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Evaluation of peak power flux densities based on full ion orbit calculation: Application to WEST ITER-like target

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ABSTRACT

The peak power flux densities from plasma ion bombardment on tokamak armor surfaces can deviate from geometric-optical projection when the ion thermal Larmor radius becomes comparable to the characteristic size of the surface relief (gaps, misalignments, shaping). We present a fast and reliable tool to estimate the effect of finite ion Larmor radius on heat load deposition for complex 3D elements. The two possible geometrical design options foreseen for WEST tungsten monoblocks are asymmetric chamfer shaping and no shaping on top of monoblocks. This paper presents an evaluation of peak power flux densities for a WEST ITER-like tungsten monoblock plasma facing component which is vertically misaligned with respect to the other components of a maximum expected value of +0.3 mm, for steady state convected plasma power with ion temperature ranging from 10 to 500 eV. With the +0.5 mm asymmetric chamfer, leading edges between plasma facing components are shadowed and there is no significant difference between the optical calculations and the full ion orbit model. For an unshaped and +0.3 mm misaligned monoblock, when considering the full ion orbit model, the heat load on the exposed edge is reduced by a factor of 3–5 compared to the geometric-optical projection. Energy is found to be deposited over several millimetres on top of the monoblock just after the leading edge which prevents the tungsten armor from melting.

1. Description of WEST ITER-like PFU

Situated at the bottom of the vacuum vessel, the lower divertor of the WEST project [1] is designed to withstand high-energy plasma particle bombardment corresponding to perpendicular heat flux up to 10 MW m^{-2} in steady state.

The lower divertor is based on high heat flux actively cooled tungsten components relevant to those foreseen for the ITER divertor vertical targets. Based on the monoblock concept, each elementary component – or plasma-facing unit (PFU) – of the WEST lower divertor will follow as closely as possible the same monoblock geometry, materials and bonding technology that is envisaged for ITER [2]. The WEST lower divertor is composed of 228 pairs of PFUs connected in series (for a total of 456 PFUs) to form a 360° toroidal ring structure [3].

With respect to the incident particle flow direction at the inner and outer strike points, two oppositely asymmetric chamfer shaping regions and a transition region composed of flat top (unshaped) monoblocks constitute the design options for WEST PFU, see Figs. 1 and 2. Geometric-optical projection of heat flux parallel to magnetic field lines (see Section 2) has been applied for the dimensioning and shaping optimization of WEST PFUs so far based on the PFCFlux code [4].

For WEST parameters, the mean ion Larmor radius is in the range of several tenths of mm ($0.1 < r_L < 1.5$ in mm), which is the same order of magnitude as surface features arising from castellation or assembly tolerances. Thus, effect of finite Larmor radius on power deposition needs to be considered to assess local power loads at the monoblock scale.

2. Geometric-optical calculation of thermal loads

In this model, the heat flux deposited on a surface is $q_\perp = q_{//} \cdot \sin(\alpha)$ where $q_{//}$ is the total convected parallel power and α the incident angle with respect to the wetted surface of the PFU.

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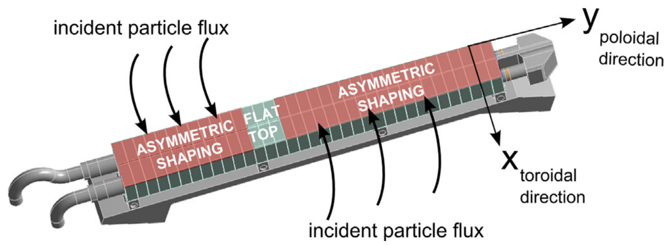

Fig. 1. Set of two WEST ITER-like PFU connected in series integrating two geometric design options: asymmetric chamfer and no shaping (flat top).

In the rest of this document, we define the geometric-optical peaking factor ($p^{optical}$) as the ratio between the perpendicular heat flux deposited on a monoblock face divided by the heat flux deposited on top of a flat monoblock without castellation. For monoblock geometries of Fig. 2 ($\alpha_{shaping} = arctan(0.5/28) \approx 1°$) and for an incident angle of $\alpha_i = 2°$ (typical angle value expected on both ITER and WEST), this definition leads to geometric-optical peaking factors of:

- $p^{optical}_{shaped} = q^{shaped}_{\perp}/q^{flat}_{\perp} = \sin(\alpha_{shaped})/\sin(\alpha_{flat}) = 1.5$ for a shaped monoblock;
- $p^{optical}_{flat} = q^{flat}_{\perp}/q^{flat}_{\perp} = 1.0$ for a flat top monoblock;
- $p^{optical}_{inter\ PFU} = q^{inter\ PFU}_{\perp}/q^{flat}_{\perp} = \sin(\alpha_i + \pi/2)/\sin(\alpha_{flat}) = 28.6$ for leading edges.

3. Ion orbit calculations of thermal loads

3.1. Code main features

This paper presents results from a full ion orbit code using a Monte Carlo method for solving stationary surface heat loads. Equations of motion are solved by the widely adopted Boris algorithm [5,6]. An electric field profile can be specified to simulate, for example, the effect of the Debye sheath on the ion orbits [7], but in this paper it is set to zero. Integration of Visualization ToolKit library (VTK [8]) to handle geometries permits to use realistic computer aided design geometries. Outputs in VTK standard file format permits to use third party software like Paraview [9] for direct visualization or data analysis.

3.2. Model assumptions

A simulation domain represented by an Axis Aligned Bounding Box (AABB: $x_{min}, y_{min}, z_{min}, x_{max}, y_{max}, z_{max}$) is used for confinement of injected particles. Periodic boundary conditions are imposed in the x- and y-directions (see Fig. 3).

A stationary and homogeneous magnetic field $\vec{B}$ with an inclination angle of $\alpha_i = 2°$ with respect to the x–y plane (or flat top surface of an unshaped monoblock) is assumed. Magnetic field magnitude is $B = 3.4$ T. A time step of $dt = 10^{-10}$ s is used to advance particle position and speed. This value has to be compared with cyclotron frequency $\omega_c = q \cdot B/m \approx 1.6 \cdot 10^8$ Hz and corresponds to an average of $2\Pi/\omega_c * 1/dt \approx 393$ time steps to describe each Larmor gyration.

Monoblock dimensions are 28 mm × 12 mm × 28 mm (respectively in x, y and z direction). The gap between two PFUs (inter PFU) is set to 0.5 mm, a representative value for both WEST and ITER.

Fig. 3 shows the three consecutive monoblocks labelled MB1, MB2 and MB3 (naming convention with respect to particle flow), in the toroidal direction with a maximum vertical misalignment between neighbouring monoblocks of +0.3 mm for MB2. Due to the periodic boundary condition imposed for the simulation, this set up corresponds to 0.0 mm, +0.3 mm and −0.3 mm misalignments for MB1, MB2 and MB3 respectively (see Fig. 3). We restrain the analysis to the toroidal direction. Intra PFU power densities are not taken into account in this study, hence the gap between two monoblocks of a same PFU (intra PFU) is set to 0.0 mm, and the poloidal (y) component of the magnetic field is ignored.

The case considered in this paper is a fully ionized magnetized plasma of singly charged deuterium ions incident on a completely absorbing, conducting wall. Ions are uniformly injected from the normative surface into the simulation box (AABB: 0, 0, 0, 85.5, 12, 32 in mm) towards the wall (see Fig. 3). In the perpendicular direction, we assume a thermal Maxwellian distribution characterized by temperature T_i ($v_{therm} = (kTi/mi)^{1/2}$). The mean velocity in the parallel direction is equal to the ion sound speed, here $(k(T_i + T_e)/mi)^{1/2}$ assuming equal ion and electron temperatures with a width of $(1/3)v_{therm}$ [10].

For each of the two design options (shaped and unshaped monoblocks of Fig. 2), four simulations with deuterium ion temperature $T_i = 10$, 50, 100 and 500 eV were performed in order to investigate the effect of mean Larmor radius ($r_L = 0.20$, 0.44, 0.64 and 1.39 mm, respectively) on the deposited heat flux profiles. The two lower values of Ti are representative of the inter-ELM divertor plasma expected in WEST, whereas the higher values are order-of-magnitude estimates of the pedestal ion temperature during edge localized modes.

Remark 1. In the following, intercepting geometries (polygonal meshes) will be referred to as M, the amount of elements (polygonal meshes) in M as n and its elements as M_j with $1 \leq j \leq n$.

For all post treated values of Sections 4.1 and 5.1, full ion orbit peaking factor of a polygon M_j noted p^{orbit}_j and given in arbitrary units (a.u.) equals to $p^{orbit}_j = \frac{P_{M_j}}{A_{M_j}} \cdot \frac{A_{Normative\ surface}}{\sum_{j=1}^{n} P_{M_j}}$ where P_{M_j} is the sum of particle energies intercepting M_j; A_{M_j} is the area of M_j; $A_{Normative\ surface}$ is the area of the normative surface of Fig. 3 (which corresponds to the ideal flat monoblock without castellation referred to in Section 2).

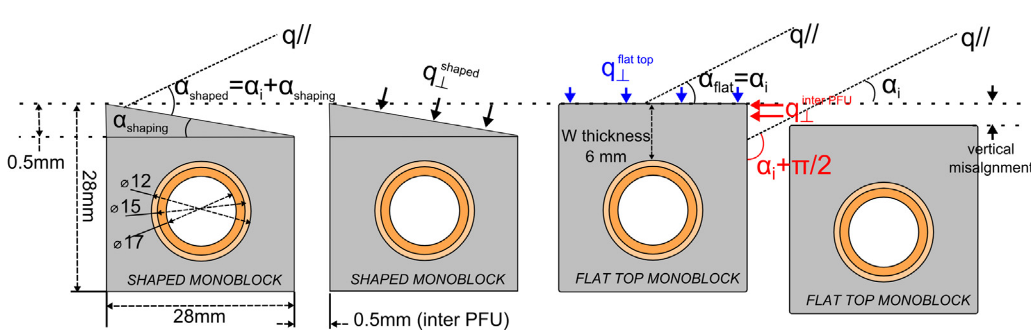

Fig. 2. Two design options for monoblocks: asymmetric toroidal chamfer shaping (shaped) and flat top (unshaped) with their associated terminology.