MAX-PLANCK-INSTITUT
FÜR PLASMAPHYSIK

Divertor concept development for the W7-X stellarator experiment

Indigo: https://event.ipp-hgw.mpg.de/category/63/

https://datashare.mpcdf.mpg.de/s/EPkFnQ5TXRYoNV8

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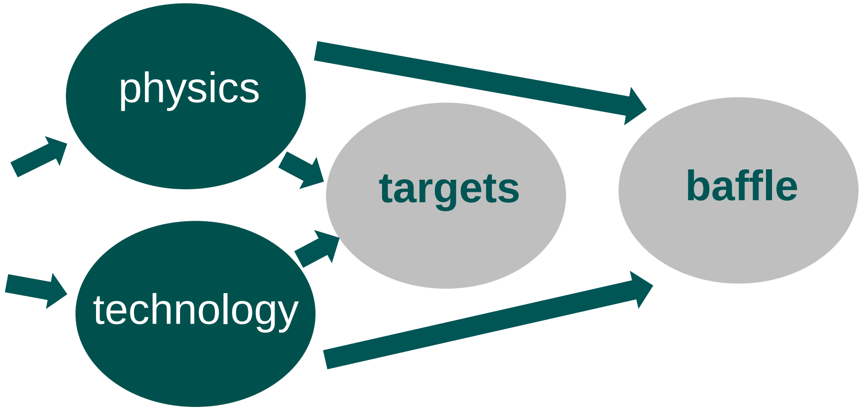
W7-X divertor setup OP3

- optimization objectives
- optimization criteria
- optimization tools



W7-X divertor setup OP3 – physical optimization objectives

power exhaust

1. **heat loads on PFCs should not exceed their specific, defined limits**
   - acceptable peak loads,
   - tolerable input energies to individual components,

   by broadening of heat load distribution (larger wetted areas),
2. **avoid localized excess heat loads** (leading edges, fast particles).

particle removal

to pump helium, the fuel gases are pumped at almost the same rate!

3. **high particle exhaust rate $\Gamma_{exhaust}$ [a/s]** (TMPs, cryopumps)

   reactor:
   - $\Gamma_{exhaust\text{-}He} = \Gamma_{Fusion\text{-}He}$

   What is $\Gamma_{Fusion\text{-}He}$ mimic in W7-X? -> NBI-He, He conc. several % <5%

   operational:
   - $\Gamma_{exhaust} = \Gamma_{source,wall} + \Gamma_{source,NBI} + \Gamma_{source,Pellet} + \Gamma_{source,gasinlet}$

impurity control

4. **acceptable net erosion**
5. **screening/retention of impurities** in divertor plasma
   - increase power dissipation in the divertor plasma/SOL (by seeding),
   - prevent core radiation losses -> exhaust of impurities

   by friction, electric ⇔ thermal forces, drift effects; reduce sputtering
   - minimize R_{eff} for impurities

W7-X divertor setup OP3 – technical optimization objectives

power exhaust

1. **heat loads on PFCs should not exceed their specific, defined limits**
2. **avoid localized excess heat loads** (leading edges, fast particles)
    - ➢ cost reduction and limitation of production time
    - ➢ reduced number of target elements/cooling circuits, i.e. aggregation of target elements into few modules
    - ➢ volume production of common and flat tungsten mosaic tiles with optimized number and dimensions avoiding leading edges
    - ➢ reduced material removal & W coating of flat tiles to comply with 3D surface
    - ➢ optimization of bonding technology between W, Cu-OFE, CuCrZr and SS
    - ➢ development of He-leak-tight heat sinks by 3D AM

particle removal

3. **high particle exhaust rate $\Gamma_{exhaust}$ [a/s]** (TMPs, cryopumps)
    - ➢ optimization of target geometry to collect particles in molecular, transitional, and continuous flow regimes
    - ➢ reduction of pump gap losses in molecular and transitional flow
    - ➢ maintain good toroidal and poloidal plugging by the divertor plasma
    - ➢ maintain small gaps in sub-divertor to minimize losses to main chamber

impurity control

4. **acceptable net erosion**
    - ➢ selection of materials with low sputtering yields, low hydrogen retention
5. **screening/retention of impurities in the divertor plasma**

W7-X divertor setup OP3 – technical constraints: TE

geometry

1. nearly flat heat sinks with mosaic of flat W95NiFe tiles of max. ~40 x 40 mm
2. radially curved edge tile with constant radius ≥ 15 mm
    - preferred thickness before final machining ≤ 2 mm to enable bent edge tile
3. final machining of W based tiles is assumed to be done by wire erosion
    - poloidal direction to be straight or convex to allow use of a straight erosion wire
    - toroidal direction can be convex or concave
    - curvature limitation of TM1h, TM9h, TM1v
4. gaps between tiles inside target module > 0.5 mm, preferably ~1.4 mm
    - 1.4 mm gap ➔ leading edge 0.13 mm (@ 5° incidence angle) ➔ heat flux limit ?
5. gaps between target modules > 5 mm (thermal expansion and assembly inaccuracies)
    - 0.43 + ~0.4 (installation) = 0.8 mm leading edge ➔ where allowed ?
    - longer slits in toroidal direction ➔ erosion in gaps due to gyro effects
6. final tile thickness: >0.5 mm (erosion), > 3 mm (Cu sputtering)

cooling water supply

1. 12x supply line Ø32 mm with 5 l/s, static pressure 10 bar
    - limits: ΔT = ~60 K, Δp = 15 bar
2. optimize cooling channel geometry
3. corrosion of tungsten alloys, Ni coating?

handling / installation

1. mass per target module < ~60 kg
2. size similar to OP2 divertor ~0.25 m^2 (400x600 mm^2 up to 300x800 mm^2)
3. installation tolerance: relative between modules ~0.4 mm, absolute ?? mm -> experiments/modeling/asymmetries (top-down, drifts)?
4. fix points are Ø32 mm inlet /outlet which should be near to each other
5. additional flexible pin support to make module statically determined

W7-X divertor setup OP3 – technical constraints: baffle

geometry

1. 250 kW/m^2 radiation load (limited by cooling water supply assuming 0.4 m^2 module size)
2. 1 MW/m^2 local convective load on 1 W based tile (~0.1x0.1 m^2 → 10 kW)
3. no intersection of plasma exposed surface with outermost surface of magnetic island
4. chamfered W based tiles to allow for default 1.5 mm tolerance
5. spring loaded contact between tiles – sigraflex – heat sink to moderate thermal stress

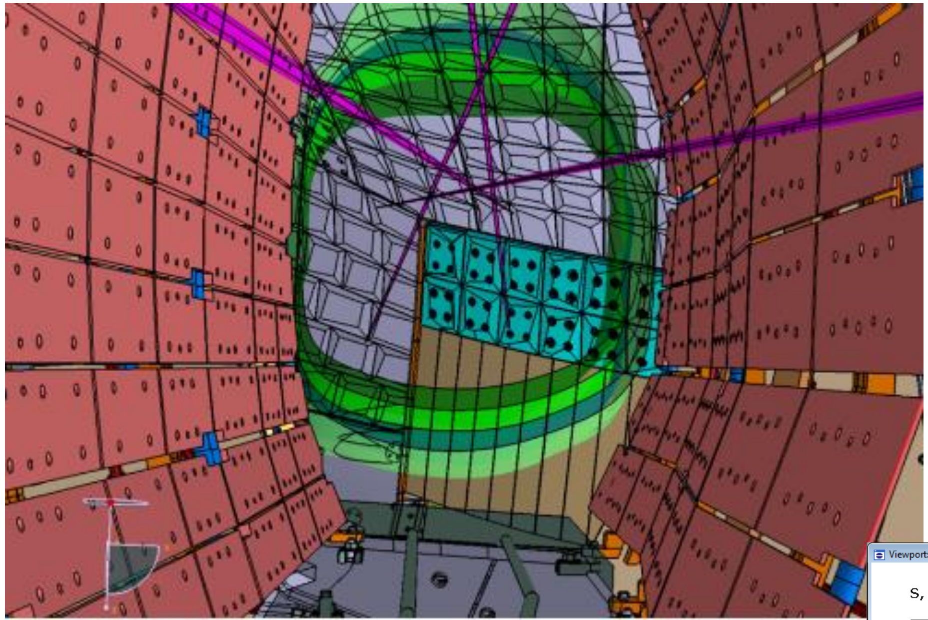
cooling water supply

1. use of existing OP2 water infrastructure
2. 12x 0.5 l/s = 6 l/s water available per divertor unit for the baffles, $\Delta T \leq 50K$ → 12 x 100 kW
3. exposed baffle area 3.86 m^2 /divertor unit
   → average heat load 12 x 100 / 3.86 = 310 kW/m^2
4. inlet & outlet Ø12x1 mm flexible pipe

handling / installation

1. separate heat sink plate and support structure. heat sink fixations accessible from plasma side
2. mass per heat sink preferably < ~40 kg, size similar to OP2 baffles ~0.40 m^2
   (11 mm Cu = 100 kg/m^2)
3. statically determined support
4. simple installation consoles to release mass before fixation
5. 4 mm W based tiles of ~0.1x0.1 m^2 with fixation accessible from plasma side (< 1 kg /tile)
6. water connection accessible

W7-X – technical constraints: NBI beam dump



- ➢ loads depend on plasma absorption up to 40 MW/m² at zero absorption
- ➢ pulse duration limited by heat load capacity of heat sinks / tiles / bolts
  - ➔ up to one second for a single source

temperature limits:

CuCrZr < 500 °C, CFC < 1200 °C, Graphite < 1800 °C, W < 1300 °C

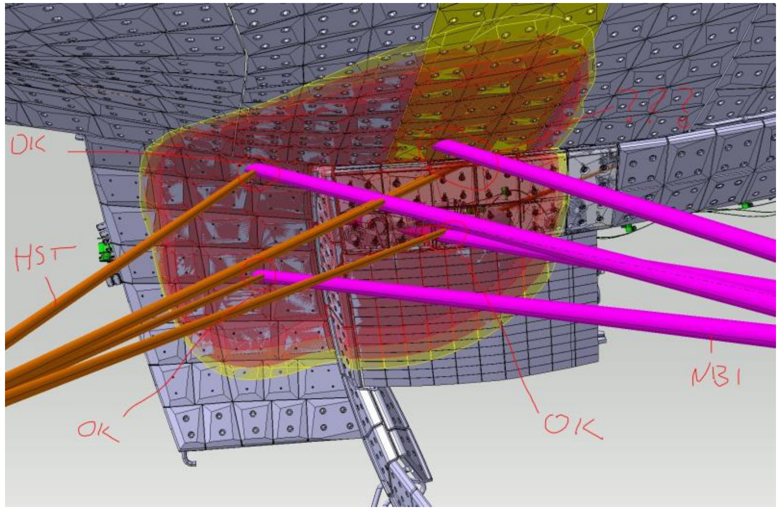
cyclic strain limit: stainless steel pipe <0.2 %

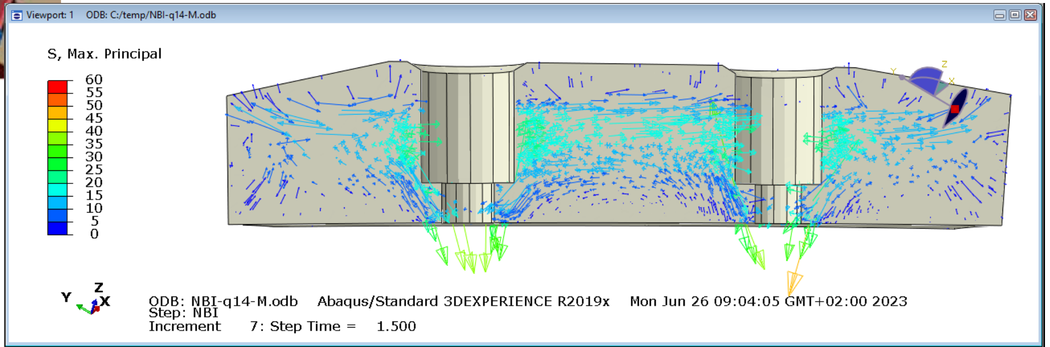
flexural stress limit: graphite < 30 N/mm², W < 700 N/mm²

bolt stress TZM: <700 N/mm²

elastic play in bolt springs: 1 mm

thermo-mechanical assessment by E5-E is pending -> design improvements?





Viewport: 1 ODB: C:/temp/NBI-q14-M.odb

S, Max. Principal

```
ODB: NBI-q14-M.odb    Abaqus/Standard 3DEXPERIENCE R2019x    Mon Jun 26 09:04:05 GMT+02:00 2023
Step: NBI
Increment     7: Step Time =     1.500
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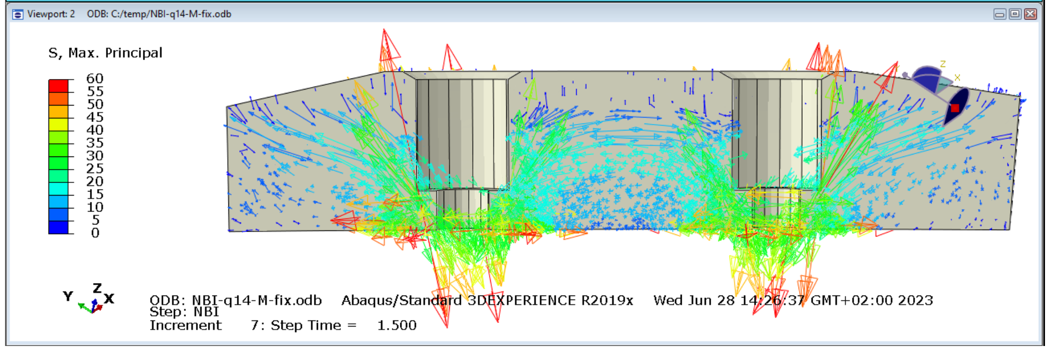

Viewport: 2 ODB: C:/temp/NBI-q14-M-fix.odb

S, Max. Principal

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Step: NBI
Increment     7: Step Time =     1.500
```

W7-X divertor setup OP3 – optimization criteria

power exhaust

1. **heat loads on PFCs should not exceed their specific, defined limits**
2. **avoid localized excess heat loads** (leading edges, fast particles).
   - $p < 10\ \mathrm{MW/m^2}$ steady state -> GLADIS tests with $15\ \mathrm{MW/m^2}$
   - $p_{max} = 10\ \mathrm{MW/m^2}$ steady state,
   - T_{max} (WNiFe) < 1300 °C, (OFE-Cu) < 600°C, CuCrZr < 475°C, channel < 200°C
   - wetted areas > 1 $\mathrm{m^2}$, incidence angles < 5°

particle removal

3. **high particle exhaust rate $\Gamma_{exhaust}$ [a/s]** (TMPs, cryopumps)

by ensuring a high exhaust efficiency, combined with throttle

$$\eta_{exhaust} = \Gamma_{Exhaust} / \Gamma_{Neutral} = \eta_{collection} * \eta_{removal}$$

- neutralize high ion influx in divertor $\Gamma_{ion\ divertor} \text{->} \Gamma_{neutra}$ He enrichment? Reactor scaling?
- high collection efficiency $\eta_{collection} = \Gamma_{Pumpgap} / \Gamma_{Neutral}$
- high removal efficiency $\eta_{removal} = \Gamma_{Exhaust} / \Gamma_{pumpgap}$
- high plugging efficiency $\eta_{plugging} = \Gamma_{Divertor\ Recycling} / \Gamma_{Recycling}$

impurity control

4. **acceptable net erosion (low Te at the W-PFCs required)**
   - net erosion rate < 0.2 nm/s ➔ @15 y * 40 days/y * 1800 s/day ➔ 0.22 mm
5. **screening/retention of impurities** in divertor plasma
   - W core concentration < 2e-05

W7-X divertor setup OP3 – optimization tools

power exhaust

particle removal

impurity control

1. **heat loads on PFCs should not exceed their specific, defined limits** (**heat loads should be concentrated on the target surfaces (>95%), <5% on other components such as baffles, heat shield, panels)**
   - fast tools: EMC3-Lite, SHFP model (➔ A. Kharwandikar / T. Kremeyer)
   - fast tools: EMC3-Lite for divertor plate optimization with second stage of magnetic field optimization via coil geometry/currents adjustments, application to HSX (➔ B. Davies)
   - state-of-the-art: EMC3/Eirene (connecting LCFS-SOL-divertor) (➔ Y. Feng, D. Boeyaert, A. Kharwandikar)

2. **avoid localized excess heat loads** (leading edges, fast particles)
   - fast tools: EMC3-Lite, ANSYS, SHFP -> LEADERS (python code) (➔ A. Menzel-Barbara) for all materials (heat sink + armor)

W7-X divertor setup OP3 – optimization tools

power exhaust

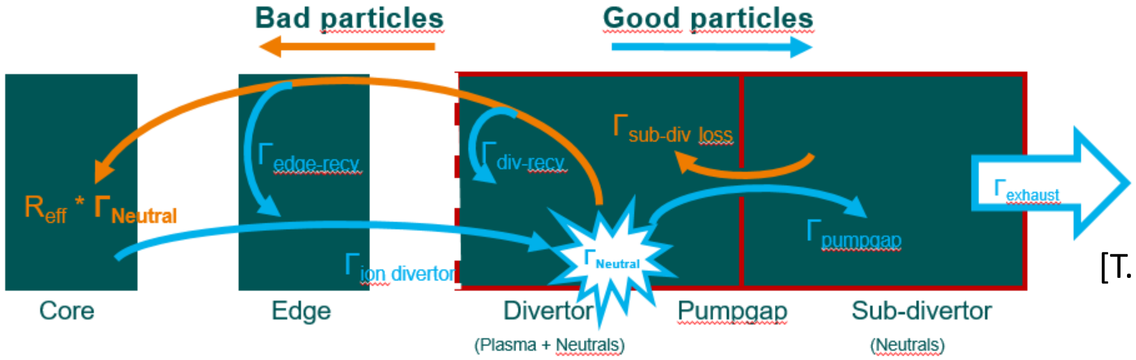
particle removal

impurity control

$$n_{0,t} \propto \Delta x \cdot \frac{n_d}{T_{id}} \cdot \frac{\left(1-f_{rad}\right)}{A_w} \cdot P_{SOL}$$

[Y. Feng, 6. 6. 2023]

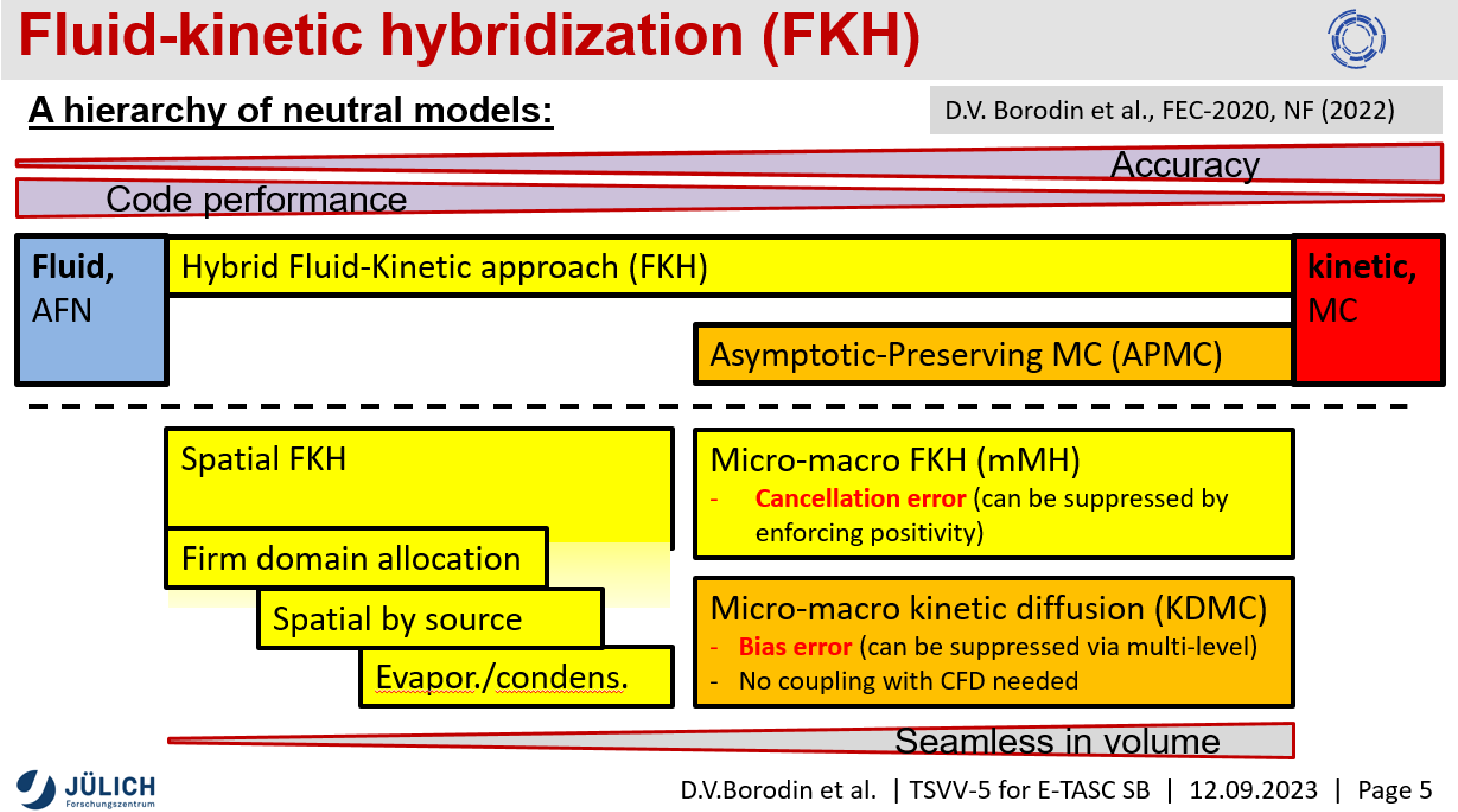
3. **high particle exhaust rate** (TMPs, cryopumps)
   - fast tools: multi-chamber models, ANSYS (➔ V. Haak)
   - fast tools: 2D-analytical model, viewing factors (➔ T. Kremeyer, S. Dräger)
   - fast tools: COMSOL (➔ T. Kremeyer)
     (molecular flow module, 0.1 < Kn < 10 (Boltzmann equ.), 0.01<Kn<0.1 (Navies-Stokes))
   - fast tools: 3D-Direct Simulation Monte Carlo (DSMC) (➔ A. Kharwandikar?)
     EMC3-Lite as source for the neutrals, plasma domain as sink,
     EMC3/Eirene (no collisions in volume).
   - state-of-the-art: EMC3/Eirene: **evaluation $p_{div,\ neutrals} = f(n_{e,sep}, n_{e,div}, P_{input} > 10\ \mathrm{MW}, P_{rad})$**
     (➔ Y. Feng, D. Boeyaert)
   - state-of-the-art HERMES-3: combined with fluid neutral model [B. Shanahan]
   - state-of-the-art: DIVGAS (only sub-div region) (➔ S. Varoutis, Ch. Tantos (KIT))
   - neutral gas modeling [cooperation (?) with KU Leuven T. Baelmans:
     advanced fluid neutral (AFN) and hybrid fluid-kinetic approaches for the neutral particles



[T. Kremeyer, 20. 6. 2023]

EUROfusion Science Meeting on Status of TSVV projects

https://indico.euro-fusion.org/event/2429/



Fluid-kinetic hybridization (FKH)

A hierarchy of neutral models:

D.V. Borodin et al., FEC-2020, NF (2022)

Accuracy

Code performance

Fluid, AFN

Hybrid Fluid-Kinetic approach (FKH)

kinetic, MC

Asymptotic-Preserving MC (APMC)

Spatial FKH

Firm domain allocation

Spatial by source

Evapor./condens.

Micro-macro FKH (mMH)
- **Cancellation error** (can be suppressed by enforcing positivity)

Micro-macro kinetic diffusion (KDMC)
- **Bias error** (can be suppressed via multi-level)
- No coupling with CFD needed

Seamless in volume

JÜLICH Forschungszentrum

D.V.Borodin et al. | TSVV-5 for E-TASC SB | 12.09.2023 | Page 5

This Science Meeting is part of the Mid-Term review of Theory Simulation Verification and Validation (TSVV) projects.

It aims at: presenting scientific achievements obtained by TSVV projects

W7-X divertor setup OP3 – optimization tools

power exhaust

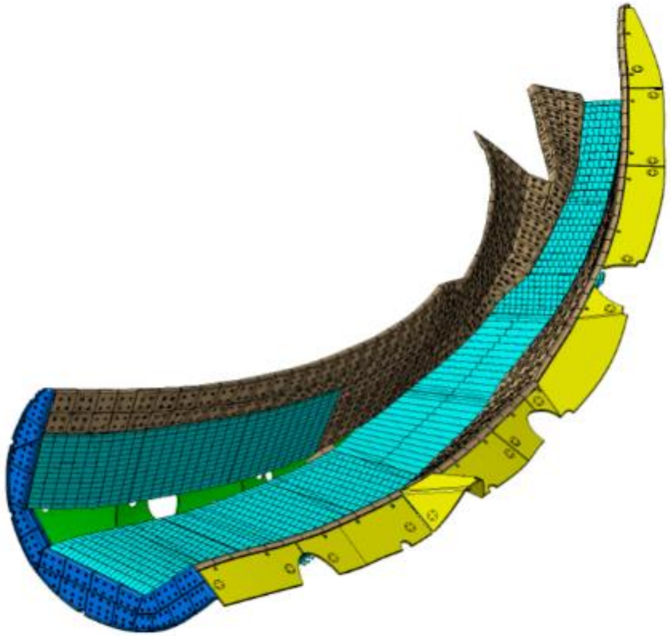
particle removal

impurity control

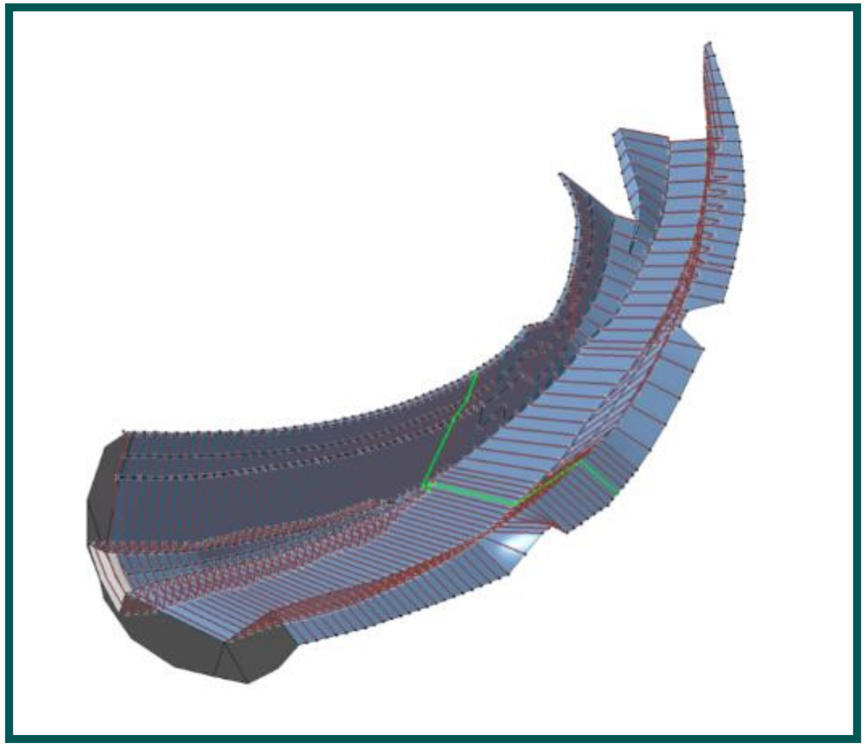
4. **acceptable net erosion (low Te at the W-PFCs required)**
   - ➢ state-of-the-art: ERO2.0 (➔ FZ Jülich (A. Kirschner, J. Romazanov))
   - ➢ erosion in gaps (experiments AUG K. Krieger, ITER design) (➔ A. Menzel-Barbara)
   - ➢ state-of-the-art: WallDYN3D (➔ IPP Garching (K. Schmid))
5. **screening/retention of impurities** in divertor plasma
   - ➢ state-of-the-art: EMC3/Eirene, ERO2.0 (➔ V. Winters, F. Reimold)

design tools -> next slide

W7-X design tools with CATIA – for modified geometries



detailed CAD geometry of
one divertor unit



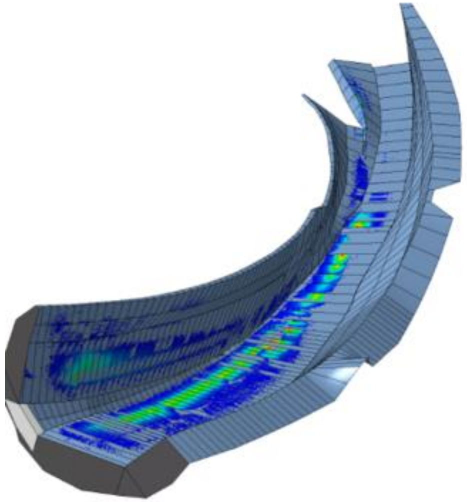
reduced grid-based stream-line model
with limited number of grid points –
recently developed by DE IPP Greifswald

Training by T. Sieber to use the grid-based model within CATIA to generate data in Kisslinger format for the EMC3 modeling.

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

W7-X design tools – for modified geometries

construction of 3D target surfaces based on the grid-based stream-line model [T. Sieber]

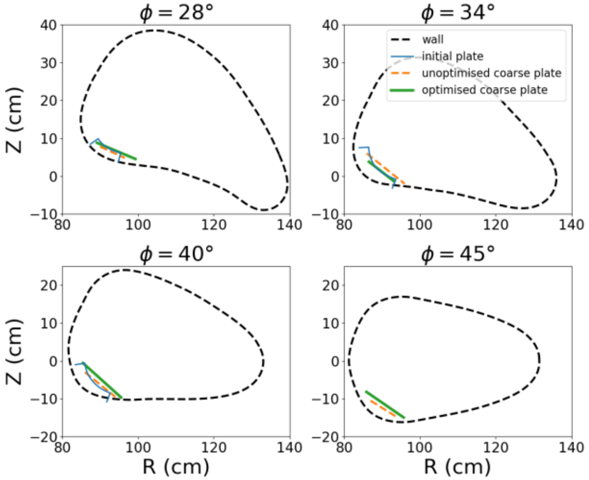


EMC3-Lite results mapped onto the grid model

construction of 3D target surfaces based on a 2D contour in one selected phi cross section, following o-lines toroidally [A. Kharwandikar]

development of python routines for the handling of single/separate modules allowing various transformations in size, shape, position, angle [A. Menzel-Barbara]

construction of 3D target surfaces based closed flux surfaces within an automated screening procedure [B. Davies]



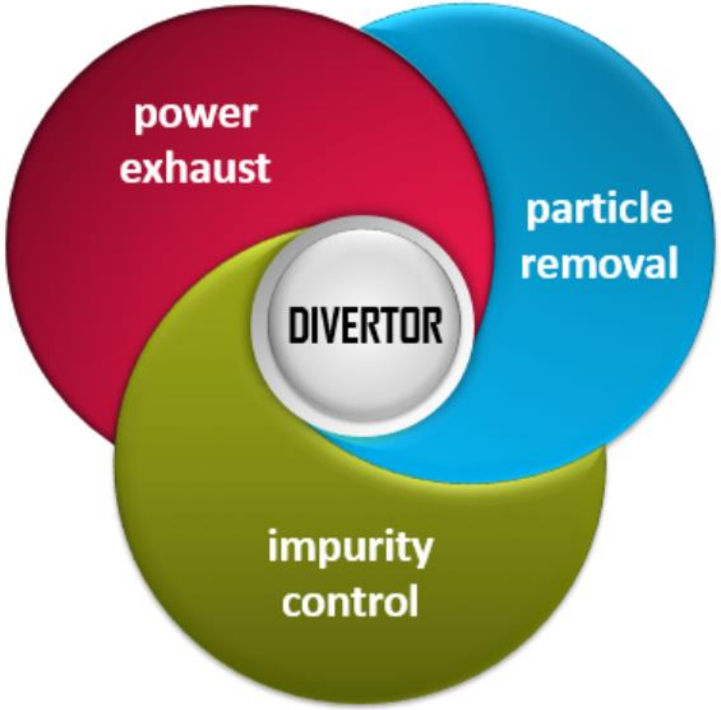
Priorities for the divertor development

power exhaust

particle removal

impurity control

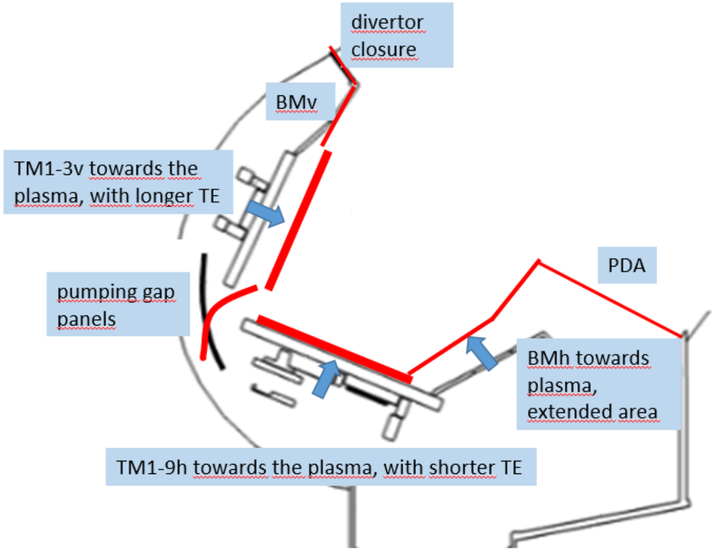
- start with power exhaust analysis for attached conditions: definition of modified geometries meeting two criteria:
    1. keep maximum heat load below 10 MW/m^2 with a heating power of at least 10 MW,
    2. keep the heat load only on the divertor targets (> 95%).
- evaluate modified geometries against particle removal requirements
- identify potential impurity retention drawbacks



Priorities for the divertor development

conservative approach

moderate modifications of the current W7-X setup in order to address the issues identified in the experiments



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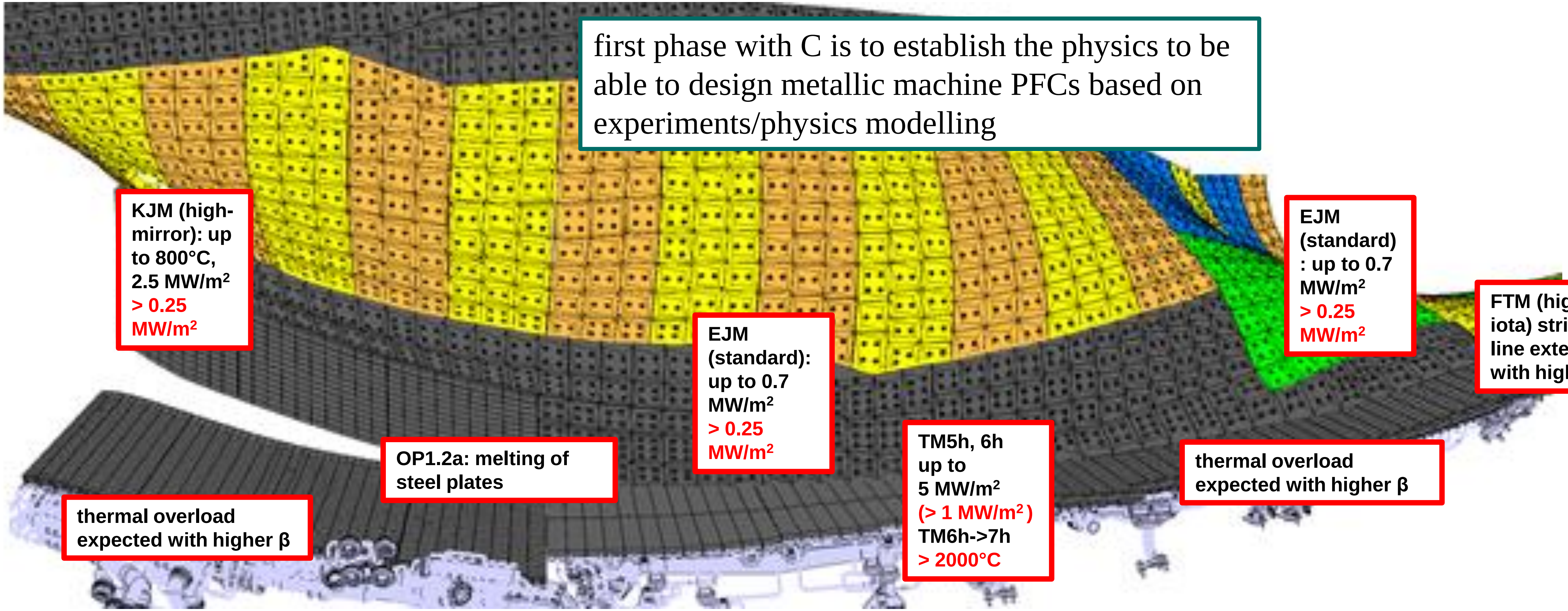
generic approach

search for an optimized plasma facing surface that can also be used for reactor studies

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

KJM (high-mirror): up to 800°C, 2.5 MW/m²
> 0.25 MW/m²

EJM (standard): up to 0.7 MW/m²
> 0.25 MW/m²

EJM (standard): up to 0.7 MW/m²
> 0.25 MW/m²

FTM (high-iota) strike line extension with higher β

OP1.2a: melting of steel plates

TM5h, 6h up to 5 MW/m²
(> 1 MW/m²)
TM6h->7h
> 2000°C

thermal overload expected with higher β

thermal overload expected with higher β

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

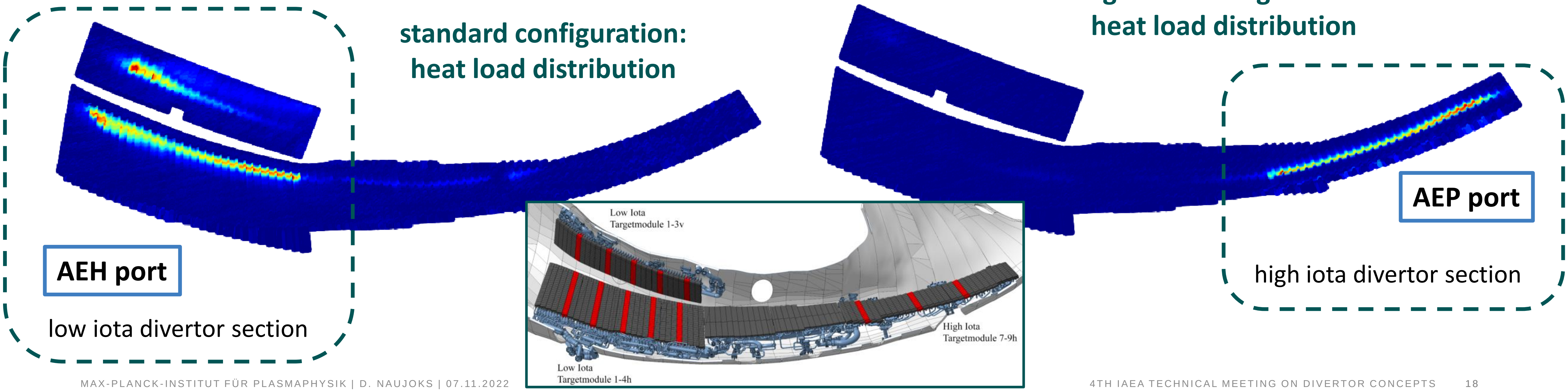
Motivation – exhaust limitation

- 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

high-iota configuration: heat load distribution

AEH port

low iota divertor section

AEP port

high iota divertor section