Lifetime analysis of the ITER first wall under steady state and off normal loads

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Outline of the talk

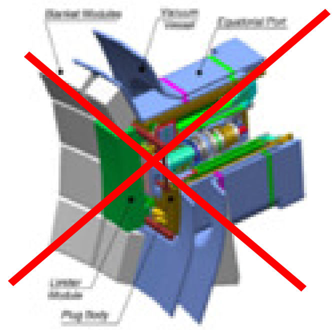
- Overview of blanket design
- Surface energy density at off-normal plasma events
- Material loss estimation & consequence on lifetime
- True heat load history during VDE
- Erosion for normal operation
- Conclusion

Context of blanket design evolution

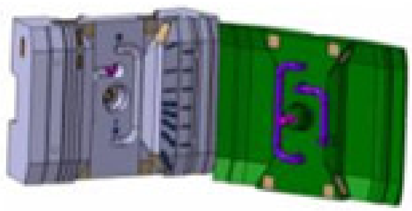
- Following PCR-93, *Thermal Load Specifications on PFCs*, a **Heat and nuclear load specification** has been annexed to the project requirement.
  - Plasma heat load to the main chamber first wall are described
  The heat loads is <u>*oriented along field lines*</u>

Concepts
2007

- The PCR-77 (*Shaped First Wall panels*) was aimed at proposing a First Wall design that can accommodate these loads, by **shaping the FW panels.**
  A shaped first wall accepts also direct limiter plasma contact at lower power, hence problematic **start-up limiters are abandoned**

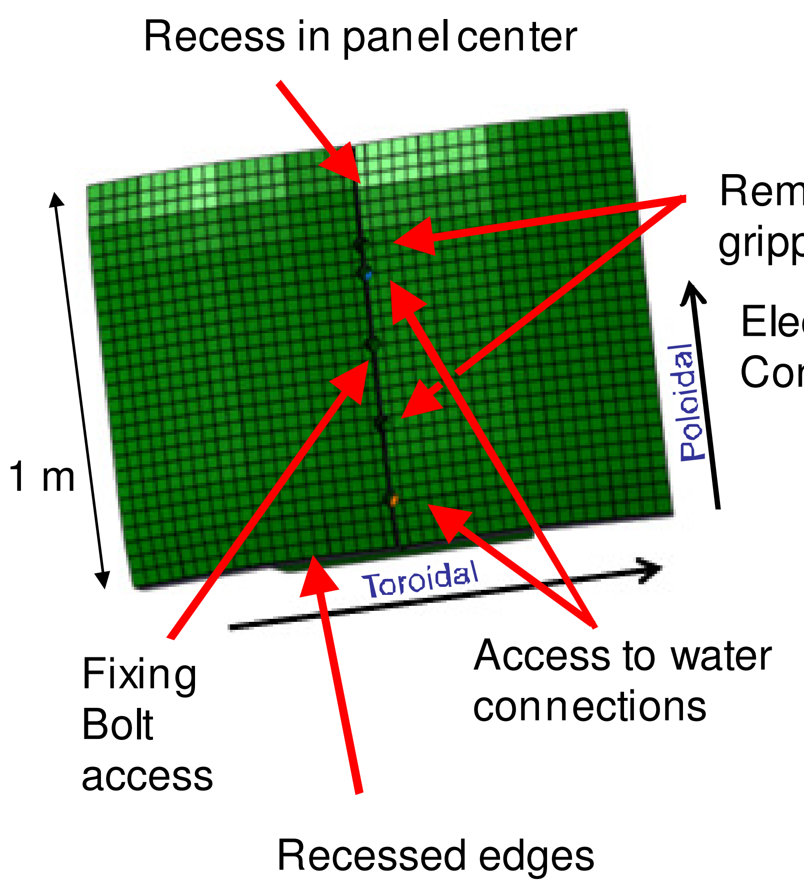


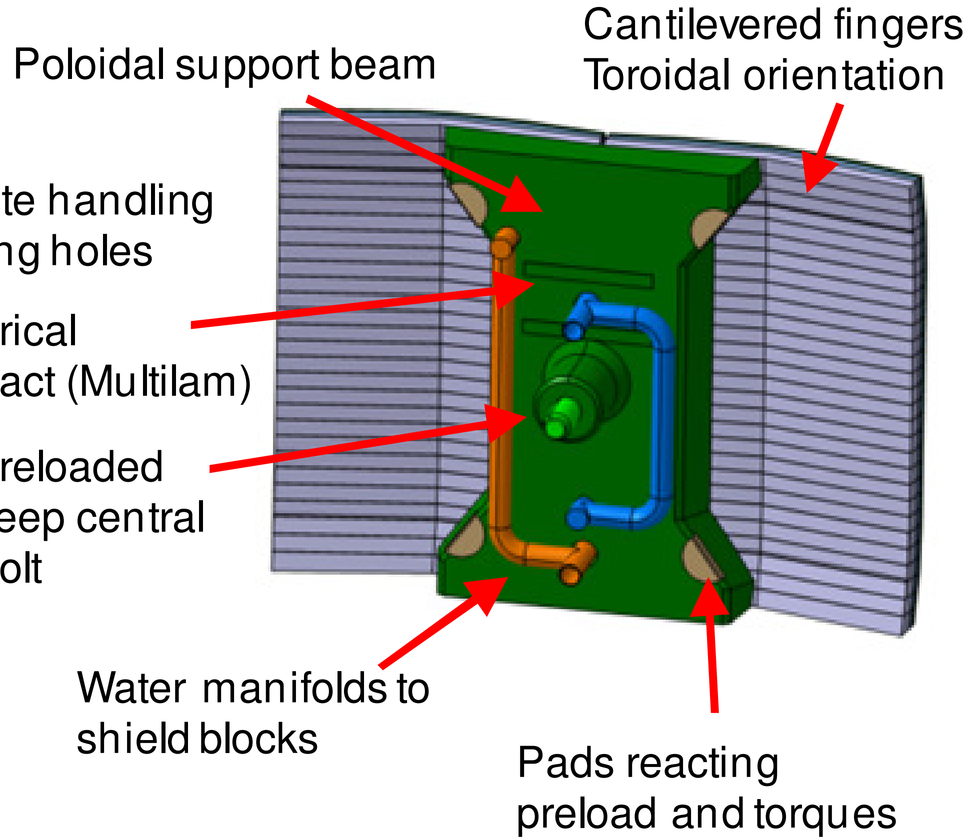
- In parallel, PCR-76 (Improved FW remote handling), and the inclusion of ELM control coil passing though the blanket shield modules have been a cause for significant redesign of the blanket system



PCR = <u>P</u>roject <u>C</u>hange <u>R</u>equest

First wall design





Status as of March 2011

Distribution of FW panel design heat load

Steady state:

$q_{||}$ ~ 8 MWm^{-2}, $\lambda_{q||}$ > 4.0 cm
$q_{||}$ ~ 24 MWm^{-2}, $\lambda_{q||}$ > 2.5 cm (ELMs)

Disruptions

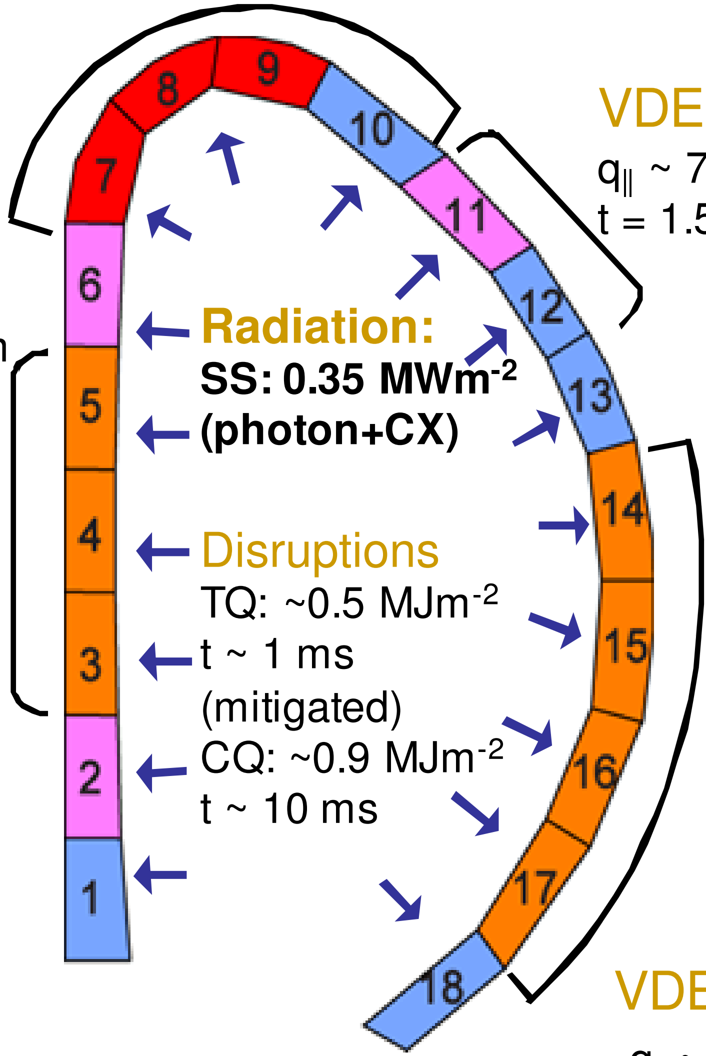
$q_{||}$ ~ 45-120 MJm^{-2}, $\lambda_{q||}$ > 20 cm
t = 3.0-6.0 ms

Start-up:

$q_{||}$ ~ 25 MWm^{-2}, $\lambda_{q||}$ ~ 5.0 cm
Several seconds

Confinement transients

$q_{||}$ ~ 250 MWm^{-2}, ~2-3 secs



VDE (up):

$q_{||}$ ~ 70-270 MJm^{-2}, $\lambda_{q||}$ > 3.0 cm
t = 1.5-3.0 ms

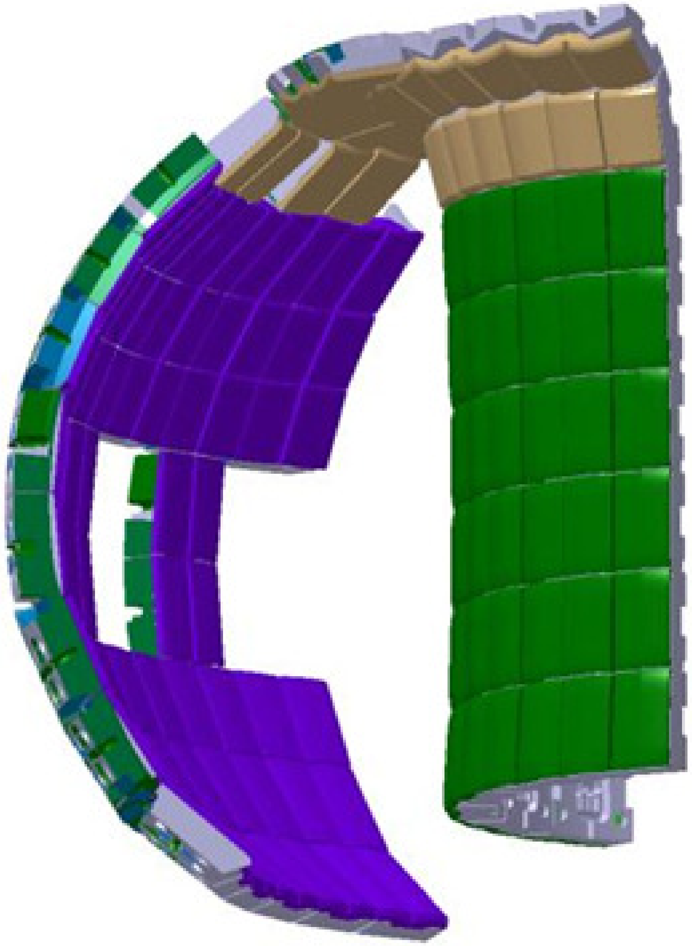
Start-up and rampdown:

$q_{||}$ ~ 40 MWm^{-2}, $\lambda_{q||}$ > 1.2 cm
Several seconds

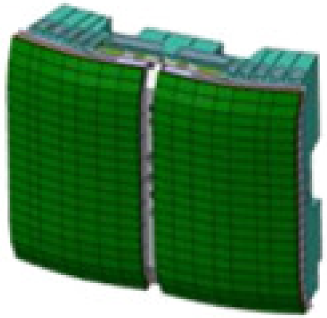
VDE (down):

$q_{||}$ ~ 90-300 MJm^{-2}, $\lambda_{q||}$ > 3.0 cm

A generic shaping solution

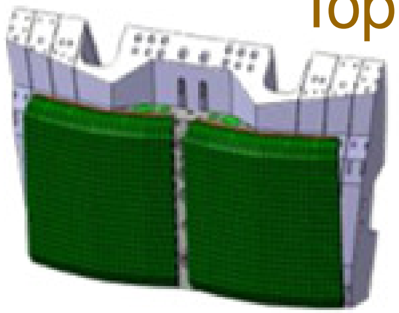


Inboard



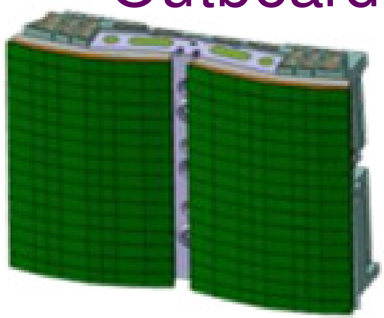
BM #1-6
Central column
HFS start-up
Toroidal & poloidal shaping

Top



BM #7-10
Secondary divertor region
Toroidal & poloidal shaping

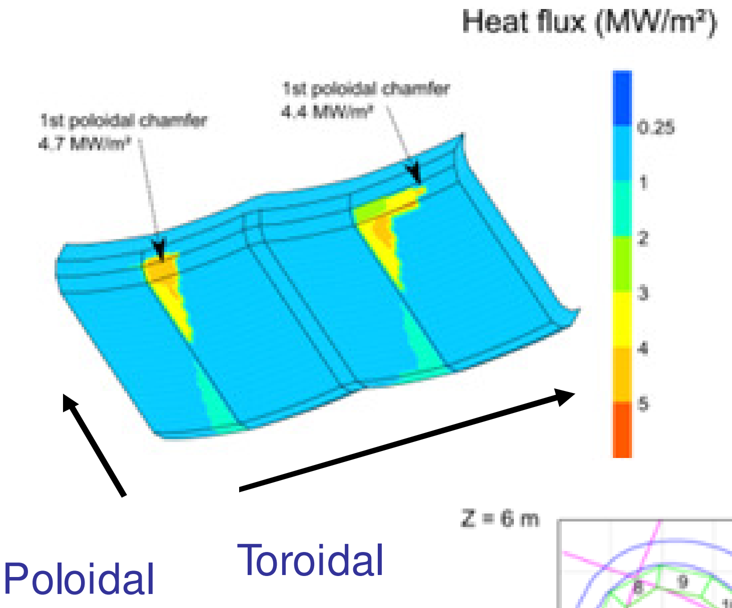
Outboard

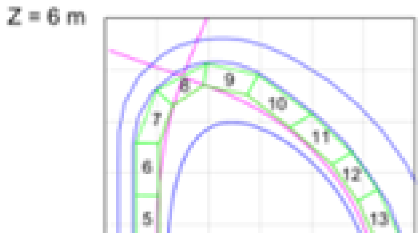


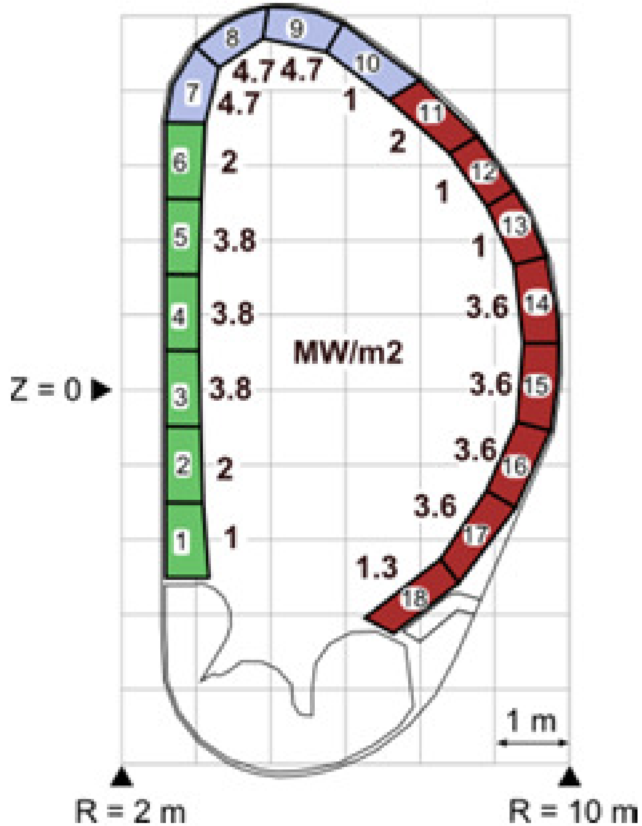
BM #11-18
Outboard
LFS start-up/ramp-down
Toroidal shaping

Design Heat load

Outboard flat top heat load (550 MW)





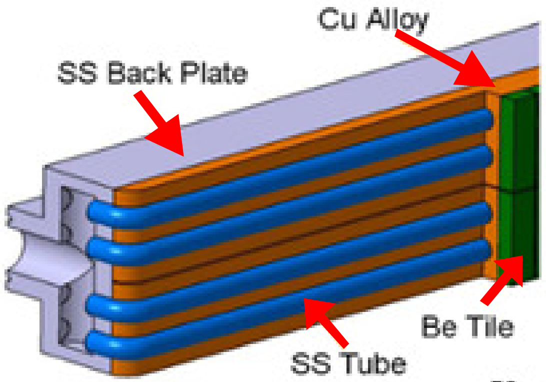


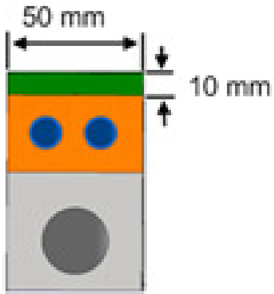
Heat flux distribution on FW panel 8 during
15 MA inductive flat top, including penalties
Equilibrium : li=0.7, PF6 Option 3
(limiter type contact),
Δ_{sep} = 40 mm q_o// = 33 MW/m²

- Group 1 : 1 – 2 MW/m²
  Normal heat flux panels
- Group 2 : 3.5 – 5 MW/m²
  Enhanced heat flux panels

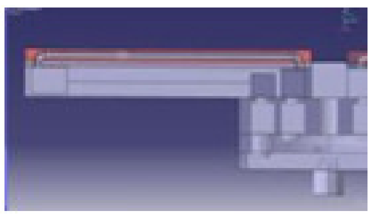
PFC technologies

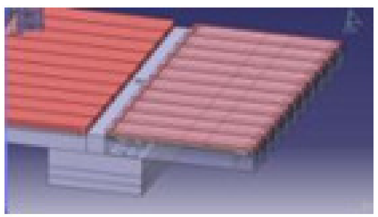
Normal heat flux finger:
concept with Steel Cooling Pipes



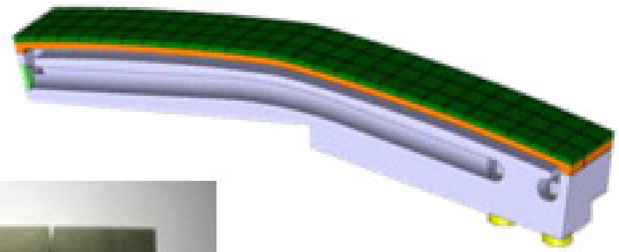


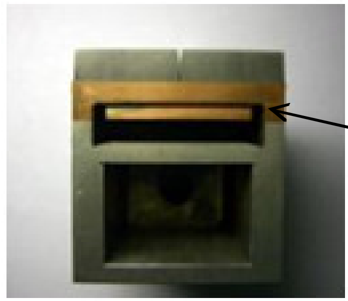
Hot isostatic pressing



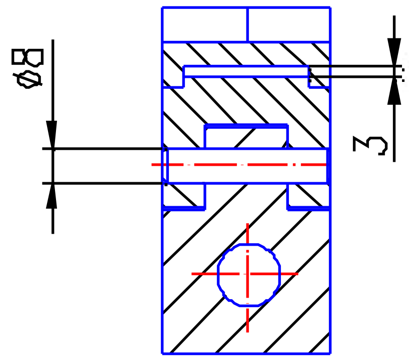


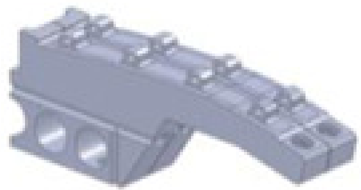
Enhanced heat flux finger:
concept with rectangular channels

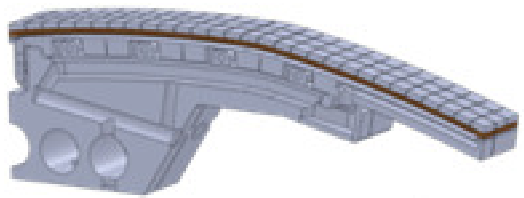




Copper alloy heat sink







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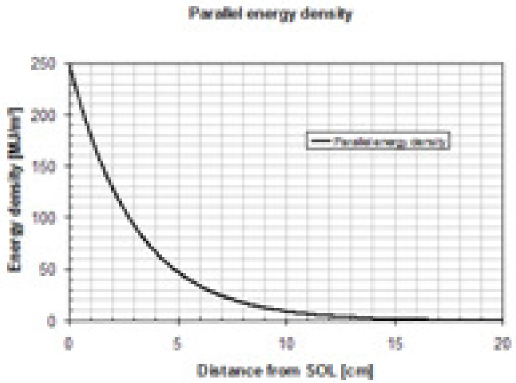
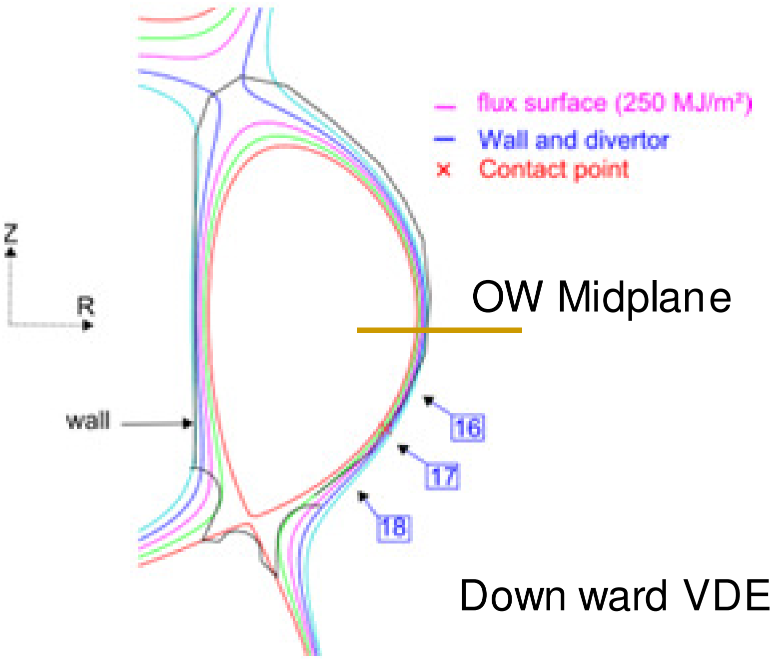
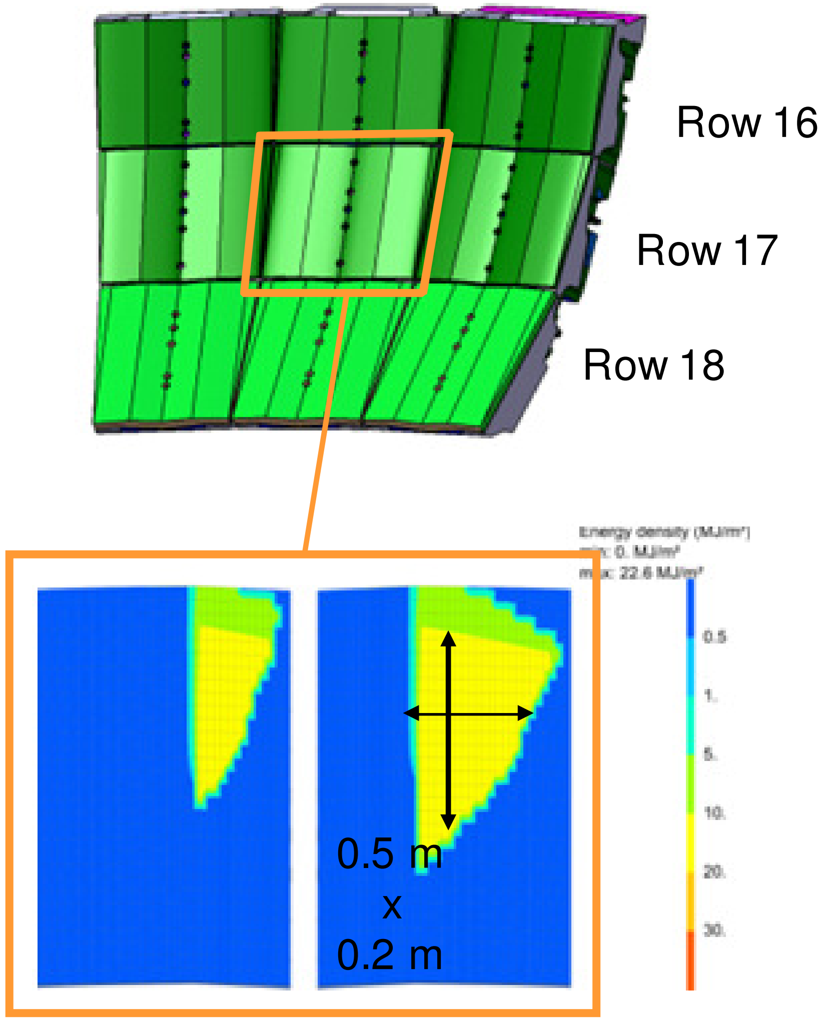
Surface energy density of row 17 panel at thermal quench



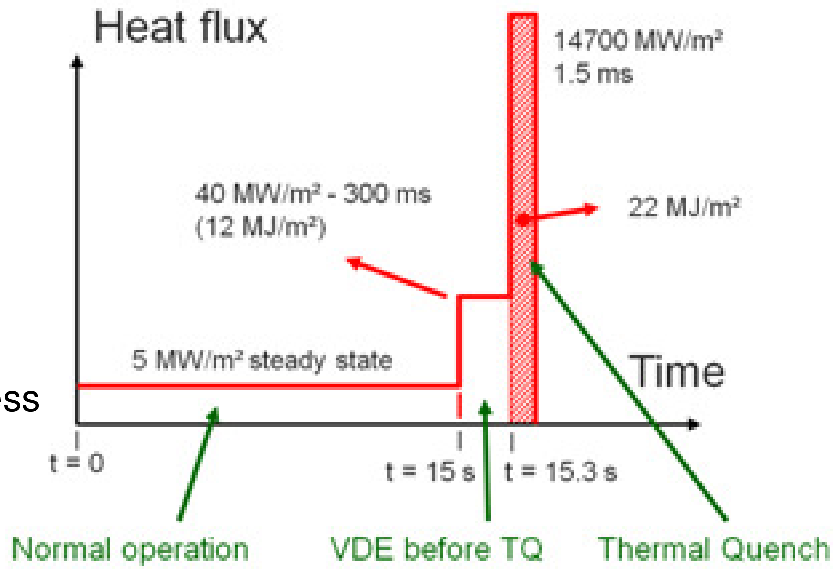




Surface energy density (MJ/m²)

Off normal events and associated energy density

- Disruption Thermal Quench (TQ))
  - 10 MJ/m^2 (top panels)
  - For $\Delta t = 3$ ms $\Rightarrow$ incident heat flux is 3 GW/m^2
  - For $\Delta t = 9$ ms $\Rightarrow$ heat flux is 1 GW/m^2
  - If DMS is successful, heat flux is divided by 10, duration unchanged
  - 1500 disruptions, 150 unmitigated, 1350 mitigated
- VDE
  - 22 MJ/m^2 at TQ (upper and lower IW/OW)
  - Hot plasma contact to wall during pre-TQ phase
  - 40 MW/m^2, 0.3 s
  - For $\Delta t = 1.5$ ms $\Rightarrow$ heat flux is 14 GW/m^2
  - If DMS is successful, TQ heat flux is divided by 10, duration unchanged
  - 150 VDEs, 15 with DMS failure, 135 with DMS success



Beyond design basis events

- Uncontrolled ELMs
  - 2 MJ/m^2 - 0.375 ms
  - 10 GW/m^2
- Loss of plasma control (ex. H-L transition)
  - 40 MW/m^2 - 3 s

DMS = Disruption Mitigation System

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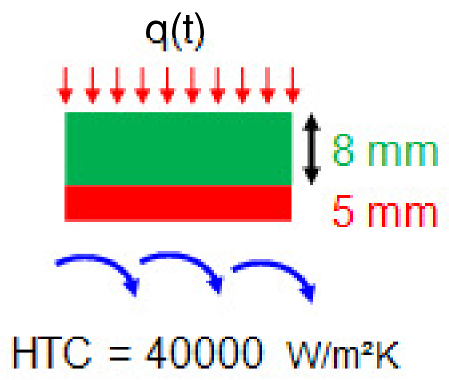
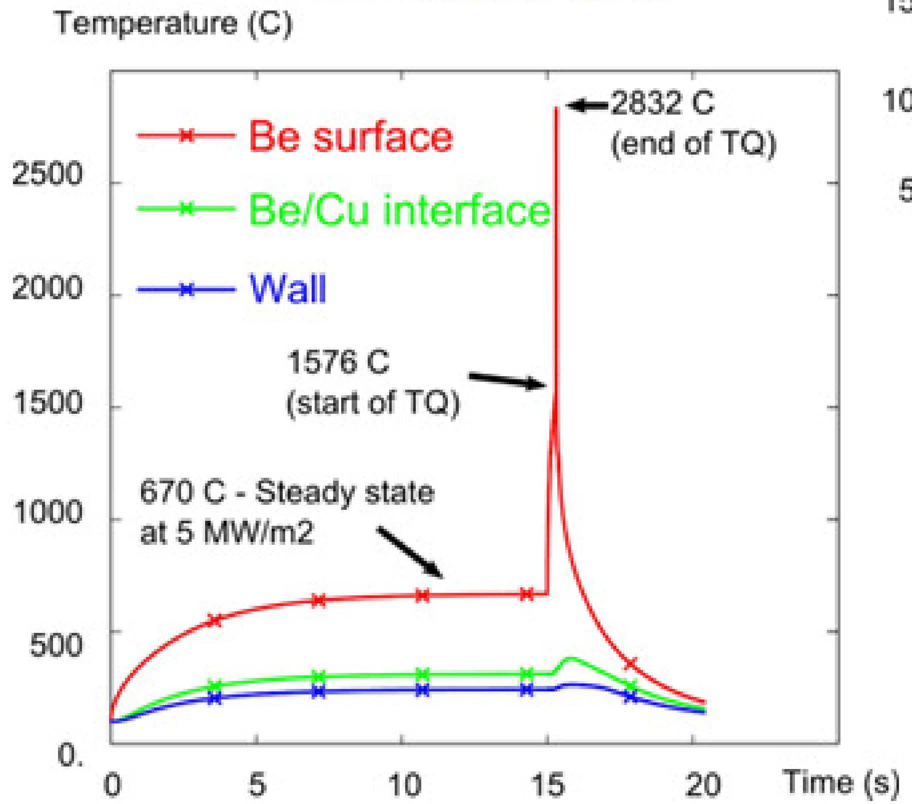
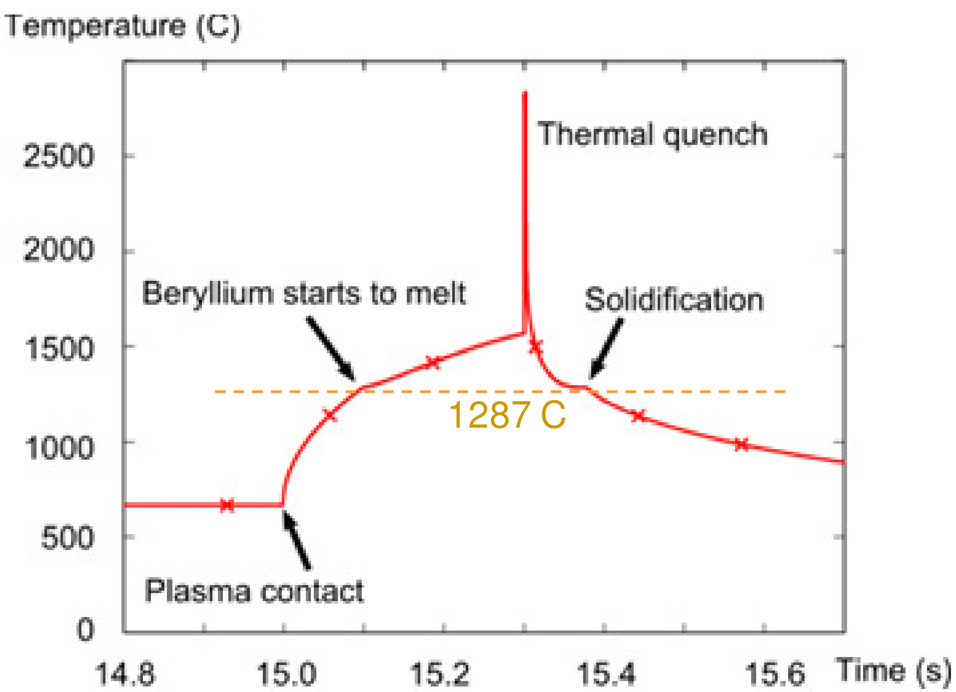
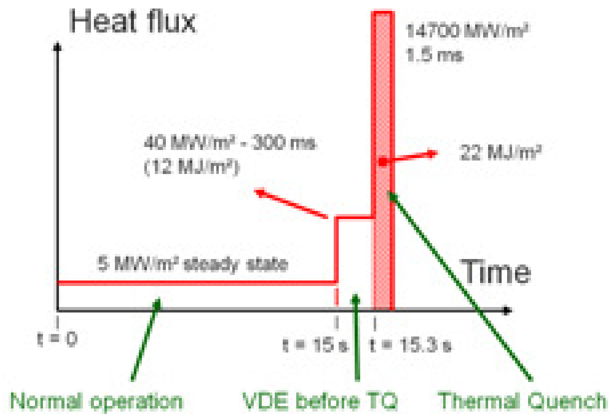
Time behavior



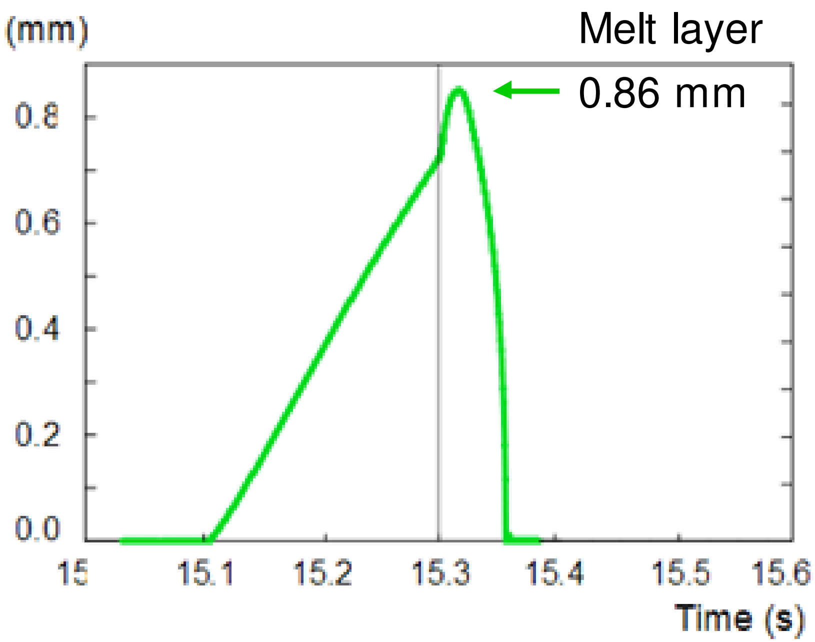


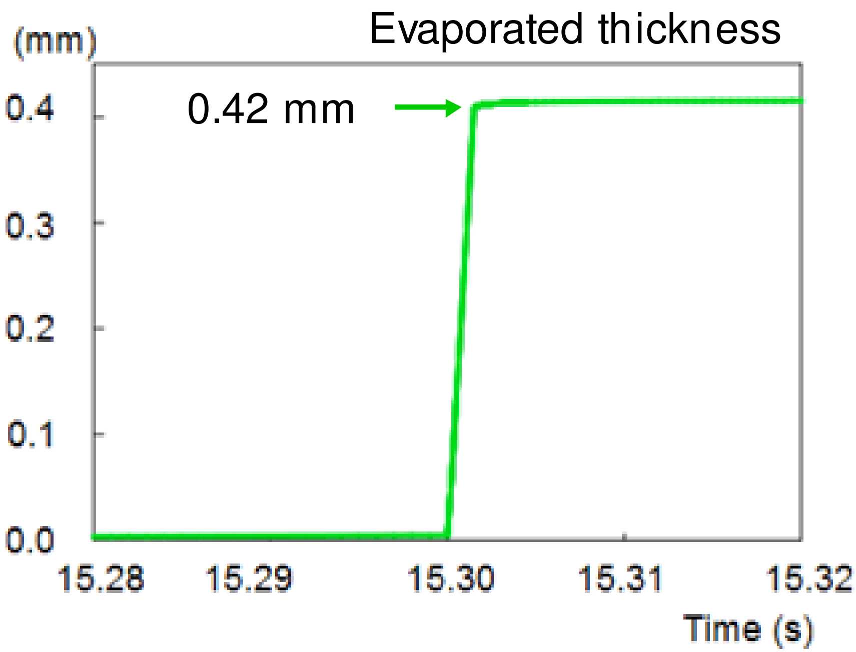




Unmitigated
VDE

Material loss estimation





- High estimate : ***melt layer remains in place***
  Loss = 0.42 mm ⇒ 19 events for 8 mm Be
  15 unmitigated VDEs over 15000 discharges (1/1000) ⇒ Lifetime is 19000 discharges

- Lower estimate : ***melt layer is lost***
  Loss = 0.86 + 0.42 mm = 1.28 mm
  ⇒ 6 events for 8 mm Be ⇒ Lifetime is 6250 discharges

Unmitigated VDE

Lifetime is calculated assuming constant frequency of VDEs throughout ITER operational life

Material loss & associated lifetime

Event	Energy density (incident on PFC) (MJ/m^2)	Duration (ms)	Heat flux Density (incident on PFC) (MW/m^2)	Number of Events	Max. Be Temp. (°C)	Max. Be/Cu Temp. (°C)	Max. Be Melt Layer Thickness (mm)	Maxi. Be Evap. Thickness (mm)	Allow. No. of events at given Loc. based on Melt + Evap.	Allow. No. of events at given Loc. Based on Evap. Only	Lifetime (lower estimate)	Lifetime (higher estimate)
Uncontrolled ELMs	2	0.375	10000	0	*2724*	*317*	*0.22*	*0.25*	*17*	*32*	Beyond design basis	
Disruptions (DMS success)	1	3.	333	1350	1559	363	0.01	$4.5\ 10^{-5}$	796	$1.77\ 10^{5}$	8849	$1.9\ 10^{6}$
Disruptions (DMS success)	1	9.	111	1350	1276	363	0	$2.5\ 10^{-6}$	$3.2\ 10^{6}$	$3.2\ 10^{6}$	$35\ 10^{6}$	$35\ 10^{6}$
Disruptions (DMS failure)	10	3.	3333	150	3000	374	0.8	0.06	9	133	930	13333
Disruptions (DMS failure)	10	9.	1111	150	2398	370	0.7	0.07	10	114	1039	11429
VDE (DMS) 1. Loss of control 2. Quench	2.2	300 1.5	40 1470	135	*2300*	*379*	*0.81*	*0.038*	*9*	*210*	*1048*	*23392*
VDE (no DMS) 1. Loss of control 2. Thermal	22	300 1.5	40 14700	15	*2832*	*381*	*0.86*	*0.42*	*6*	*19*	*6250*	*19048*
Loss of control (H-L transition)	120	3000	40	0	1746	519	0.4	0.8	7	11	Beyond design basis	

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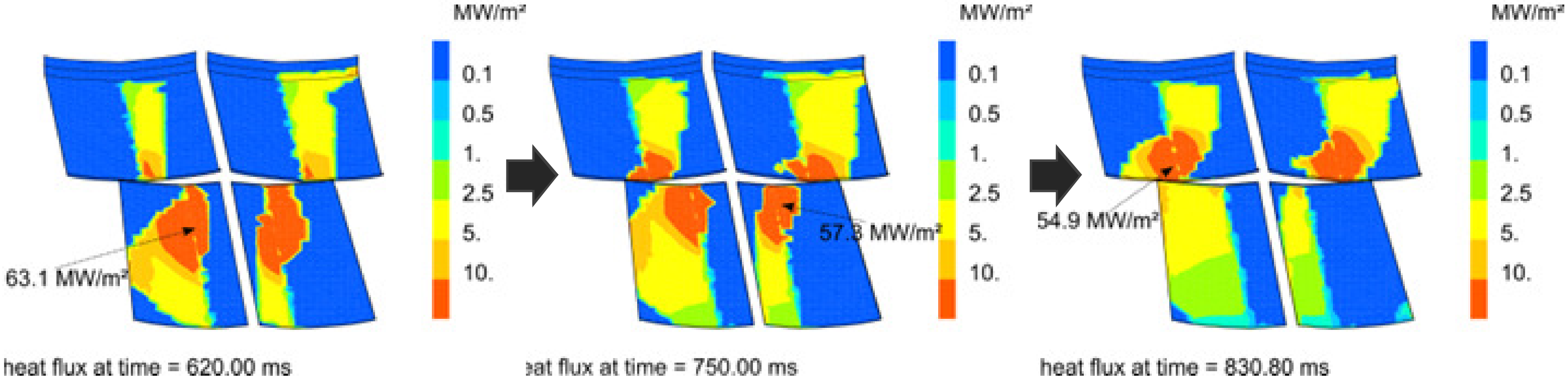
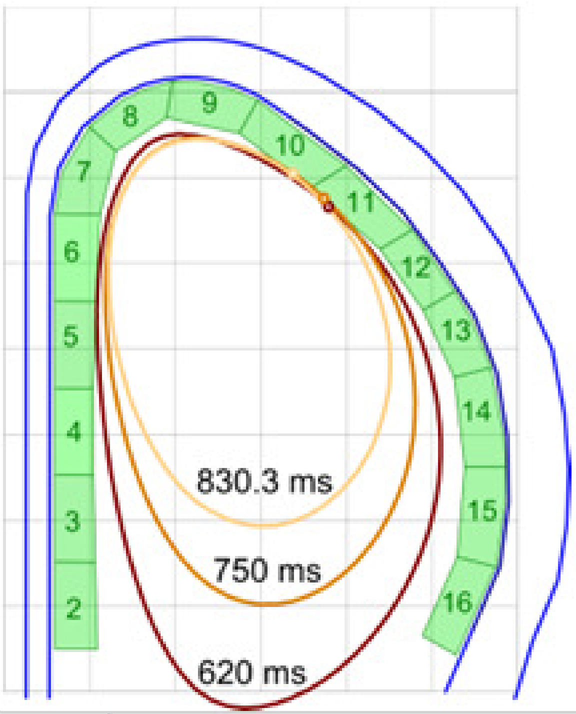
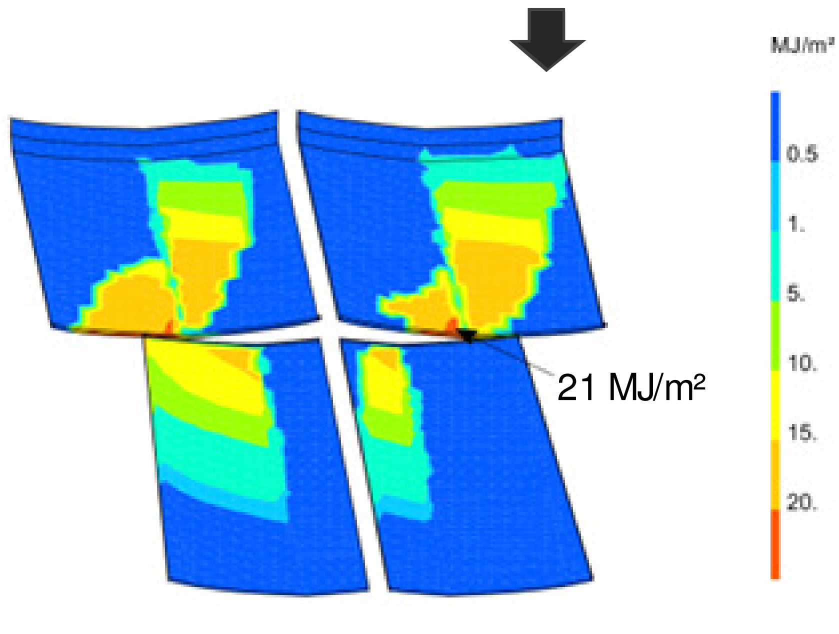
Heat Load History During VDE



- True definition of power flux to the wall
- Step by step calculation
- 34 time slices

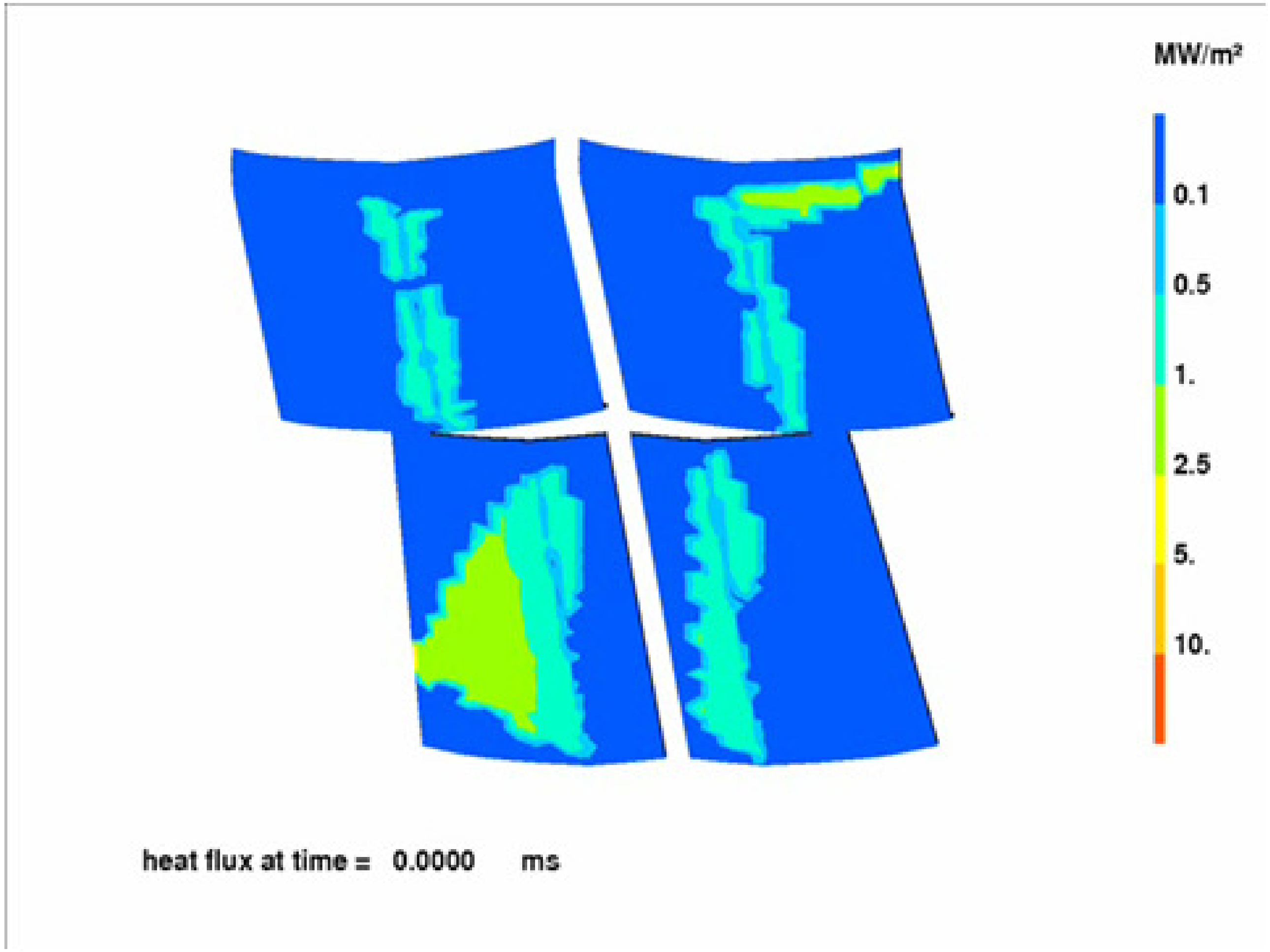




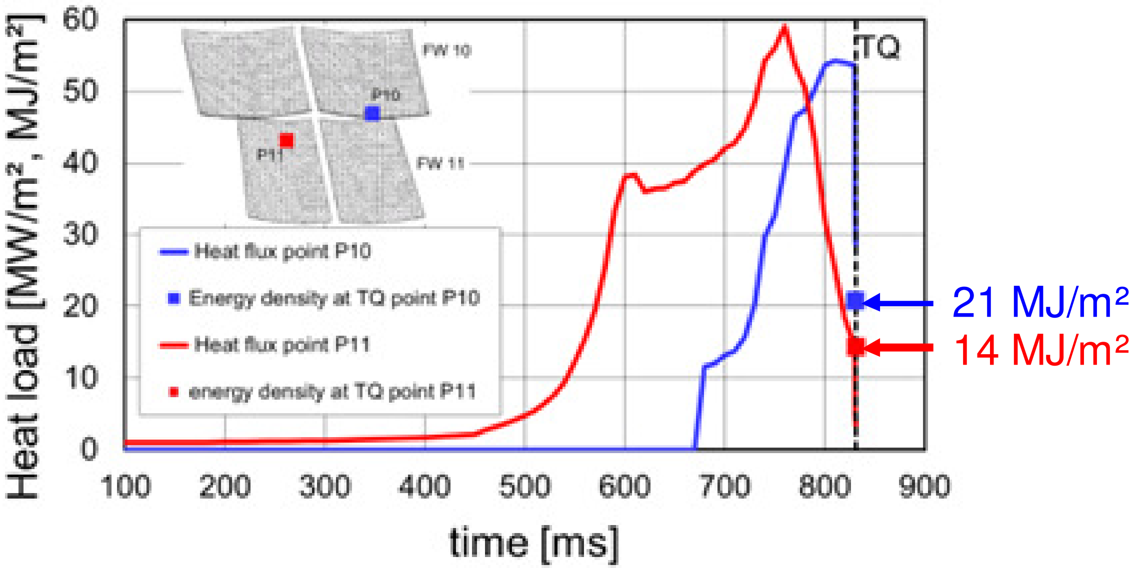
energy density at time = 831.10 ms

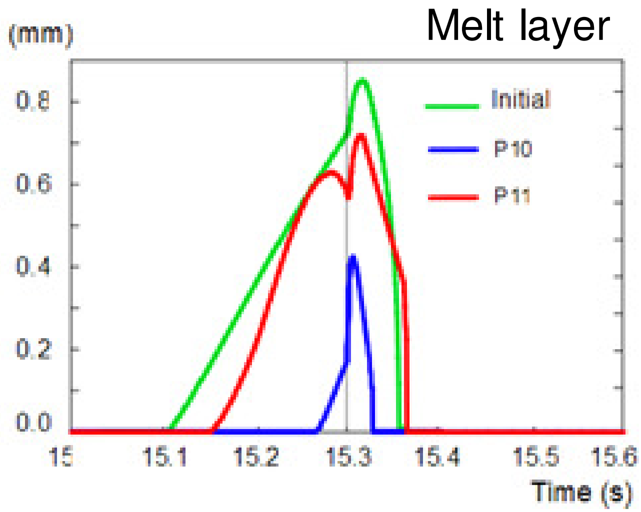
Thermal quench

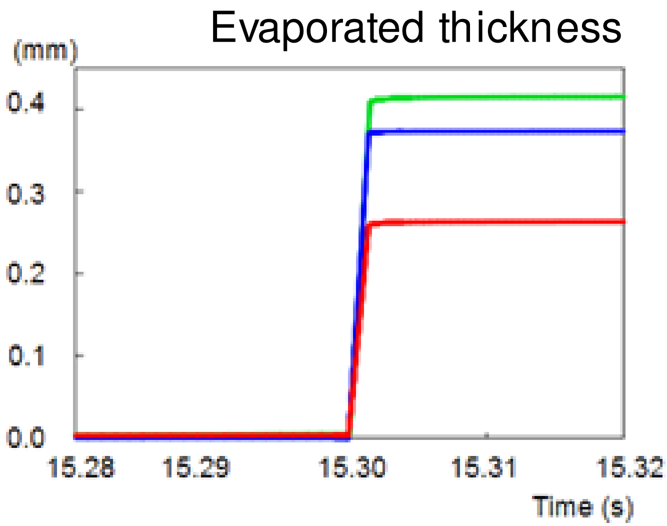
Movie



Material loss for true heat load time sequence







- Partial combination of heat load instead of full combination
- Update lifetime estimate is 8163 to 30,303 discharges
- An improvement of 30/60 % of the calculated lifetime

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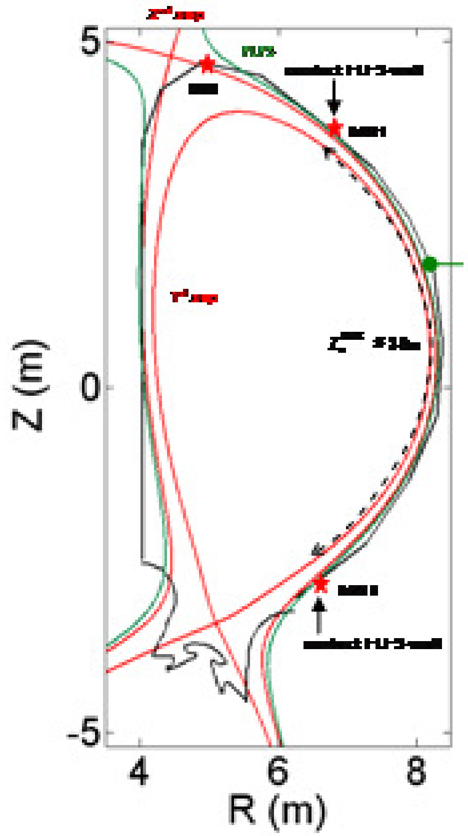
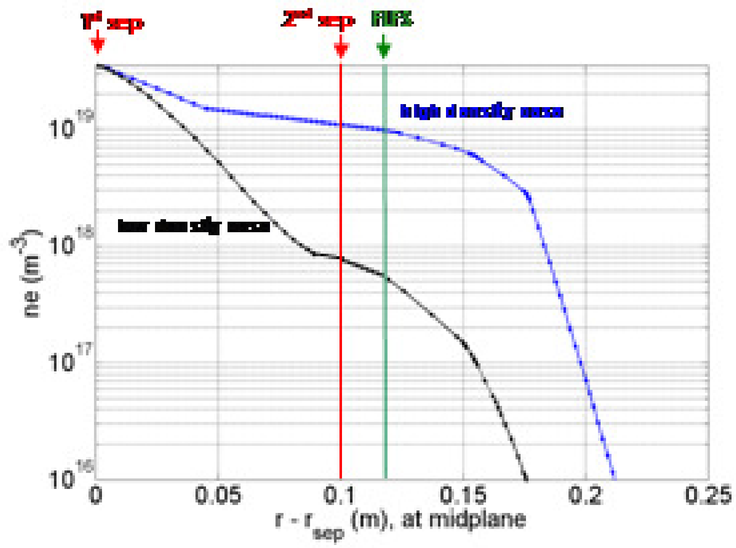
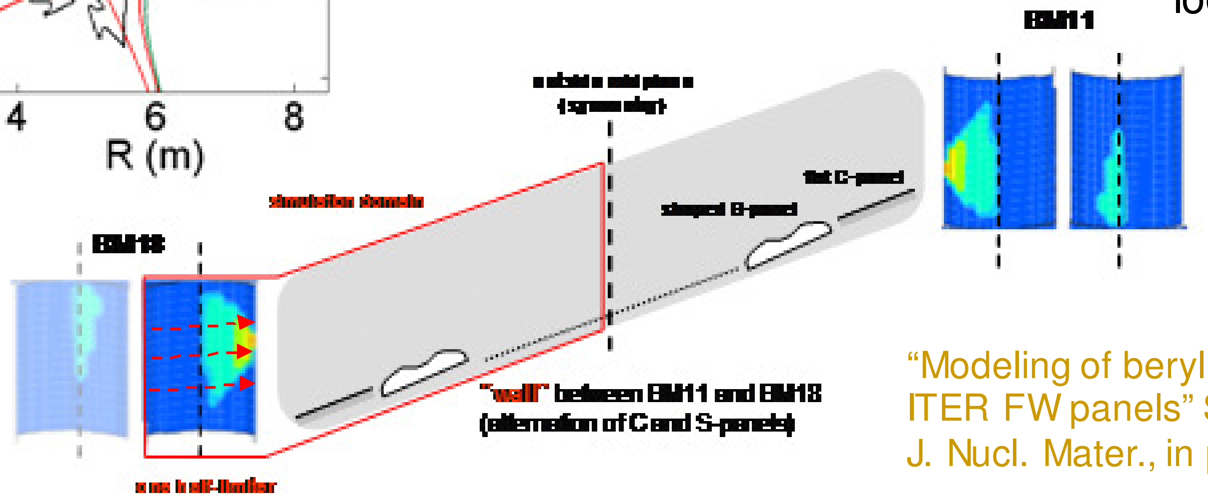
Beryllium armor erosion during normal operation (1/2)



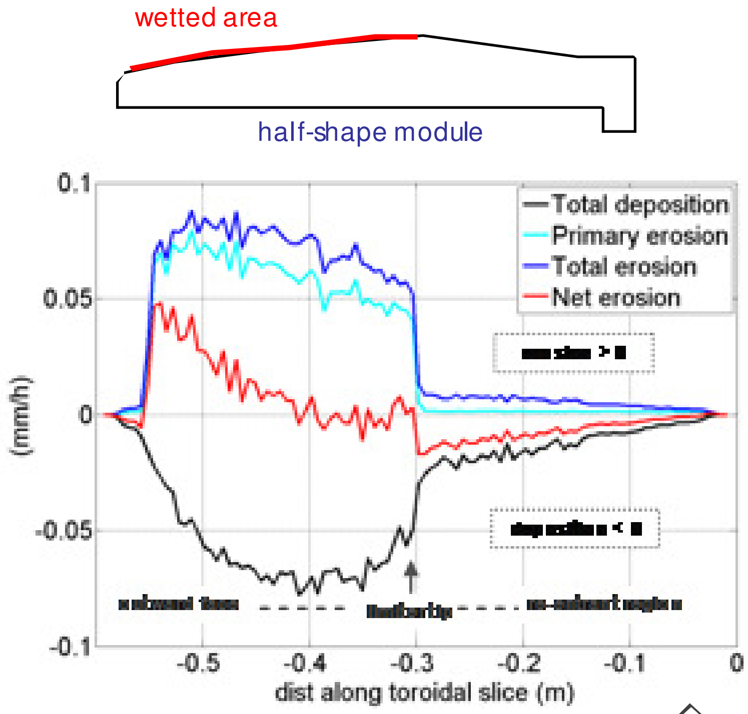


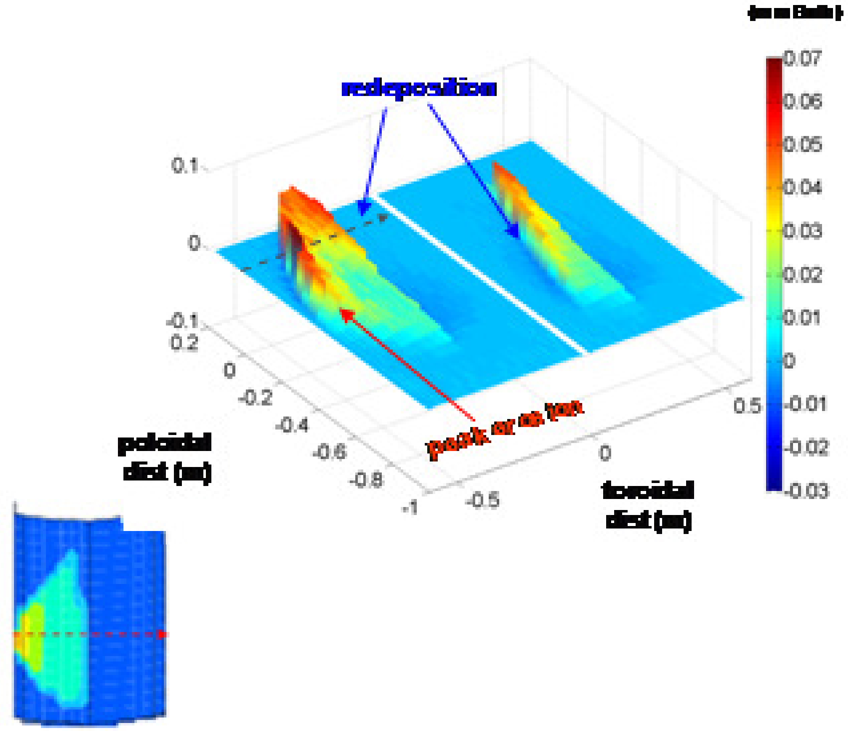
- ✓ Negligible contribution of CX (CX fluxes << ions fluxes) and ELMs (represents only 3.5% of the steady-state duration)
- ✓ Primary / Total erosion ~90% ➔ BM wear mainly due to primary sputtering
- ✓ Peak net erosion rate > 70% of peak gross erosion ➔ concern for PFC lifetime
- ✓ Absorbers ➔ influence the local redeposition



"Modeling of beryllium erosion–redeposition on ITER FW panels" S. Carpentier, R.A. Pitts et al., J. Nucl. Mater., in press.

Armor erosion during normal operation (2/2)





High density case	Low density case
• $<Y_{eff}>$ ~ 7%, ~50% particles locally redeposited • Net peak erosion ~ 0.06 mm/h ➔ PFC lifetime ~ 1500 shots	• <Yeff> ~ 6%, ~10% particles locally redeposited • Net peak erosion ~0.0025 mm/h ➔ PFC lifetime ~ 36,000 shots

Factors with beneficial / detrimental influence on lifetime

- Beneficial
  - Power flux to surface before off normal event is less than design heat flux
  - Time waveform is triangular, not rectangular
  - Melt layer incidents are spread over a certain area, so partial addition
  - Progressive plasma power increase are careful approach toward operation
- Detrimental
  - Combination of material loss events
    (normal erosion + VDE/disruptions)

Conclusion

- Beryllium armor loss estimates end up with **large range** of values.
- This is true for both **normal operation** erosion as well as beryllium loss during **off – normal events**
- FW panel lifetime estimates are **roughly consistent** with the range of erosion/damage due to the expected thermal loading.
- Meeting expected lifetime will necessitate **careful plasma operation** and **progressive achievement** of the scientific program.
- Good example of the **experimental nature** of the ITER project
- Current first wall design makes best use of current available technologies / design capabilities. The design is progressing toward a timely start of experiments by 2019.