DE LA RECHERCHE À L'INDUSTRIE

Shape design of plasma facing components for stationary and transient power fluxes

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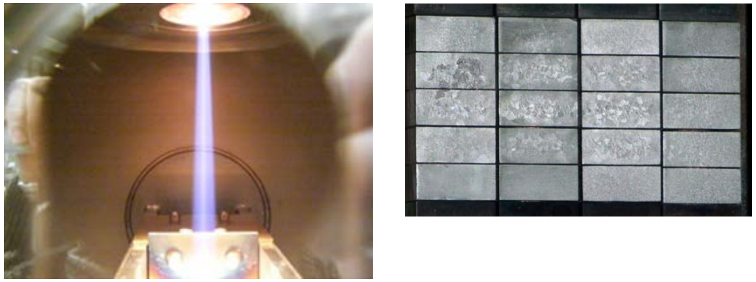
INTRODUCTION

Full-W divertor from start of ITER operations



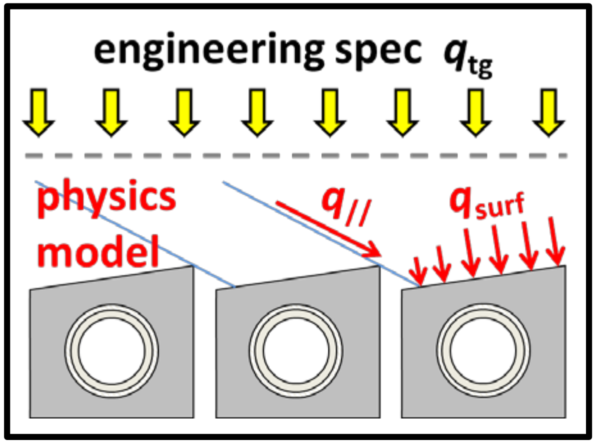
engineering qualification - nearly perpendicular irradiation of MB surfaces

Heat load specifications prescribe maximum heat flux perpendicular to an ideal, axisymmetric divertor with no castellations or MB shaping. The commonly heard phrase "steady state heat flux must be limited to 10 MW/m^2" has its origin in such high heat flux tests.

-specific to ITER MB technology. Other technologies have different limits.

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

-near glancing B-field incidence angle ~3°; shaping; Larmor gyration around field lines



J. P. Gunn, et al. , "Ion orbit modelling of ELM heat loads on ITER divertor vertical targets", Nuclear Materials and Energy (2017).

J. P. Gunn, et al., "Surface heat loads on the ITER divertor vertical targets", Nucl. Fusion 57, 046025 (2017).

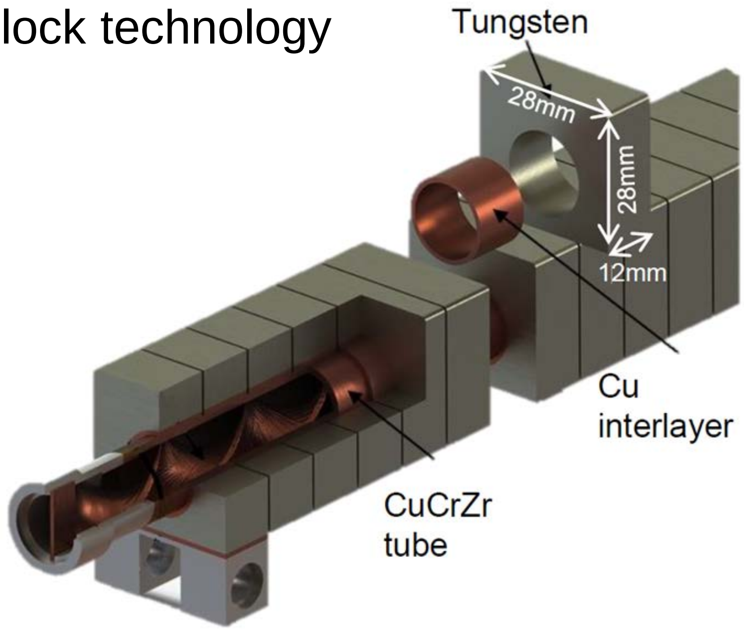
HISTORICAL HEAT LOAD SPECIFICATIONS (FOR AN IDEAL AXISYMMETRIC DIVERTOR TARGET)

Steady State (SS) **inter-ELM detached regime**	**10 MW/m^2**	**to avoid W recrystallization**
Slow Transient (ST) **reattachment (300 events)**	**20 MW/m^2 →10 s**	**to avoid critical heat flux (boil-out)**
Fast Transient (FT) ELMs	**~ 0.5 MJ/m^2**	**factor 2 margin against full surface melting of an initially cold monoblock**

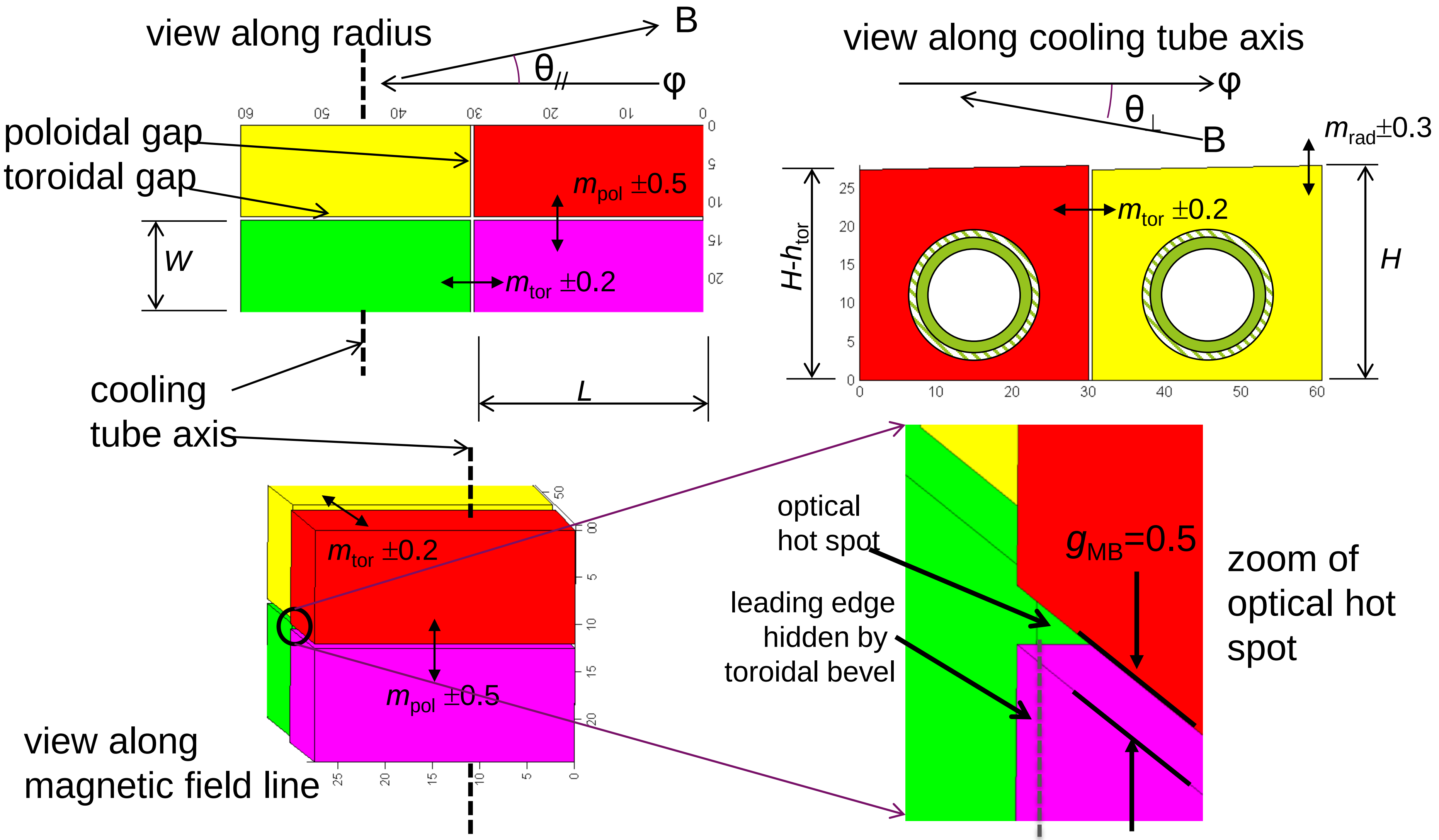
first part of talk

second part

ITER monoblock technology



MONOBLOCK GEOMETRY AND B-FIELD ORIENTATION



view along radius

B

$\theta_{//}$

φ

poloidal gap

toroidal gap

m_{pol} ±0.5

m_{tor} ±0.2

W

L

cooling tube axis

view along cooling tube axis

φ

$\theta_{\perp}$

B

m_{rad}±0.3

m_{tor} ±0.2

H-h_{tor}

H

m_{tor} ±0.2

m_{pol} ±0.5

view along magnetic field line

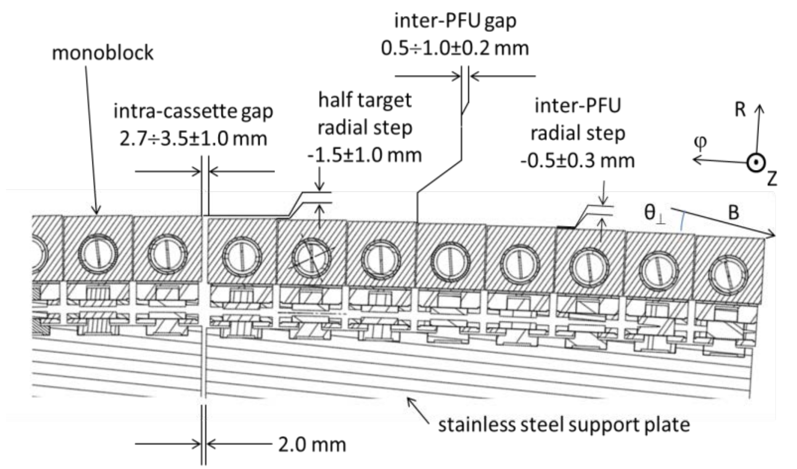
optical hot spot

leading edge hidden by toroidal bevel

g_{MB}=0.5

zoom of optical hot spot

MANUFACTURING AND ASSEMBLY TOLERANCES



feature	location	dimension [mm]	tolerance [mm]
gap	intra-PFU	$g_{MB} = 0.4$	IVT: $m_{pol} = {}^{+0.2}_{-0.1}$ OVT: $m_{pol} = \pm 0.1$
	inter-PFU	IVT: $g_{PFU} = 0.5 \rightarrow 1.0$ OVT: $g_{PFU} = 0.5$	$m_{tor} = \pm 0.2$
	intra-cassette	IVT: $g_{PFU} = 2.7 \rightarrow 3.5$ OVT: $g_{PFU} = 3.2$	$m_{tor} = \pm 1.0$
	inter-cassette	$g_{PFU}=20$	$m_{tor} = \pm 5$
radial step	intra-PFU	$\Delta r = 0.0$	$m_{rad} = \pm 0.3^{*}$
	inter-PFU	$\Delta r = -0.5$	$m_{rad} = \pm 0.3$
	intra-cassette	$\Delta r = -1.5$	$m_{rad} = \pm 1.0$
	inter-cassette	$\Delta r = -4.0$	$m_{rad} = \pm 2.0$
toroidal chamfer	both VTs	$h_{tor}=0.5$	±0.1

Some of these tolerances have already been relaxed as a result of feedback from industrial suppliers, and they are complaining about others that are still too tight -consequences on divertor cost and performance

The studies reported here provide physics-based guidelines that give solid arguments for negociations with suppliers

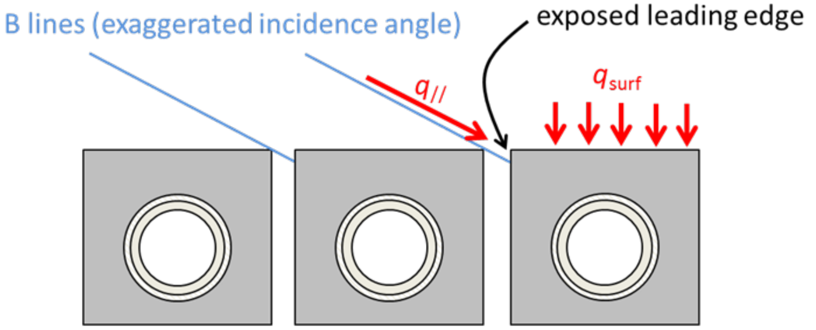
Literally thousands of 3D heat flux + thermal simulations were necessary to scan all tolerances and shaping alternatives

Message: good old analytic calculations and simple approximations remain a powerful tool - ANSYS is not God! Trust in your own brain.

Part 1
inter-ELM
(i.e. "steady state")

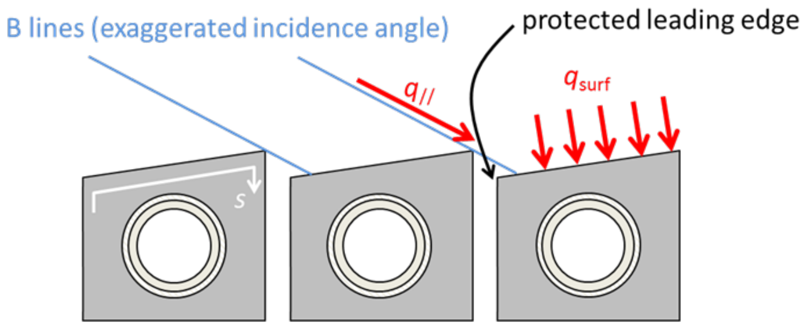
DESIGN: MB TOROIDAL BEVELING + TARGET TILTING TO PROTECT POLOIDAL LEADING EDGES

monoblock castellation results in exposed leading edges

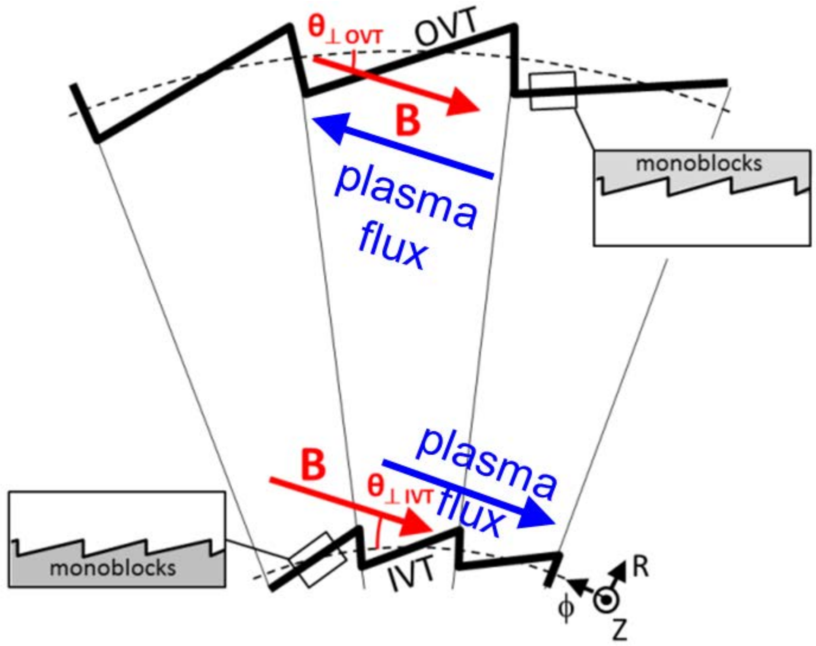


view along cooling tube axis
(exaggerated gap width between monoblocks)

0.5 mm toroidal chamfer protects leading edges from SS and ST loads



schematic view of divertor illustrating target tilting and monoblock chamfer



<u>target tilting and monoblock toroidal chamfer result in increased MB heat loads</u>

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

heat flux delivered by plasma perpendicular to ideal target

component tilting

toroidal bevel

$$q_{surf} \simeq \boxed{q_{tg}} \frac{\theta_{\perp} + \overset{\text{component tilting}}{0.5°} + \overset{\text{toroidal bevel}}{1°}}{\theta_{\perp}}$$

Percentage increase of plasma heat load

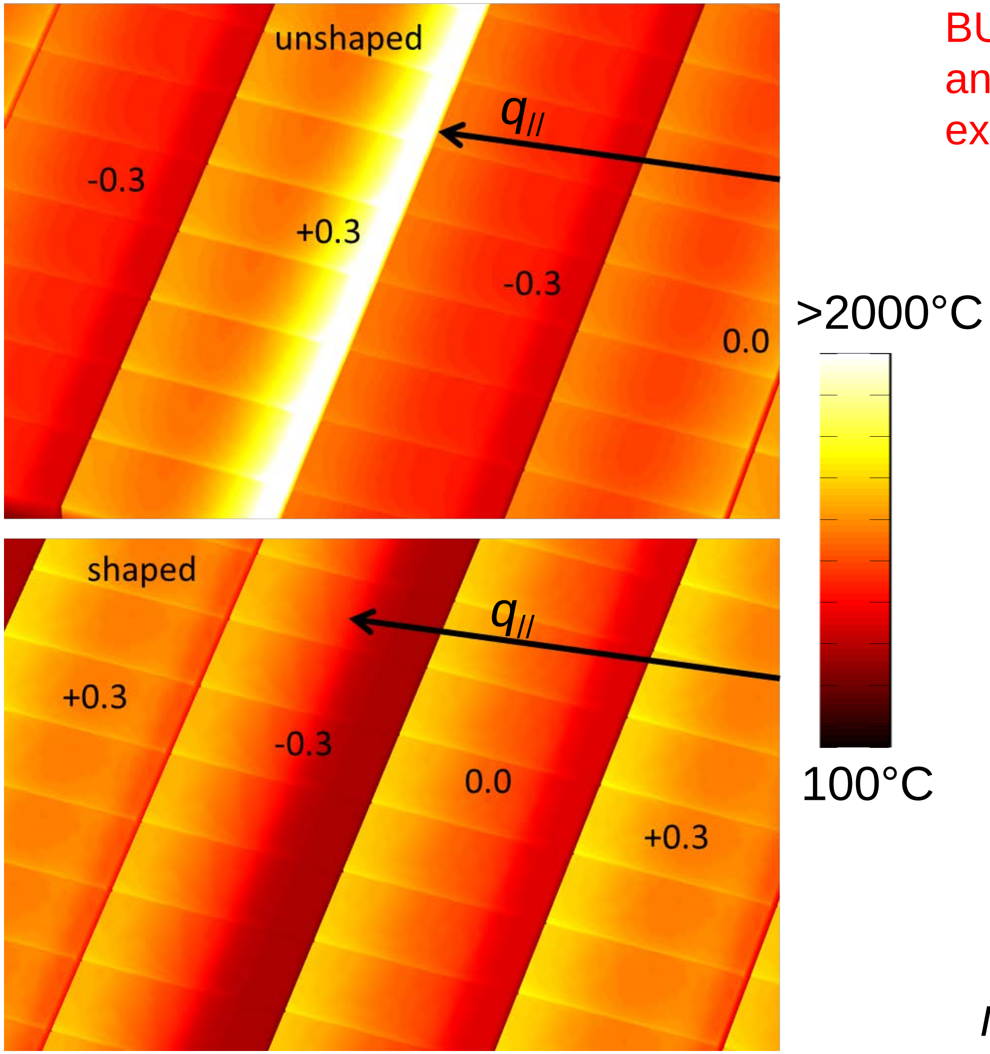
target	tilting+unshaped	tilting+bevel
IVT ($\theta_{\perp}$=3.2°)	+16%	+47%
OVT($\theta_{\perp}$=2.7°)	+19%	+56%

ST leading edge melting

No leading edge melting, but...
SS recrystallization
ST marginal surface melting
FT ~90% surface melt threshold

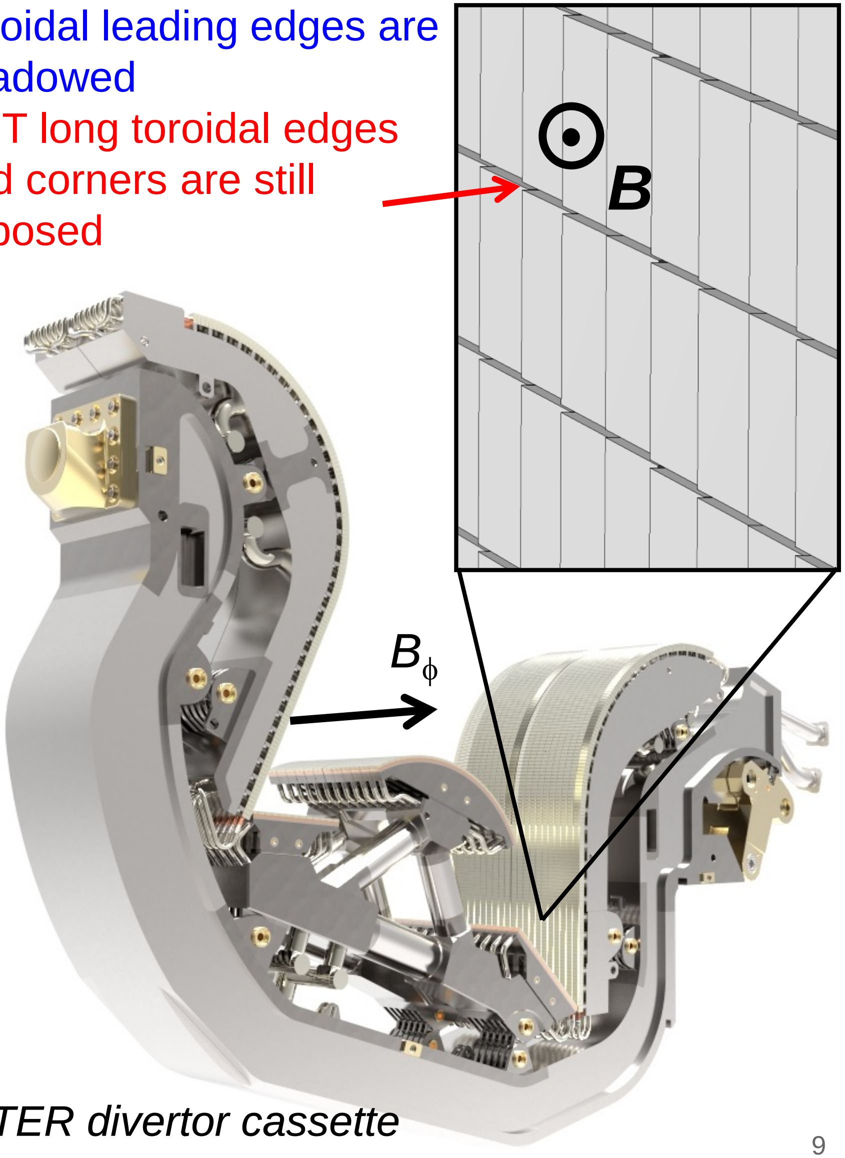
POLOIDAL EDGES MOSTLY PROTECTED BY BEVELING: WHAT ABOUT TOROIDAL EDGES?

steady state thermal response of misaligned PFUs at outer vertical target



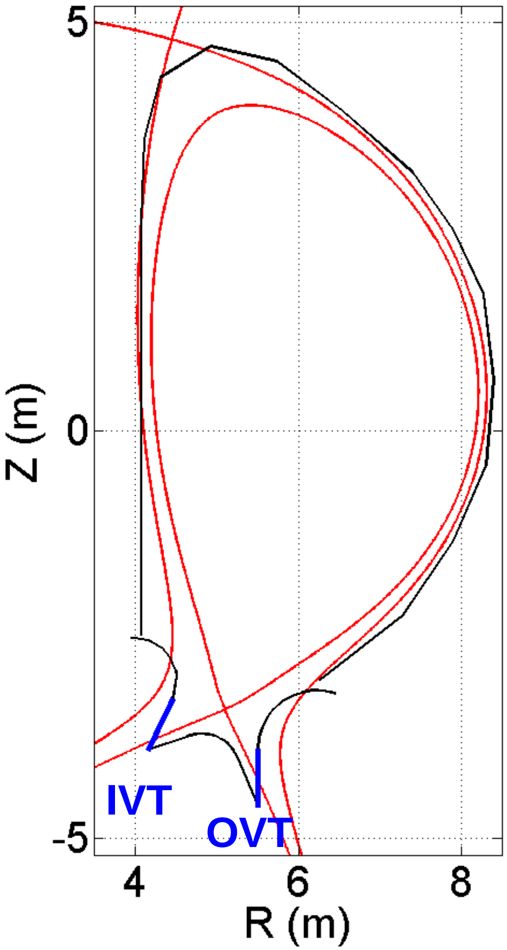
poloidal leading edges are shadowed

BUT long toroidal edges and corners are still exposed



ITER divertor cassette

GUIDELINES FOR STATIONARY TARGET POWER FLUX PROFILES FROM SOLPS SIMULATIONS

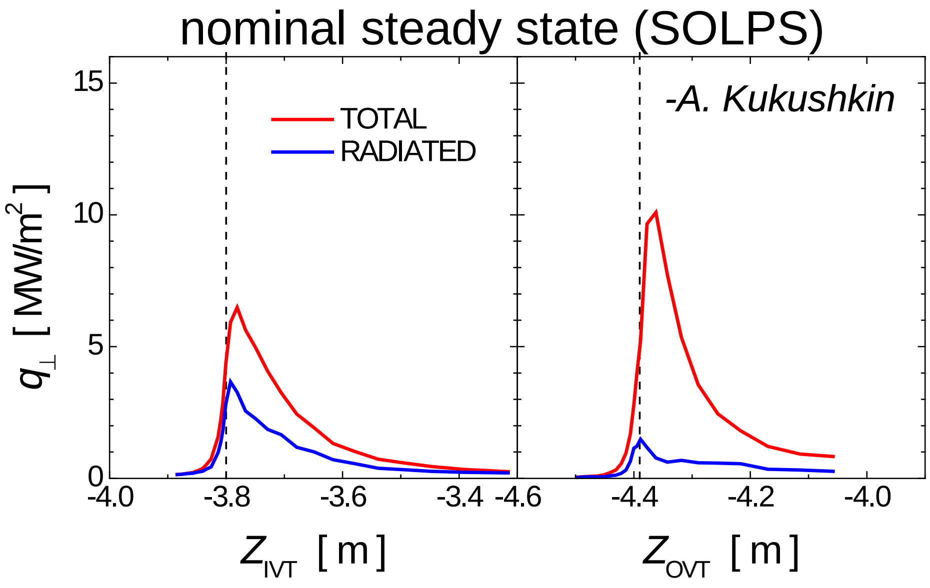

15 MA burning plasma

P_{SOL}=100 MW

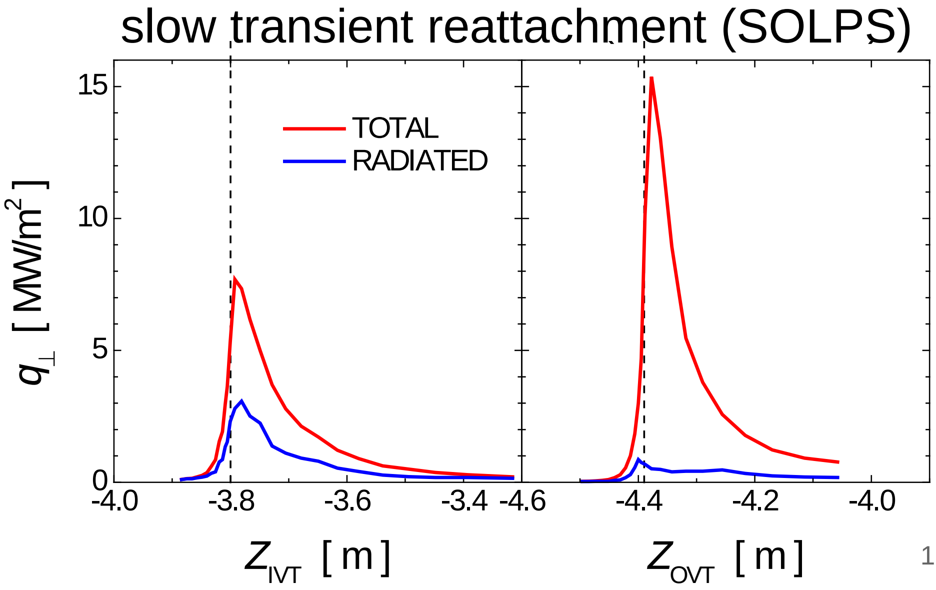
~2/3 to OVT
~1/3 to IVT

power dissipation by Neon injection

total power flux to divertor
=
plasma +
photons +
neutrals


nominal steady state (SOLPS)

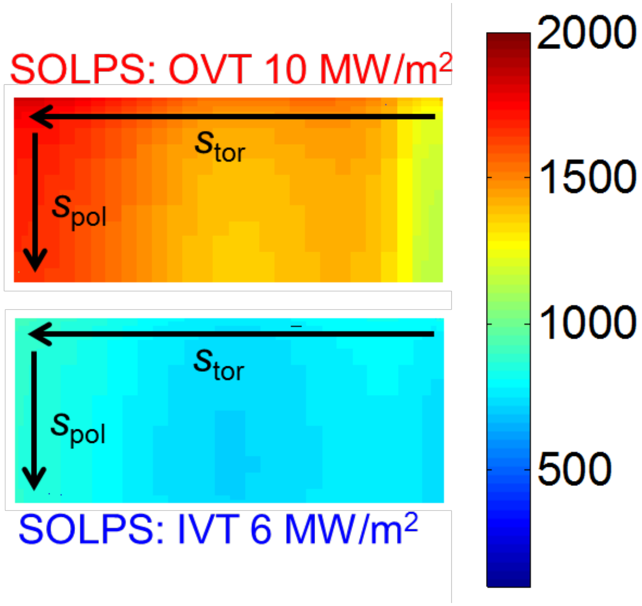
-A. Kukushkin

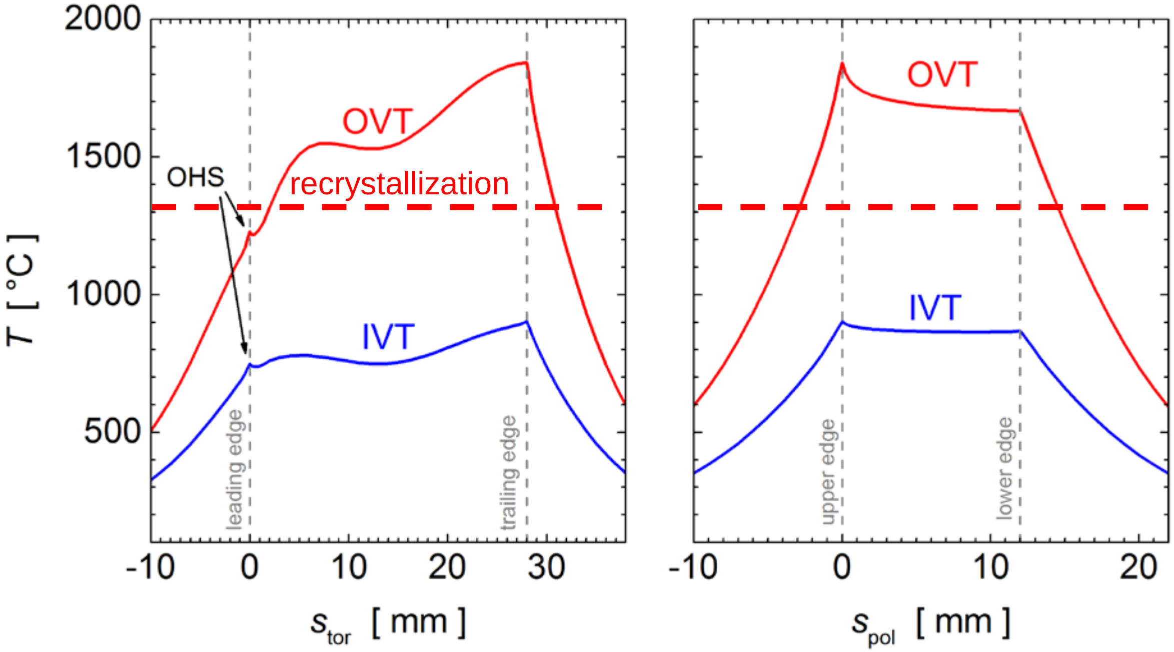

slow transient reattachment (SOLPS)

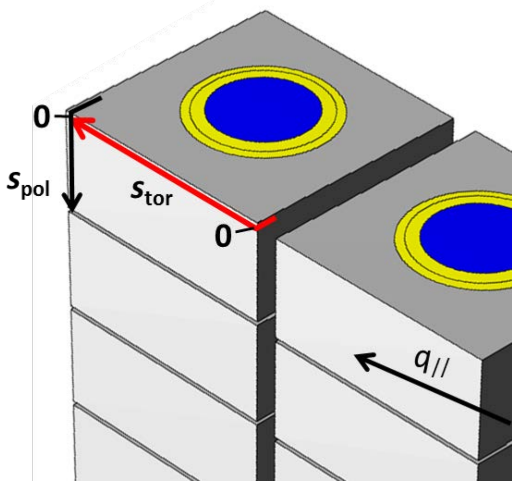
MB HEATING AT INTER-PFU GAPS IN BASELINE 15 MA BURNING PLASMA SCENARIO

Long toroidal edges heat up ~100°C more than top surface due to plasma entering toroidal gaps

target	q_{tg} [MW / m^2]	q_{rad} [MW / m^2]
IVT	6	3
OVT	10	1



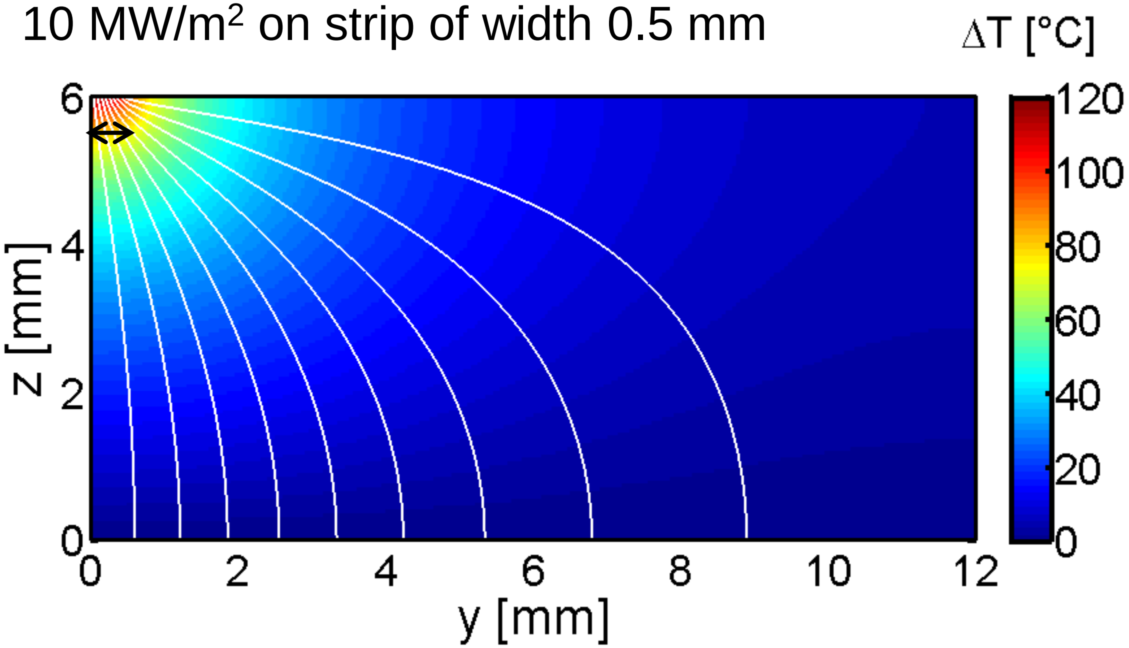




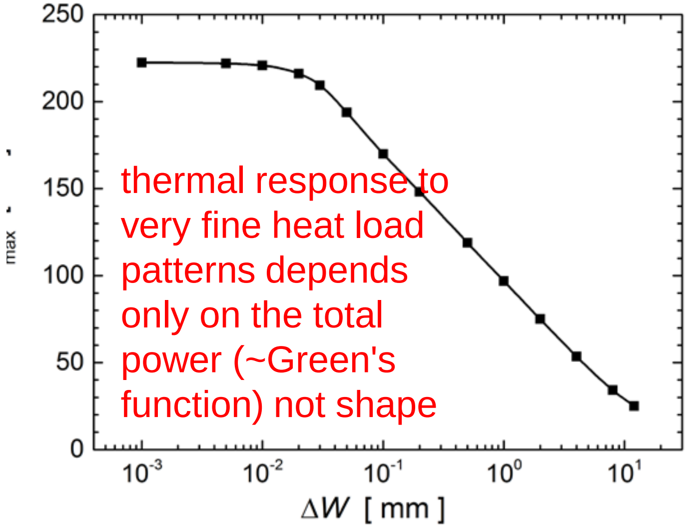
All the different heat sources can be decomposed and studied individually to understand the thermal response... Next slides

TEMPERATURE INCREASE AT LONG TOROIDAL EDGES CAN BE ESTIMATED ANALYTICALLY

10 MW/m^2 on strip of width 0.5 mm



peak temperature vs width of strip
(@ constant deposited power)



thermal response to very fine heat load patterns depends only on the total power (~Green's function) not shape

$$\Delta T(y,z) = \frac{-q_0}{\kappa}\left[\frac{\Delta W}{W_{MB}} z + \sum_{n=1}^{\infty} \frac{2W_{MB}}{(n\pi)^2 \cosh\frac{n\pi H}{W_{MB}}} \sin\frac{n\pi\Delta W}{W_{MB}} \sinh\frac{n\pi z}{W_{MB}} \cos\frac{n\pi y}{W_{MB}}\right]$$

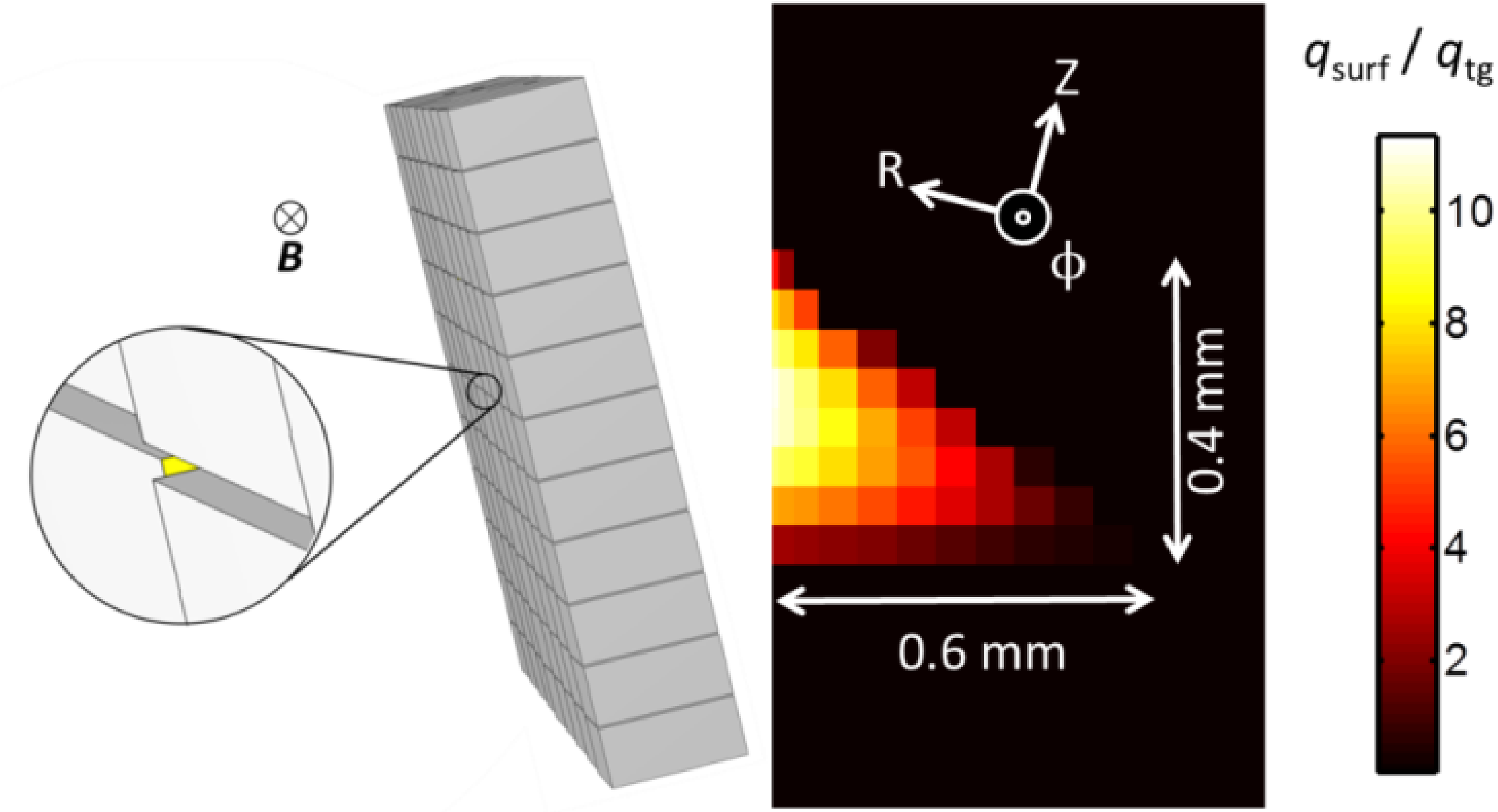
solution by separation of variables

Thermal properties of materials vary with temperature, but not dramatically, so linear approximation is valid (principle of superposition: the thermal response to multiple heat loads is the sum of the individual responses)

This is a 2D problem

- 1D linear source on boundary of 3D volume
- heat spreads in 2D, so small temperature gradient

THE LITTLE DEVIL : THE OPTICAL HOT SPOT

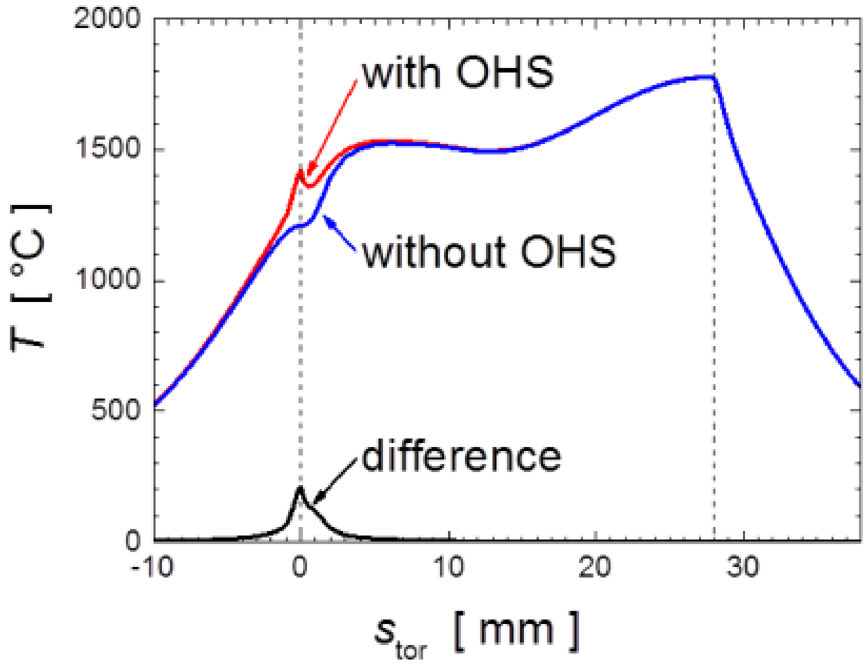


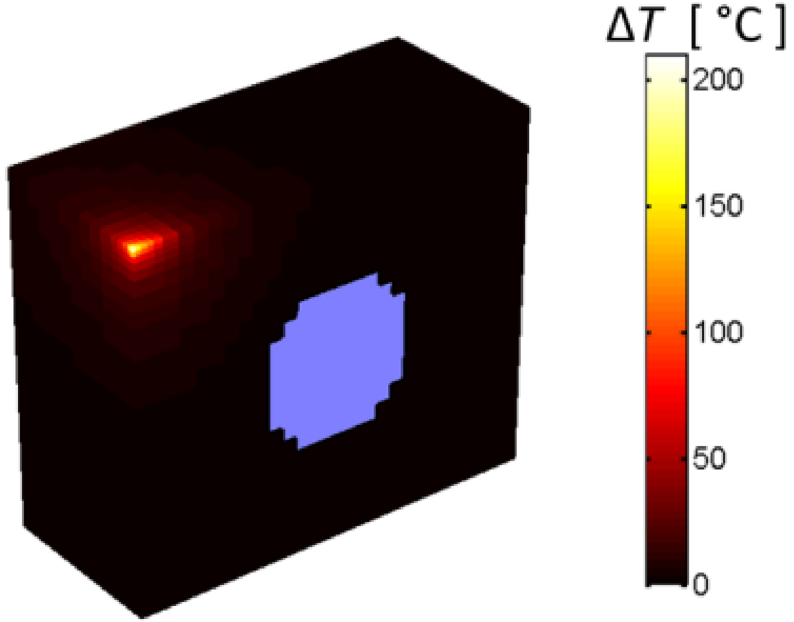
poloidal leading edge visible through gap crossings

-direct irradiation by parallel heat flux (~200 MW/m^2 in steady state)

OPTICAL HOT SPOT NOT A PROBLEM FOR INTER-ELM LOADS

IVT q_{tg}=10 MW/m^2 q_{rad}=0





This is a 3D problem

- 0D point source on boundary of 3D volume
- heat spreads in 3D, so small temperature gradient

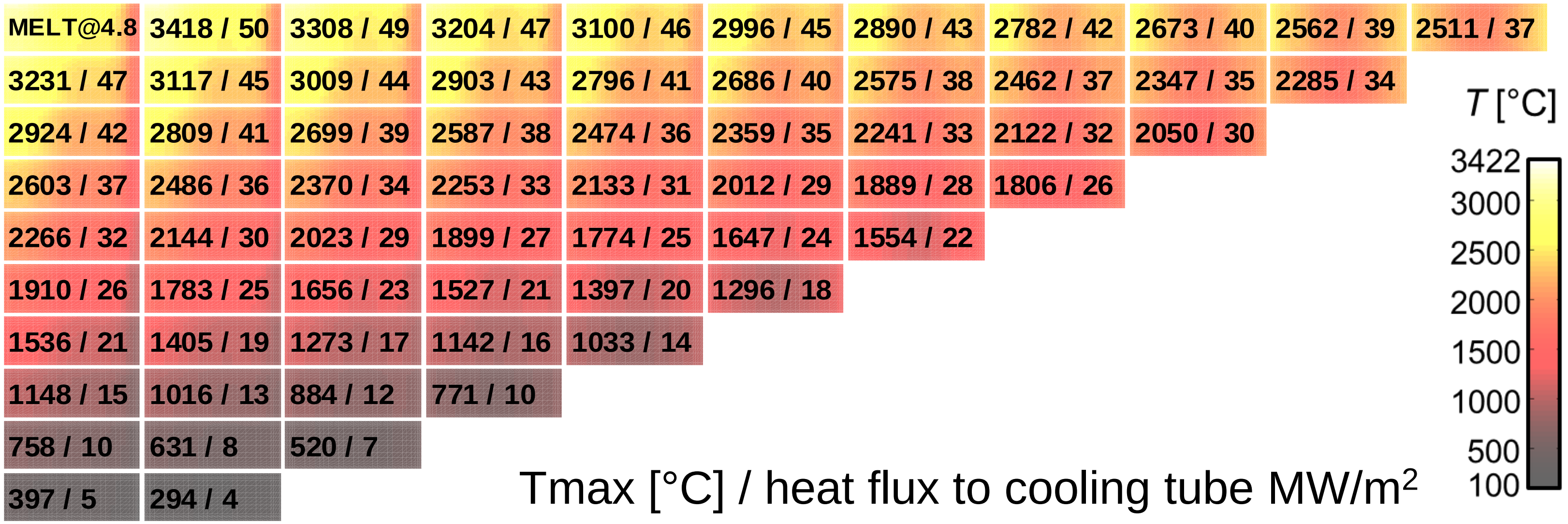
N.B. temperature increase similar to hot strip, despite heat flux ~20X higher!
We'll hear more about the OHS when we talk about ELMs later...

SCAN OVER ALL POSSIBLE COMBINATIONS OF PLASMA AND RADIATION LOADS

surface temperatures ~50% higher than high heat flux tests
(because of tilt)

q_{tg} [MW/m^2]

OVT intra-cassette



MELT@4.8	3418 / 50	3308 / 49	3204 / 47	3100 / 46	2996 / 45	2890 / 43	2782 / 42	2673 / 40	2562 / 39	2511 / 37
3231 / 47	3117 / 45	3009 / 44	2903 / 43	2796 / 41	2686 / 40	2575 / 38	2462 / 37	2347 / 35	2285 / 34	
2924 / 42	2809 / 41	2699 / 39	2587 / 38	2474 / 36	2359 / 35	2241 / 33	2122 / 32	2050 / 30		
2603 / 37	2486 / 36	2370 / 34	2253 / 33	2133 / 31	2012 / 29	1889 / 28	1806 / 26			
2266 / 32	2144 / 30	2023 / 29	1899 / 27	1774 / 25	1647 / 24	1554 / 22				
1910 / 26	1783 / 25	1656 / 23	1527 / 21	1397 / 20	1296 / 18					
1536 / 21	1405 / 19	1273 / 17	1142 / 16	1033 / 14						
1148 / 15	1016 / 13	884 / 12	771 / 10							
758 / 10	631 / 8	520 / 7								
397 / 5	294 / 4									

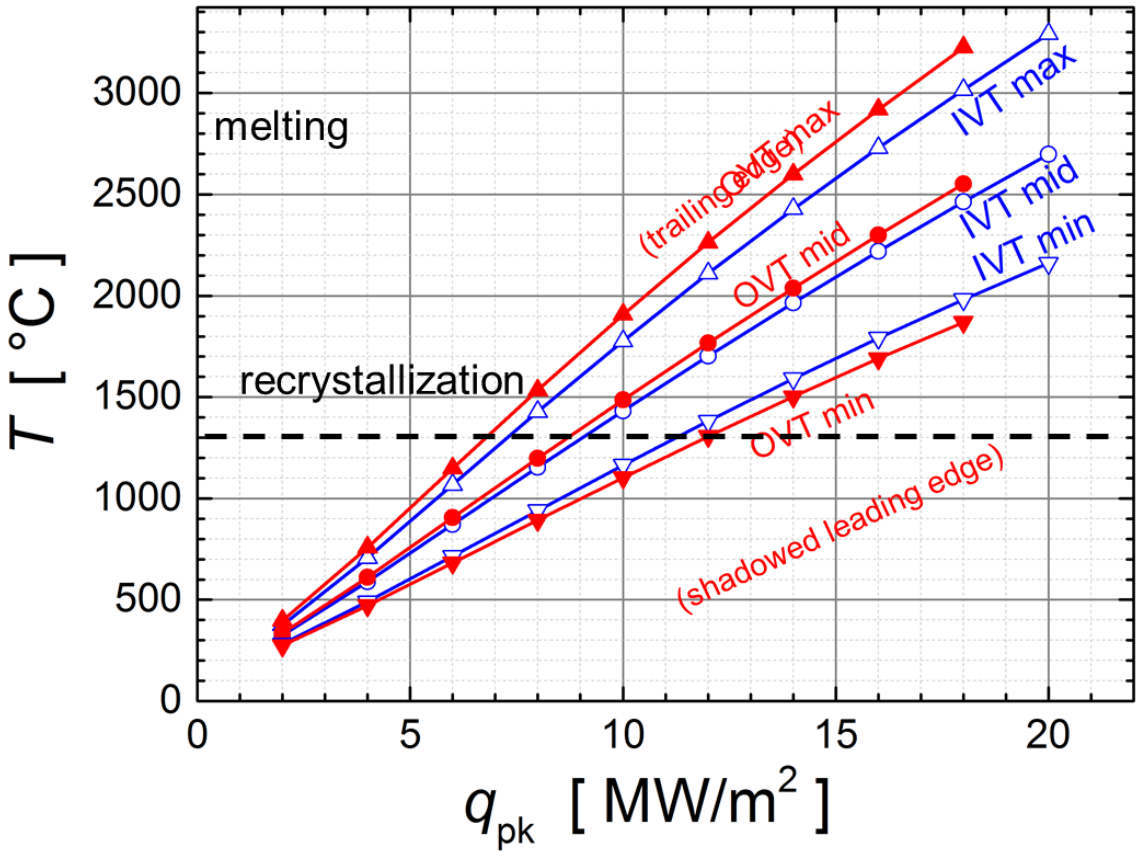
Tmax [°C] / heat flux to cooling tube MW/m^2

q_{rad} [MW/m^2]

*assuming worst case misalignments

critical heat flux 40 MW/m^2 (formation of vapour layer, loss of heat handling, burnout)

COMPILED RESULTS FOR WORST CASE (100% CONVECTED POWER)



Consequence of shaping - power flowing to divertor must be reduced ~2/3 to avoid recrystallization

SUMMARY OF INTER-ELM ANALYSIS

inter-ELM loads

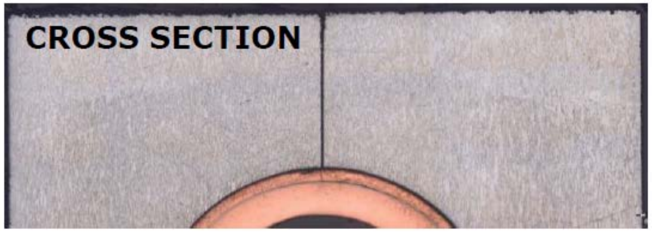
- shaping pushes surface temperature into recrystallization for steady state loads, and to marginal melting for slow transient loads (because of tilt)

-long toroidal edges heat up ~100°C more than top surface (plasma flux into gaps)

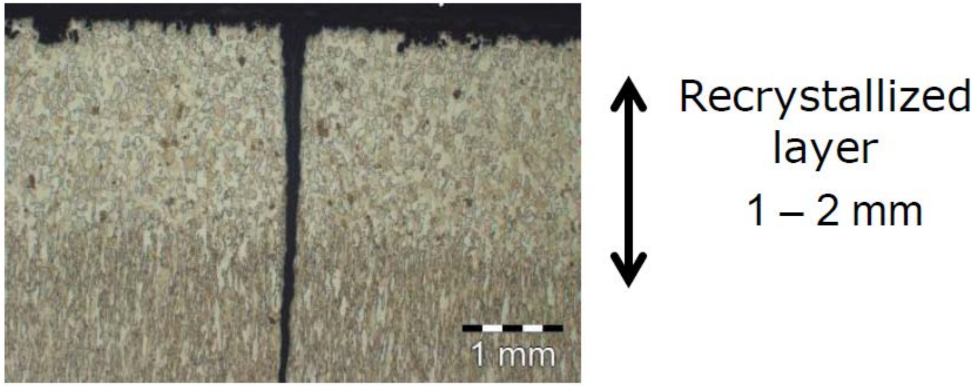
- power to divertor would have be reduced if recrystallization is to be avoided

increase rate of Ne/N injection?

deeper detachement = loss of confinement (A. Huber, JET)



cracking of some W grades
during slow transients
S. Panayotis (PSI Rome, 2016)



G.Pintsuk, et al., SOFT2014

Part 2
ELMs

define ELM energy ΔW_{ELM} pedestal T_i → choose surface energy density waveform → calculate heat flux distribution on MB → calculate thermal response

- -scaling laws
- -modelling

- -experiment
- -modelling
  - -JOREK
  - -SOLPS
  - -PIC...

- -optical approximation
- -ion orbit modelling
- -PIC code

- -heat flux factors
- -finite elements

BASIS FOR ELM ENERGY FLUENCE LIMIT ~0.5 MJ/m²

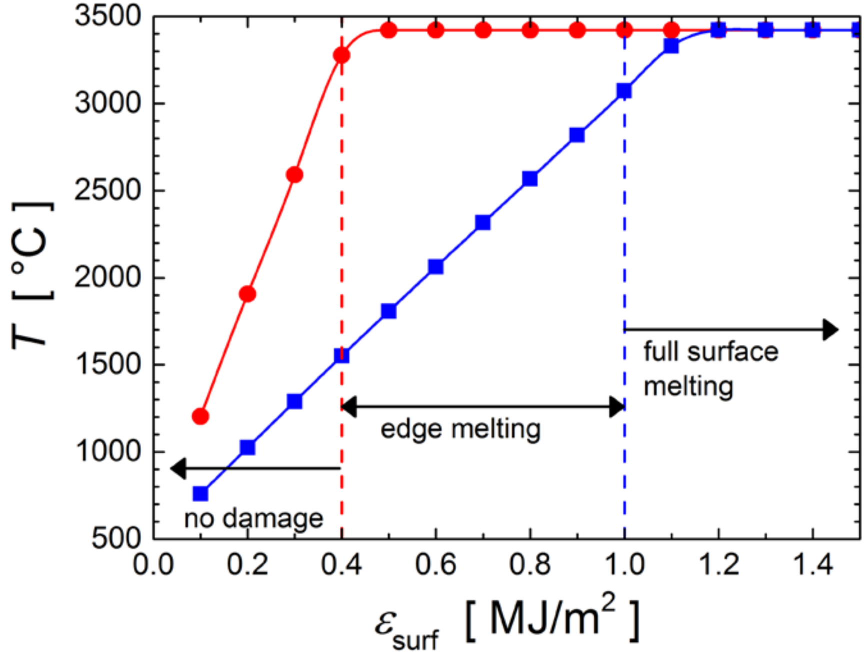
historical ITER limit $\varepsilon_{surf} \leq 0.5$ MJ/m^2

-factor 2 margin against full surface melting (i.e. T_{surf} < 1700°C)

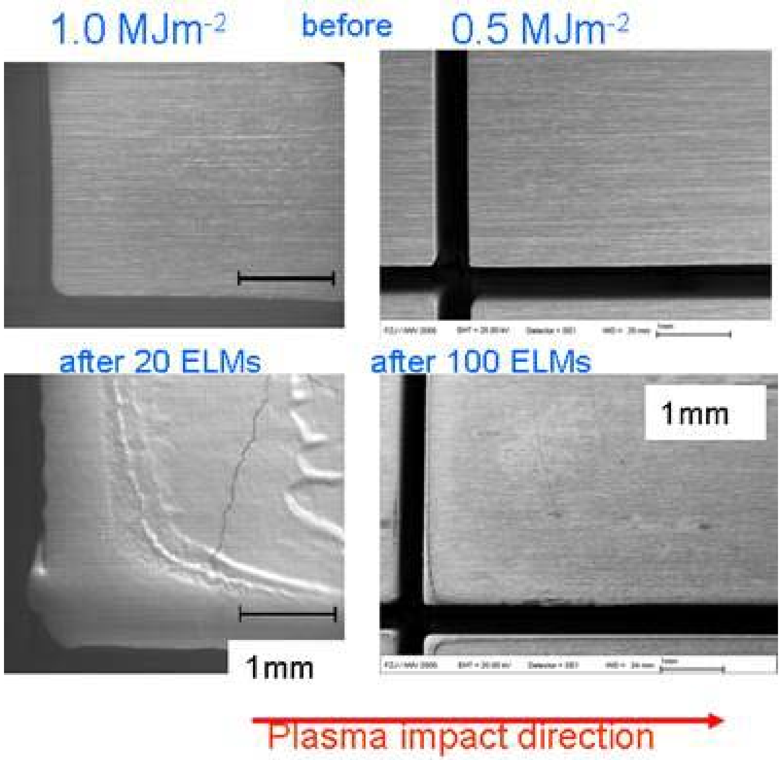
-marginal edge melting

N. Klimov, et al. JNM 390-391 (2009).

QSPA **square pulse**



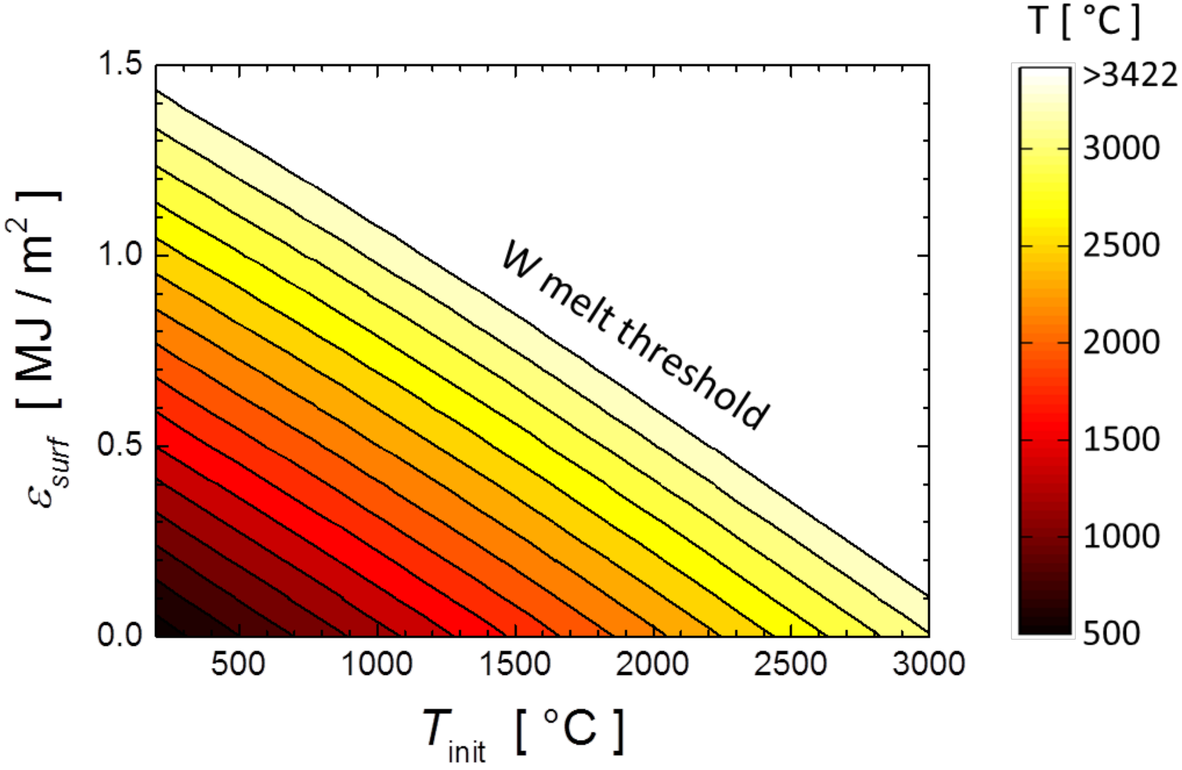
data points from thermal model compared to visual evaluation of damage (dashed lines)



REFERENCE CASE FOR ELM ANALYSIS: 1D THERMAL RESPONSE TO A TRIANGULAR PULSE

triangular pulse, 250 µs rise time, 500 µs decay time

ε = ELM energy fluence i.e. total energy deposited during ELM event (time integral of heat flux)

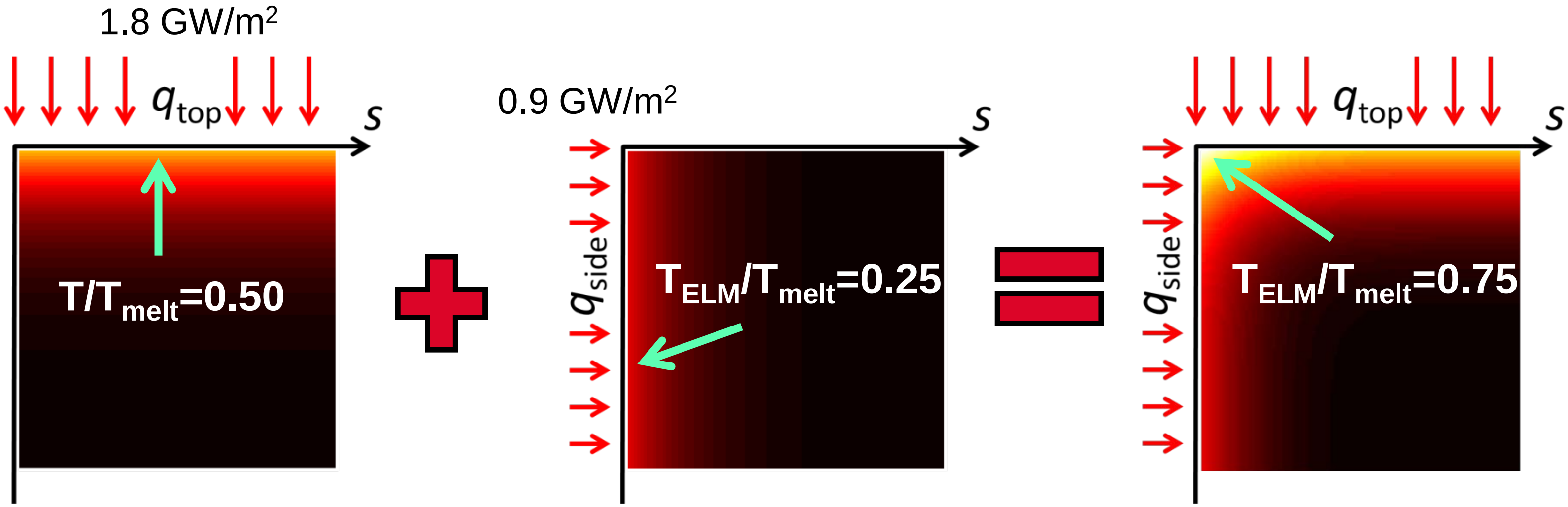


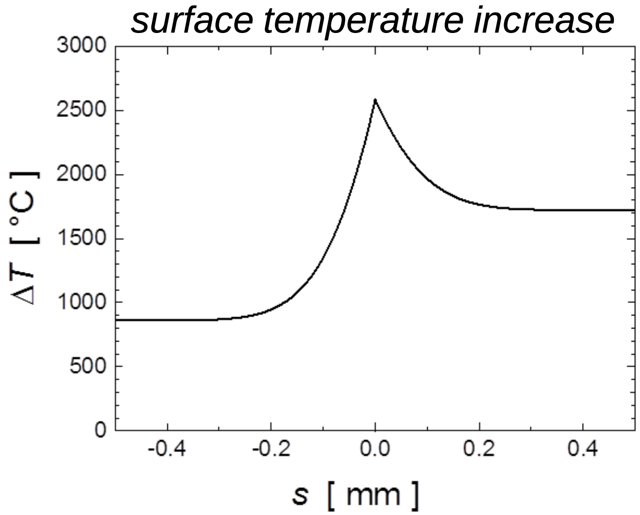
historical ITER ELM limit (ε_{tg}=0.5 MJ/m^2) generates temperature spikes ΔT~1100 °C

This factor 2 margin against melting is degraded for initially hot monoblocks

N.B. this limit applies to ideal, axisymmetric divertor with no castellations or shaping

AT A SHARP EDGE OR CORNER, THERMAL RESPONSE IS THE SUM OF 1D HEATING AT INDIVIDUAL FACETS





Exactly correct for linear case (temperature-independent thermal properties) (and 90° angles)
Very good (<5%) approximation for non-linear (temperature-dependent thermal properties)

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

1) For a given magnetic field angle and specified ELM energy density, we calculate the corresponding $q_{//}=q_{tg}/\sin\alpha$

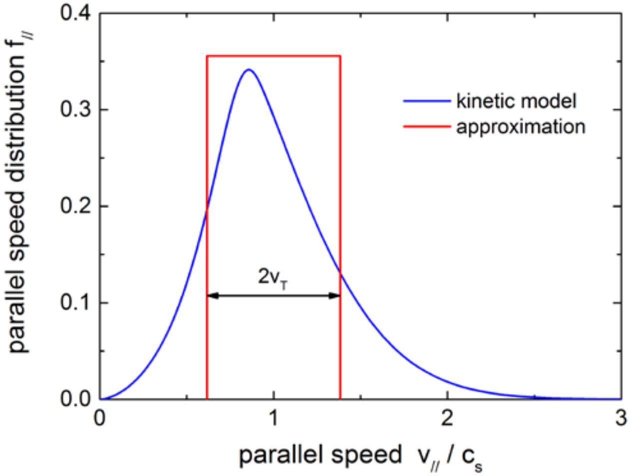
2) We then launch that $q_{//}$ at the monoblocks and calculate the local heat flux at all the surfaces of <u>*shaped monoblocks*</u> + <u>*worst case misalignments*</u> by 3D ion orbit simulations.

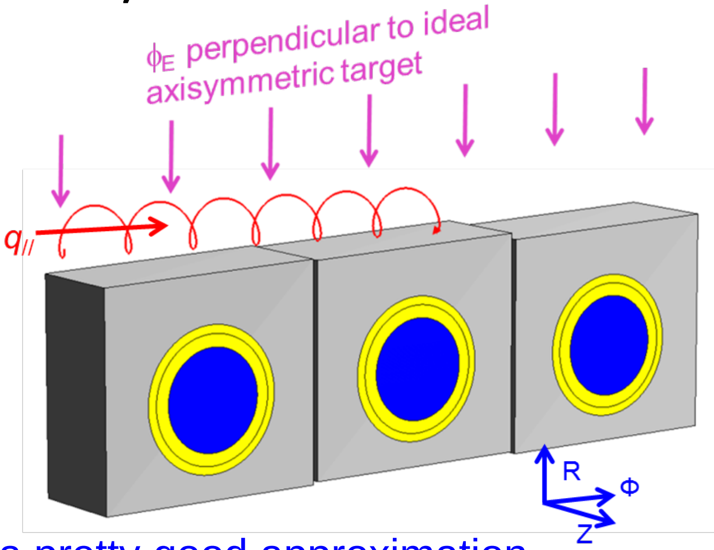
(weighting based on floating, ambipolar sheath)

ion component:
-parallel speed distribution from kinetic model of SOL
-Maxwellian perpendicular speed distribution

$$q_{surf} = \frac{5}{7} q_i + \frac{2}{7} q_e$$

electron component:
-optical approximation (field line tracing)

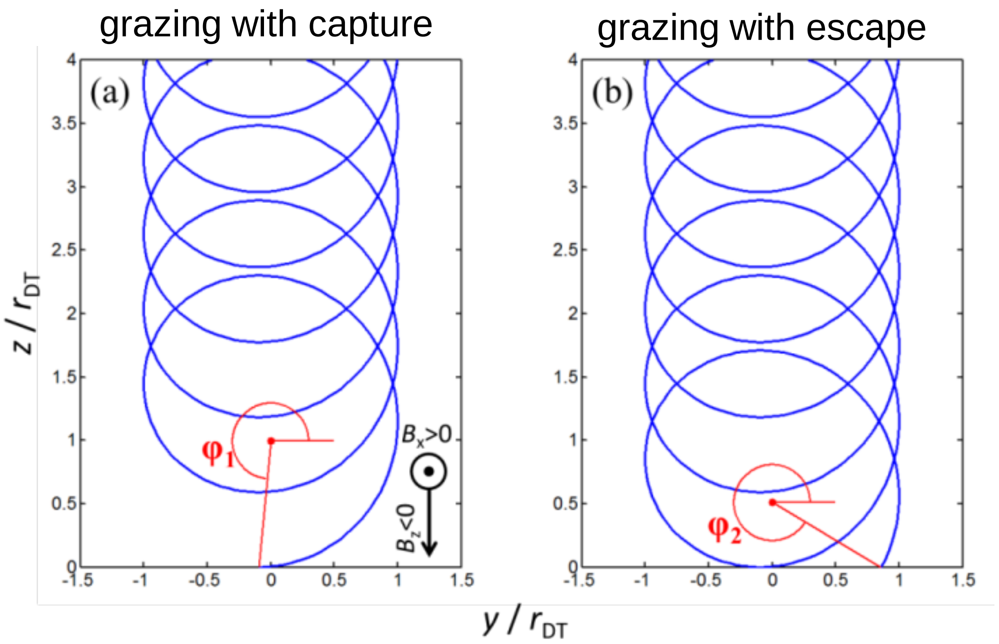




Surprisingly (even to us) neglecting sheath E-fields is a pretty good approximation.

Confirmed by comparison with 2D particle-in-cell code SPICE
(M. Komm, et al., Nucl. Fusion **57**, 046025 (2017).

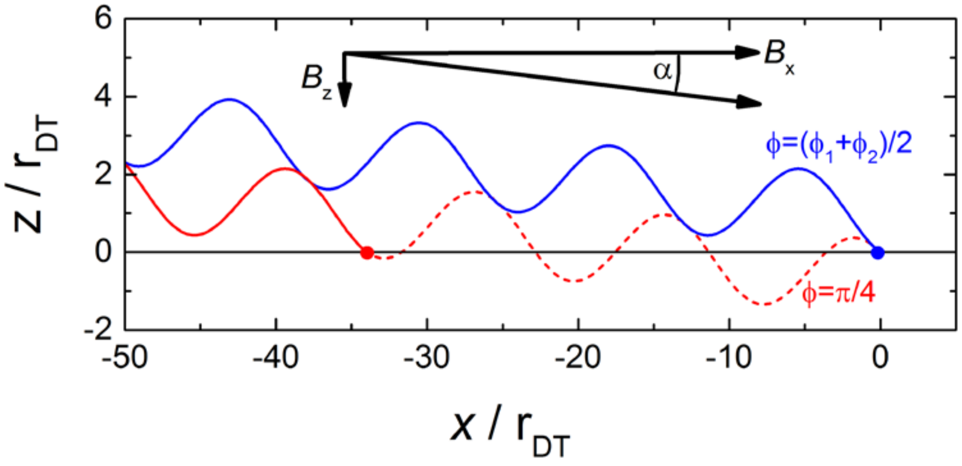
MOST HEAT FLUX PATTERNS CAN BE UNDERSTOOD FROM ANALYSIS OF HELICAL TRAJECTORIES


grazing with capture

grazing with escape

Ions striking the surface have a restricted range of impact angles (nearly grazing)

Angles outside this range do not exist because the ion would have struck the surface earlier

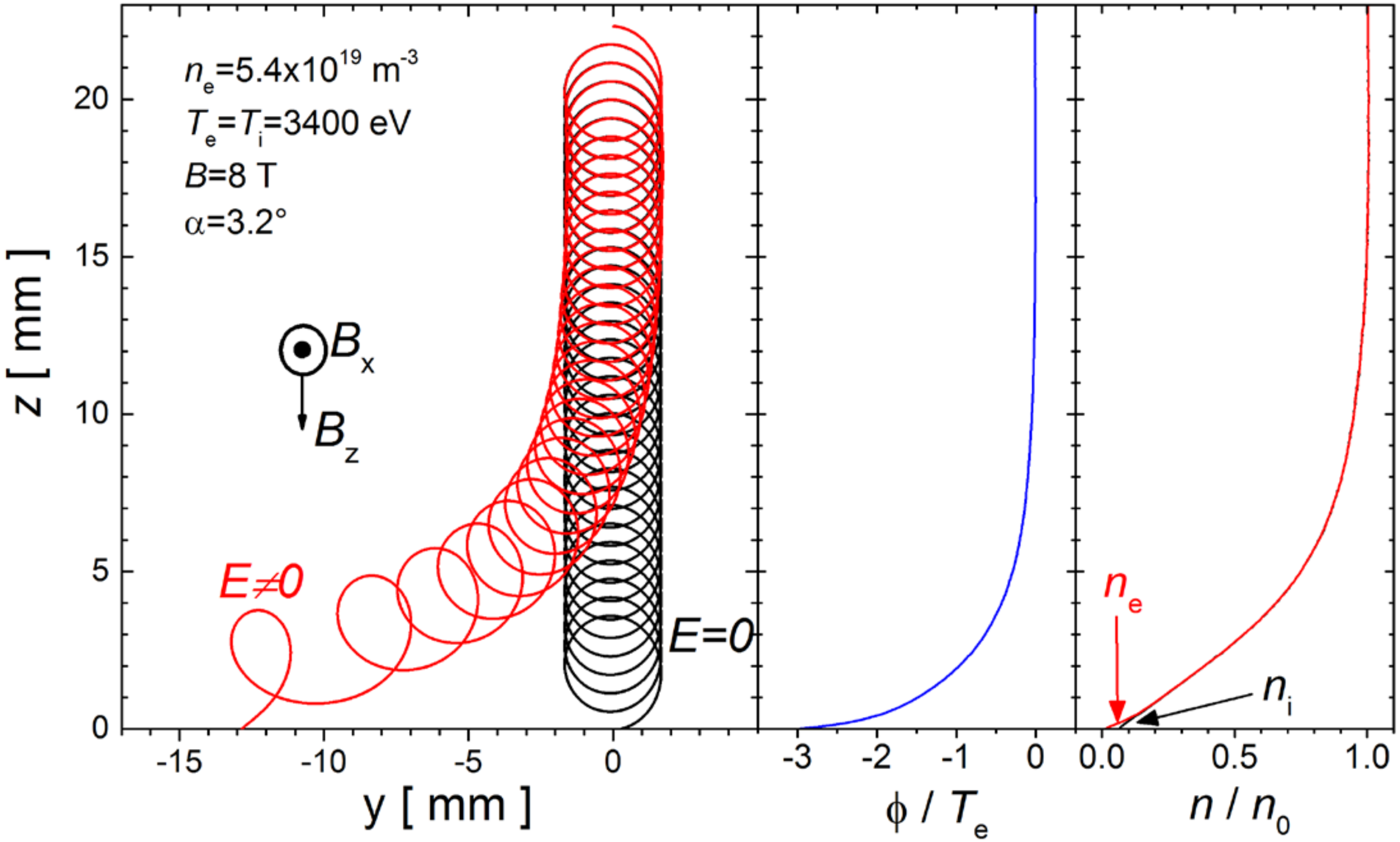


REMARKABLY LITTLE DISCREPANCY BETWEEN SIMPLE MODEL AND SELF CONSISTENT SHEATH

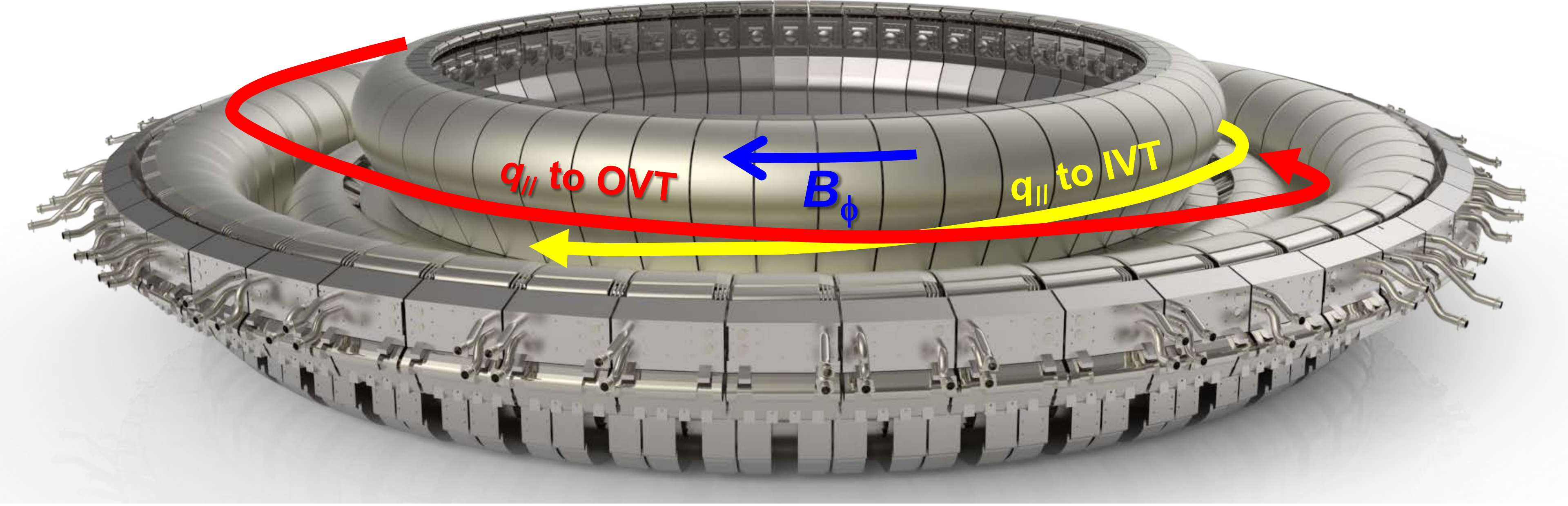
Electrostatic sheath (thin layer of strong electric field $E \sim T_e/\lambda_D$) separates surfaces from plasma, keeping the plasma electrically neutral

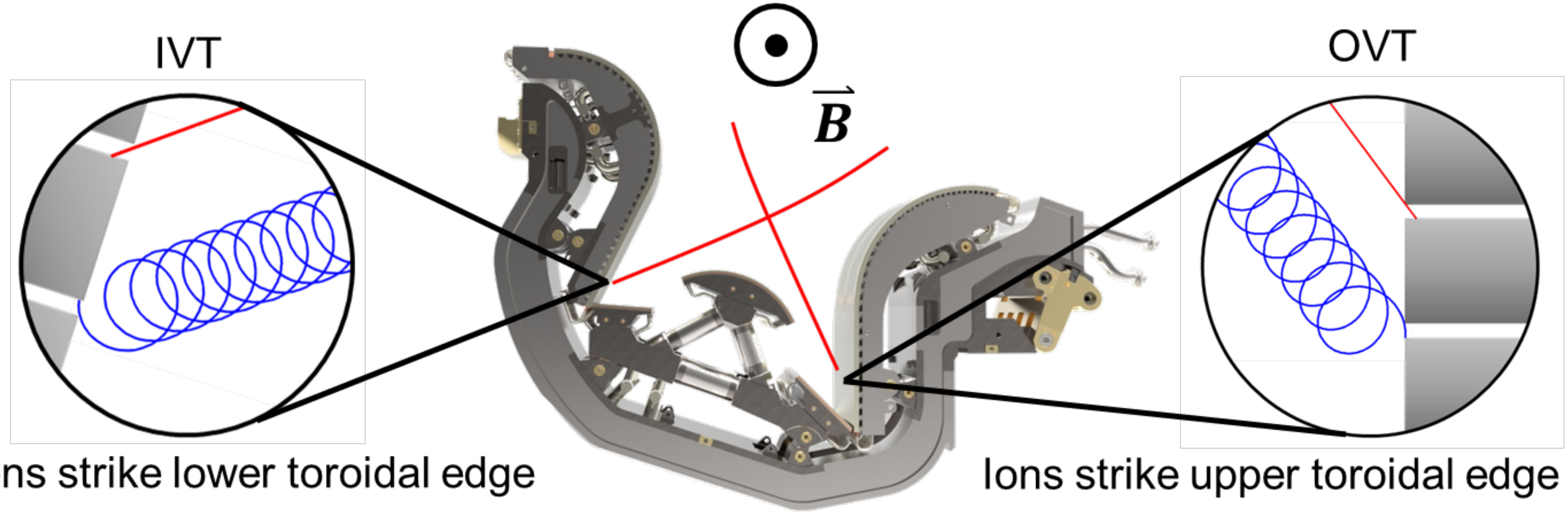
Main effect is EXB drift parallel to surface - impact angles do not change much

Assuming E=0 seems dumb, but the approximation is "good enough"



HELICITY OF ION ORBITS INTRODUCES ASYMMETRY BETWEEN IVT AND OVT TOROIDAL GAPS



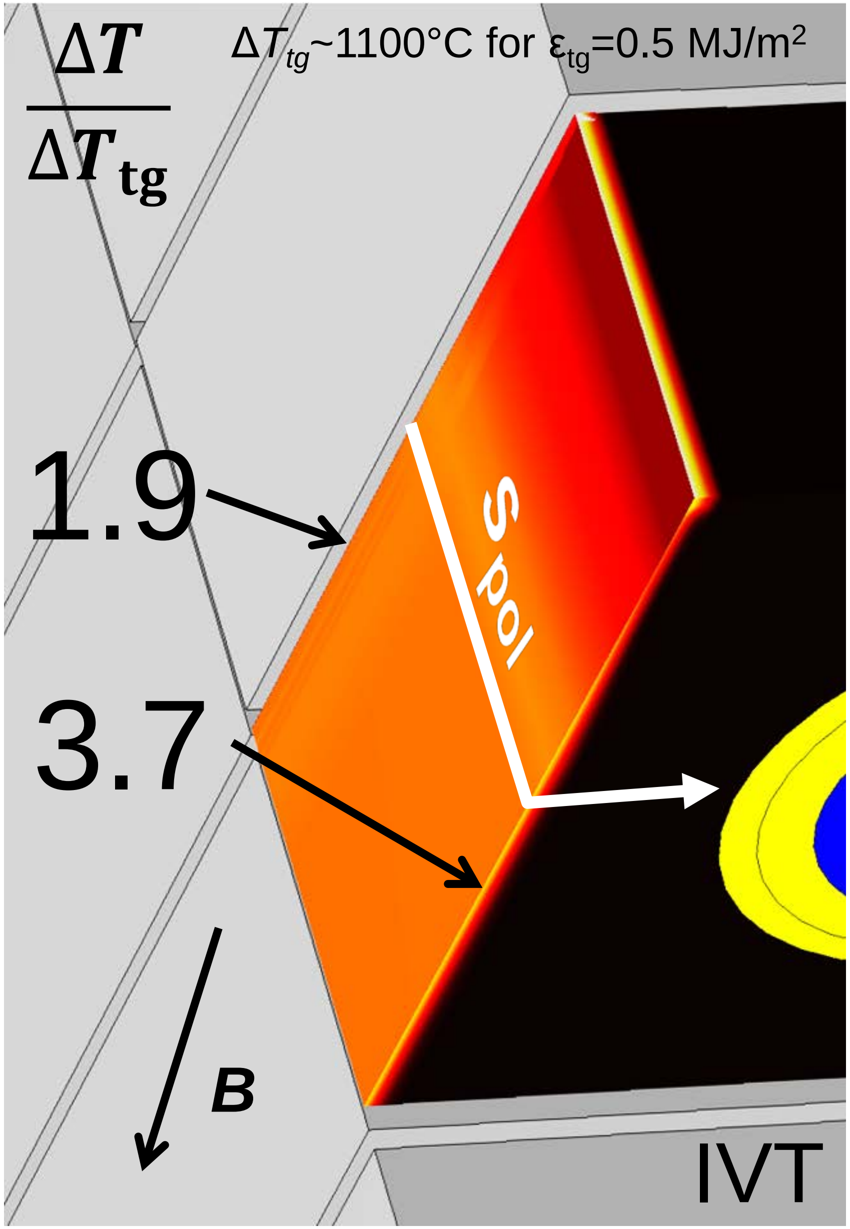


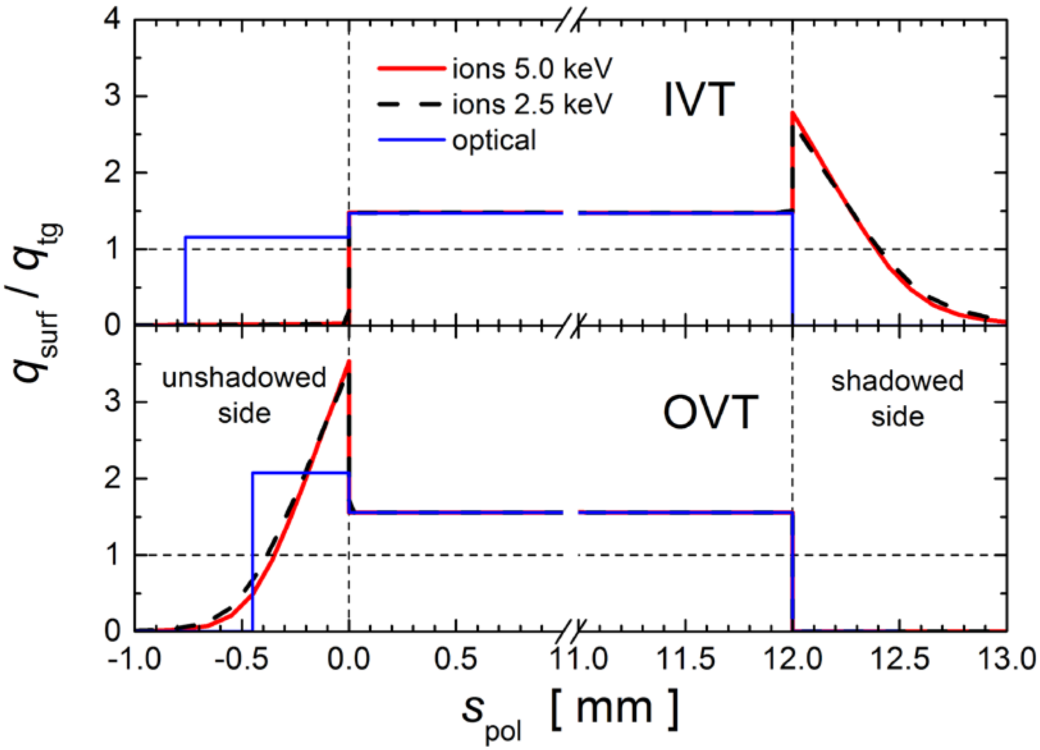
Ions strike lower toroidal edge

Ions strike upper toroidal edge

electrons strike upper edges at both targets (tiny Larmor radius)

STRONG HEATING AT IVT LOWER TOROIDAL EDGES AND OVT UPPER TOROIDAL EDGES





IVT: ions strike shadowed bottom side
OVT: ions strike wetted top side
-at both targets, electrons hit top side

First experimental confirmation of this asymmetry in COMPASS (for inter-ELM heat loads)
R. Dejarnac, et al.,Nucl. Fusion **58**, 066003 (2018).

INPUT PARAMETERS FOR PRE-NUCLEAR AND NUCLEAR SCENARIOS

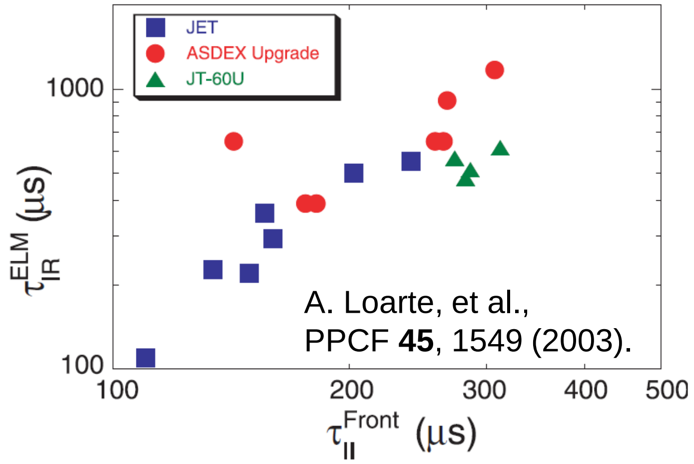
plasma	H	D or He	D+T
A/Z	1	2	2.5
I_p [MA]	5.0	7.5	15
B [T]	1.76	2.65	5.3
n_e [10^{20} m^{-3}]	0.3	0.4	0.8
T_i [keV]	1.7	2.5	5.0
Δt_{ELM} [μs]	271	316	250
steady state q_{tg} [MW/m^2]	2.5	5	10
T_{init} [°C] surface (edge)	450 (550)	800 (1000)	1500 (1900)

→ from inter-ELM thermal analysis with shaping

$$\Delta t_{ELM} = 250 \sqrt{\frac{2A}{ZT_i}} \quad [\mu s]$$

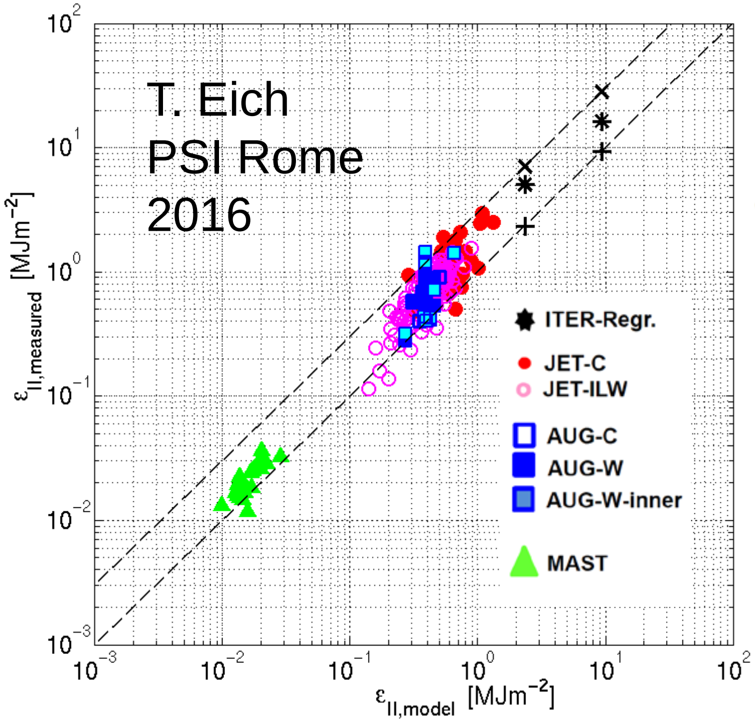
ELM rise time:

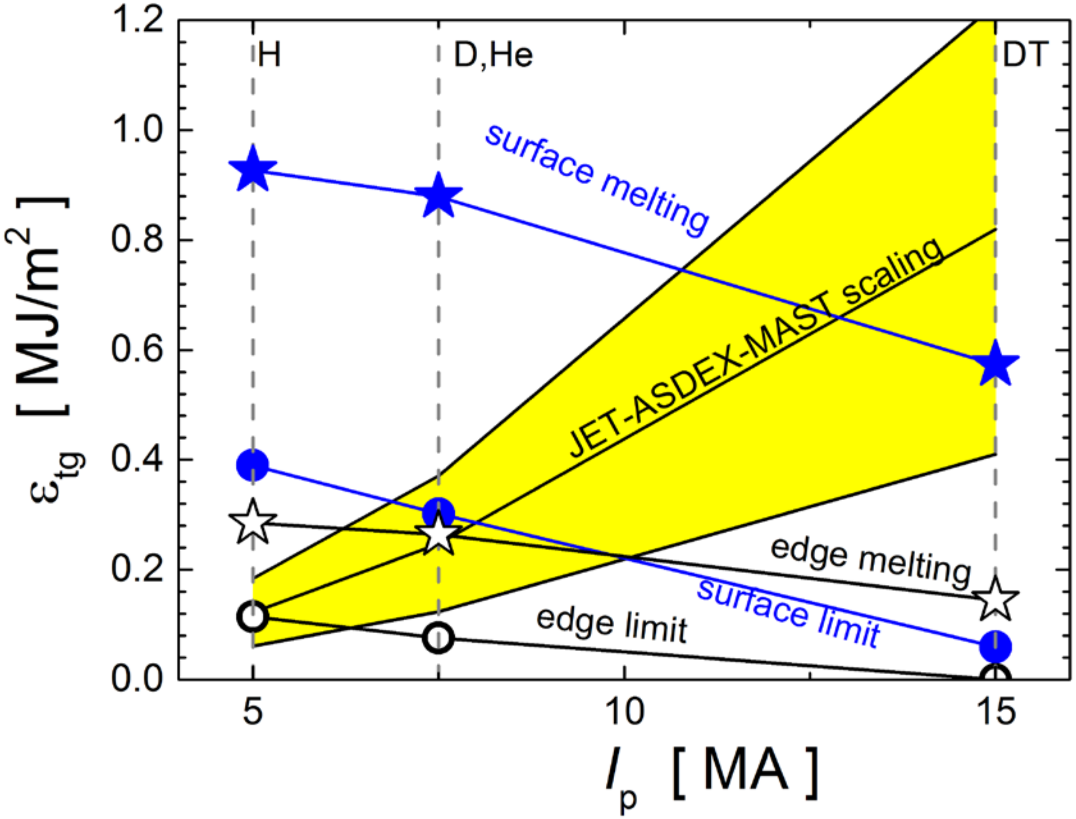
empirical scaling assuming free streaming from midplane to target at ion sound speed



A. Loarte, et al., PPCF **45**, 1549 (2003).

PREDICTIONS FOR ITER BASED ON RECENT ELM SURFACE ENERGY DENSITY SCALING

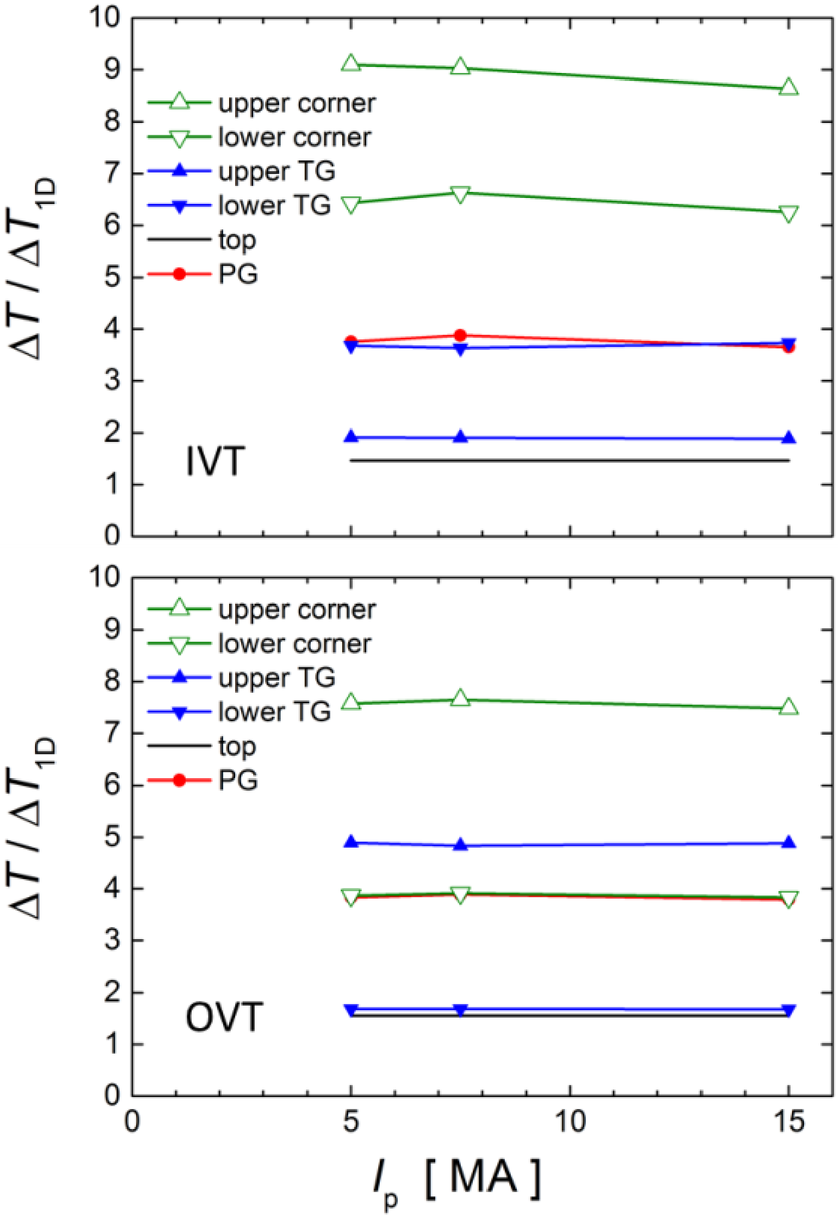

T. Eich
PSI Rome
2016

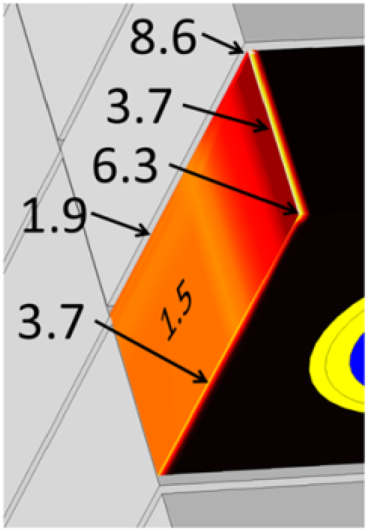


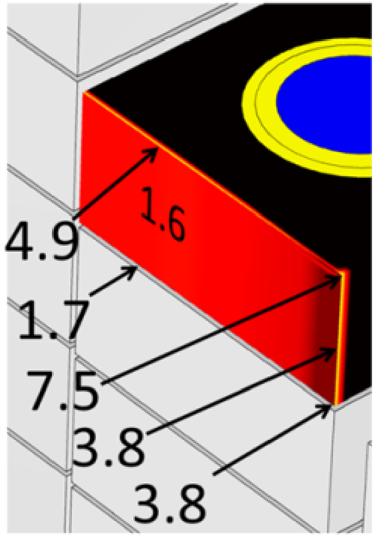
scenario	full surface melting?	edge melting?
pre-nuclear hydrogen 5MA	avoided with wide margin	avoided with narrow margin (less than 2)
pre-nuclear D or He 7.5 MA	avoided with narrow margin (less than 2)	possible during largest ELMs
DT nuclear burn 15 MA	unavoidable	unavoidable

EDGES AND CORNERS (EVEN WHEN SHADOWED) ARE EXTREMELY VULNERABLE

Bonus:
optical hot spot!
heat load is
sufficient to trigger
tungsten *BOILING*
at every ELM



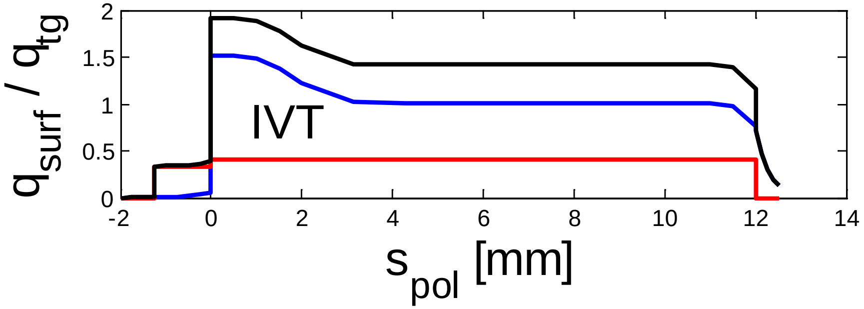


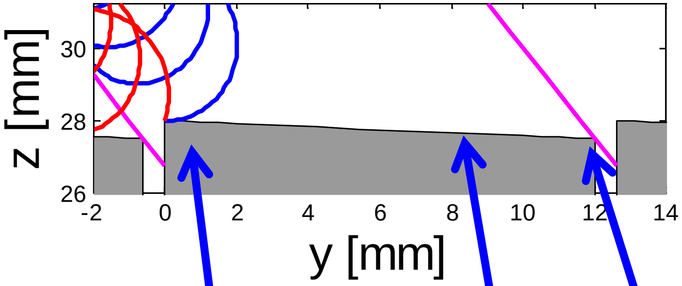


WHAT ABOUT A COMBINED POLOIDAL - TOROIDAL BEVEL ?

At IVT, ions and electrons flow to opposite sides of the toroidal gap

-poloidal beveling to protect against ELMs cannot fully succeed because either ions or electrons are affected, but never both





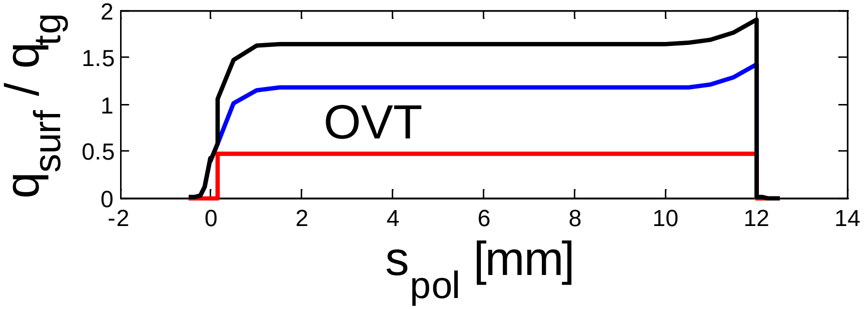
increased heating at upper edge

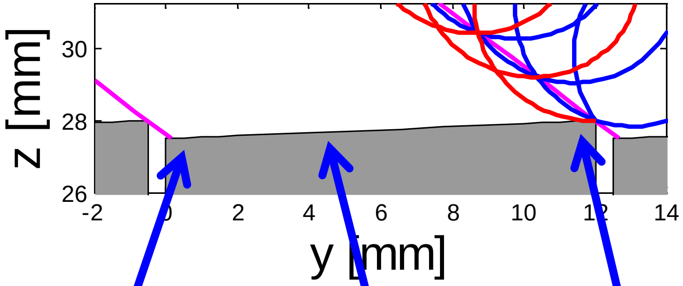
decreased heating on main surface

shadowing of lower edge from ELM ions

At OVT, both electrons and ions flow to the same side

Combined poloidal and toroidal bevels has the potential to mitigate the ELM and inter-ELM TG loading problem



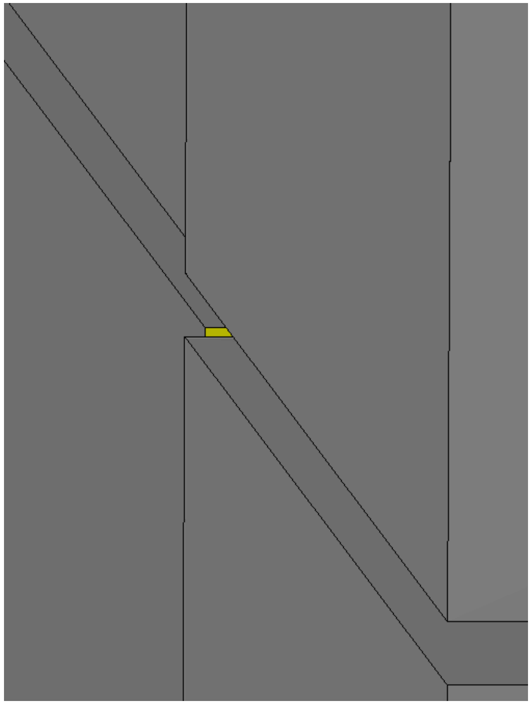


shadowing of upper edge from both ion and electron loads

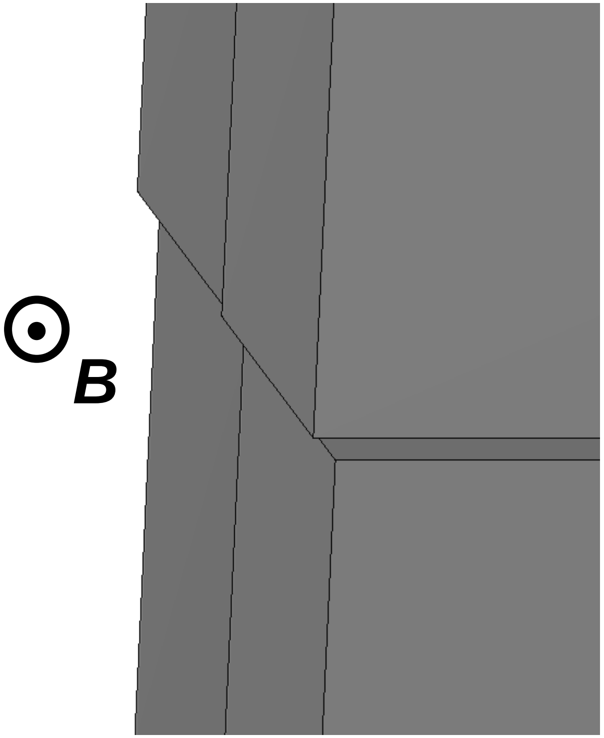
slightly increased heating on main surface

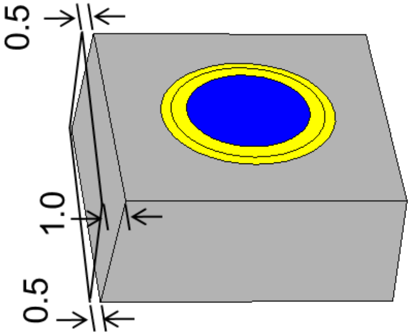
slight increase of ion heating at lower edge

POLOIDAL BEVEL CAN SHADOW TOROIDAL GAP EDGE AND ELIMINATE OHS AT OVT



reference 0.5 mm toroidal bevel
no poloidal bevel
worst case misalignments
TG edge and OHS are visible

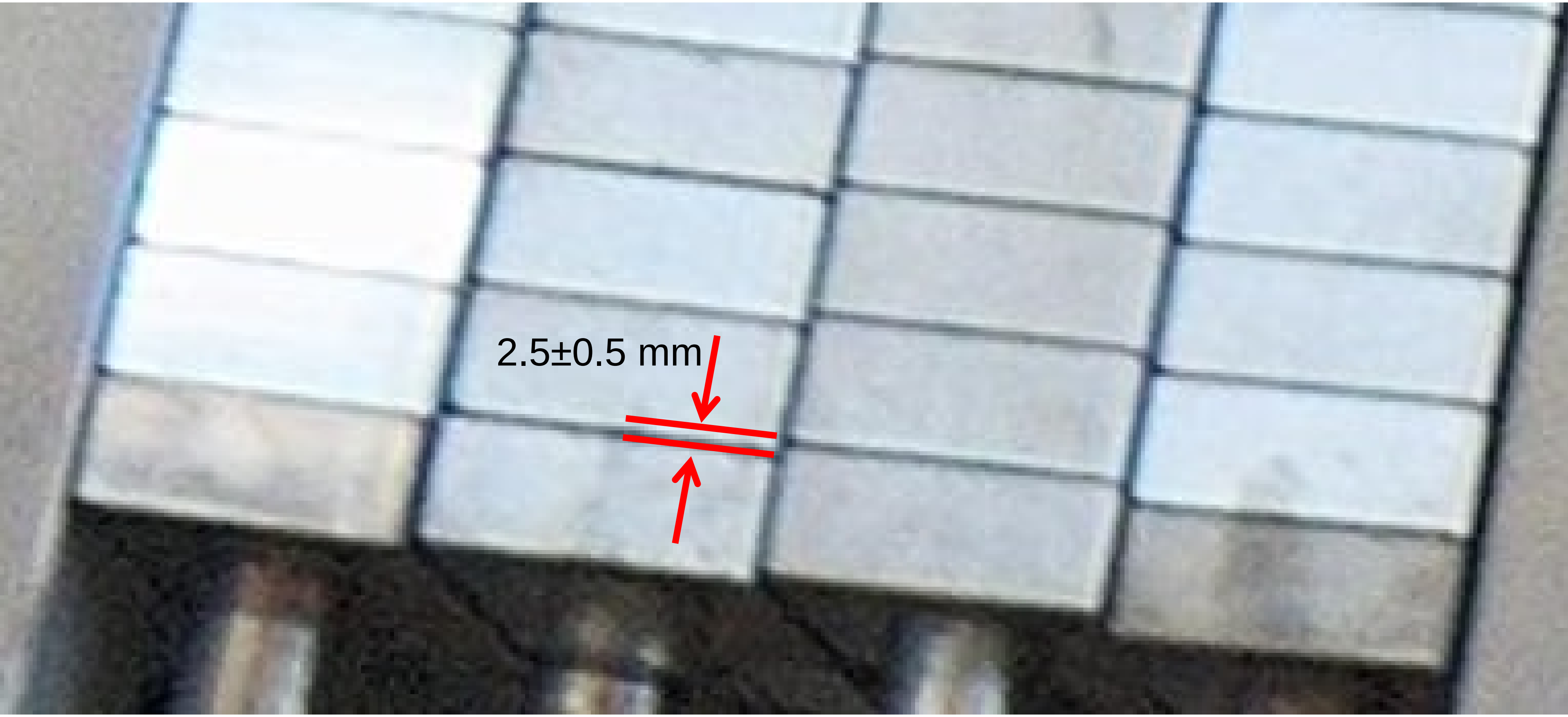




reference 0.5 mm toroidal bevel
+ additional 0.5 mm poloidal bevel
→ "shallow poloidal bevel"
Chosen to shadow TG edge for all possible radial misalignments and gap tolerances
Bonus! → no OHS ... IF TOROIDAL GAPS ARE POLOIDALLY ALIGNED

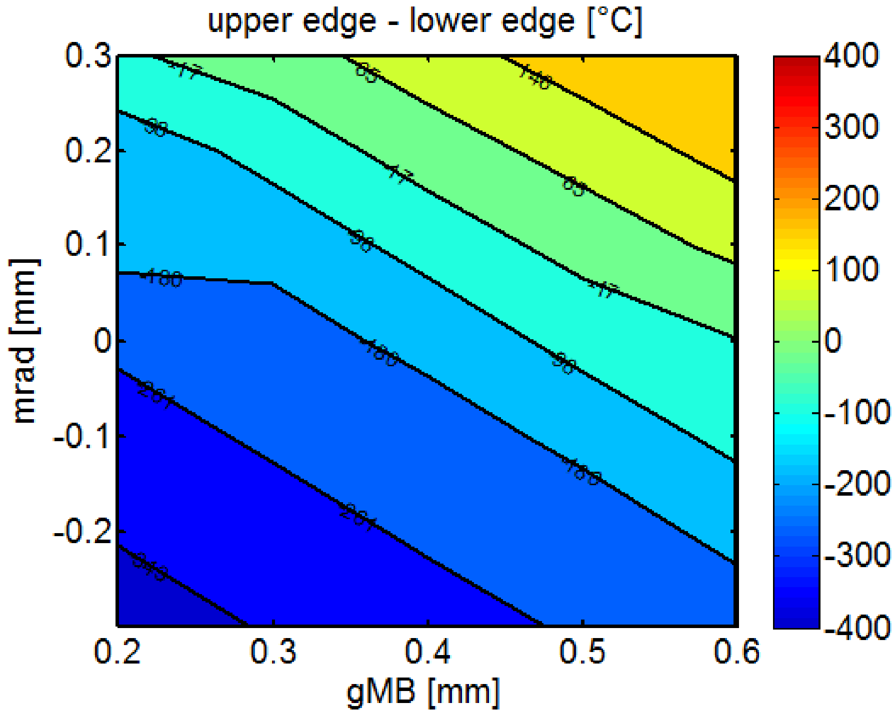
POLOIDAL ALIGNMENT BETWEEN ADJACENT MBS IS NOT SPECIFIED IN WEST (OR ITER) DESIGN

Only individual TGs are toleranced



nominal TG width g_{MB}=0.5 mm

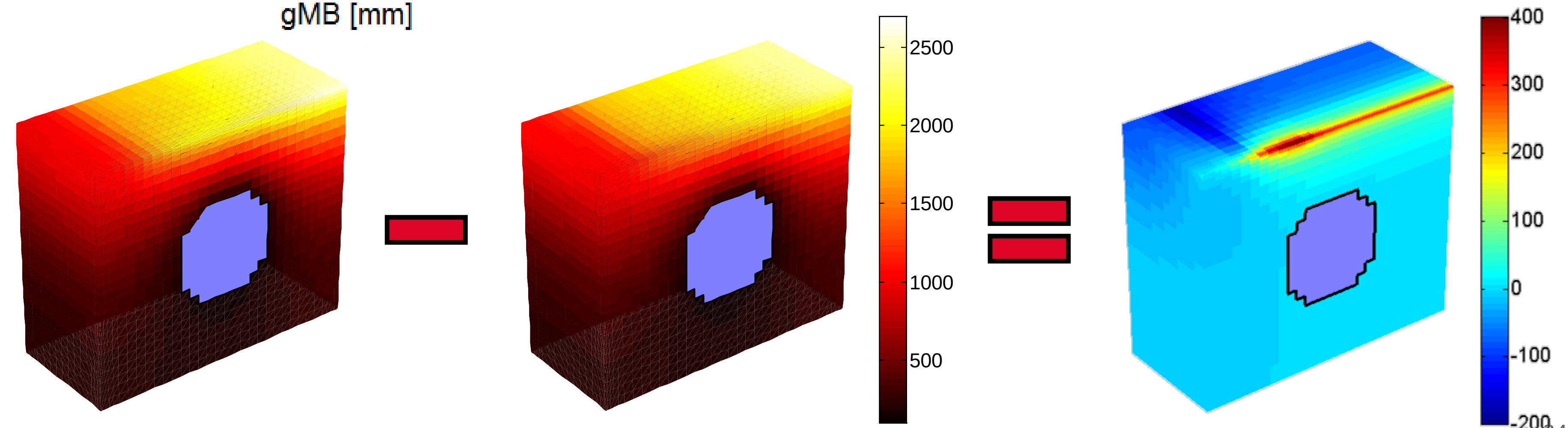
POLOIDAL BEVEL ELIMINATES EDGE HEATING PROBLEM BETWEEN ELMS



negligible increase of top surface heating
simple toroidal bevel - $q_{surf} / q_{tg} = 1.56$
shallow poloidal bevel - $q_{surf} / q_{tg} = 1.64$

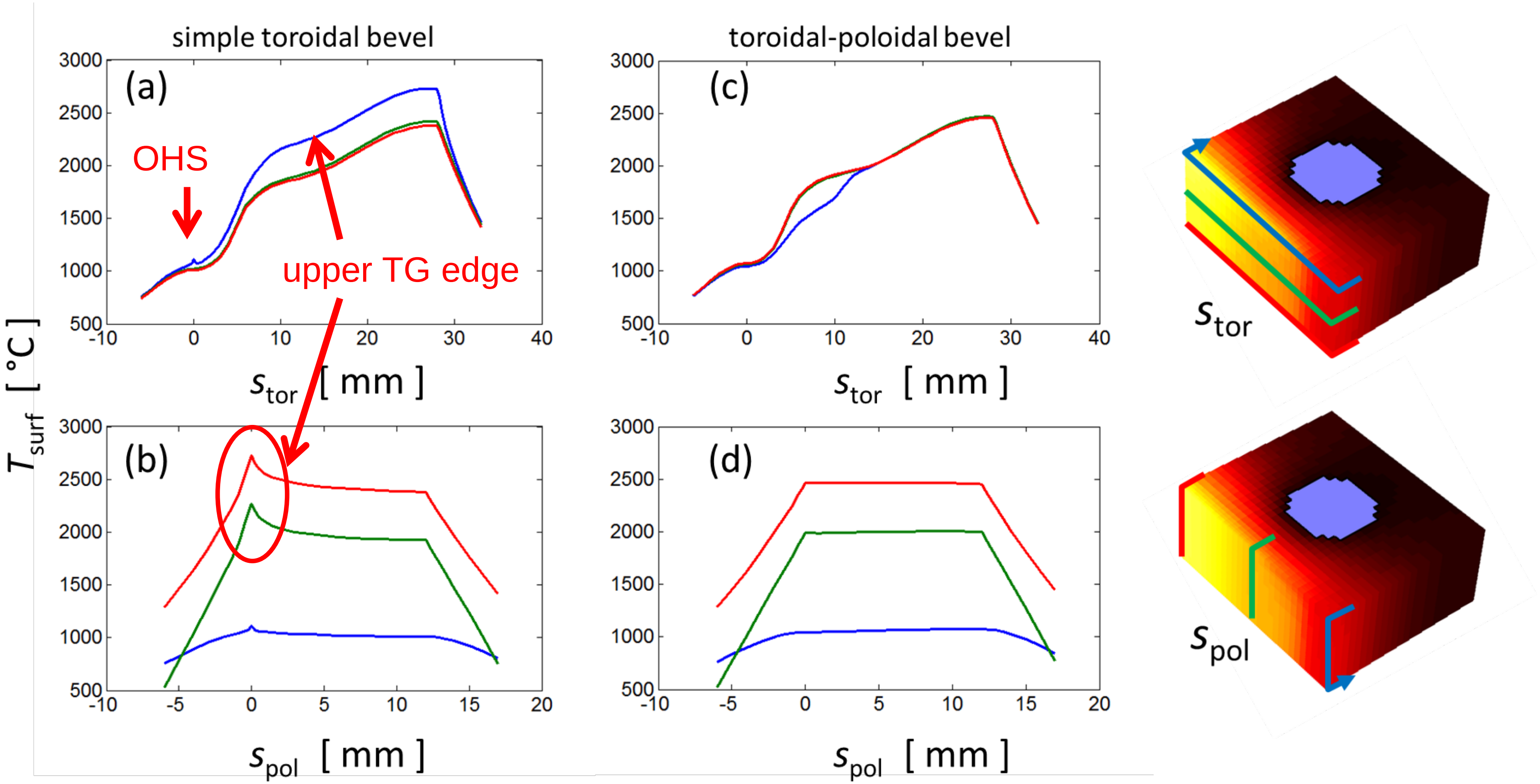
suppression of toroidal edge heating (now cooler than top surface because of shadowing)

suppression of OHS heating



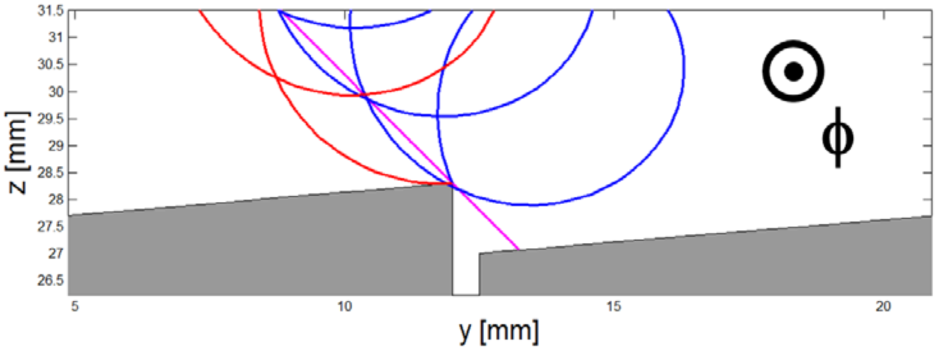
simple toroidal bevel − shallow poloidal bevel = difference

TEMPERATURE PROFILES IN TOROIDAL AND POLOIDAL DIRECTIONS



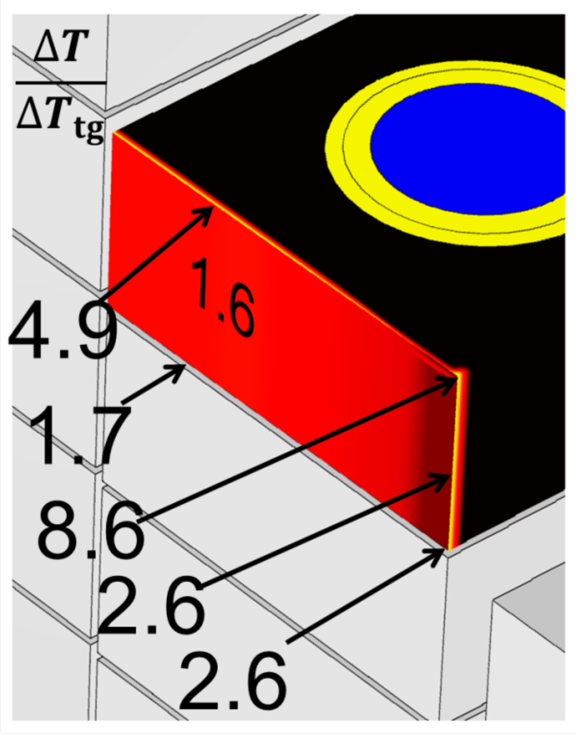
POLOIDAL BEVEL ELIMINATES UPPER EDGE AND CORNER HEATING PROBLEM DURING ELMS

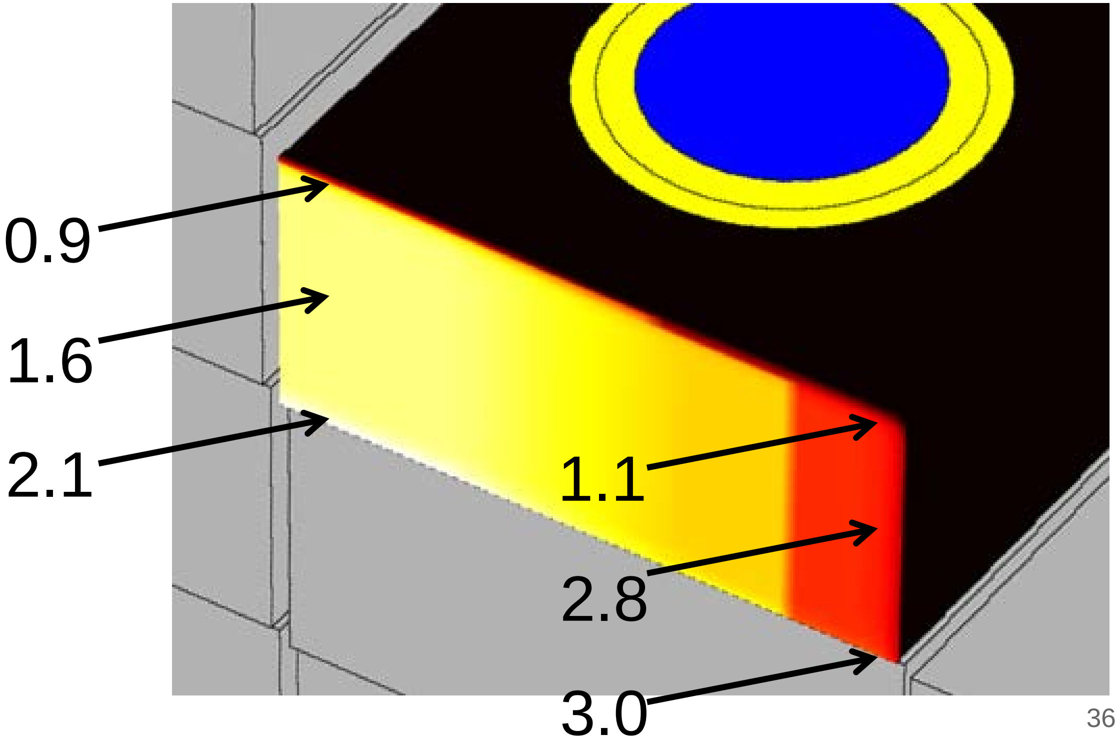
... at the expense of a slight increase along the lower edge



simple toroidal bevel

toroidal-poloidal bevel





THE BOTTOM LINE

According to ion orbit modelling (and PIC), uncontrolled ELMs will melt all monoblock surfaces and edges at both vertical targets in burning nuclear scenario.

Exposed points (<1 mm^2) at optical hot spot will be melted or even vapourized.

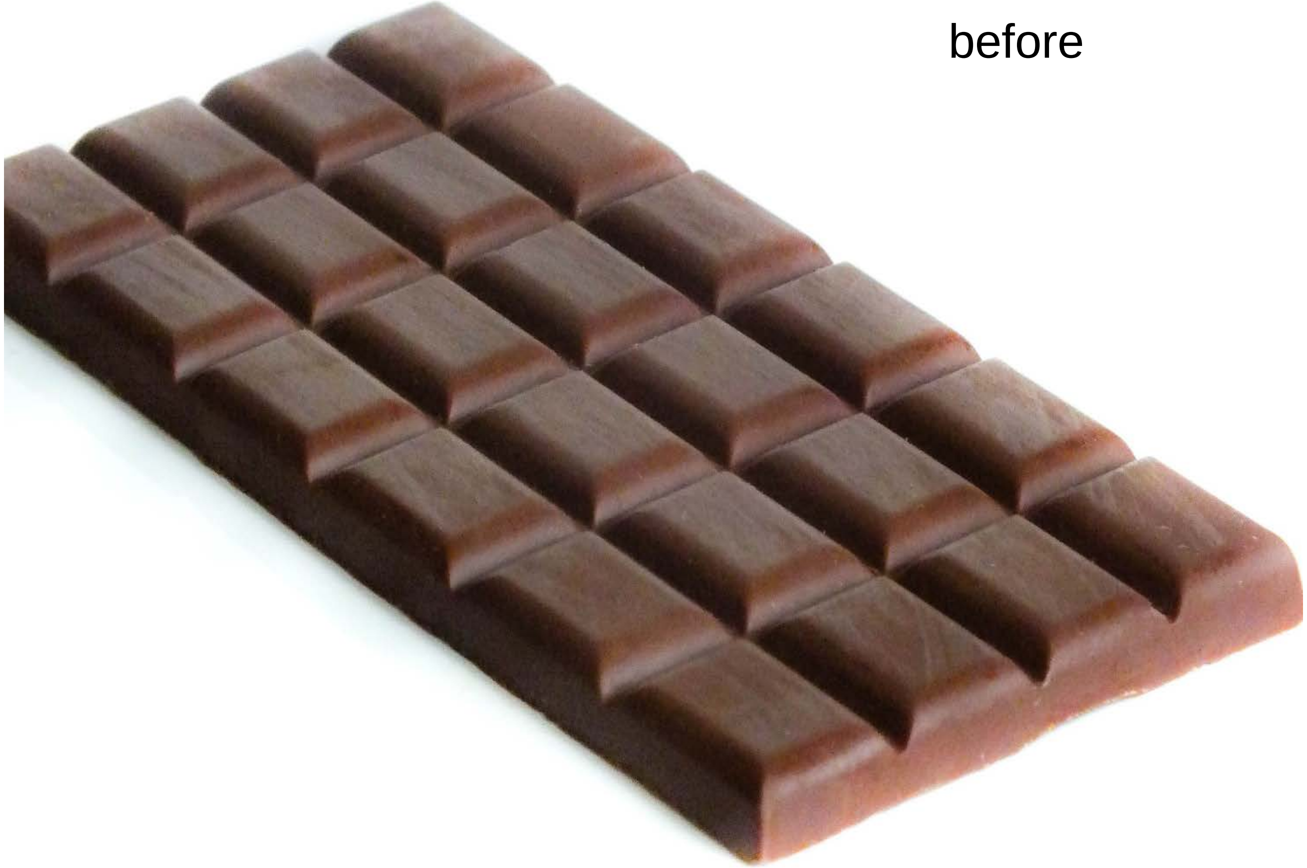
Edge melting is possible in half-field pre-nuclear scenario.
The reason: a combination of plasma physics (Larmor radius), geometry (enhancement of heating ×2 at edges, ×3 at corners), and high MB temperatures.

The simple toroidal bevel solution has been retained for ITER.
It is too late and would be too expensive to implement a more complex outer target shaping solution at this stage.
In any case there is no solution at the inner target (because of ion Larmor effect)

These findings will be useful for divertor design in future fusion devices.
(Detailed analysis submitted "soon" to Nuclear Fusion journal)

It is imperative to find ELM-free regimes in ITER.

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



before

after