EUROfusion

Strategy of an integrated limiter design for EU-DEMO first wall protection from plasma transient events

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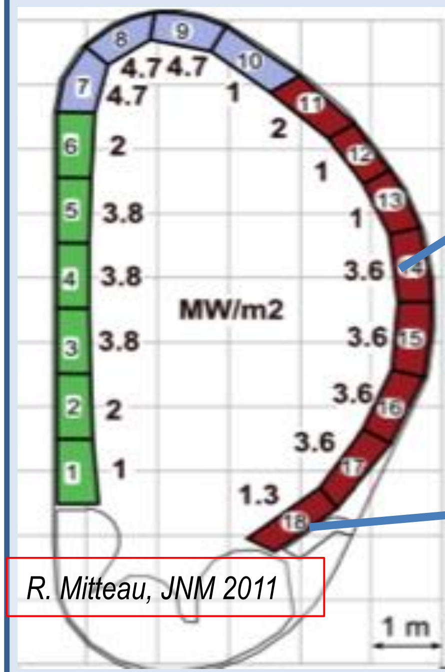
Outline

- Introduction: ITER and DEMO heat load requirements
- First wall protection from plasma transients
  1) Plasma transient identification
  2) Plasma simulations
  3) 3D heat flux (HF) calculations ↔ Limiters surface design
  4) Thermal calculations
  5) Limiters design
- Conclusions

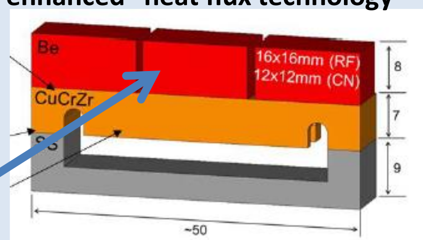
KDII1: ITER and DEMO heat load requirements

ITER:

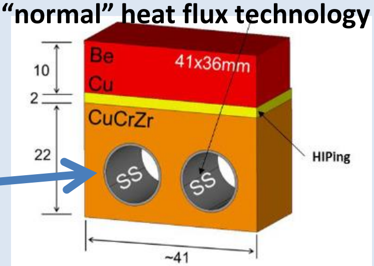
- FW has no tritium breeding requirements.
- A large fraction of ITER's <u>Cu-alloy</u> first-wall can be designed for up to **~5 MW/m²**. (CuCrZr has extremely high K~300 W/mK but irradiation lifetime of only ~10 dpa)



"enhanced" heat flux technology



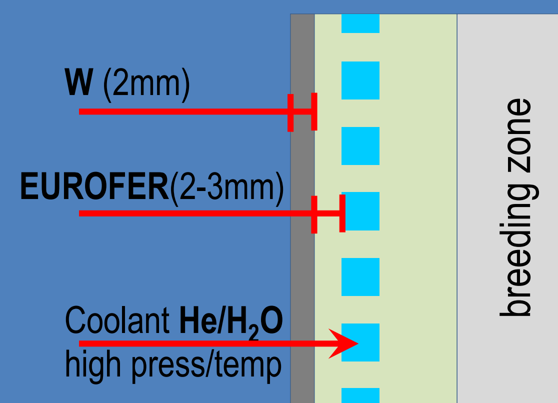
"normal" heat flux technology



DEMO:

- Tritium breeding: FW with thin layer of materials.
- DEMO FW structural material: <u>EUROFER</u> (much lower thermal conductivity K~30 W/mK, but high irradiation lifetime) → Steady state heat loads limited to **~1-2 MW/m².**
- W armour (high melting point) conducts heat to the heat sink overheating the cooling channels, evaporation only at very high T → poor resistance against heat load transients.

First wall - breeding blanket



ITER conformal wall: precision required difficult to achieve with DEMO ≈9m tall BB segments
Present ITER SS limit up to 4.7MW/m²: DEMO (~1-2 MW/m²)load specification developed independently

EU-DEMO FW protection from plasma transients

Design, performance and feasibility of wall protection limiters during plasma transients

Design process:

1) Transient identification:
- transport simulations
- ITER HNLS
- Experimental (JET, AUG, TCV, EAST)

2) Electromagn. sim.:
- 2D/3D EM models
- Closed loop sim.
- Magnetic + kinetic (ongoing)

3a) 3D Heat Flux calc.:
- Charged particles
- Radiation loads
- Misalignment, e-folding length sensitivity studies

3b) Limiters shaping:
- shape + protrusion
- poloidal location
- number

4) Thermal calc./PFC des.:
- 1.5D/3D
- Vapour shielding
- Runaway electrons (REs)
- Advanced Materials

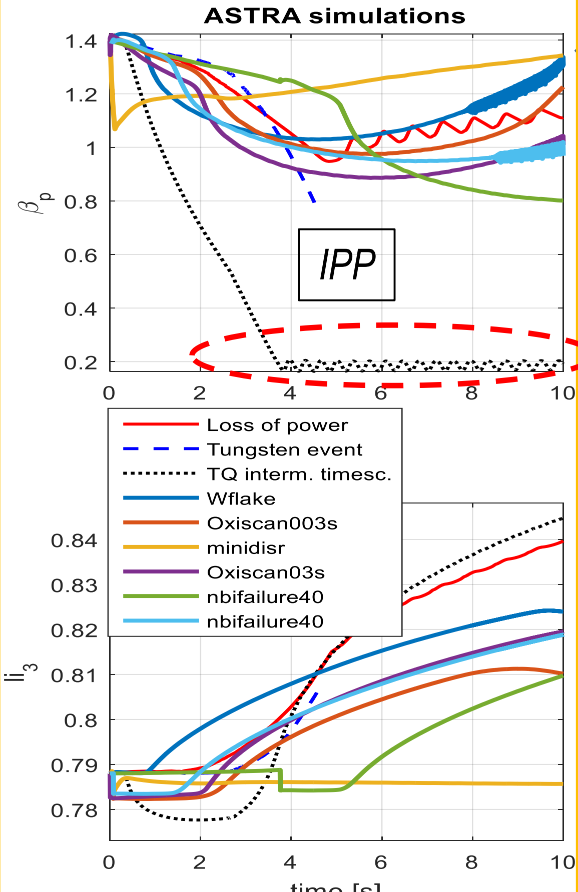
5) Limiter design:
- Integration
- Remote maintenance
- Inspection
- TBR

Plasma transient identification

Several activities launched to predict possible contact points:

- Transport simulations (ASTRA code) to evaluate plasma perturbations (***$\Delta\beta_{pol}$, Δl_i, ΔI_p***)
- Inter-machine perturbation database: JET, ASDEX, EAST, TCV (ongoing)
- ITER **H**eat and **N**uclear **L**oad **S**pecifications: *e.g.* U/D-VDE, unmitigated/mitigated disruptions

Synthetic



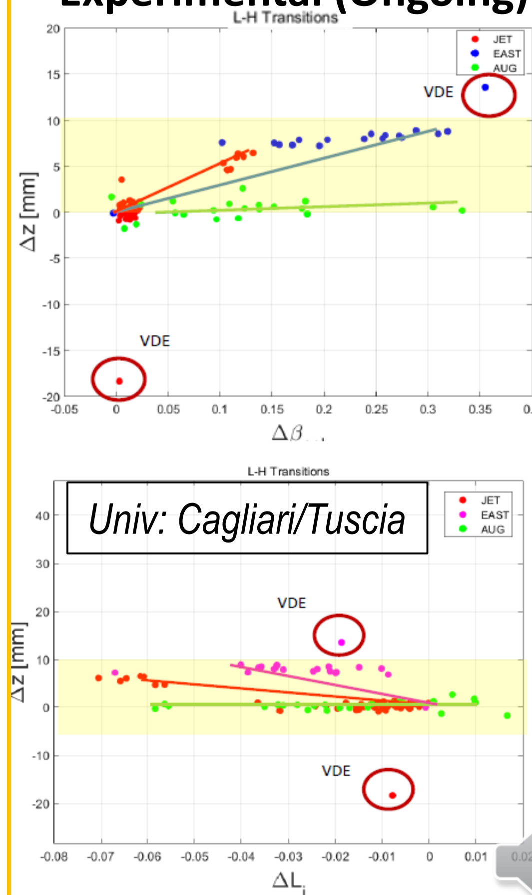
Synthetic (ASTRA) database, perturbations generated for:

- Loss of confinement
- ntm—like
- W influx
- H_2O influx
- ELM like
- Minor disruption
- TQ interm. timesc. (conserv.)

Experimental database,

- JET, ASDEX, EAST, TCV:
- H-L, L-H
- ELMs
- Minor disruption
- SN/DN

Experimental (Ongoing)



Plasma simulations: Electromagnetic model

3D code CARMA0NL (computationally expensive), and **2D codes CREATE-NL** and **MAXFEA** codes. **2D equivalent structures** and **vacuum vessel** tuned on 3D model features (*e.g.* vacuum vessel ports, non toroidally continues breeding blanket and divertor). The more precise and faster 2D simulations used to predict possible plasma-wall impact locations

These codes are benchmarked with each other and experimentally.

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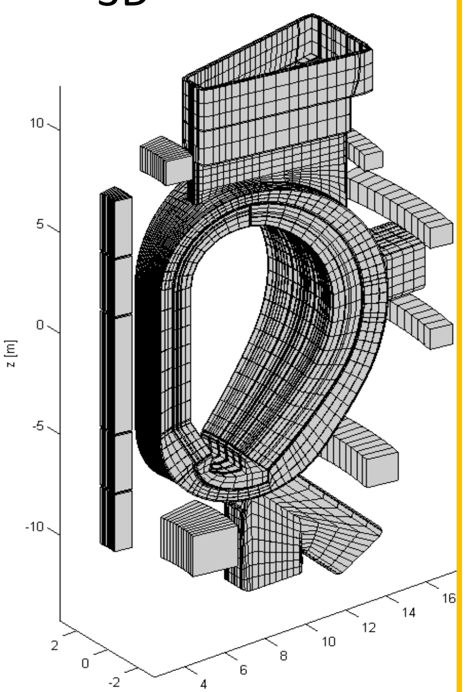
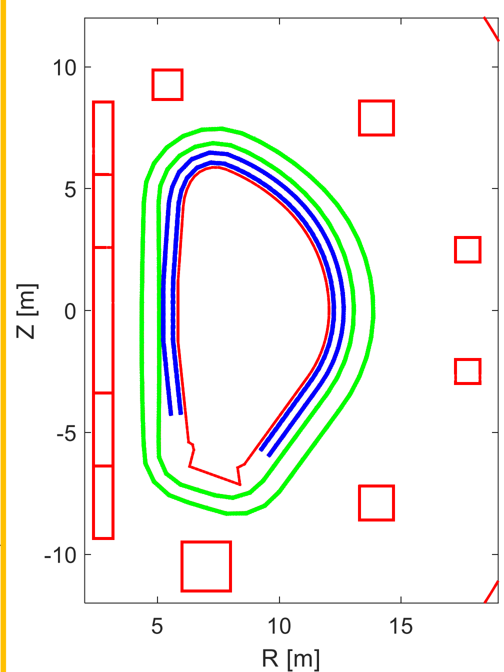
3D



CARMA0NL

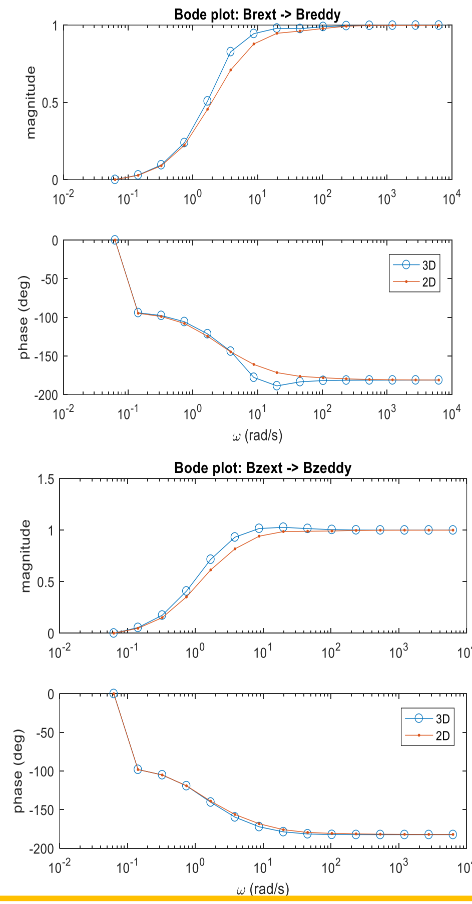
F. Villone *et al.* 2018 EPS
S.L. Chen, *et al.* NF 2019

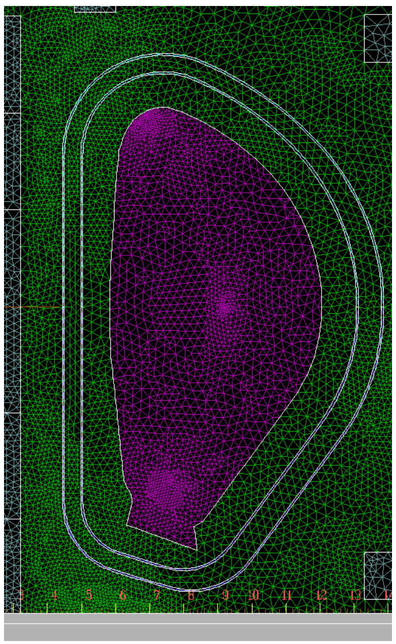
2D, with 3D corrections



CREATE-NL

R. Albanese, *et al.* 2019 FED





MAXFEA

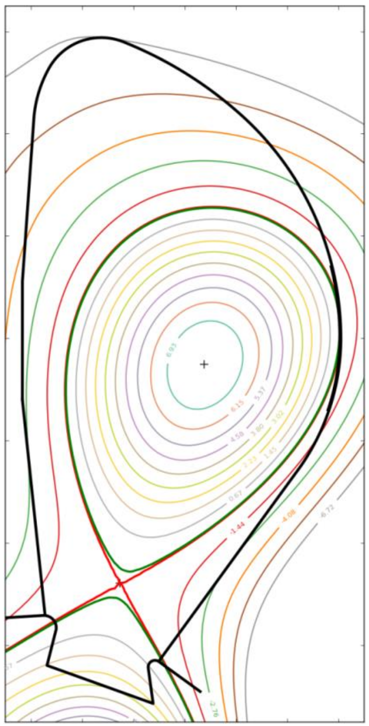
P. Barabaschi, 1993 Naka

3D HF calculations and limiter surface design

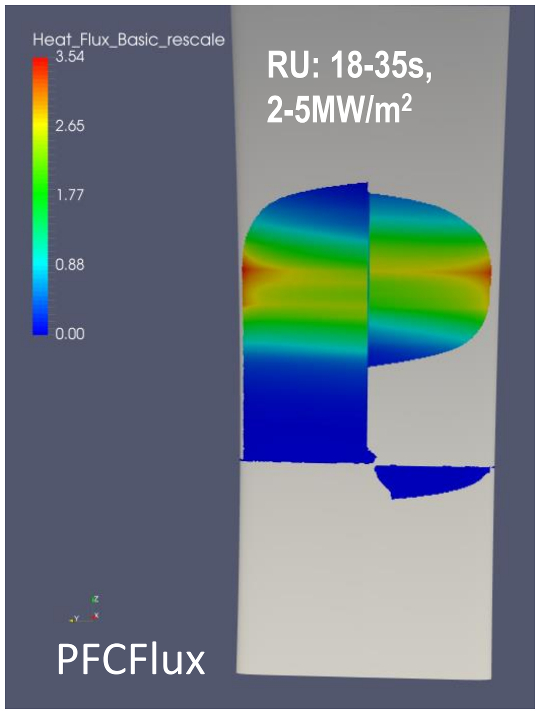
Normal transients: ramp-up/down on Outer Midplane Limiter (OML)

- Plasma ramp-up/down assumed [0.1; 0.2]MA/s.
- **λ_q = 6mm, Psol[MW] = Ip[MA]** assumption (ITER like)
- RU: x-point formation in range at **[3.5; 6]MA: t_{RU}= 18 to 60s**

RU: Limited eq. 6MA, #4 OML

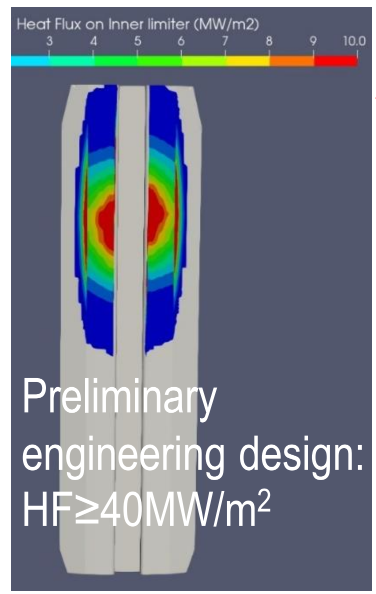


P_{SOL} = 6MW λ_q = 6mm



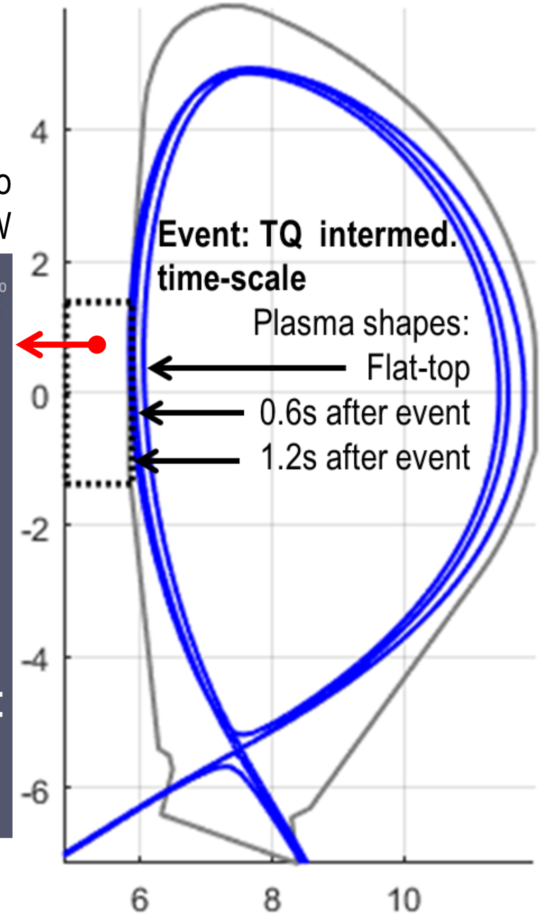
Max HF = 3.5MW/m² (ITER rescale)

#4 IML used to prevent FW



Off-normal transients

Loss of confinement: Conservative case on Inner Midplane Limiter (IML)



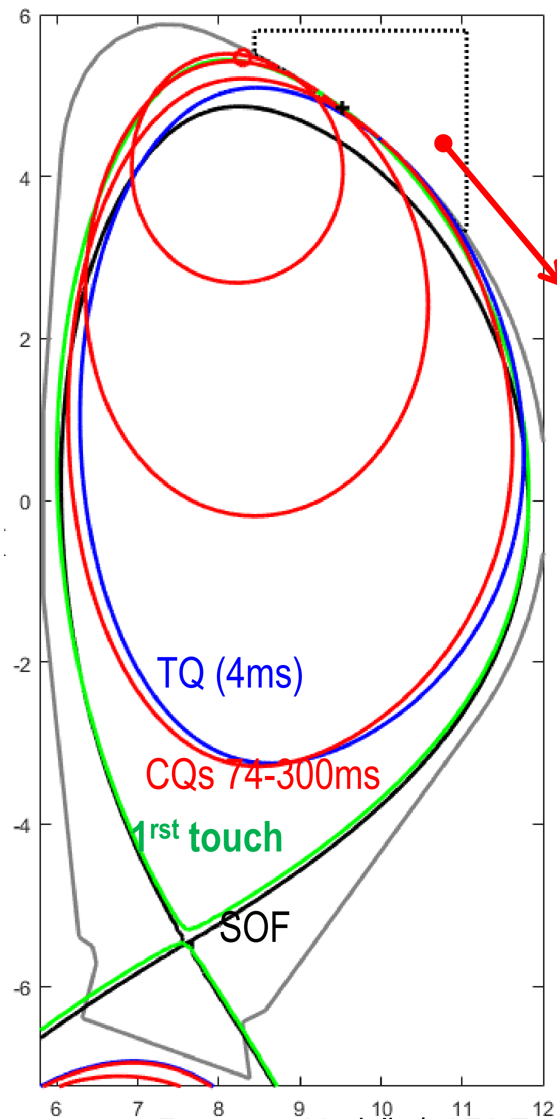
Misalignments may be reduced if limiter adjustable at OMP port. Bare wall HF ≈3-4MW/m²

No relevant HF found on other BB modules, nor on the limiter during flat-top phases

3D HF calculations and limiter surface design

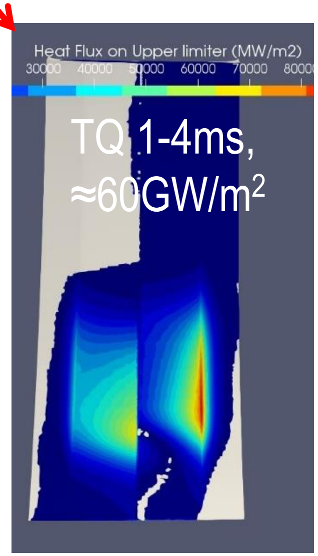
Off-normal transients: Upward/Downard Vertical Displacement Event

U-VDE on Upper Limiter (UL)



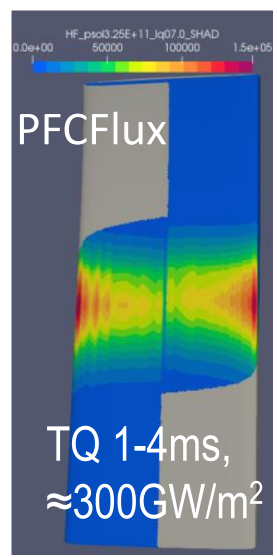
Typical plasma VDE evolution:

1) SOF (Start Of Flat-top)
2) **1rst touch** (**+** plasma moves vertically)
3) TQ (W_{th} from 1.3GJ to 0, in 4ms, **λ_q=7mm**)
4) CQs (I_p from 19MA to 0, in 74-300ms)

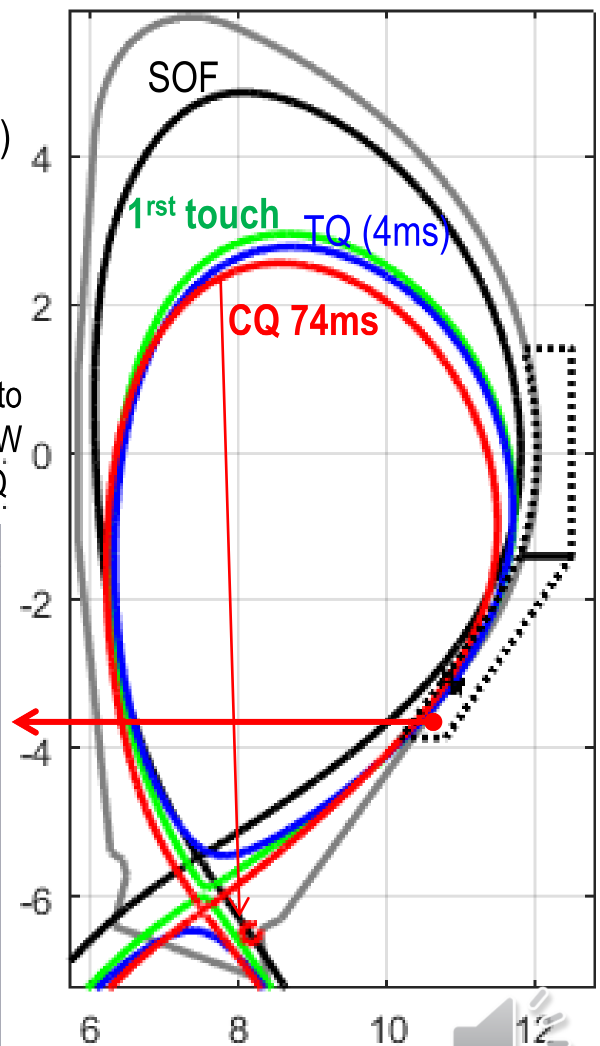


#8 UL used to prevent large charged particle reaching FW at TQ

#4 OLL used to prevent FW damages during TQ



D-VDE on Outer Lower Limiter (OLL)

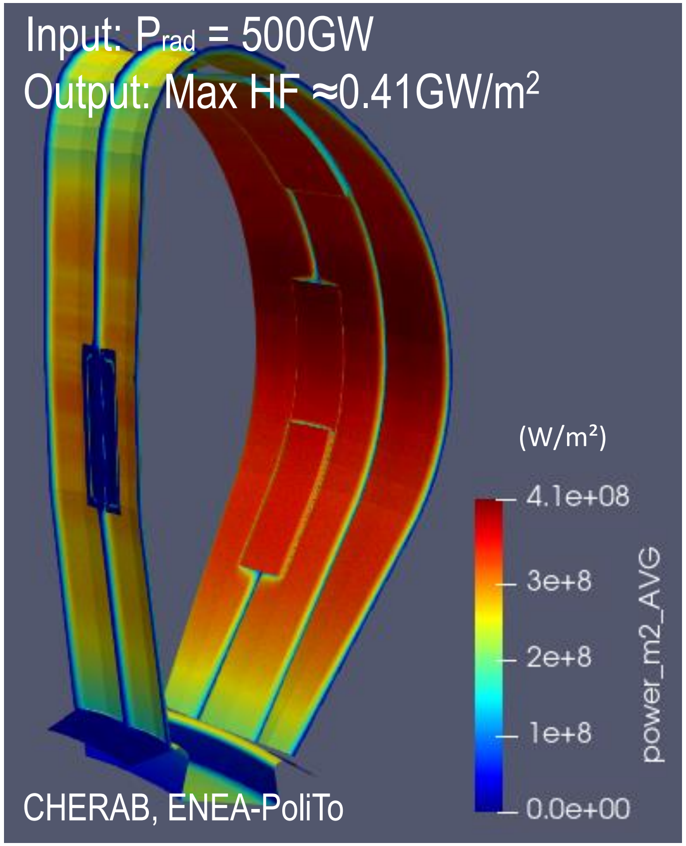


Radiation during mitigated disruptions

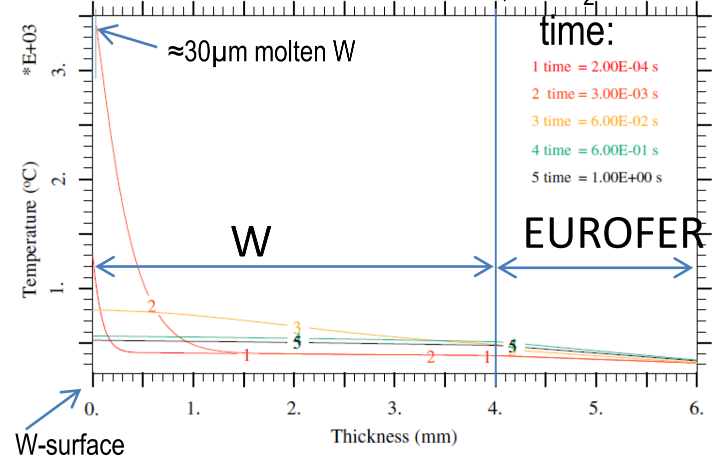
Calculations on TQ mitigated disruption started (mainly based on ITER HNLS scaling)

Preliminary results: Mitigated Major Disruption or U-VDE :

- Initial thermal energy W_{th}=1.3GJ: 20% radiated at pre-TQ at MGI/SPI: remaining ≈ 1GJ
- At TQ ITER aims at radiating 80% in 1-3ms (controllable) -> P_{rad}≈800GW



RACLETTE 1GW/m² for 3ms, on H_2O FW:



If Tor. & Pol. peak. fact.(TPF)*=***2.8***, for P_{rad} = **800GW** (hence P_{rad} = 2.2TW) → max HF ≈ **2GW/m²**

*ITER uses TPF= 1.8 (tor.) and 1.5-4.5 (pol.).

80% radiation in 3ms may be above FW W-limit

TQ radiation time may be slowed down with MGI/SPI

Mitigation techniques to consider FW damages (limiters ineffective)

Cooling pipe below limits

3D HF calculations and limiter surface design

DEMO essential requirement to operate minimizing disruptions.

All considered perturbations and relative HF on limiters and FW:

Inputs for: 3D field-line tracing charged particle HF (PFCflux, SMARDDA)					Outputs: max HF (MW/m^2)	
Scenario (main limiter)	Case(s)	P_{SOL} (MW)	λ_q (mm)	Deposition time (s)	On limiters (ρ-rescaled)	On FW (ρ-rescaled)
SOF/EOF (all)	Diverted	69	50	Steady state	2.11	0.67
Min. disr. & ELM (all)	Diverted	69	50	15 – 50 ms	1.31	**1.48** [1]
Ramp-Up (OML)	Limited	3.5	6	17.5 - 35	2.40	0.32
Ramp-Down (OLL)	Limited	5	6	25 - 50	3.61	0
			50	25 - 50	4.51	0.47
		7.5	6	37.5 - 75	4.19	0
			50	37.5 - 75	3.14	0.42
U-VDE (UL) *unmitigated*	First touch	69	1	20 – 35 ms	**100** [5]	0
			5	20 – 35 ms	15.9	0.04
	TQ	325GW	7	1 - 4 ms	**58,800** [6]	**286** [2]
	CQ1 & CQ2	10	10	74 – 200 ms	4.68	0.05
			30	74 – 200 ms	6.07	0.22
D-VDE (OLL) *unmitigated*	First touch	69	1	15- 35 ms	**623** [7]	0
			5	15 - 35 ms	**51.8** [8]	0
	TQ	325GW	7	1 - 4 ms	**300,000** [9]	**5.9** [3]
	CQ1 & CQ2	10	10	74 – 200 ms	10.8	0
			30	74 – 200 ms	19.2	0.14
H-L transition (IML)	Limited (inboard)	30	2	1 - 5	**39.56** [10]	0.12
			4	1 - 5	14.78	1.81

Inputs for: 3D radiation HF (CHERAB)				Outputs: max HF (MW/m^2)
	Case	P_{SOL} (MW)	Deposition time (s)	On limiters & FT, with TPF 2.8
Mitigated disruption (all)	Mitig. - TQ	800GW	1-3 ms	**≈3,000-1,000** [4]

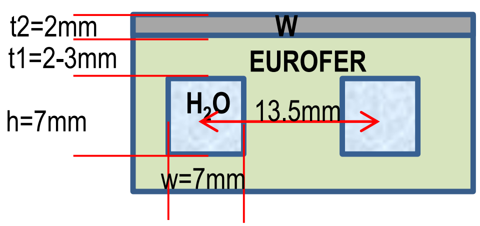
critical cases in red

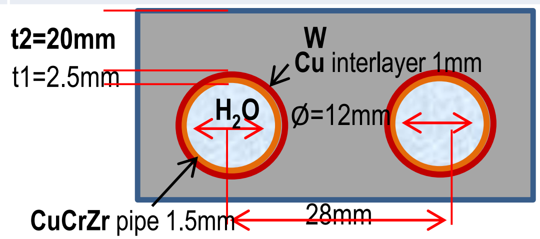
Preliminary misalignment studies ongoing for penalty factors.

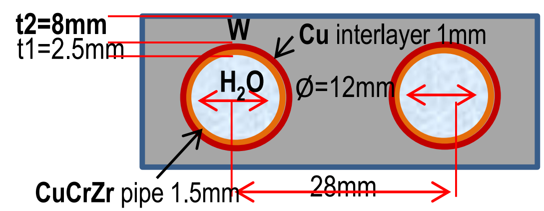
Thermal calculations

RACLETTE code used to quickly simulate thermal behaviour of PFC designs:

1 BB FW simplified model	2 Sacrificial limiter model	3 Divertor like limiter model
H_2O coolant, <u>EUROFER</u> heat-sink	**H_2O coolant, <u>CuCrZr</u> heat-sink**	**H_2O coolant, <u>CuCrZr</u> heat-sink**
Coolant parameters: Vel = 8m/s Pres = 15 MPa T_coolant = 300°C	Coolant parameters: Vel = 8m/s Pres = 5 MPa T_coolant = 160°C	Coolant parameters: Vel = 8m/s Pres = 5 MPa T_coolant = 160°C







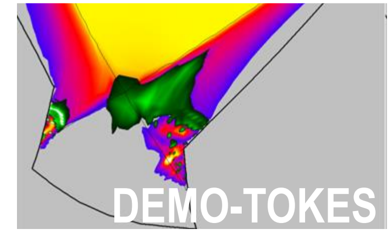
Case	W-Evap. (µm)	W-Melt. (µm)	Heat sink temp. (°C)
1 → **First Wall**			**(EUROFER limit 550°C)**
(1)Control. Pert.	0	0	394
(2) U-VDE TQ	0	0	448
(3) D-VDE TQ	0	0	384
(4) Mitig. Disr.	0	38	545
2 → **Sacrificial limiter:**			**(CuCrZr limit 350°C)**
(4) Mitig. Disr.	0	38	172
(5) U-VDE 1st touch	0	0	171
(6) U-VDE TQ	2560	988	176
(7) D-VDE 1st touch	82	698	179
(8) D-VDE 1st touch	0	0	171
(9) D-VDE TQ	Not converged		
(10) H-L conservative	120	3470	280
3 → **Divertor like limiter:**			**(CuCrZr limit 350°C)**
(4) Mitig. Disr.	0	23	184

- **All heat sink below limits**
- **FW armour protected, mitig. disr., to be tuned**
- **For VHHF sophisticated codes are being used**

RACLETTE is conservative when W vaporisation ≥tens µm: <u>possible</u> mitigation from vapour shielding

Vapor shielding model in Major Disruption

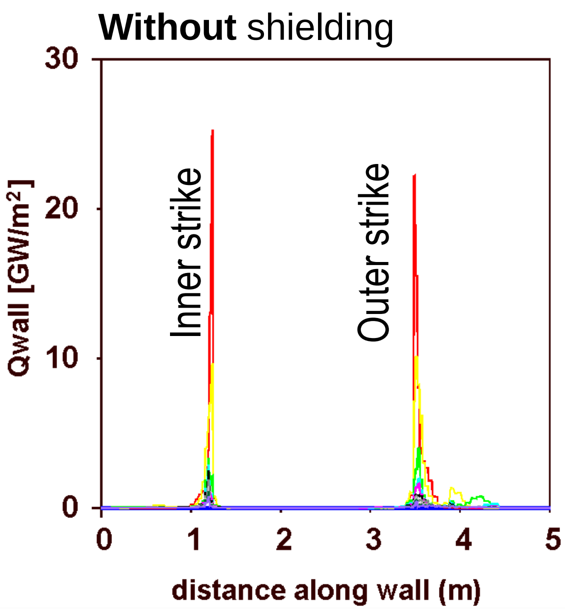
S. Pestchanyi, et al., *FST (2019)*
S. Pestchanyi, et al., NME (2020)



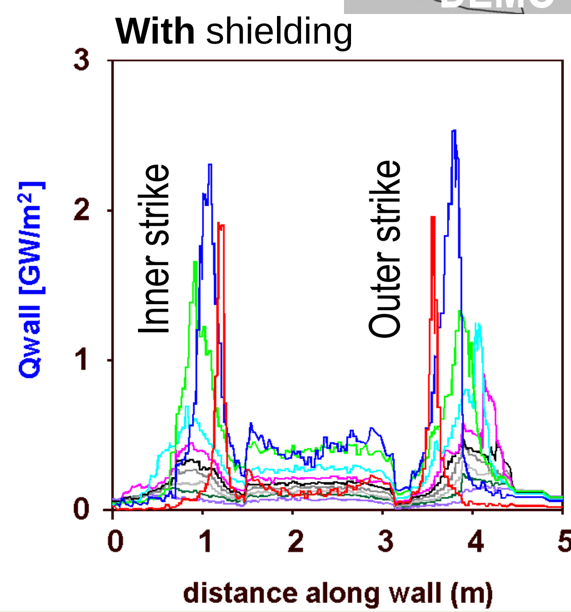
Preliminary simulations including vapor shielding have been performed on DEMO using TOKES code on:

Major (Central) Disruption (plasma in diverted configuration):

- Thermal quench duration **4ms**
- Charged particles energy = **0.65GJ** (1/2 E_{KIN_tot}) (to 1.3GJ)



Colors represent different instants from 1 to 10ms

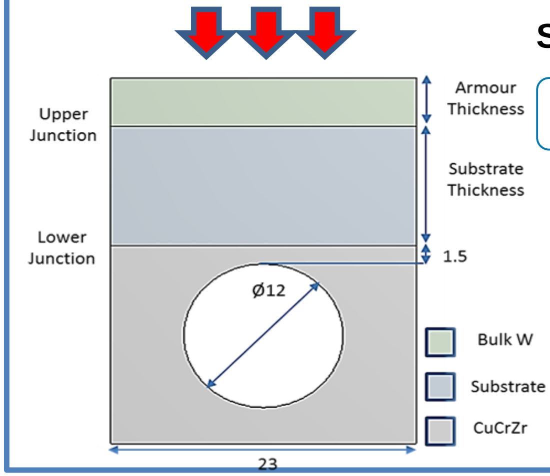


With vapor shielding factor 10 reduction in Qwall (from 25 GW/m² to 2.5 GW/m²).
Max vaporization is reduced from 700μm (in line with RACLETTE▲) to 4μm, melting from 400μm to 150μm
Preliminary results. In line with ITER modelling [1] and (old) exp. Validation [2]

[1] S.Pestchanyi, et al., FED, vol. 109, p. 141, 2016
[2] S.Pestchanyi, et al., FED, vol. 124, p. 401, 2017

Further DEMO experimental validation requested in QSPA

Armour R&D



Sacrificial limiter as the last protection resource of the reactor wall

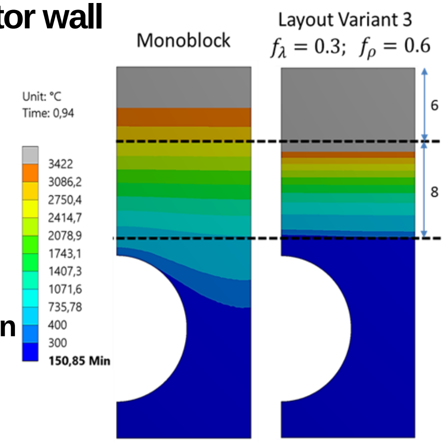
Heat Flux Reduction + **Longer lifetime**

Heat Flux Reduction

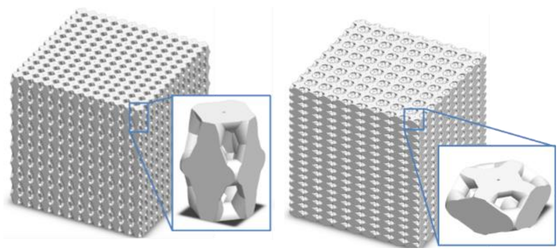
I. **Prompt vapour shielding**
II. Acceptable thermal conductivity
III. High S/V ratio

Longer lifetime

I. **Less thermal stress and more ductile behaviour**
II. **Avoid overloading of the heat sink**
III. **Hindered crack propagation**



W lattice: tailored metamaterial designed to get desired characteristics and realized in additive manufacturing



e.g.: Anisotropy A=0.5
Constant profile ligament
ligament length L=0.33mm
ligament radius section R=0.15mm
Relative density 53.3%
Thermal Condutivity 48.8 W/mK

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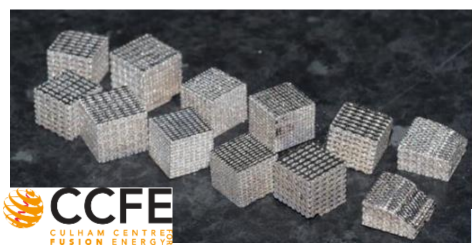
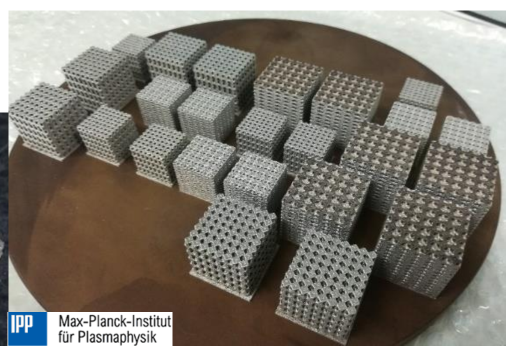
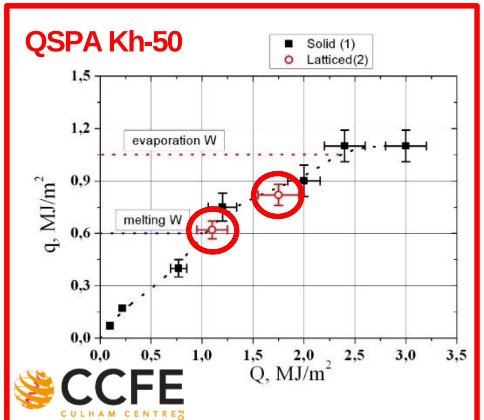
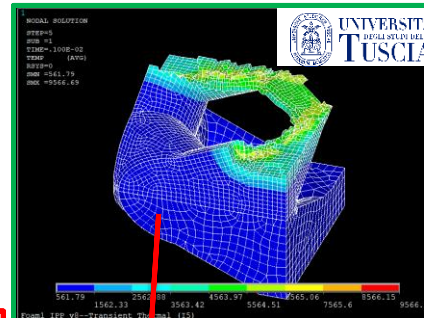
Ongoing activities:

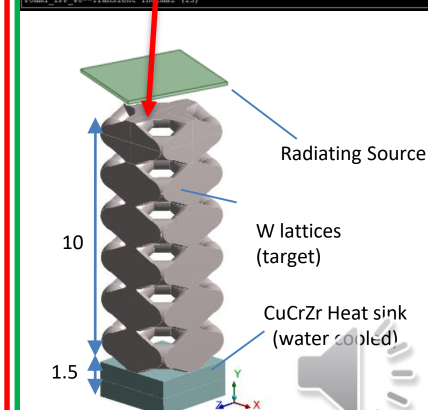
→ Different geometries samples production
→ Microscopic inspection
→ Material characterization (density, thermal diffusivity, mechanical testing)
→ Plasma compatibility and H-retention tests
→ **HHF experiments on linear plasma devices (QSPA Kh-50)**
→ **FEM-based tools for thermal simulation with melting / vaporization**







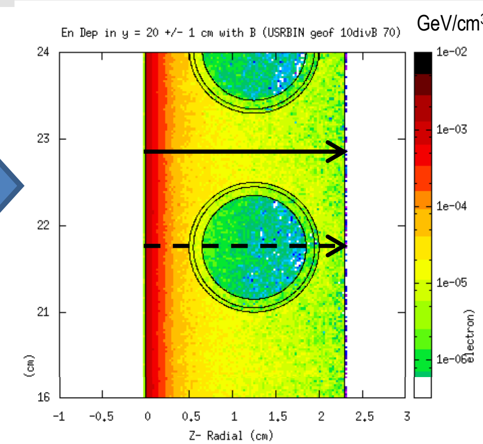




Runaway Electrons preliminary calculations

The FLUKA code [1-3] is used to estimate the REs energy deposition profile for different PFC. Simplified assumptions:

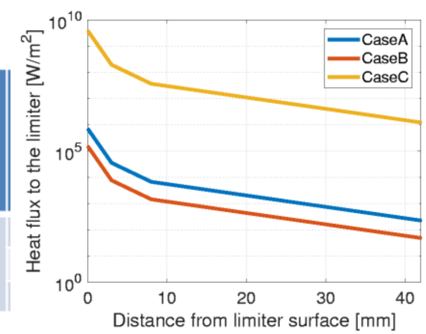
- REs **current = 4MA** (EU-DEMO max curr. =20MA),
- **e**$^-$ energy **20MeV** (mono-energetic), incidence angle **α**=[1,**10**]°
- **R**$_{RE}$**=9m**, **a**$_{RE}$**=1.5m** (1/2 of pl.), **cross section 7m**;



FLUKA: single 20MeV e⁻ energy deposition in the divertor (α= 10°, BT = 5.8 T)

Beam duration: wide range: **A**)1ms (**E**$_{KIN}$**= 15MJ**) **B**) 100ms (≈CQ time **E**$_{KIN}$ + **E**$_{MAG}$ **= 305MJ**). **C**) Conservative τ=16µs (**E**$_{KIN}$**= 1.3GJ**)

Case	RAE current I_{RA} (MA)	Electron flux Γ_e (s^{-1})	Energy per electron E (MeV)	Beam duration τ (s)	Magnetic energy (J)	Kinetic energy (J)	Total beam energy (J)	Beam cross section A (m^2)
A				1×10^{-3}	0	1.5×10^{7}	1.5×10^{7}	
B	4	2.50×10^{25}	20	1×10^{-1}	3.05×10^{8}	1.5×10^{7}	3.2×10^{8}	7.1
C				1.6×10^{-5}	-	-	1.3×10^{9}	



Heat load per unit surface for cases **A**, **B**, **C**, rescaling FLUKA

Input table used to run FEM analysis of PFCs (with W armor 8 and 20mm).

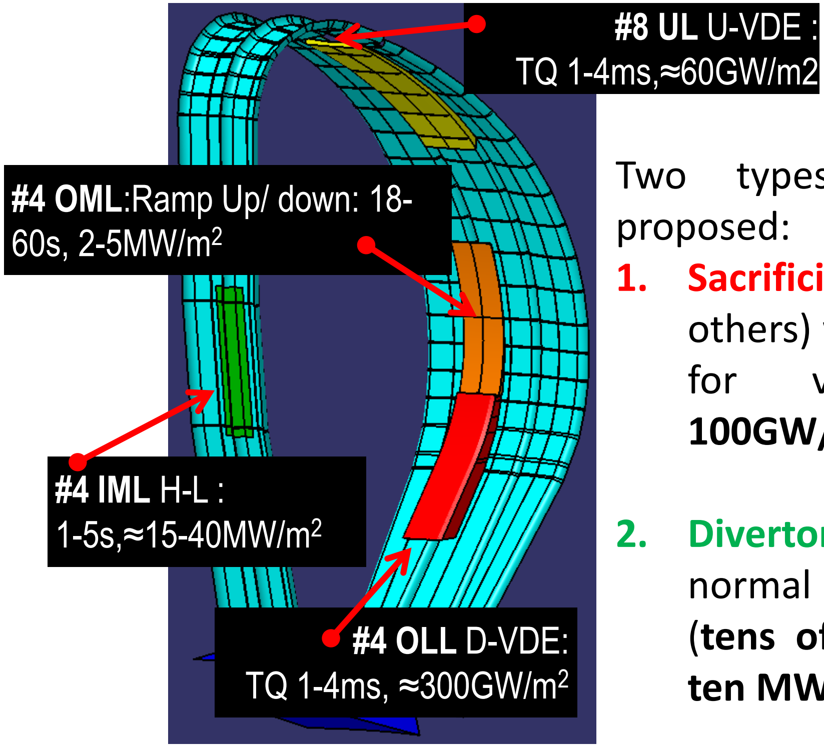
No cooling pipe melting observed in sim. (with present assumptions)

FLUKA being benchmarked with stopping power (ESTAR), and MEMOS-ENDEP[4]

[1] T. Böhlen, et al., *"The FLUKA Code: Developments and Challenges for High Energy and Medical Applications"* Nuclear Data Sheets 120, 211-214 (2014)
[2] A. Ferrari, et al.*"FLUKA: a multi-particle transport code"*, CERN-2005-10 (2005), INFN/TC_05/11, SLAC-R-773
[3] G. Maddaluno et al., "Energy deposition and thermal effects of runaway electrons in ITER-FEAT plasma facing components" JNM (2003)
[4] Y. Igitkhanov, B. Bazylev, S. Pestchanyi, "EFFECT OF RUNAWAY ELECTRONS ON THE DEMO WALL EROSION", ICFRM-(2019).

Limiters design

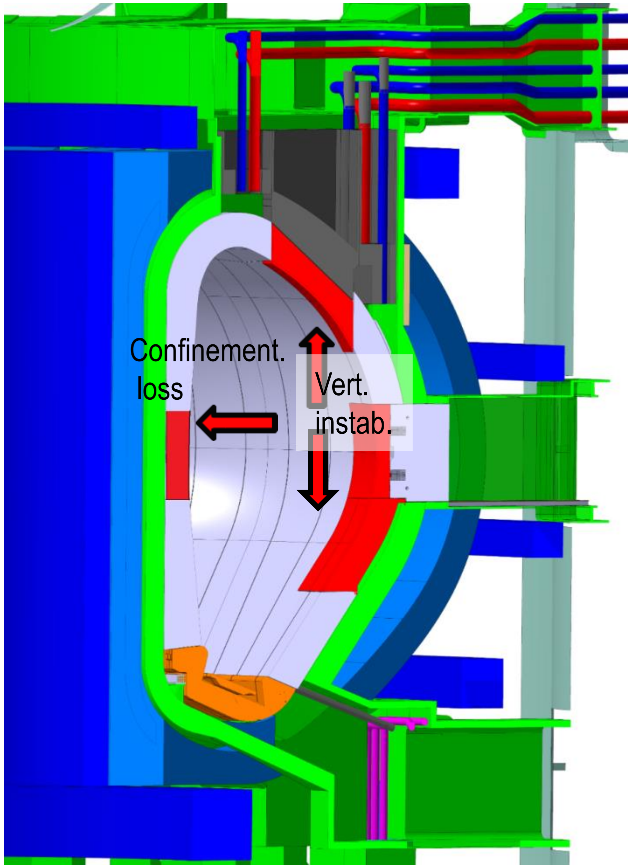
1) **#8 Upper Limiters** (UL), designed for U-VDE.
2) **#4 Outboard Lower Limiters** (OLL), designed for D-VDE.
3) **#4 Inboard Mid-plane Limiters** (IML), designed for H-L transitions, and in general for all the events characterized by a sudden loss of the plasma confinement energy.
4) **#4 Outboard Mid-plane Limiters** (OML), designed for plasma ramp up and down.



Two types of limiters are proposed:

1. **Sacrificial limiters** (for the others) with **20mm** W- armor for very high **≈0.1-100GW/m²** up to ≈**100ms**

2. **Divertor-like** (for OML), for normal transients RU/RD (**tens of seconds** and up to **ten MW/m²**):



Sketch of proposed limiter locations. Arrows indicate plasma movement due to **vertical instability** (**up/down**), and **loss of energy** (**inwards**)

Conclusions

- DEMO requirements are different from ITER: wall load specification being developed independently.
- Present DEMO first wall heat load limits of $1MW/m^2$
- Radiation and charged particles heat loads are evaluated, and four poloidal location proposed for limiters (divertor-like and sacrificial).
- Proposed discrete limiters able to protect the BB FW in all the considered cases. Some requirements are needed on the mitigated disruptions.
- Misalignment studies started on Limiters and FW.
- More sophisticated simulations (e.g. vap. shielding, REs), and hardware R&D and testing proposed for proposed PFC.
- Limiter design and integration initiated

Thank you for your attention!

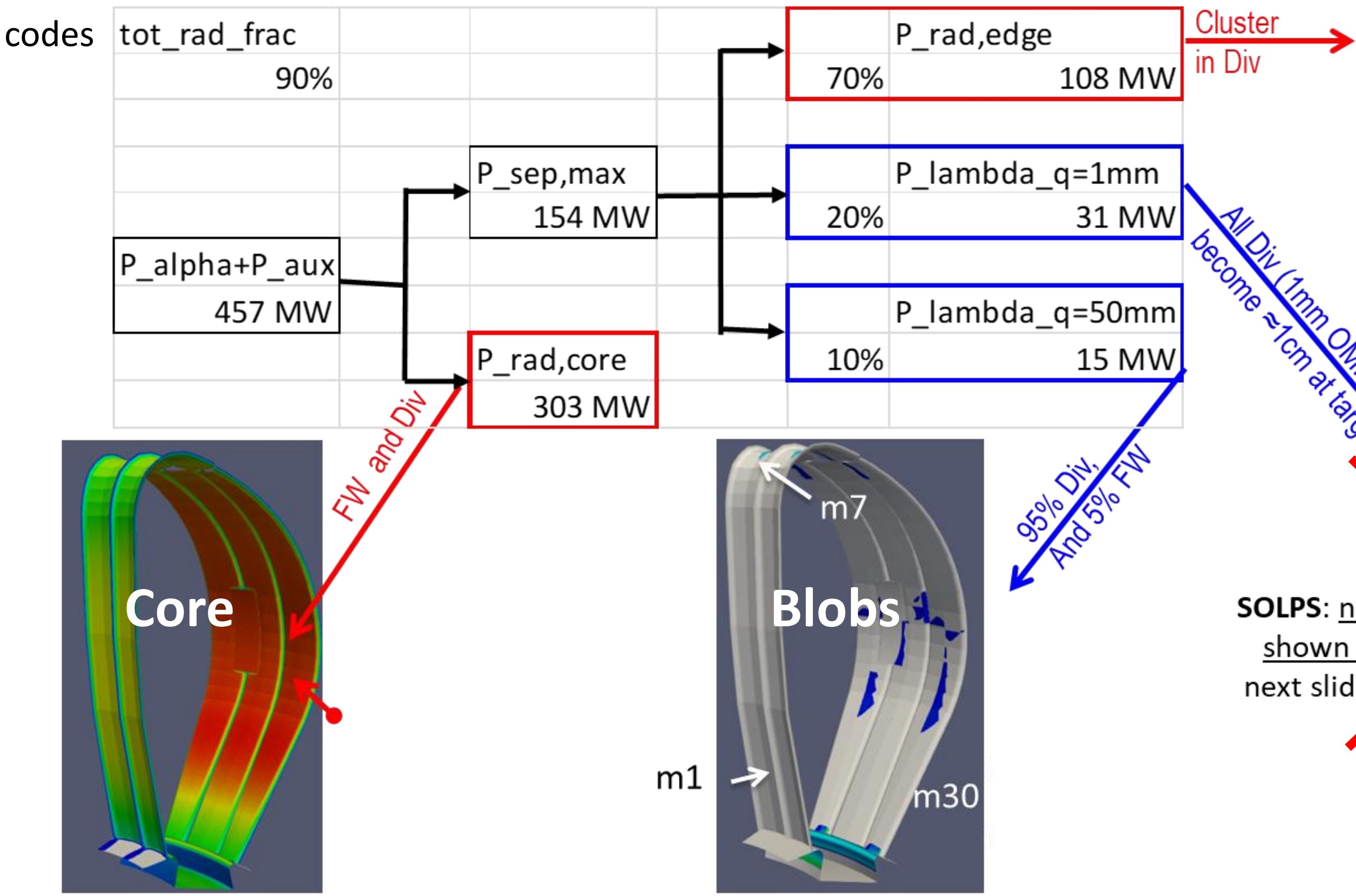
DEMO Static loads: Conservative – P_{sep} slow trans (backup slide)

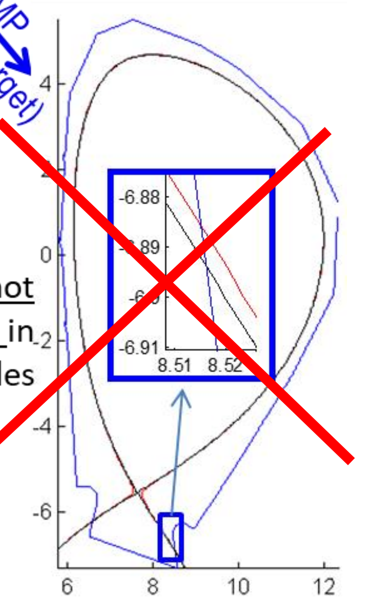
Conservative, R. Wenninger, NF 2017

EOF:*CHERAB/SOLPS*

Radiation loads: **CHERAB** code using Core (**ASTRA**) + SOL (**SOLPS**) photonic radiation

Charged particles: **PFCflux/SMARDDA** 3D field-line tracing



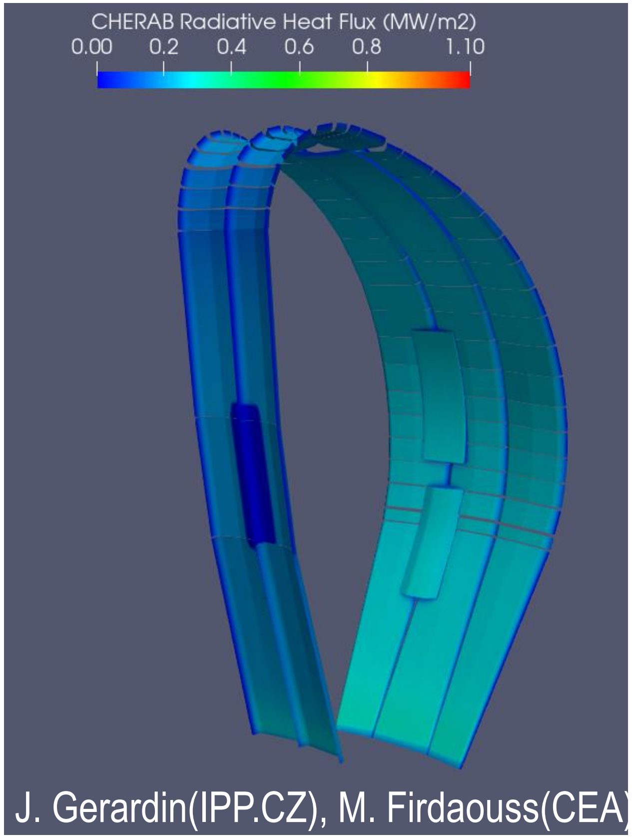


EOF: *CHERAB/ASTRA*

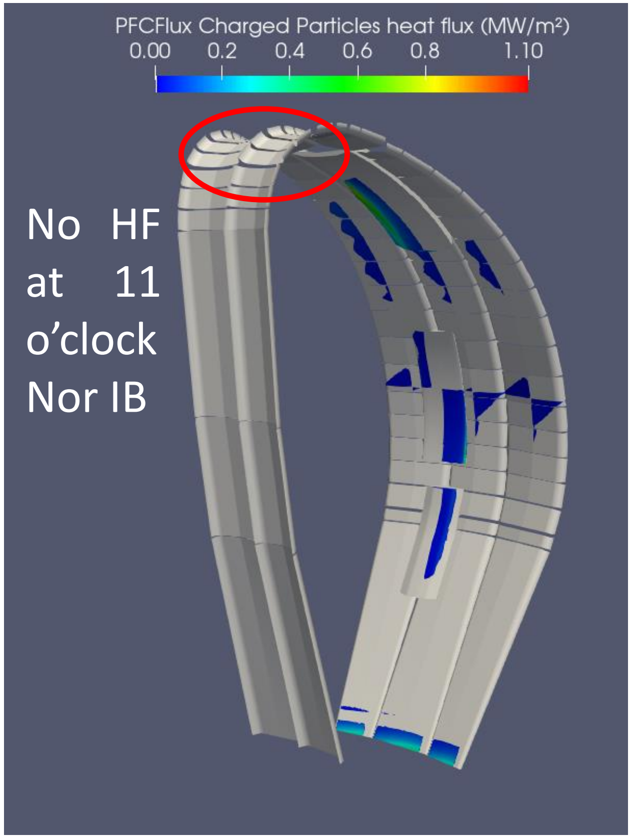
Results : SOF, Total heat flux

(backup slide)

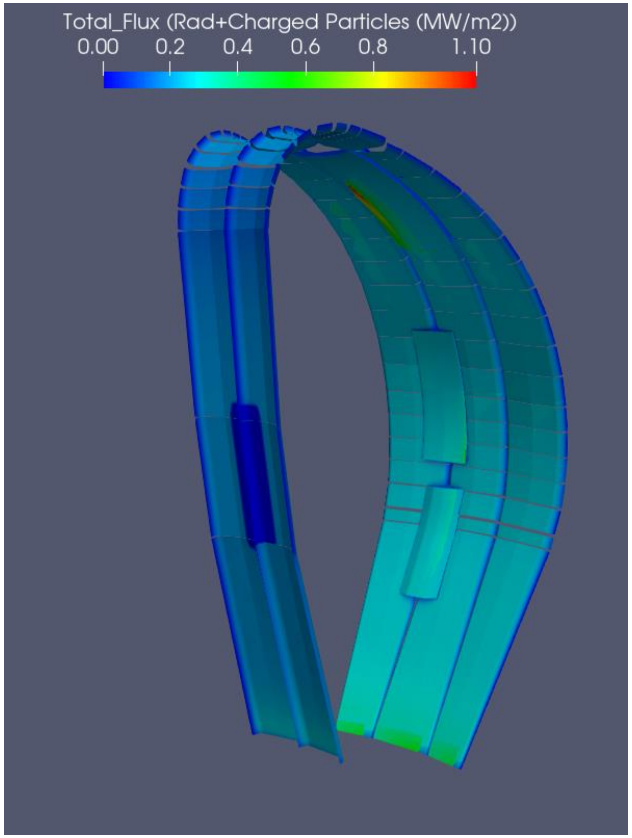
Radiative HF: CORE+SOL



Far SOL Charged particles HF



Total HF



3D HF maps produced (and continuously updated) with WPBB, and WPDIV for FW + Limiter design

- Maximum total heat flux located on upper limiter : 1.1MW/m²
- Module 7-8 shadowed from charged particles HF by limiter, and upper x-point rotation

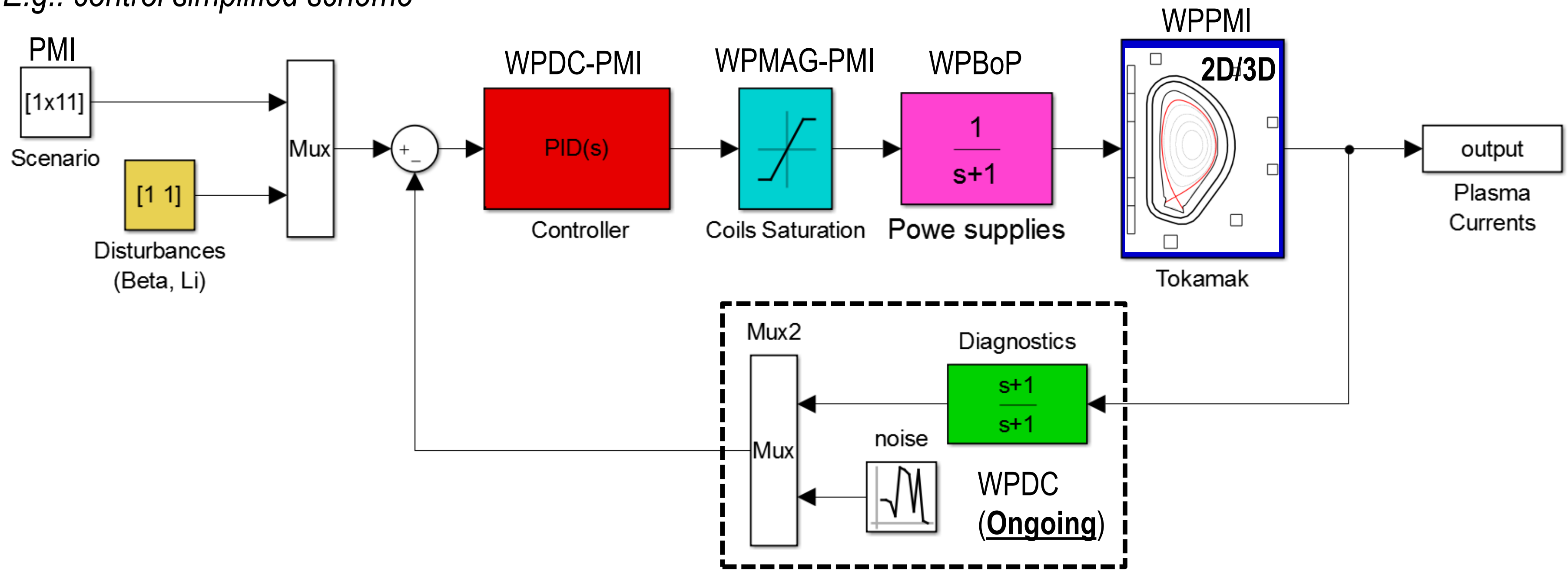
Plasma simulations: control loop

(backup slide)

Definition of disruption cases, and relative inputs, *e.g.*:

- perturbation time evolution B_{pol}, L_i, I_{pla}
- Control perturbations
- Electromagnetic simulations
- 2D heat flux (HF) calculation of radiated and charged particle
- Plan to use realistic diagnostics from end 2019

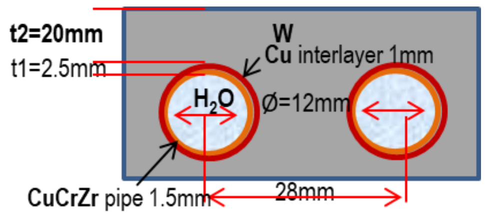
E.g.: control simplified scheme



Energy density [MJ/m²]– deposition time [ms] maps

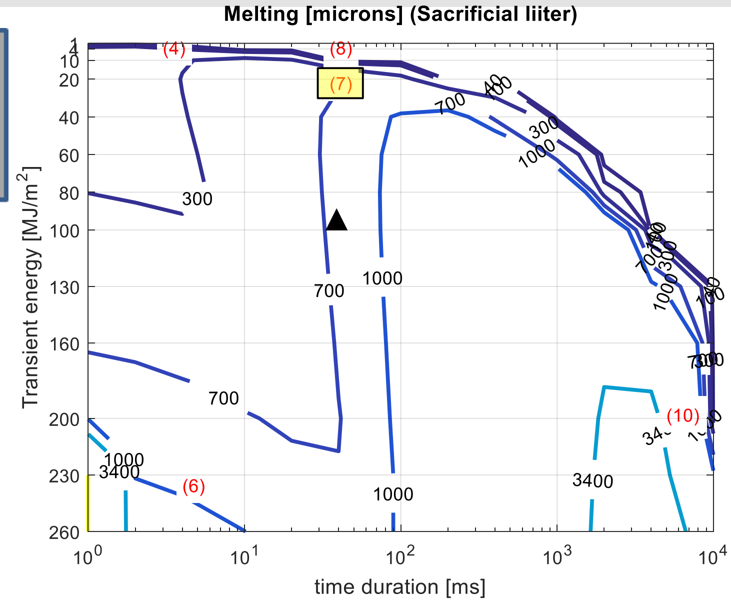
(backup slide)

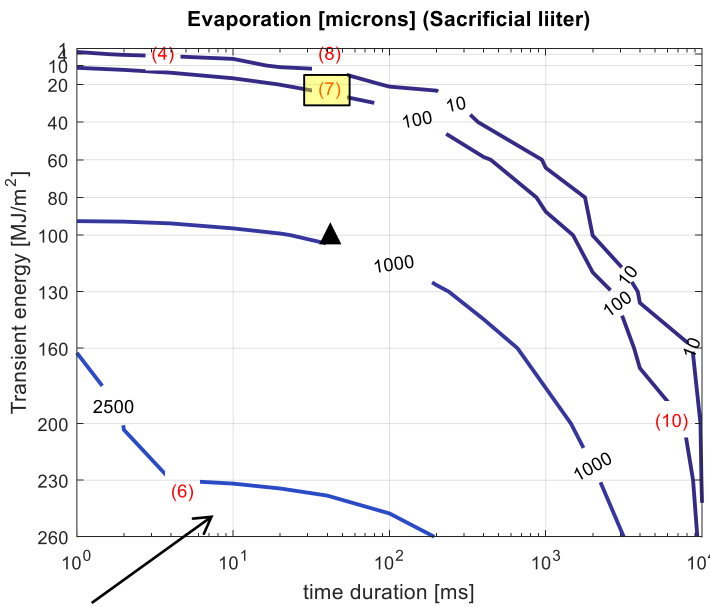
E[MJ/m²]/**τ**[ms] scan created for each PFC, to quickly assess vap./melt./temp./CHF



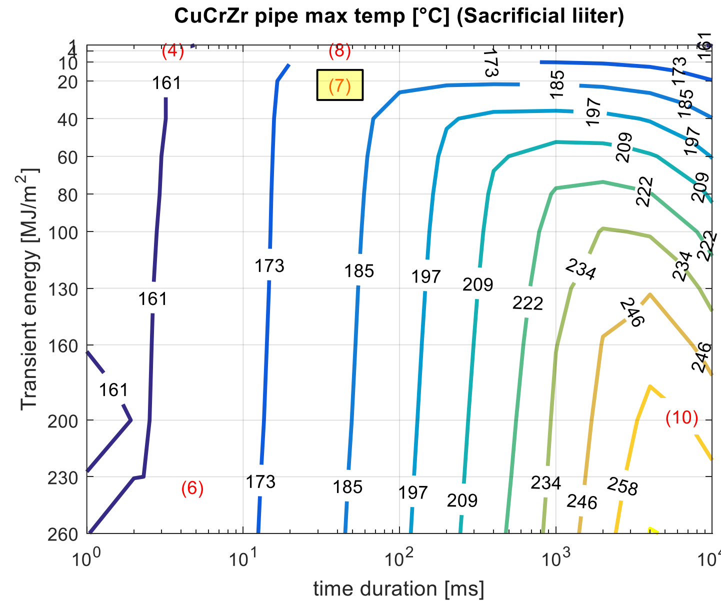
Example: Sacrificial limiter

Case	W-Evap. (µm)	W-Melt. (µm)	Heat sink temp. (°C)
Sacrificial limiter: (CuCrZr heat sink temp. lim. 350°C)			
(4) Mitig. Disr.	0	38	172
(5) U-VDE 1st touch	0	0	171
(6) U-VDE TQ	2560	988	176
(7) D-VDE 1st touch	82	698	179
(8) D-VDE 1st touch	0	0	171
(9) D-VDE TQ	Not converged		
(10) H-L conservative	120	3470	280





▲ -TOKES equivalent, next page



RACLETTE is conservative when W vaporisation ≥tens µm: possible mitigation from vapour shielding

Preliminary misalignment studies

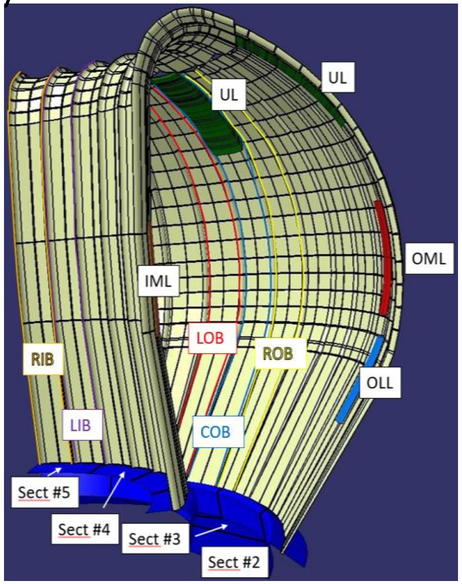
(backup slide)

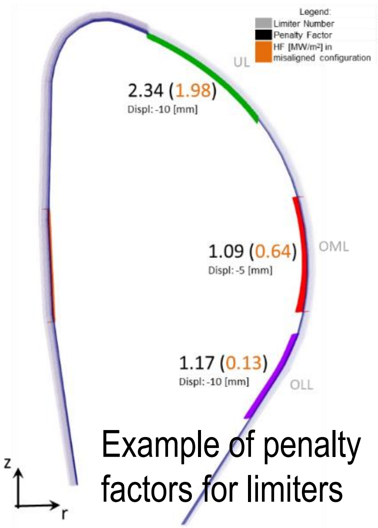
Vertical/radial misalignment studies ongoing to evaluate **penalty factors** (= HF $_{misaligned}$/HF $_{nominal}$):

- First wall: ±20mm, ±10mm (**L**eft/**C**entral/**R**ight **O**uter, & **L**eft **R**ight **I**nner **B**lanket)
- OLL and UL: ±10mm, ±5mm, ±2mm.
- OML: ±5mm, ±2mm.

Test Matrix										
	SOF (PSOL=69 [MW] - λq=50 [mm])						RU (PSOL=3.5 [MW] - λq=6 [mm])			
Components	Rigid radial translation [mm]						Rigid radial translation [mm]			
LOB		-20	-10	10	20		-20	-10	10	20
COB		-20	-10	10	20		-20	-10	10	20
ROB		-20	-10	10	20		-20	-10	10	20
LIB		-20	-10	10	20		-20	-10	10	20
RIB		-20	-10	10	20		-20	-10	10	20
	Rigid vertical translation [mm]						Rigid vertical translation [mm]			
LOB		-20	-10	10	20		-20	-10	10	20
COB		-20	-10	10	20		-20	-10	10	20
ROB		-20	-10	10	20		-20	-10	10	20
LIB		-20	-10	10	20		-20	-10	10	20
RIB		-20	-10	10	20		-20	-10	10	20
	Rigid radial translation [mm]						Rigid radial translation [mm]			
OML		-5	-2	2	5		-5	-2	2	5
	Rigid radial translation [mm]									
UL	-10	-5	-2	2	5	10				
	Rigid radial translation [mm]									
OLL	-10	-5	-2	2	5	10				
	Flexible deformations [mm]									
Component	TBD									

CCFE/EEG M.L. Richiusa
TB presented @ SOFT 2020





Example of penalty factors for limiters

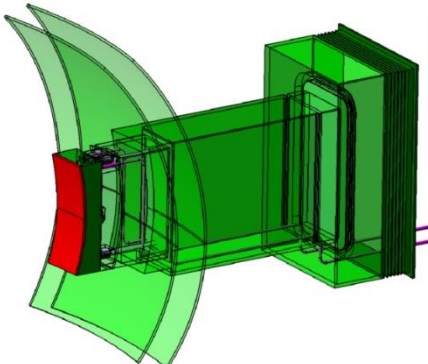
Limiters shadow FW in critical areas (close to 2nd inactive x-point, & baffles) also in SOF/EOF (DEMO plasma-FW clearance ≥23 cm)

Misalignments mainly affects limiter edge exposure to HF

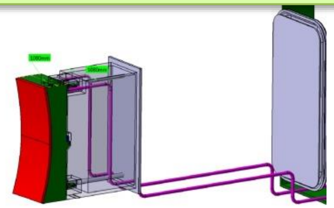
Limiter protrusion (chosen at the moment for FW protection) can be revised if BB tolerances require it. Flexible deformation ongoing.

Equatorial Port Limiter (Outboard Limiter)

(backup slide)



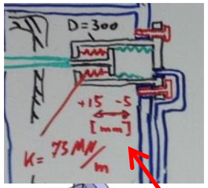
a) Limiter port plug inside EQ port



b) Limiter port plug + closure plate

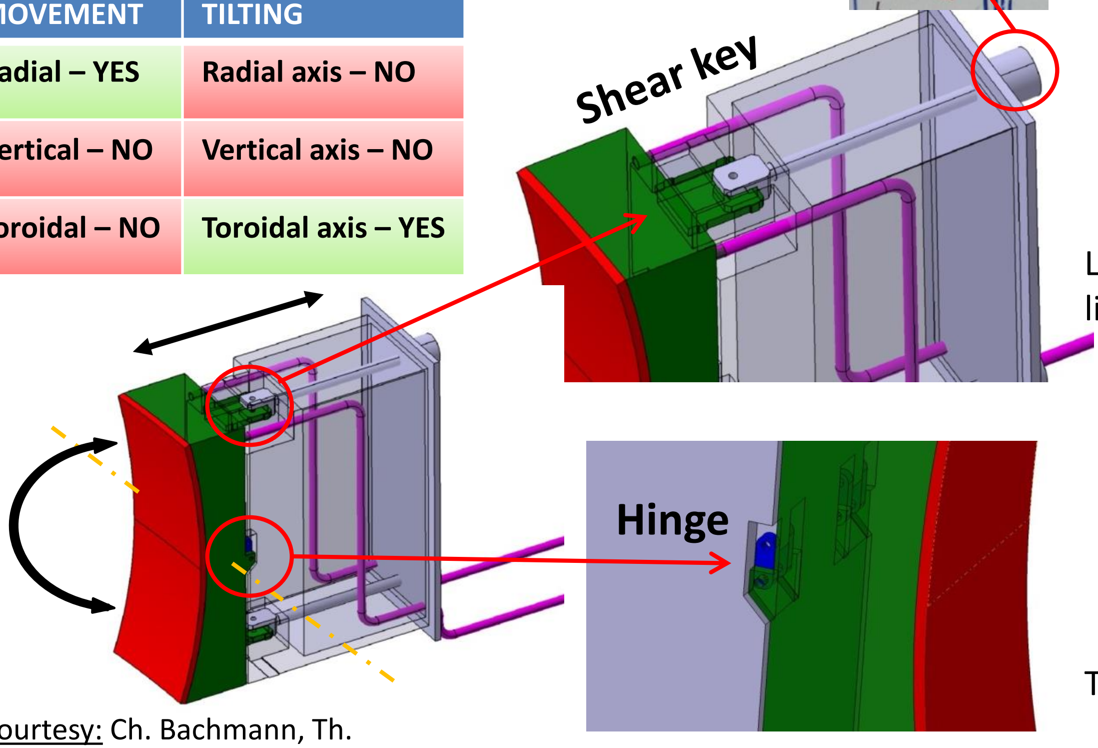
Design for replacement of PFCs together with shield block, and reuse of Port Plug

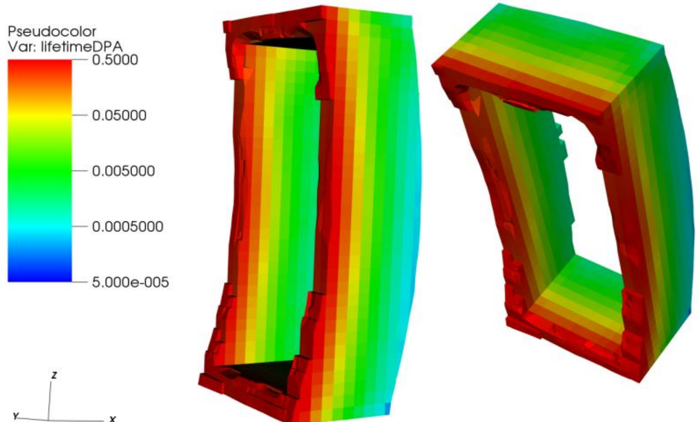
- Radial protrusion to FW 2 cm (at assembly in Port Plug under B-field) with radial alignment from control room without physical access requirement of alignment **+/-3 mm variation with 0.2 mm precision!**
- Actuators by spring + He-filled bellow w/o motor!



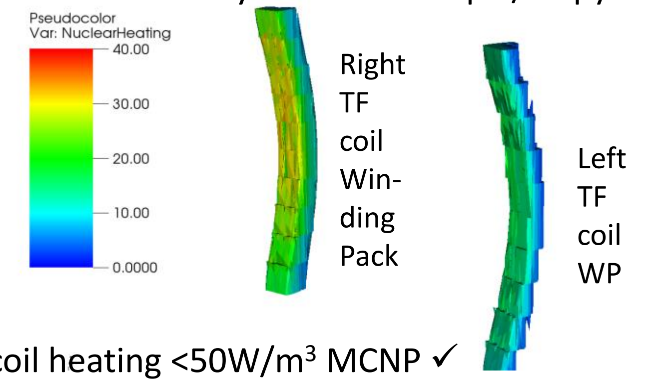
From 6 degrees of freedom, 2 are needed:

MOVEMENT	TILTING
Radial – YES	Radial axis – NO
Vertical – NO	Vertical axis – NO
Toroidal – NO	Toroidal axis – YES





Lifetime limit 2.75 dpa / 6 fpy in VV around the limiter confirmed by MCNP < 0.5 dpa / 6 fpy ✓



TF coil heating <50W/m³ MCNP ✓

Courtesy: Ch. Bachmann, Th. Franke, R. Mozzillo, A. Cufar

TBR preliminary estimation with limiters

(backup slide)

Present preliminary assumptions: : The change of the neutron spectrum also in the BB due to the presence of water in the limiters is not considered in this simple estimate and will be assessed by Pavel Pereslavtsev in 2019.

16 equatorial and 16 upper port plugs. In addition 4 top limiter, 4 inboard limiters, 4 lower inboard limiters, and 8 lower outboard limiters

Required TBR of hypothetical blanket configuration dependent on:

- TBR requirement for final BB design configuration, see previous req., i.e. 1.05
- Assumed fraction of FW not covered by BB, i.e.:

Component	Surface
8 upper port plugs, ~1.0 m² each	8 m²
3 NB ducts, ~1.3 m² each	4 m²
4 EC launchers, ~4 m² each	16 m²
5 Diag. plugs, ~4 m² each	20 m²
Total 1	**48 m²**
4 equat. limiters, ~3m² each	12 m²
8 upper port limiters, ~4.5 m² each	36 m²
4 inboard limiters, ~2.5 m² each	10 m²
4 lower mid-plane limiters, ~3 m² each	12 m²
Total 2	**70 m²**
Total 1 + Total 2	118 m²

FW surface area (excl. BB penetrations): 1473 m².

Non-breeding fraction = 118/1473=8.0% → TBR increase factor = 1.087. → required TBR = 1.087*1.05 = 1.14

The change of the neutron spectrum also in the BB due to the presence of water in the limiters is not considered in this simple estimate and will be assessed by Pavel Pereslavtsev in 2019.

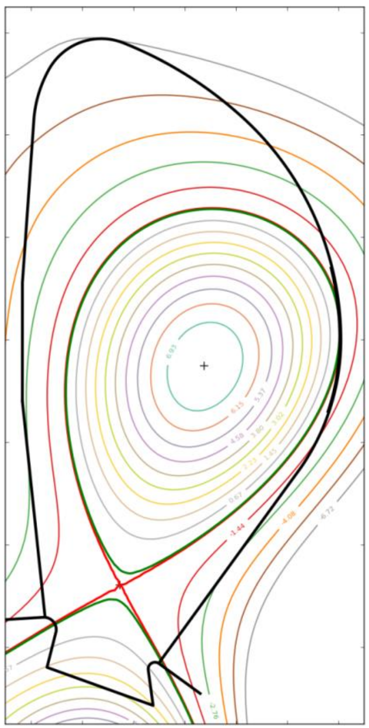
3D HF calculations and limiter surface design

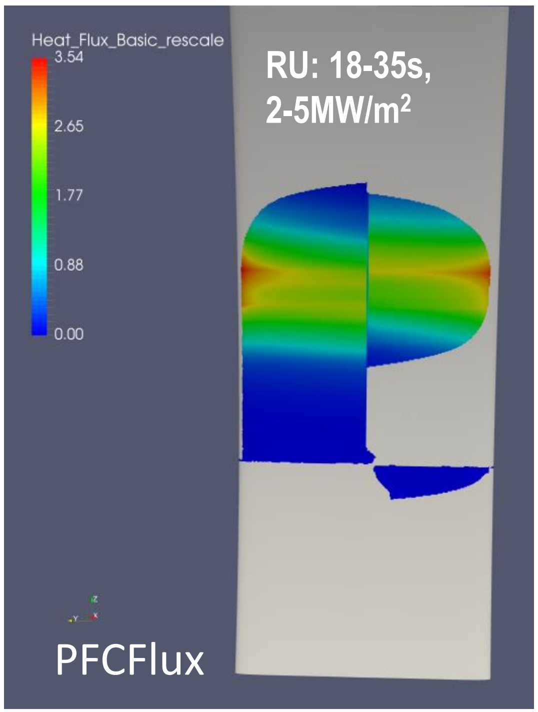
(backup slide)

Normal transients: ramp-up/down

- Plasma ramp-up/down assumed from +0.1 MA/s up to + 0.2 MA/s.
- λ_q = 6mm, Psol[MW] = Ip[MA] assumption (ITER like)
- RU: x-point formation in range at 3.5MA to 6MA: t_{RU}= 18 to 60s
- RD: x-point kept down range 7.5MA – 5 MA: t_{RD} = 20s to 80s

RU: Limited eq. 6MA, 4 limiters

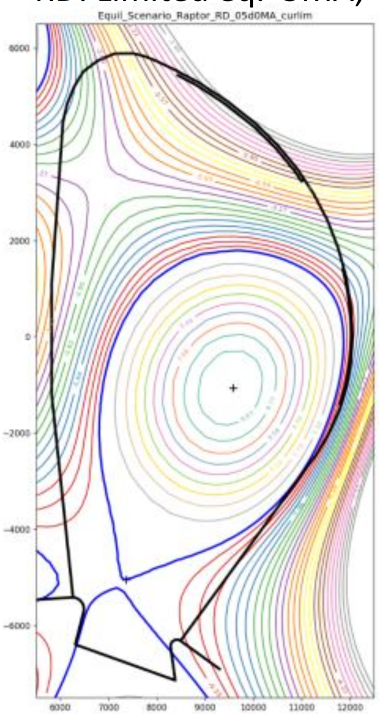


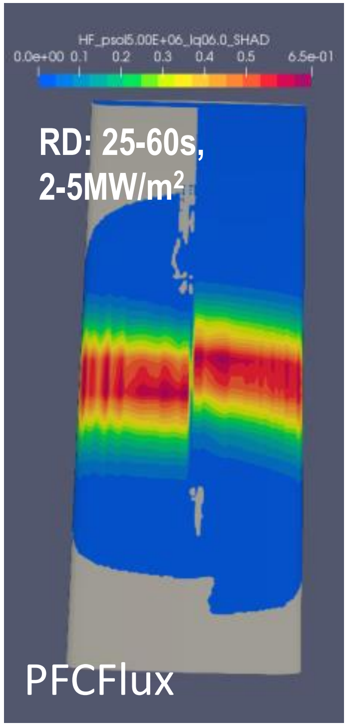


P_{SOL} = 6MW λ_q = 6mm

Max HF = 3.5MW/m² (ITER rescale)

RD: Limited eq. 5MA, 4 limiters





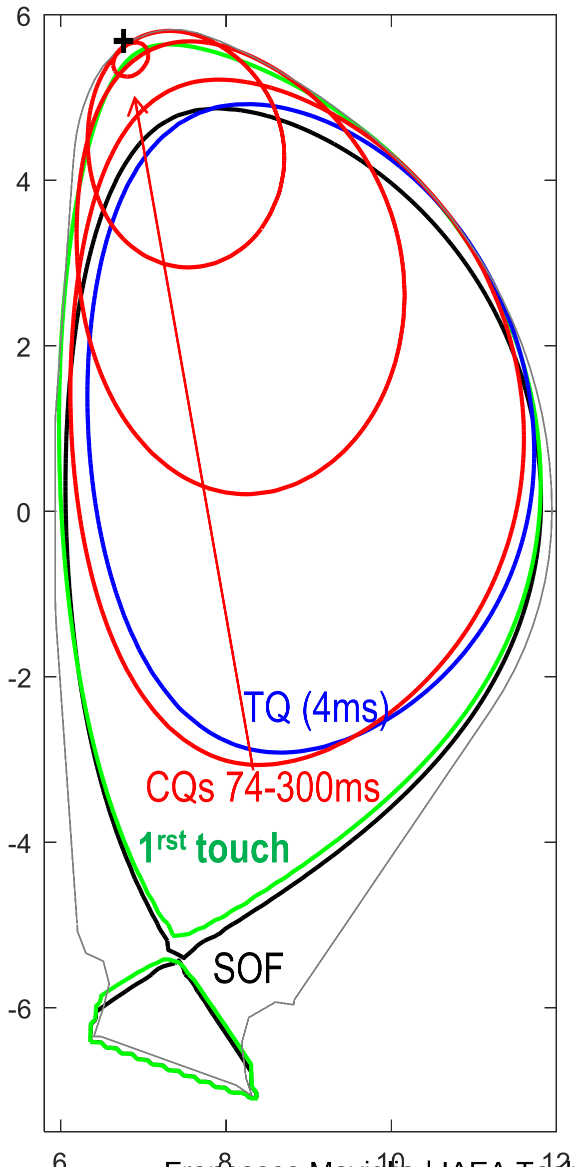
Misalignments may be reduced if limiter adjustable at OMP port. Bare wall HF ≈3-4MW/m²

No relevant HF found on other BB modules, nor on the limiter during flat-top phases

Off-normal transients: Unmitigated VDE

(backup slide)

Off-normal transients: **Upward Vertical Displacement Event** and **scenario optimization**



Typical plasma VDE evolution:

1) SOF (Start Of Flat-top)
2) 1rst touch (+ plasma moves vertically)
3) TQ (W_{th} from 1.3GJ to 0, in 4ms)
4) CQs (I_p from 19MA to 0, in 74-300ms)

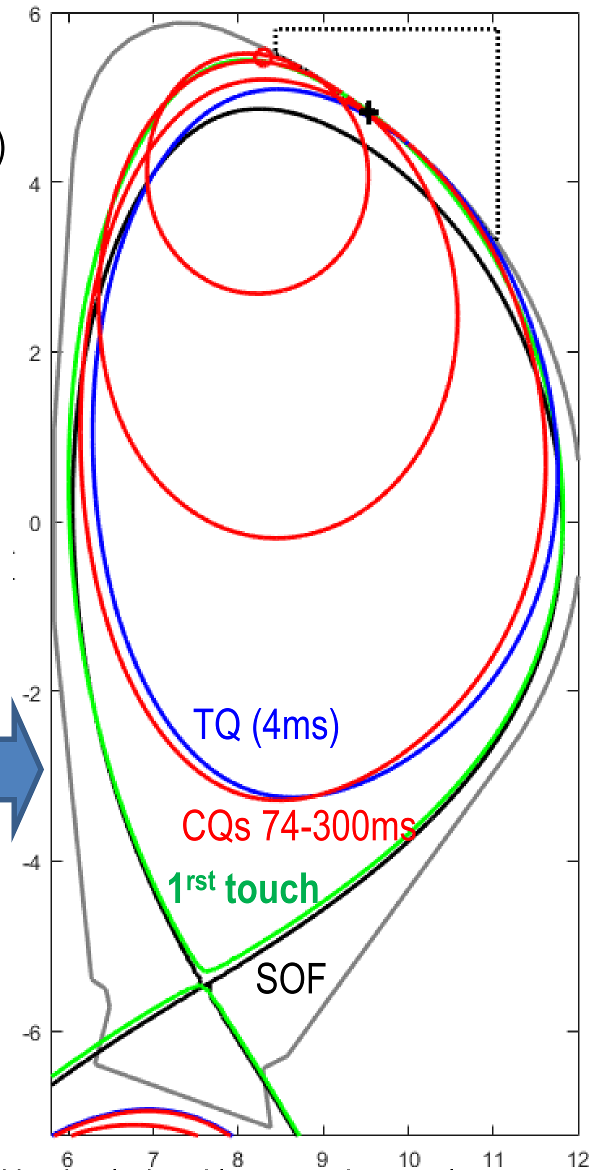
Baseline

- **1rst touch** close or at 11 'O clock
- **CQ** ends up at 11 'O clock

Optimised scenario

- **1rst touch**, TQ and CQ moved towards upper port area.

Obtained by moving upper x-point clockwise (reduced upper-triangularity, $\delta_{95\%}$ from 0.33 to 0.25)

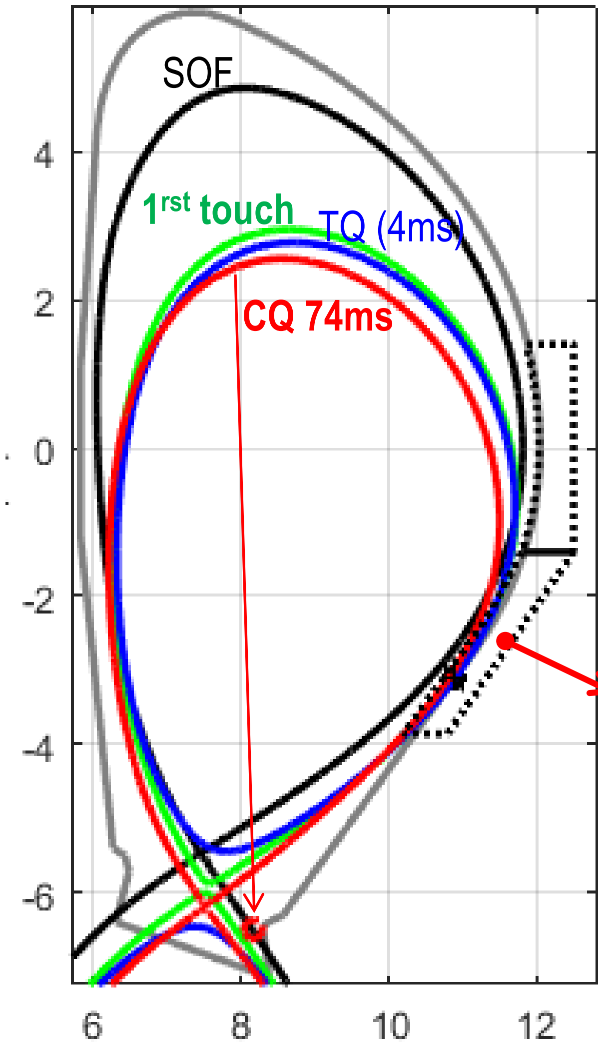


3D HF calculations and limiter surface design

(backup slide)

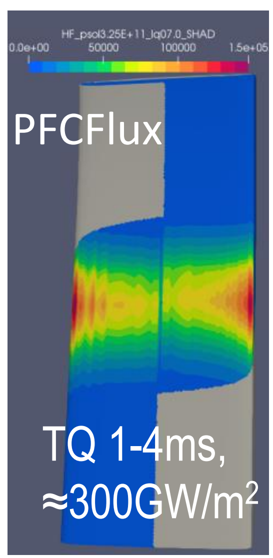
Off-normal trans.: Downward-VDE and conservative loss of confinement

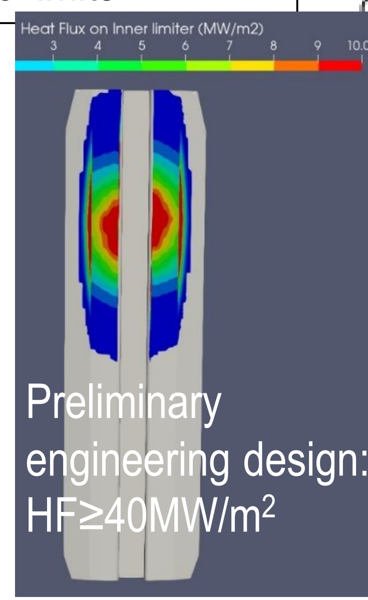
D-VDE (*unmitigated*)



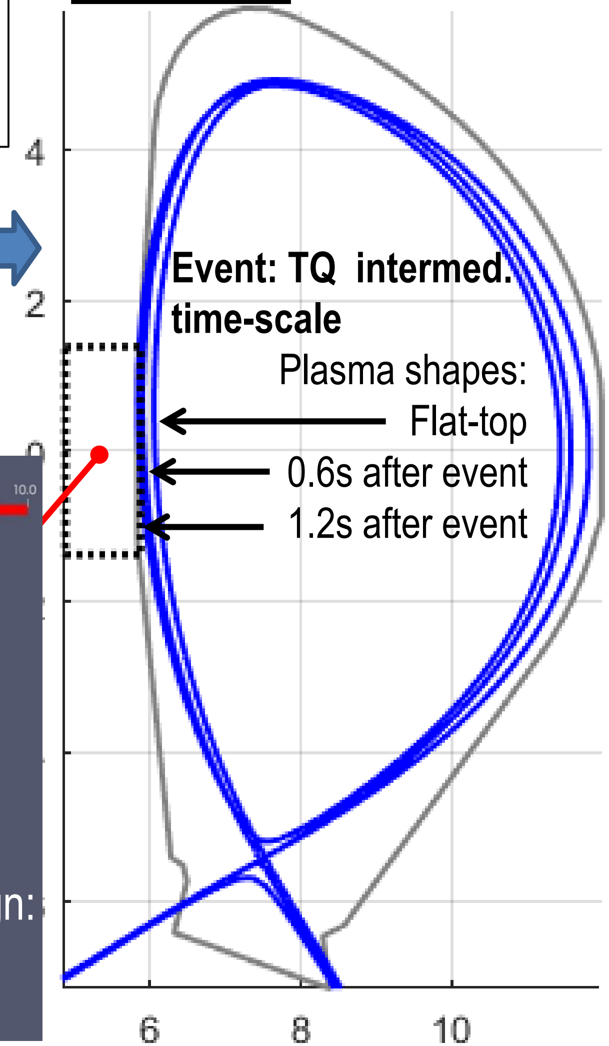
- **1rst touch** right below OMP at 4 ‘O clock, Far from baffle
- TQ shrinks plasma which become diverted again.

None on the presently considered **loss of confinement** leads to inboard plasma contact: <u>conservative case</u> chosen deliberately above limits





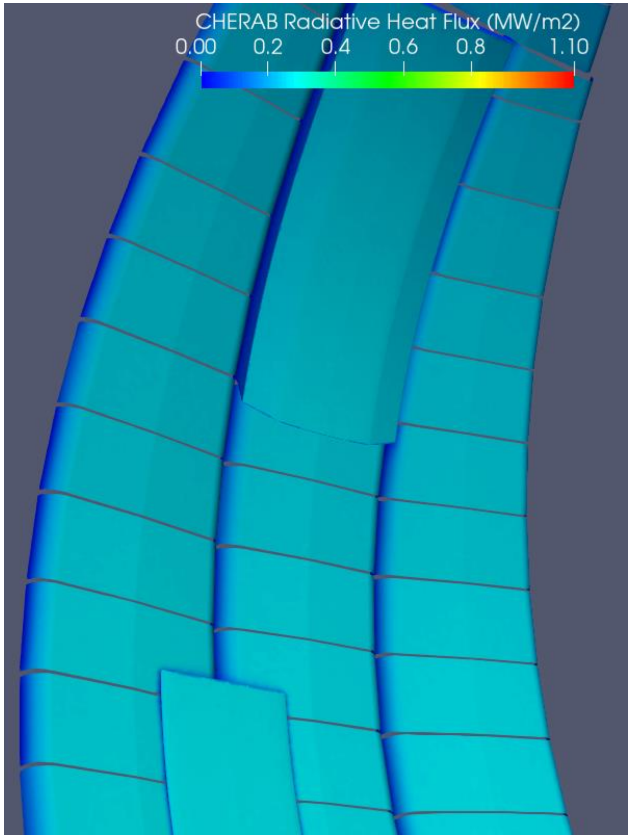
Loss of confinement:
<u>Conservative</u> case



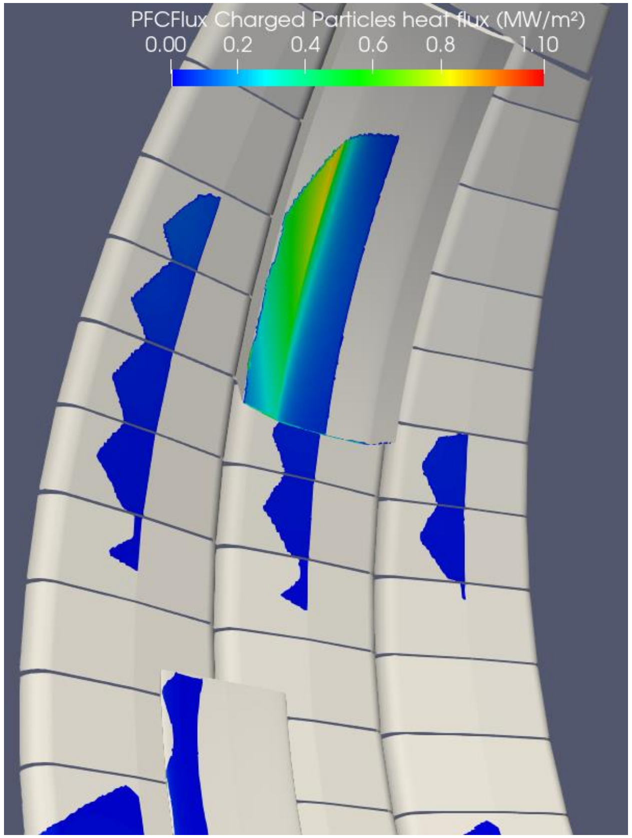
Results : SOF, Total heat flux

(backup slide)

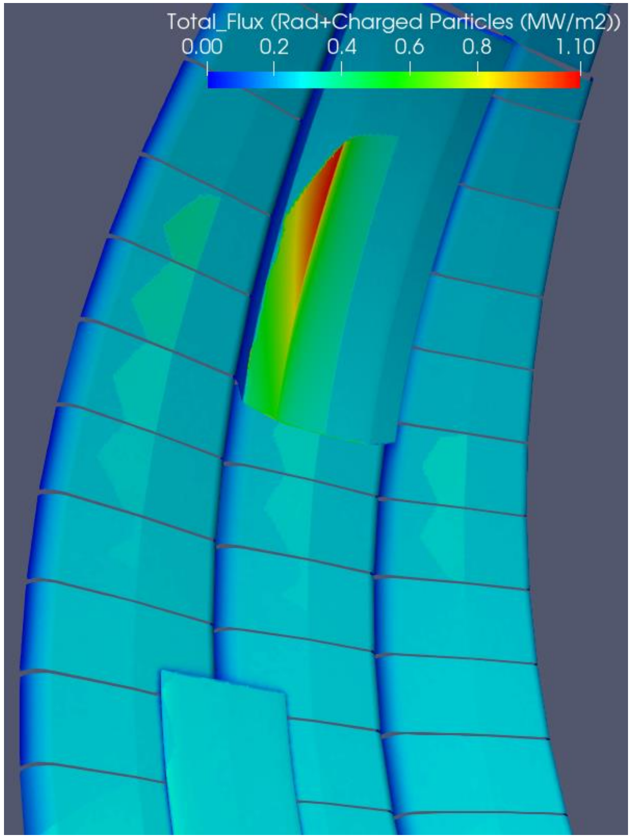
Radiative heat flux

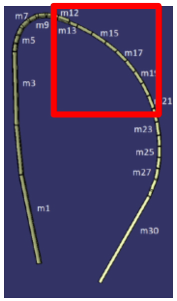


Charged particles heat flux



Total heat flux





- Maximum total heat flux located on upper limiter : 1.1MW/m²
- Module 7-8 shadowed from charged particles HF by limiter, and upper x-point rotation