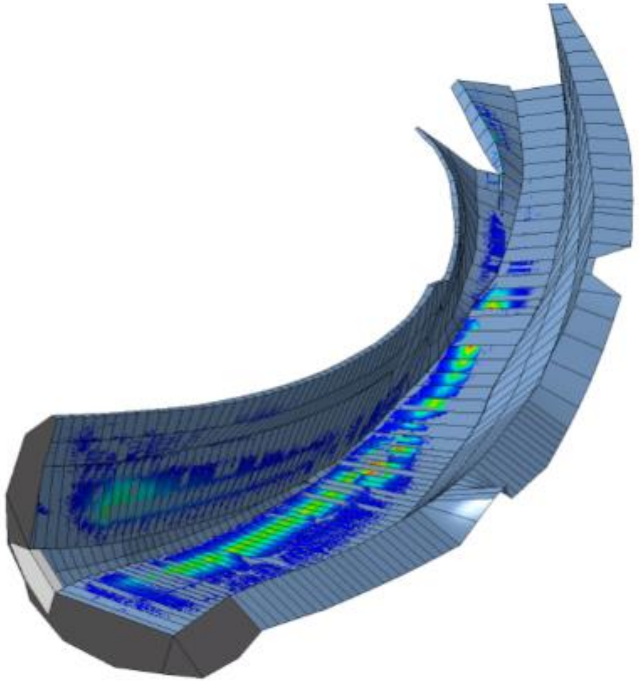
Design tools with CATIA



detailed CAD geometry of
one divertor unit



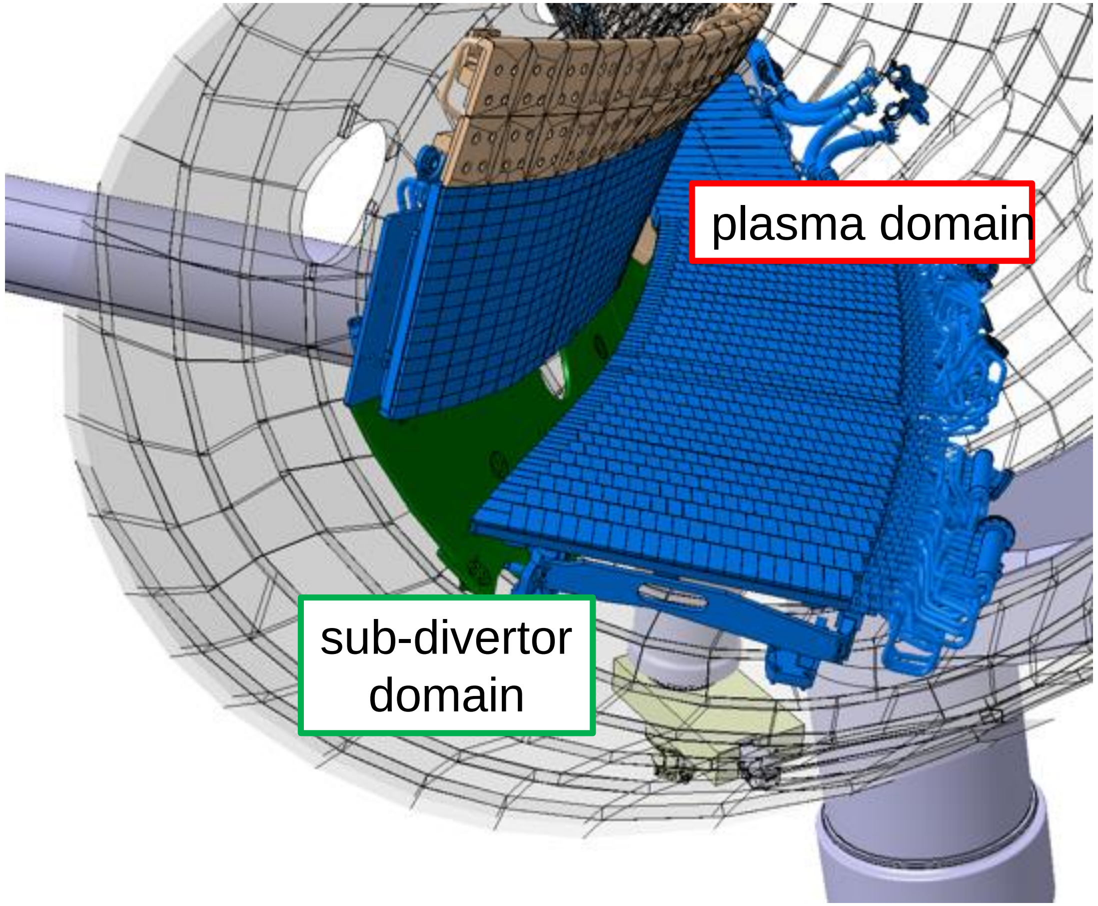
grid model together with
Poincare-plot



EMC3-Lite results mapped
onto the grid model

the grid model is used to modify the plasma facing surface as input for the physics modeling

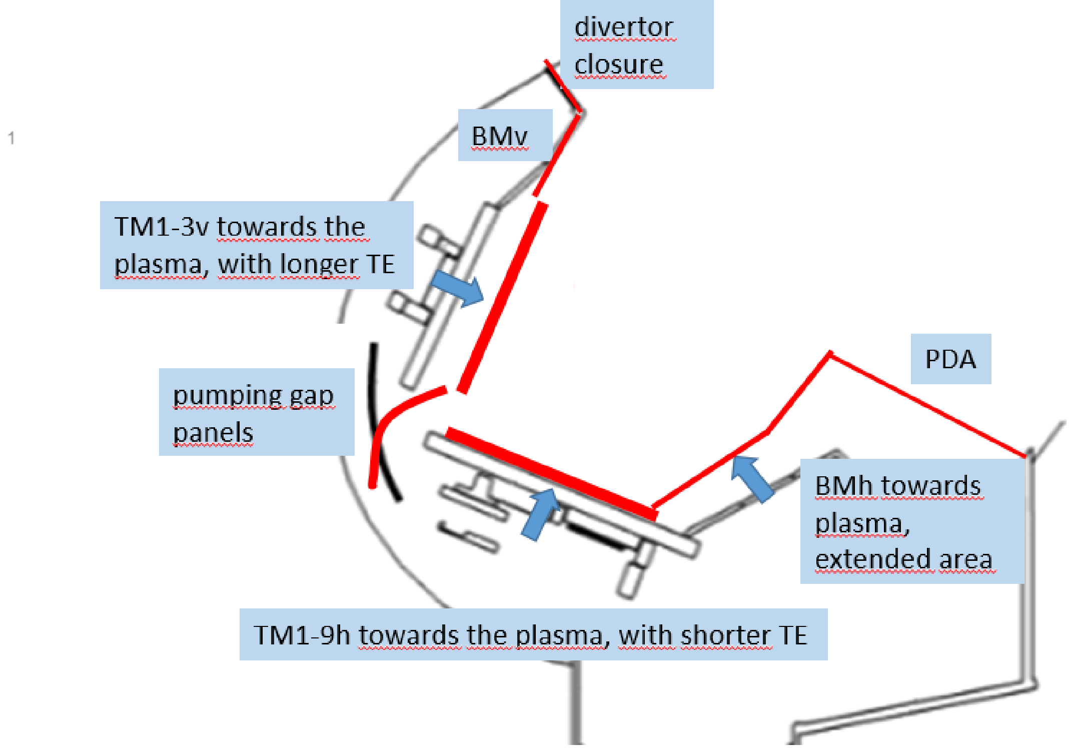
Geometry modifications



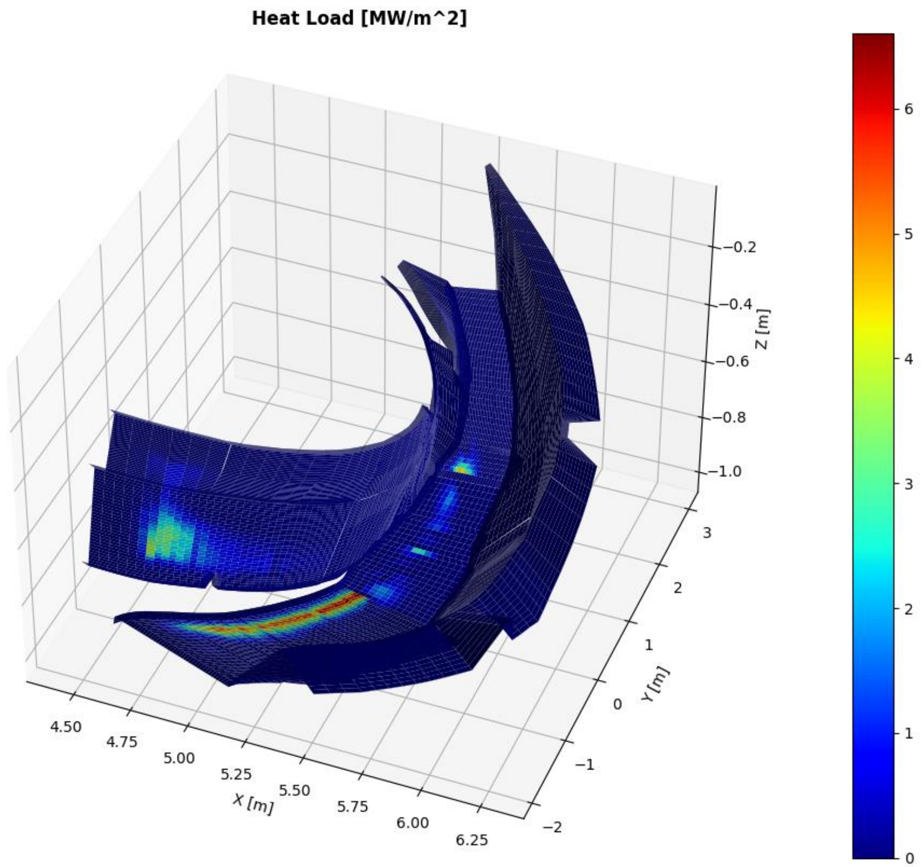
Definition of the plasma facing surface (PFS)

using diffusive field line tracing (DLFT), EMC3-Lite, EMC3/Eirene

aims: heat load optimization + high neutral gas density at the pumping gap

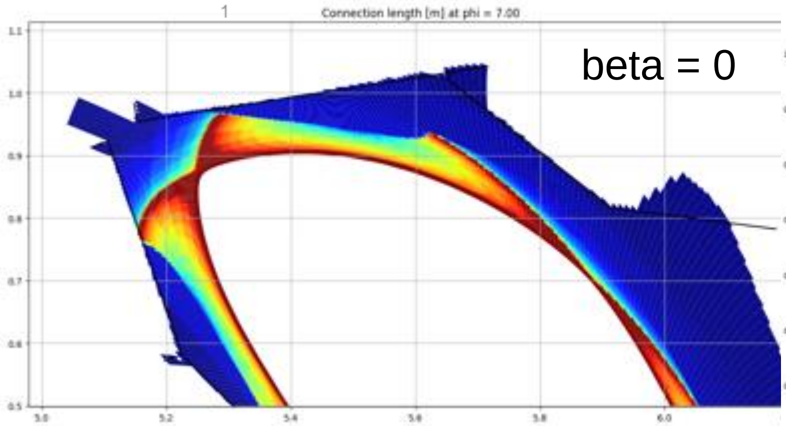


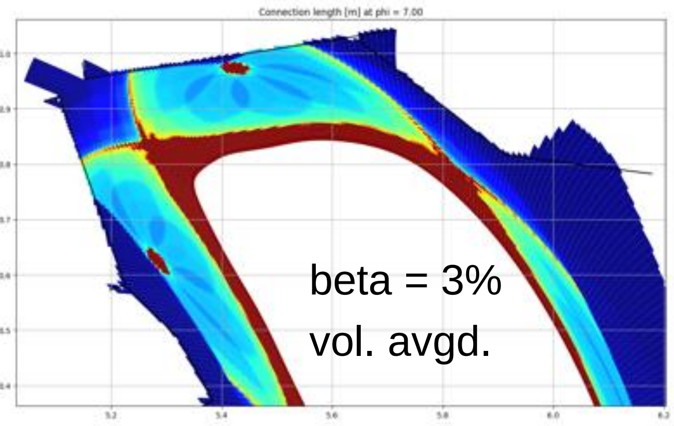
Steps of concept development – physics studies



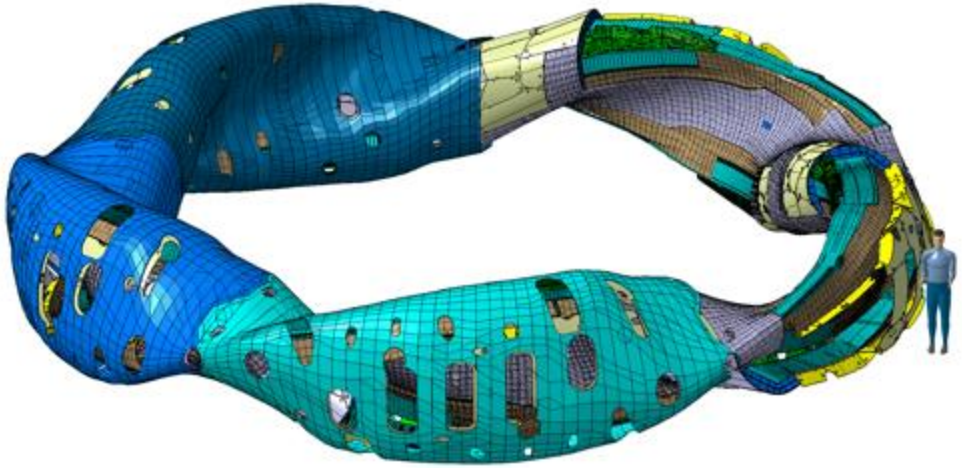
Peak heat load Vertical target (MW/m^2): 4.44
Peak heat load Horizontal target (MW/m^2): 6.6
Peak heat load Vertical baffle (MW/m^2): 1.3
Peak heat load Horizontal baffle (MW/m^2): 0.0162

P_Incident (W): 1.00e+07
P_depo Vertical target (W): 2.24e+05
P_depo Horizontal target (W): 7.45e+05
P_depo Vertical baffle (W): 2.96e+04
P_depo Horizontal baffle (W): 1.09e+02
P_lost (W): 1.21e+03



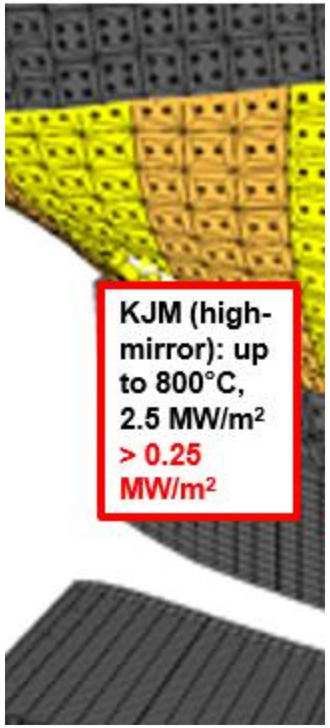


detailed assessment of heat-load redistribution due to geometry modifications for three main configurations (standard, high-iota, high-mirror) and different beta values => in progress

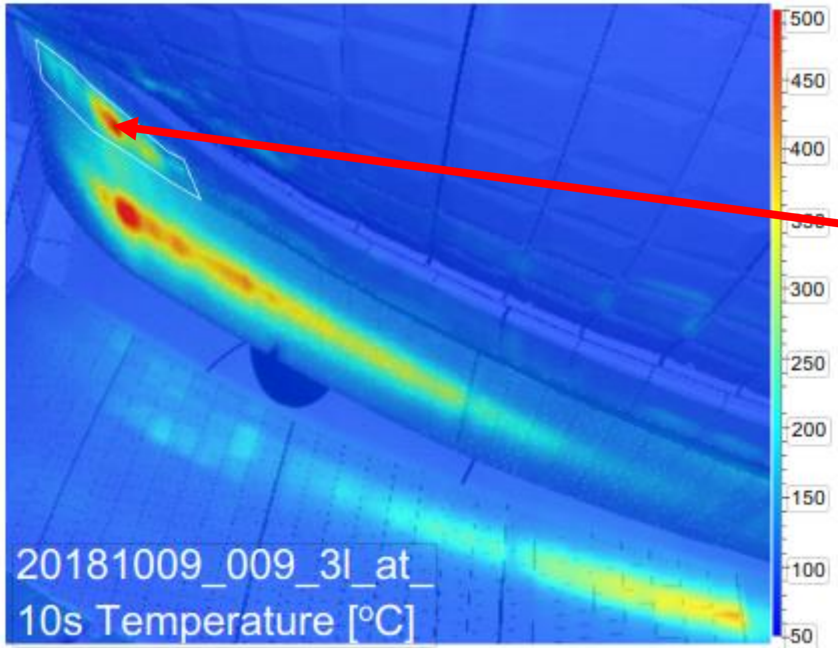


- Motivation – new tungsten divertor for W7-X
- Optimization criteria, goals, constraints
- Steps of concept development
- Tools for physics simulation/optimization:
  - [1] heat load calculations (EMC3-Lite, EMC3/Eirene)
  - neutral gas modeling (ANSYS, DIVGAS)
  - design tools (CATIA)
- **Experimental verification of the concept ideas**
- Summary

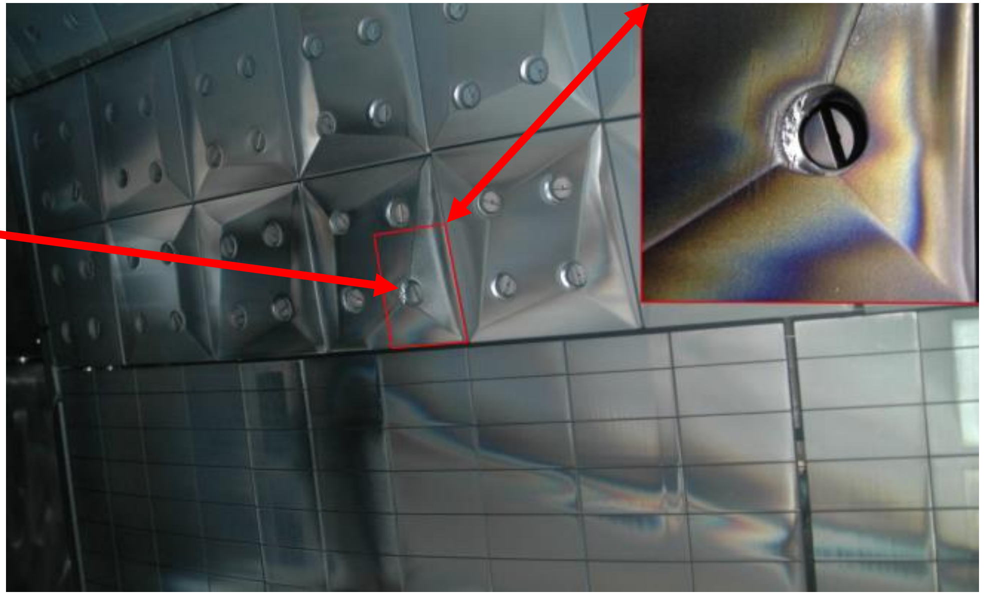
Experimental verification of the concept ideas



see on p. 6



the IR image is overlaid with the image of the CAD components associated with the camera view.

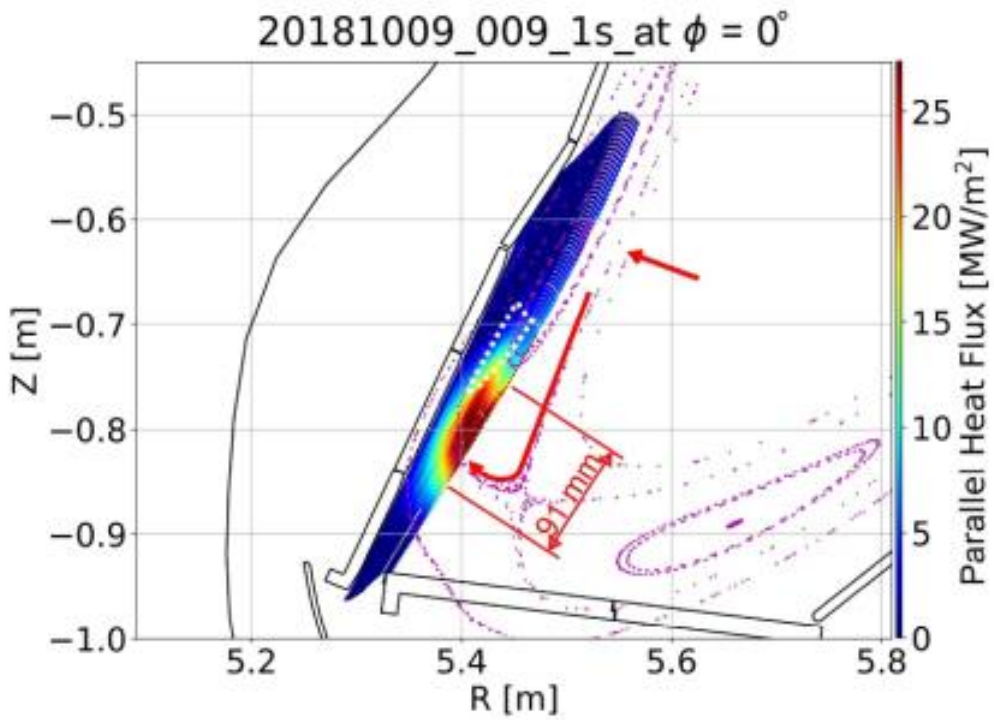


erosion and deposition pattern see at these positions

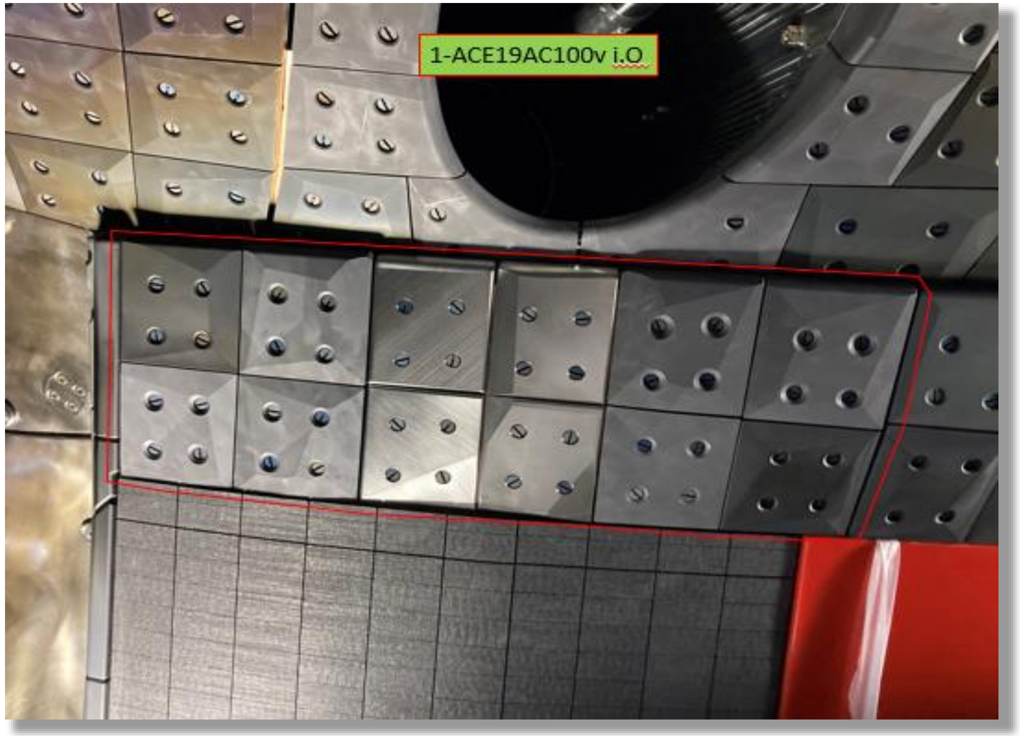
Source: Yu Gao *et al* 2020 *Nucl. Fusion* **60** 096012

overload of baffles (BM1v) observed in former campaigns (OP1.2)

Experimental verification of the concept ideas –> thinner tiles



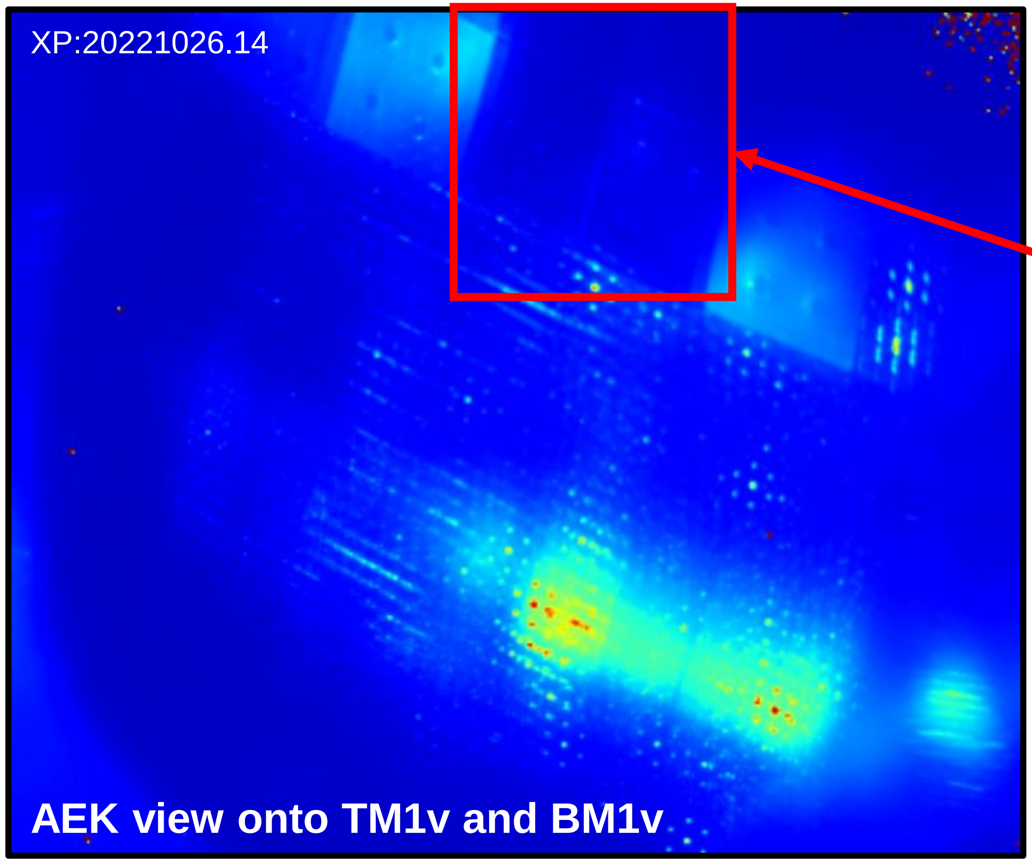
Source: Yu Gao *et al* 2020 *Nucl. Fusion* **60** 096012

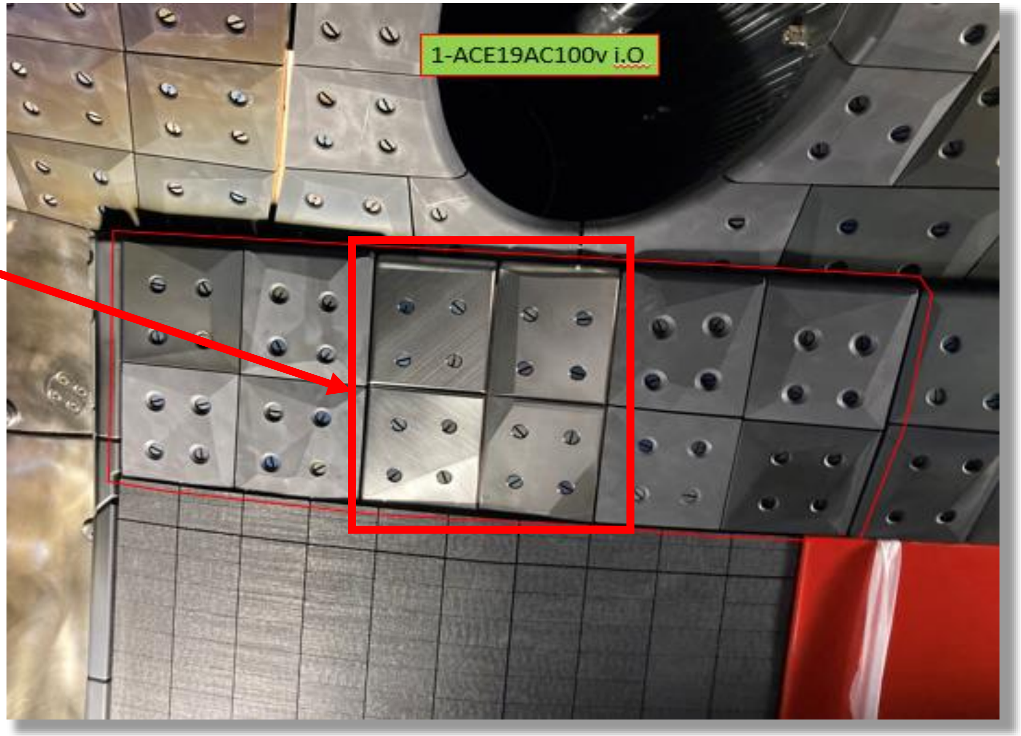


BM1v: thin W/WCuNi tiles together with modified graphite tiles (photo taken in module 1, lower divertor with 4 WCuNi tiles in the center of this baffle module)

reduction of heat loads for higher energy input

Experimental verification of the concept ideas





BM1v: thin **W/WCuNi tiles** together with modified graphite tiles (photo taken in module 1, lower divertor with 4 WCuNi tiles in the center of this baffle module)

OP2.1 commissioning phase: first indications that the design change works

Summary

- new W divertor for W7-X is planned: with reactor relevant PFCs and favorable geometry modifications appropriate for improved heat load capabilities and efficient exhaust
- consideration of both technical and physical constraints during concept development
- intensive modeling and verification against the experimental results as multi-stage iteration process – prediction for high-beta operation
- parallel development of single target elements with tungsten based materials as plasma facing surface – prototype development and testing in high-heat flux facilities -> part of EUROfusion WPDIV

110. Synergies in the technological developments of the W7-X and JT-60SA metallic divertor plasma facing components
Marianne Richou
08/11/2022, 14:30

- definition of a new plasma facing surface as basis for the integrated design of target modules and sub-divertor components, supported by newly developed, unique design tools in the CATIA environment