DE LA RECHERCHE À L'INDUSTRIE

Surface Heat Load Modelling on Tungsten Monoblocks in the ITER Divertor

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INTRODUCTION AND SUMMARY

Full-W divertor from start of ITER operations
Outstanding issue now is W monoblock shaping design
Decision to be taken by end of 2015

Seeking a design solution that will withstand highest stationary loads and mitigated ELMs during baseline burning operation DT at end of first divertor lifetime
(but non-mitigated ELMs a problem already for low active phases)

- heat load specifications
- shaping solutions under investigation
- ion orbit modelling of heat deposition
- thermal response of monoblocks to inter-ELM heat loads
- penetration of ELM energy into poloidal and toroidal gaps

HEAT LOAD SPECIFICATIONS

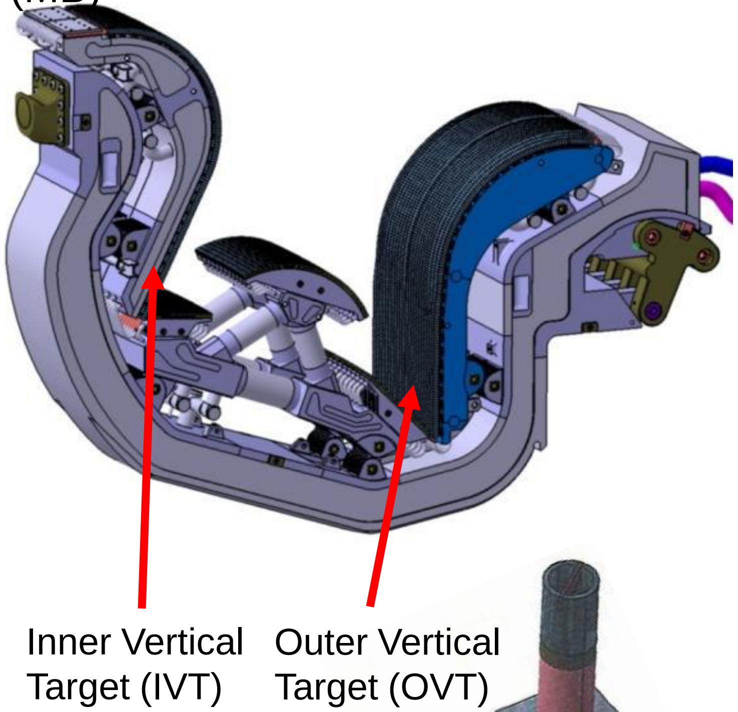
Full tungsten divertor in ITER: water-cooled W monoblocks (MB)
MB design must satisfy heat load specifications

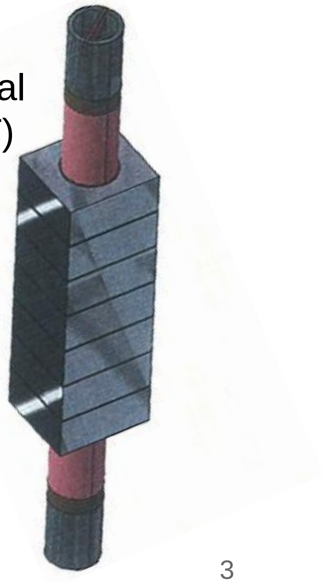
Steady State (SS) inter-ELM detached regime	**10 MW/m²**
Slow Transient (ST) reattachment (300 events)	**20 MW/m² up to 10 s**
Fast Transient (FT) mitigated ELMs	**0.6 MJ / ELM ~ 0.5 MJ/m²**

These specifications correspond to heat flux perpendicular to an ideal, axisymmetric divertor with no castellations or MB shaping.

Question: what will be the thermal response if we expose shaped MBs to a physics-based model of divertor plasma that delivers the specified power loads?

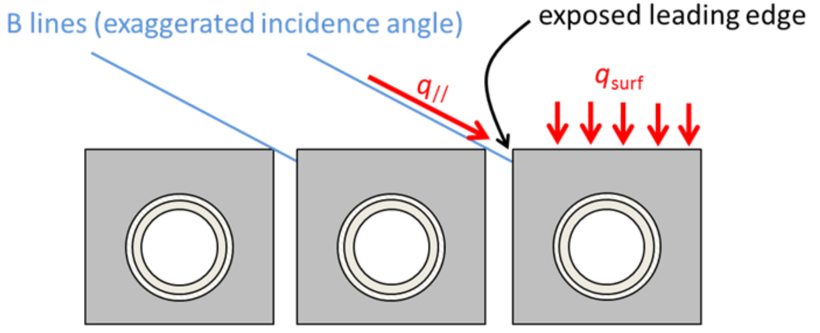
-subject of contract SSA-29 between CEA and ITER (2013)





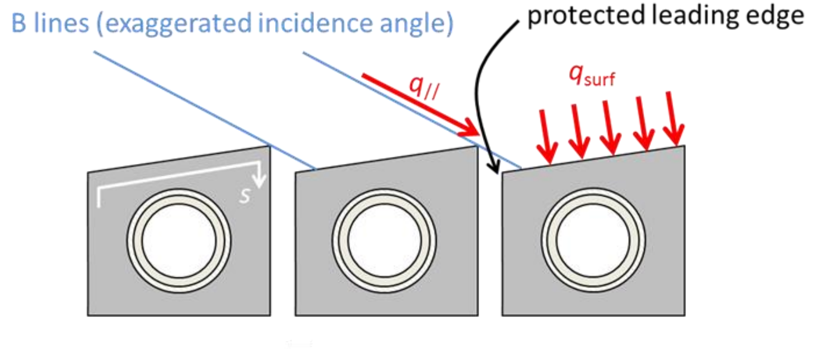
DESIGN: MB TOROIDAL CHAMFERING + TARGET TILTING TO PROTECT POLOIDAL LEADING EDGES

monoblock castellation results in exposed leading edges

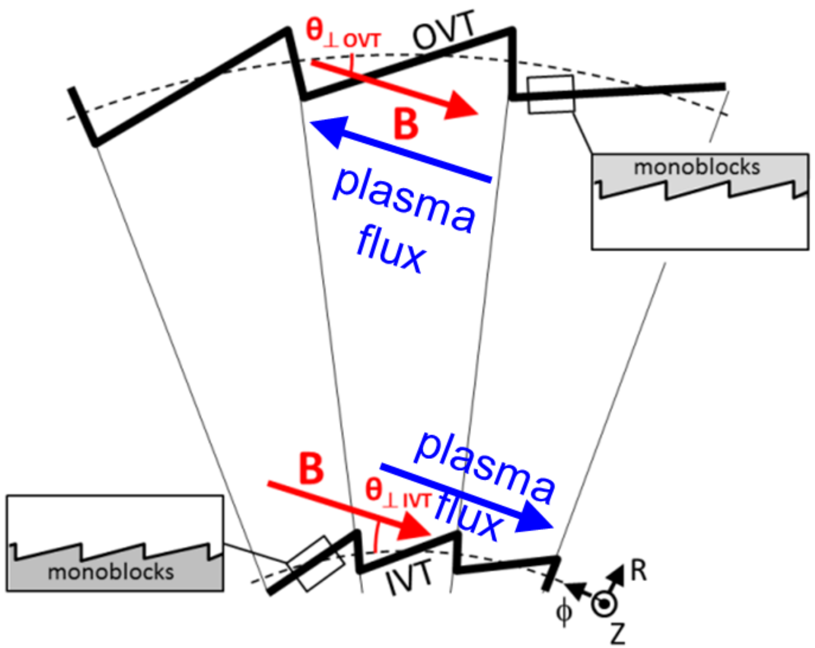


view along cooling tube axis
(exaggerated gap width between monoblocks)

0.5 mm toroidal chamfer protects leading edges from SS and ST loads (but not ELM loads... see Slide #12)



schematic view of divertor illustrating target tilting and monoblock chamfer



<u>increased peak plasma heat loads</u>

e.g. at OVT

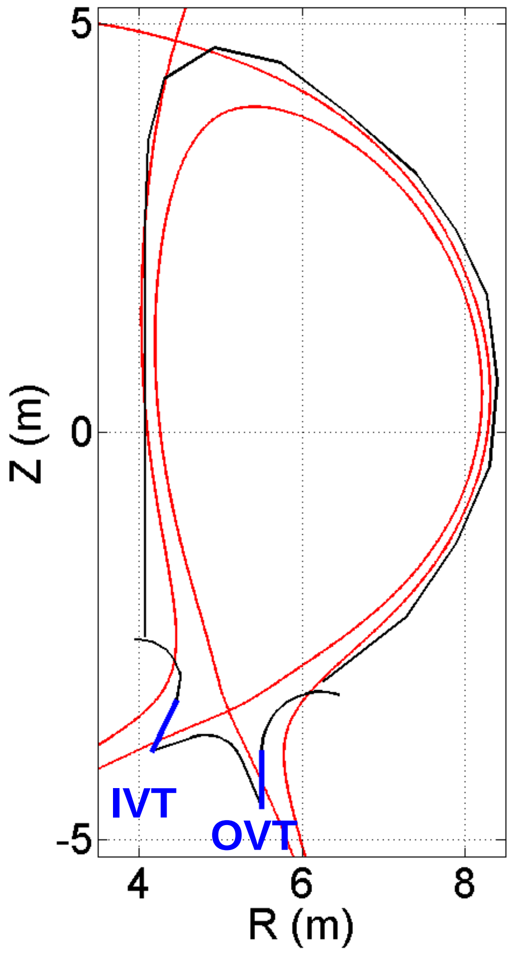
target tilting: up to +19%

0.5 mm toroidal chamfer: up to +37%

ST: up to 31.1 MW/m^2 instead of 20 MW/m^2 (concentrated on a smaller wetted fraction)

GUIDELINES FOR STATIONARY TARGET POWER FLUX PROFILES FROM SOLPS SIMULATIONS

15 MA burning plasma



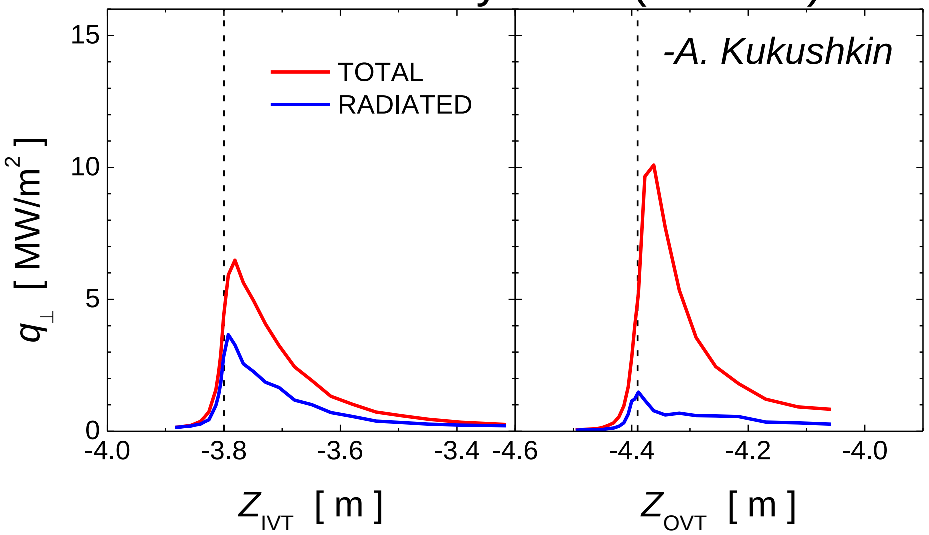
P_{SOL}=100 MW

~2/3 to OVT
~1/3 to IVT

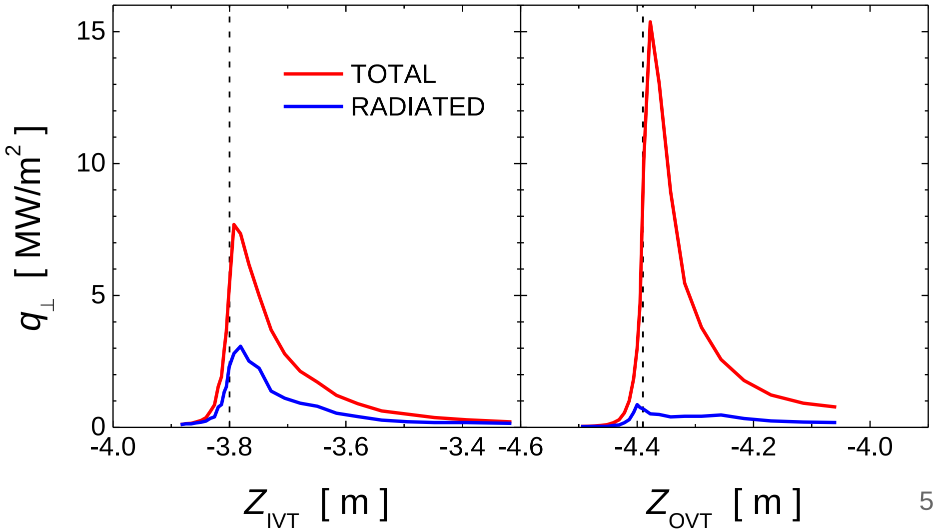
power dissipation by Neon injection

total power flux to divertor
=
plasma + photons + neutrals

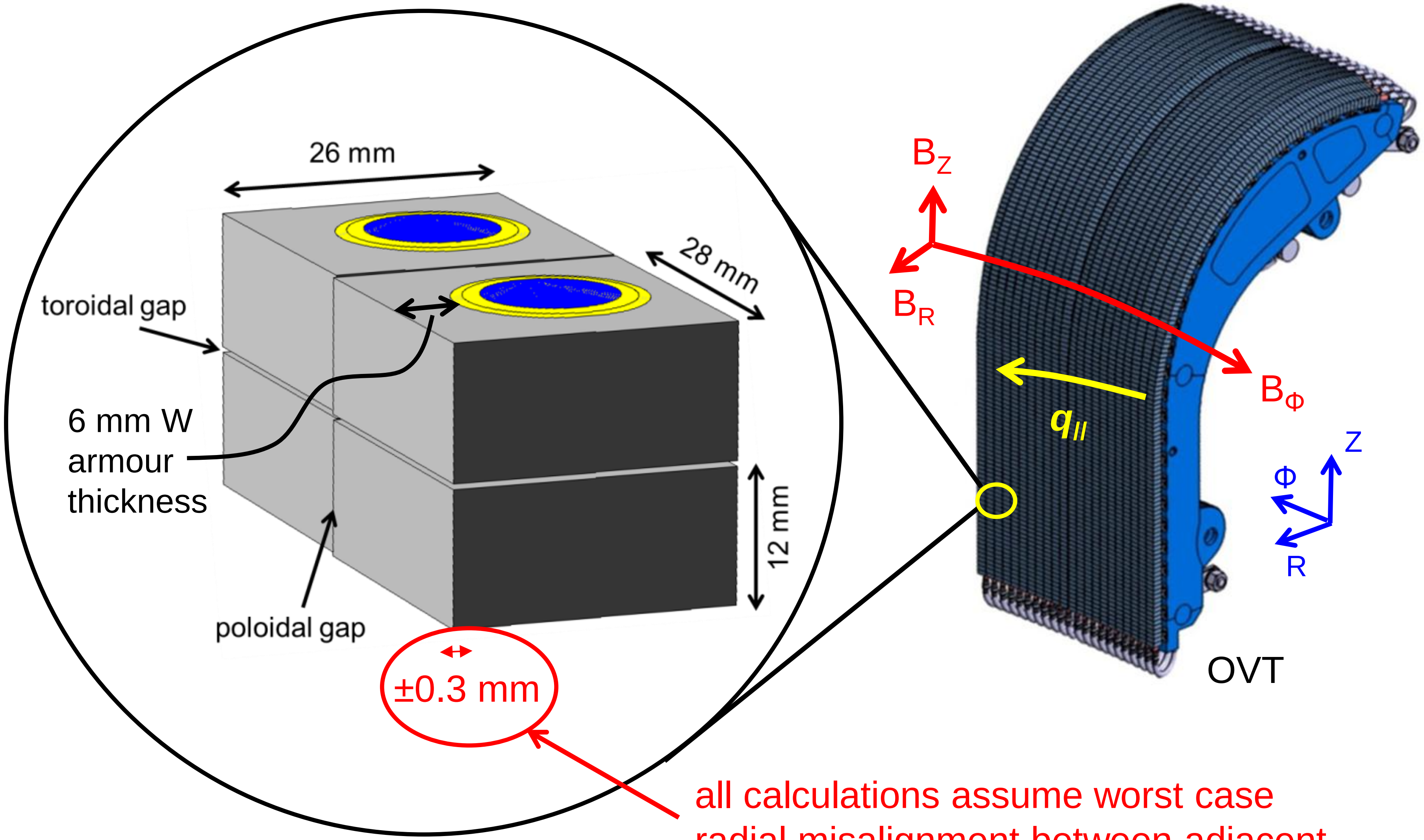
nominal steady state (SOLPS)



slow transient reattachment (SOLPS)



MONOBLOCK GEOMETRY AND B-FIELD ORIENTATION



all calculations assume worst case radial misalignment between adjacent plasma-facing units (PFU)

CALCULATION METHOD - HELICAL ION ORBIT APPROXIMATION (GYROMOTION ONLY, NO E-FIELDS)

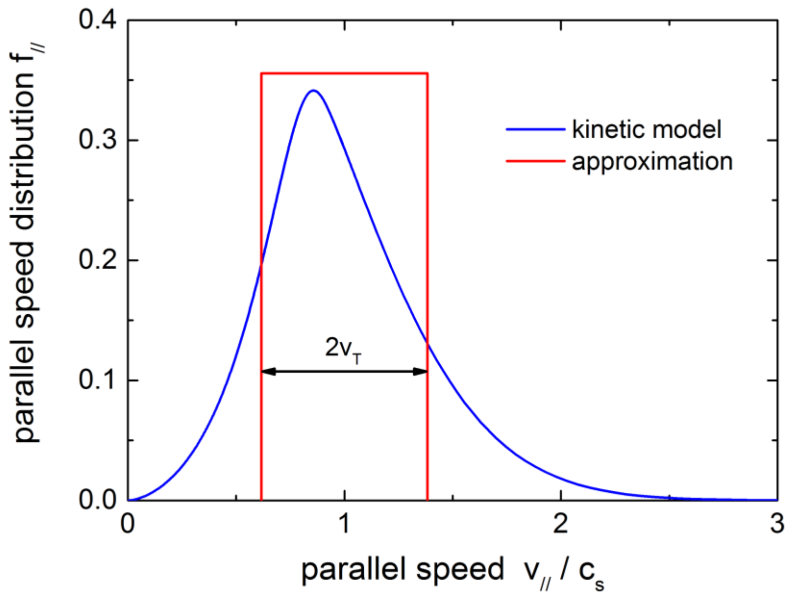
How do we go about modelling power deposition to the monoblock surface?

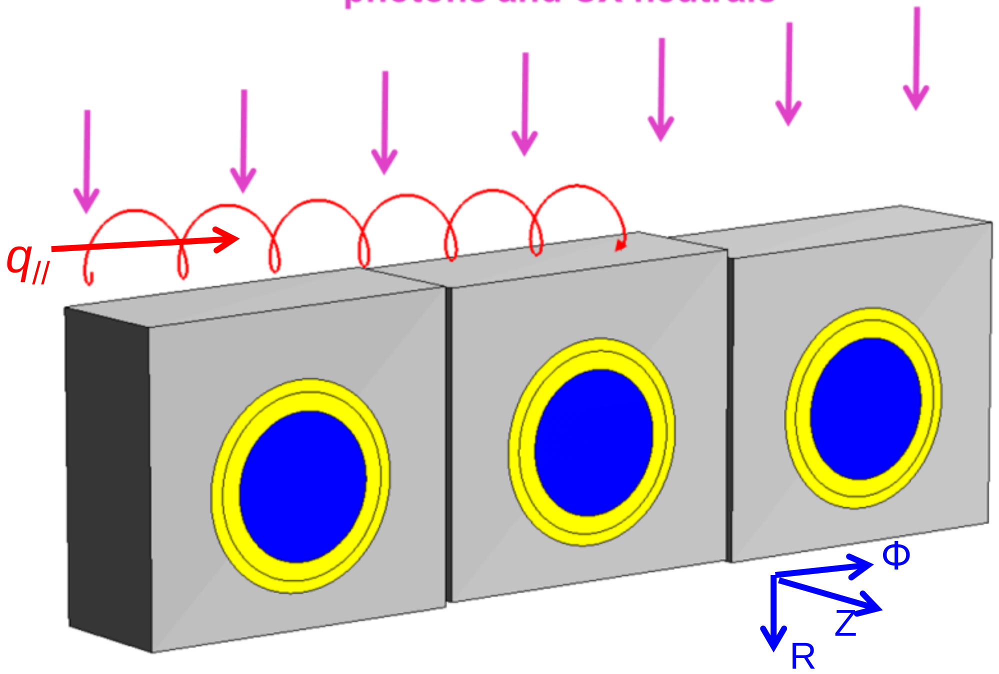
1) For a given magnetic field angle and q_{rad}, we calculate the corresponding $q_{//}$

2) We then launch that $q_{//}$ at the monoblocks and calculate the local heat flux at all the surfaces of <u>*shaped monoblocks*</u> using 3D ion orbit simulations.

-parallel speed distribution from kinetic model of SOL

-perpendicular speed distribution assumed to be Maxwellian

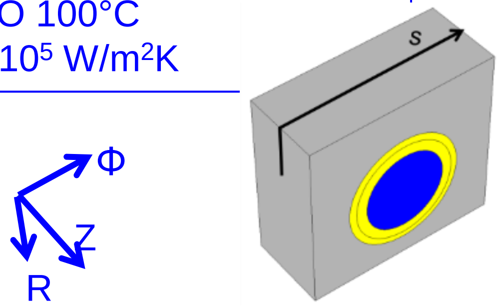


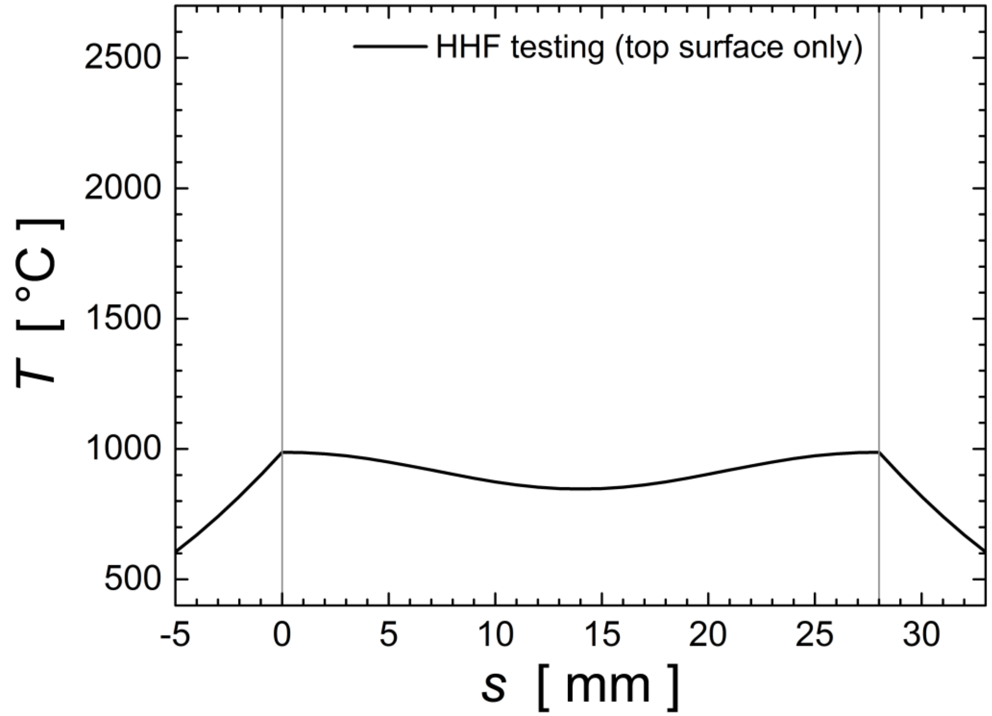


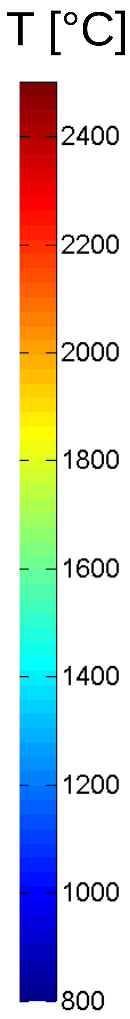
STRATEGIES TO PROTECT LEADING EDGES WORK BUT AT EXPENSE OF INCREASED T_{SURF}

OVT monoblocks
SS loads
6 mm W armour thickness
H_2O 100°C
h=10^5 W/m^{2}K

1) T_{surf}<1000°C







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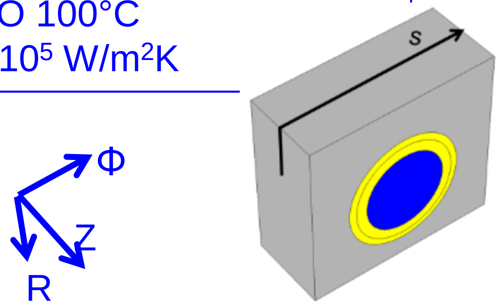
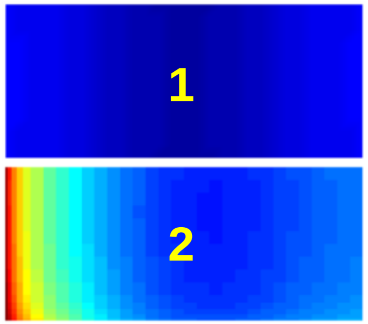
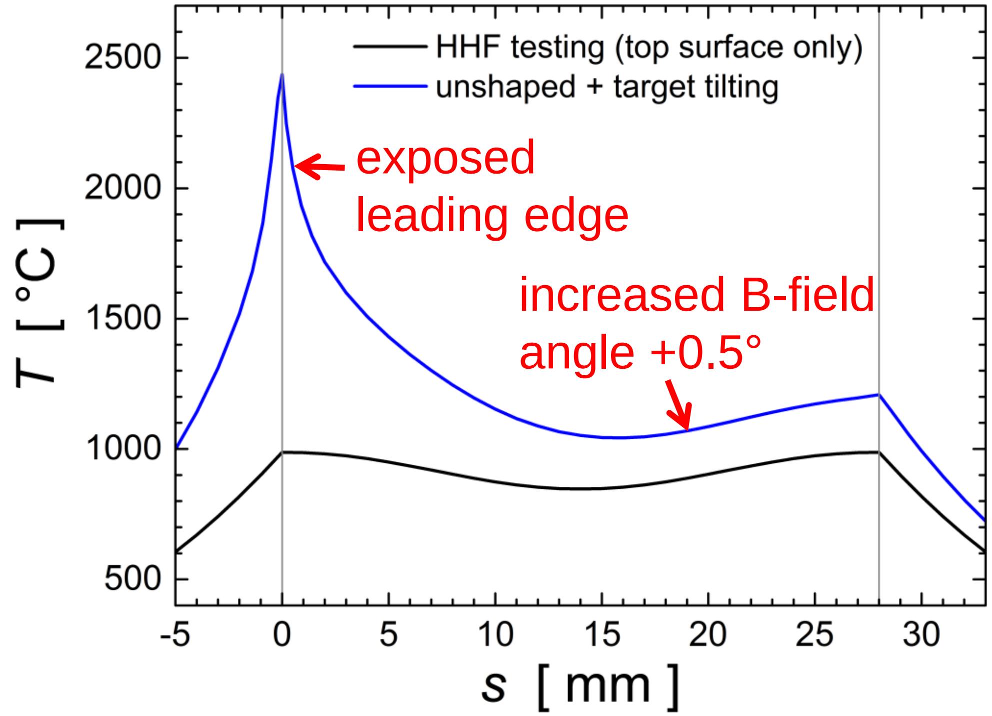
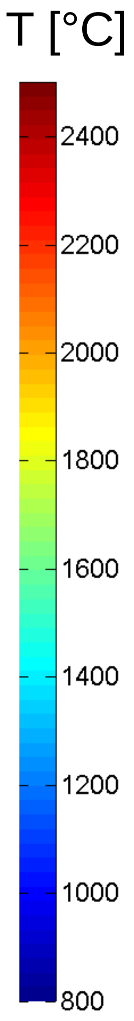






1) T_{surf}<1000°C

2) unshaped + target tilting
   $q_{//}$ into gaps
   intense leading edge (LE) heating
   (MELTING for ST loads!)



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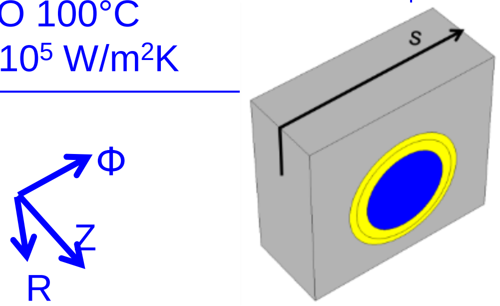
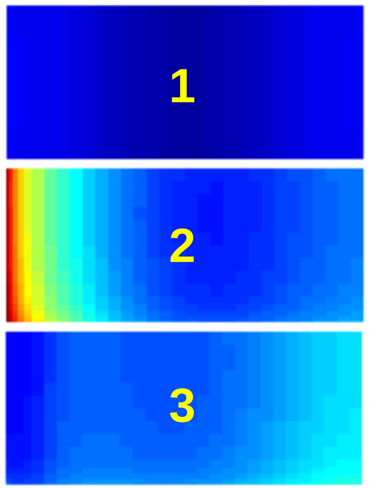
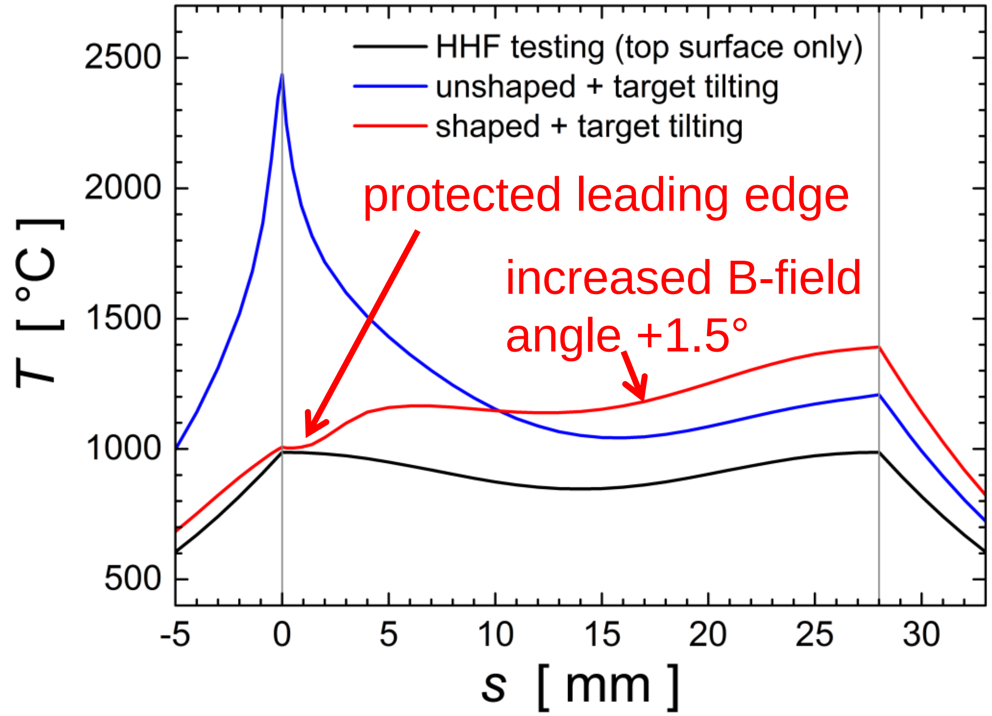




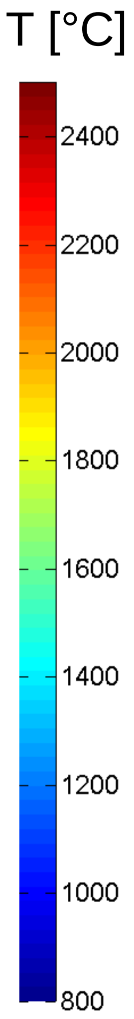


1) T_{surf}<1000°C

2) unshaped + target tilting
   $q_{//}$ into gaps
   intense leading edge (LE) heating
   (MELTING for ST loads!)

3) shaped + target tilting
   protected leading edge
   BUT
   heat load concentrated on plasma-wetted surface
   T_{surf}~1500°C in steady state
   →*tungsten recrystallization*

(For ST loads, T_{surf}~3400°C)
→*marginal melting*



EVALUATION OF MELTING RISK DURING MITIGATED ELMS

ELMs deposit a huge amount of energy in a very short time.
ELM mitigation requirements based on avoidance of melting

These numbers were derived for an ideal divertor surface with no local shaping

maximum energy per mitigated ELM	0.6 MJ
ELM rise time Δt_{ELM}	250 µs
maximum fraction f_{div} of ELM energy to IVT	2/3
maximum fraction f_{div} of ELM energy to OVT	1/2
maximum temperature of ELM ions T_i	5 keV
ELM heat flux parameter ε_{ELM} at nominal IVT	28.1 $MJ/m^2s^{1/2}$ (square pulse)
ELM heat flux parameter ε_{ELM} at nominal OVT	13.6 $MJ/m^2s^{1/2}$ (square pulse)

factor ~2
margin

ELM heat flux factor:

$$\varepsilon_{ELM} = \frac{f_{div} W_{ELM}}{A_{div}\sqrt{\Delta t_{ELM}}}$$

tungsten melting threshold $\varepsilon_{melt} = 48\ MJ/m^2s^{1/2}$

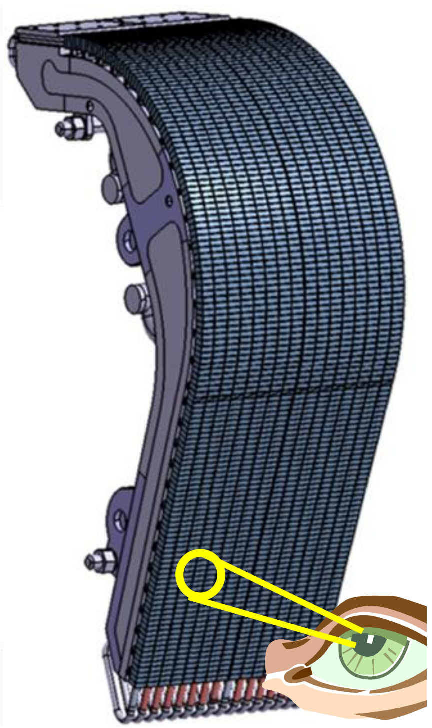
NB: UNCONTROLLED ELMS (~a few MJ / ELM) already potentially problematic in non-active phases → not just a problem for mitigated ELMs in nuclear phase

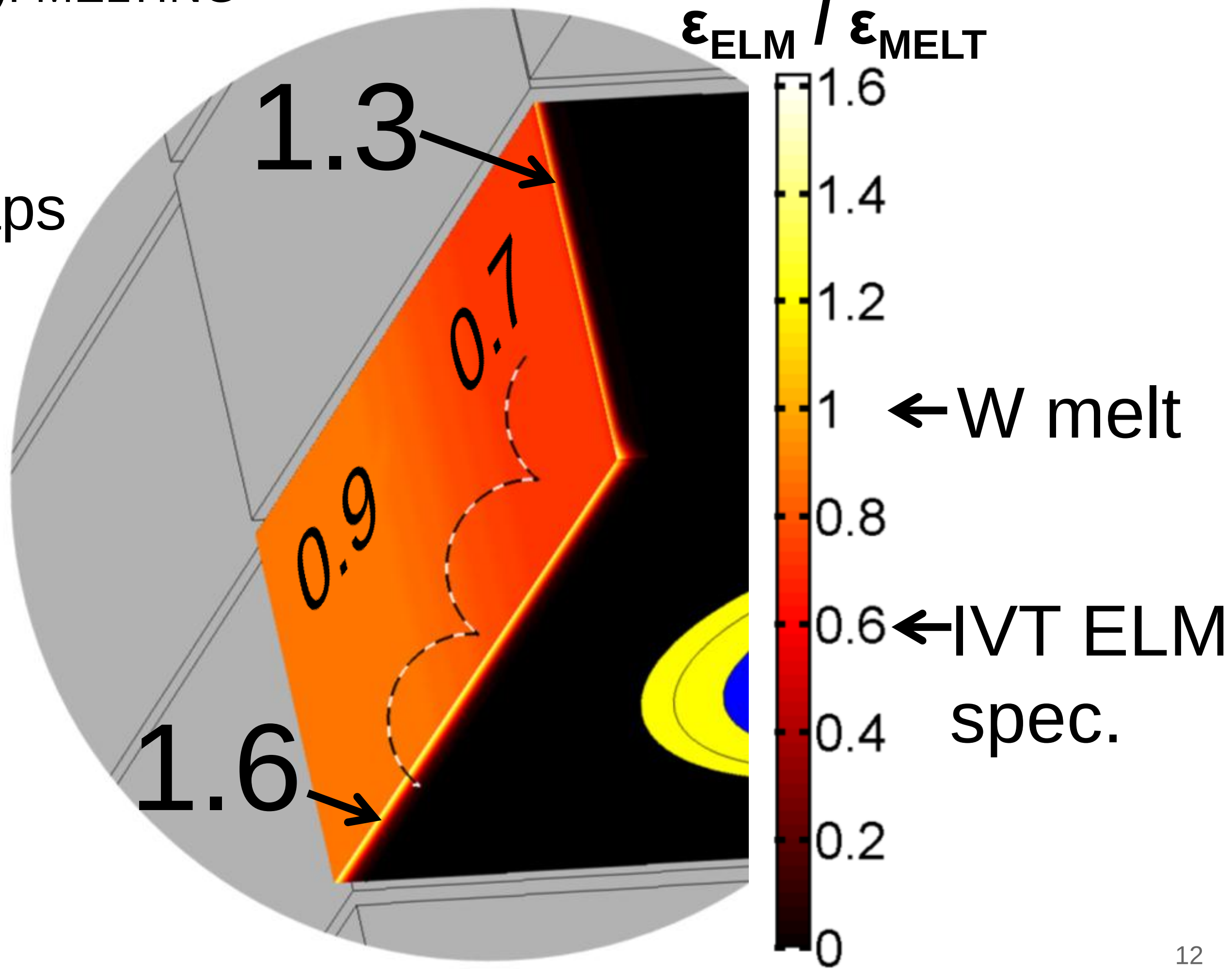
ELM IONS (UP TO 5 keV) HAVE LARGE LARMOR RADII - THEY CAN PENETRATE EASILY INTO GAPS

top surface: margin against melting LOST due to target tilting and shaping
poloidal edge (magnetically shadowed by chamfer): MELTING
toroidal edge (not shadowed): MELTING

IVT

0.5 mm inter-PFU gaps





CONCLUSIONS

Based on 3D ion orbit calculations (now being verified by PIC),
Monoblock shaping in the ITER W divertor appears mandatory to *avoid leading edge melting* under highest stationary loads in burning plasmas
BUT
Leads to higher surface temperatures on main wetted areas
AND
ELMs can be immune to shaping
→ experiments urgently needed with relevant dimensionless scaling (Larmor radius / height of surface features)

HOWEVER
load specifications could be too conservative → work ongoing
PHYSICS OF EDGE LOADING AT GLANCING ANGLES NOT COMPLETELY UNDERSTOOD
→ JET lamella melting experiment (Guy Matthews, EX/4-1 Wednesday afternoon)
→ Further experiments planned or underway on ASDEX-Upgrade, MAGNUM-PSI, COMPASS, JET, ….

ITER INTENDS TO TAKE A MONOBLOCK SHAPING DECISION BY END 2015.

DISCLAIMER - The views and opinions expressed herein do not necessarily reflect those of the ITER Organization.

STRATEGIES TO PROTECT LEADING EDGES WORK BUT AT EXPENSE OF INCREASED T_{SURF}

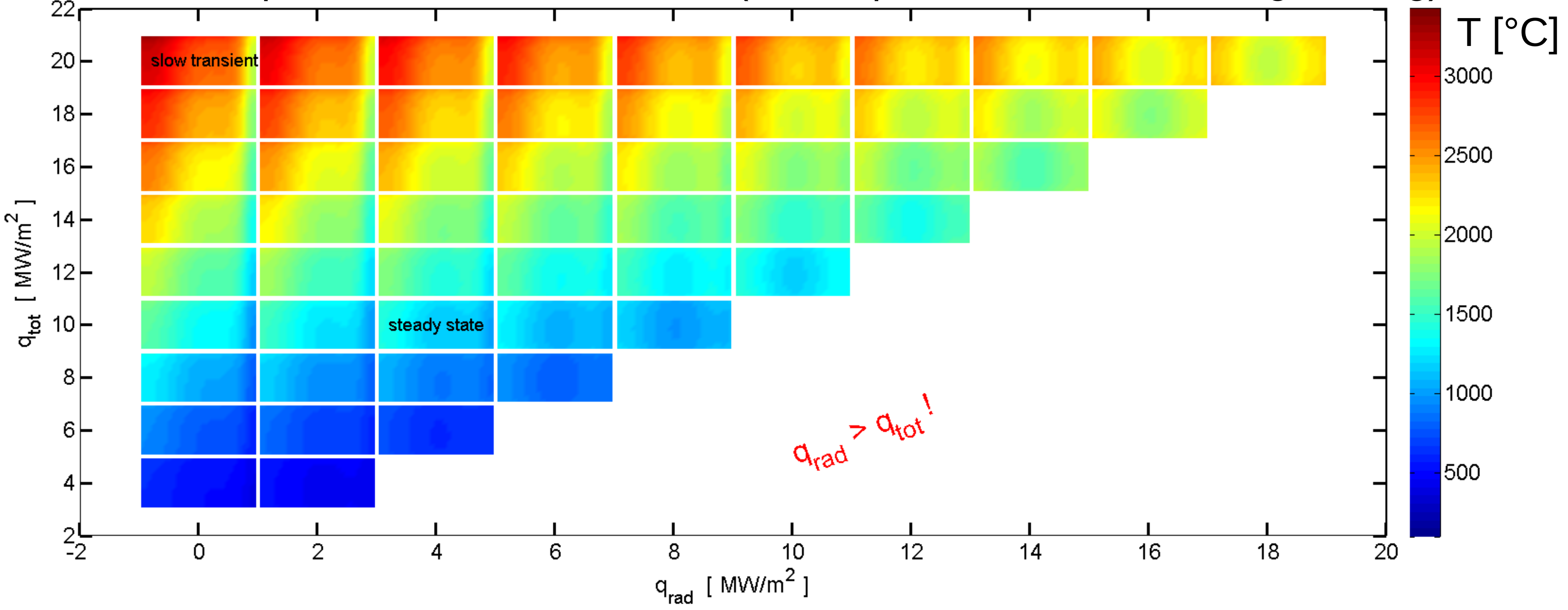
target tilting	gaps	shaping	0.5 mm inter-PFU gaps T_{peak} / T_{center}	
			SS	ST
no	no	no	987/846	2055/1767
yes	yes	no	2604/1066	LE melting
yes	yes	yes	1497/1139	3406/2680

With shaping

steady state loads:
→W recrystallization

slow transient loads:
→marginally close to melting

thermal response vs radiated fraction (for shaped OVT MBs with target tilting)



ION ORBIT CALCULATION AT TOROIDAL GAPS PREDICTS EDGE MELTING AT BOTH IVT AND OVT

Opposite deposition at IVT and OVT (due to opposite helicity of gyromotion)

Increased peaking with decreasing ELM temperature

Full PIC simulations with self-consistent E-fields are showing these calculations to be correct (IO Contract with IPP Prague → SPICE2 code)