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

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/m²" 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

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

<table>
<thead>
<tr>
<th>Steady State (SS) inter-ELM detached regime</th>
<th>10 MW/m²</th>
<th>to avoid W recrystallization</th>
</tr>
</thead>
<tbody>
<tr>
<td>Slow Transient (ST) reattachment (300 events)</td>
<td>20 MW/m² → 10 s</td>
<td>to avoid critical heat flux (boil-out)</td>
</tr>
<tr>
<td>Fast Transient (FT) ELMs</td>
<td>~ 0.5 MJ/m²</td>
<td>factor 2 margin against full surface melting of an initially cold monoblock</td>
</tr>
</tbody>
</table>

**ITER monoblock technology**

![ ITER monoblock technology diagram ](image)
MONOBLOCK GEOMETRY AND B-FIELD ORIENTATION

poloidal gap

m\textsubscript{pol} \pm 0.5

toroidal gap

m\textsubscript{tor} \pm 0.2

cooling tube axis

view along radius

\theta_{//}

B

m\textsubscript{pol} \pm 0.5

m\textsubscript{tor} \pm 0.2

view along magnetic field line

view along cooling tube axis

\theta

B

m_{\text{rad}} \pm 0.3

H

H-h\textsubscript{tor}

view along cooling tube axis

\theta

B

m_{\text{rad}} \pm 0.3

H

H-h\textsubscript{tor}

optical hot spot

g_{MB}=0.5

zoom of optical hot spot

leading edge hidden by toroidal bevel

zoom of optical hot spot

leading edge hidden by toroidal bevel
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 negotiations 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

B lines (exaggerated incidence angle)

Exposed leading edge

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

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

B lines (exaggerated incidence angle)

Protected leading edge

Schematic view of divertor illustrating target tilting and monoblock chamfer

Target tilting and monoblock toroidal chamfer result in increased MB heat loads
STRATEGIES TO PROTECT LEADING EDGES WORK BUT AT EXPENSE OF INCREASED $T_{\text{SURF}}$

heat flux delivered by plasma perpendicular to ideal target

$q_{\text{surf}} \approx \frac{q_{\text{tg}}}{\theta_{\perp}} + 0.5^\circ + 1^\circ$

Percentage increase of plasma heat load

<table>
<thead>
<tr>
<th>target</th>
<th>tilting+unshaped</th>
<th>tilting+bevel</th>
</tr>
</thead>
<tbody>
<tr>
<td>IVT ($\theta_\perp=3.2^\circ$)</td>
<td>+16%</td>
<td>+47%</td>
</tr>
<tr>
<td>OVT ($\theta_\perp=2.7^\circ$)</td>
<td>+19%</td>
<td>+56%</td>
</tr>
</tbody>
</table>

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

unshaped

shaped

$q_{\parallel}$

$q_{\parallel}$

>2000°C

100°C
GUIDELINES FOR STATIONARY TARGET POWER
FLUX PROFILES FROM SOLPS SIMULATIONS

$P_{\text{SOL}} = 100 \text{ MW}$

~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)

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

<table>
<thead>
<tr>
<th>target</th>
<th>$q_{tg}$ [ MW / m$^2$ ]</th>
<th>$q_{rad}$ [ MW / m$^2$ ]</th>
</tr>
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<tbody>
<tr>
<td>IVT</td>
<td>6</td>
<td>3</td>
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<tr>
<td>OVT</td>
<td>10</td>
<td>1</td>
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</table>

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/m² on strip of width 0.5 mm

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

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
poloidal leading edge visible through gap crossings
-direct irradiation by parallel heat flux (~200 MW/m² in steady state)
OPTICAL HOT SPOT NOT A PROBLEM FOR INTER-ELM LOADS

IVT \( q_{tg} = 10 \text{ MW/m}^2 \quad q_{rad} = 0 \)

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)

\[ q_{tg} \quad [\text{MW/m}^2] \]  

<table>
<thead>
<tr>
<th>q_{tg} [MW/m^2]</th>
<th>Tmax [°C]</th>
<th>q_{rad} [MW/m^2]</th>
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<td>MELT@4.8</td>
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<td>294 / 4</td>
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*assuming worst case misalignments

critical heat flux 40 MW/m² (formation of vapour layer, loss of heat handling, burnout)
Consequence of shaping - power flowing to divertor must be reduced ~2/3 to avoid recrystallization
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 detachment = 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

1. Define ELM energy $\Delta W_{ELM}$ and pedestal $T_i$
   - Scaling laws and modelling

2. Choose surface energy density waveform
   - Experiment and modelling
     - JOREK
     - SOLPS
     - PIC...

3. Calculate heat flux distribution on MB
   - Optical approximation
     - Ion orbit modelling
     - PIC code

4. Calculate thermal response
   - Heat flux factors
   - Finite elements
historical ITER limit $\varepsilon_{\text{surf}} \leq 0.5 \text{ MJ/m}^2$
-factor 2 margin against full surface melting (i.e. $T_{\text{surf}} < 1700^\circ\text{C}$)
-marginal edge melting


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

historical ITER ELM limit ($\epsilon_{tg}=0.5$ MJ/m$^2$) generates temperature spikes $\Delta T \sim 1100$ °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)
1) For a given magnetic field angle and specified ELM energy density, we calculate the corresponding \( q_{\parallel} = q_{\perp} g / \sin \alpha \).

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

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

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

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)).
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.

Most heat flux patterns can be understood from analysis of helical trajectories.
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

$\Delta T_{tg} \approx 1100^\circ C$ for $\varepsilon_{tg} = 0.5$ MJ/m$^2$

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)
## INPUT PARAMETERS FOR PRE-NUCLEAR AND NUCLEAR SCENARIOS

<table>
<thead>
<tr>
<th>plasma</th>
<th>H</th>
<th>D or He</th>
<th>D+T</th>
</tr>
</thead>
<tbody>
<tr>
<td>A/Z</td>
<td>1</td>
<td>2</td>
<td>2.5</td>
</tr>
<tr>
<td>(I_p) [MA]</td>
<td>5.0</td>
<td>7.5</td>
<td>15</td>
</tr>
<tr>
<td>B [T]</td>
<td>1.76</td>
<td>2.65</td>
<td>5.3</td>
</tr>
<tr>
<td>(n_e) ([10^{20} \text{ m}^{-3}])</td>
<td>0.3</td>
<td>0.4</td>
<td>0.8</td>
</tr>
<tr>
<td>(T_i) [keV]</td>
<td>1.7</td>
<td>2.5</td>
<td>5.0</td>
</tr>
<tr>
<td>(\Delta t_{ELM}) [(\mu s)]</td>
<td>271</td>
<td>316</td>
<td>250</td>
</tr>
<tr>
<td>steady state (q_{tg}) [MW/m(^2)]</td>
<td>2.5</td>
<td>5</td>
<td>10</td>
</tr>
<tr>
<td>(T_{init}) [(^\circ C)] surface (edge)</td>
<td>450 (550)</td>
<td>800 (1000)</td>
<td>1500 (1900)</td>
</tr>
</tbody>
</table>

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

**ELM rise time:**
empirical scaling assuming free streaming from midplane to target at ion sound speed

---


from inter-ELM thermal analysis with shaping
**PREDICTIONS FOR ITER BASED ON RECENT ELM SURFACE ENERGY DENSITY SCALING**

T. Eich  
PSI Rome  
2016

<table>
<thead>
<tr>
<th>scenario</th>
<th>full surface melting?</th>
<th>edge melting?</th>
</tr>
</thead>
<tbody>
<tr>
<td>pre-nuclear hydrogen 5MA</td>
<td>avoided with wide margin</td>
<td>avoided with narrow margin (less than 2)</td>
</tr>
<tr>
<td>pre-nuclear D or He 7.5 MA</td>
<td>avoided with narrow margin (less than 2)</td>
<td>possible during largest ELMs</td>
</tr>
<tr>
<td>DT nuclear burn 15 MA</td>
<td>unavoidable</td>
<td>unavoidable</td>
</tr>
</tbody>
</table>
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.

At OVT, both electrons and ions flow to the same side.
- Combined poloidal and toroidal bevels have the potential to mitigate the ELM and inter-ELM TG loading problem.

Increased heating at upper edge
Decreased heating on main surface
Shadowing of lower edge from ELM ions

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 tolerated
nominal TG width $g_{MB}=0.5$ mm
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
TEMPERATURE PROFILES IN TOROIDAL AND POLOIDAL DIRECTIONS

(a) simple toroidal bevel

(b) toroidal-poloidal bevel

\[ T_{\text{surf}} \quad [^\circ C] \]

\[ s_{\text{tor}} \quad [\text{mm}] \]

\[ s_{\text{pol}} \quad [\text{mm}] \]

OHS

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

simple toroidal bevel
toroidal-poloidal bevel
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 mm²) 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 \( \times 2 \) at edges, \( \times 3 \) 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.*
before
after