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Simplified heat load modeling for design of DEMO discrete limiter

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Abstract

The design of the Plasma Facing Components (PFCs) requires to model the charged particles heat load circulating in the Scrape-Off Layer (SOL). Ray-tracing codes like PFCFlux or SMARDDA can model charged particles heat load assuming that particles follow the magnetic field lines. Calculations on limited equilibria with discrete objects like limiters show an important underestimation of heat load. In fact, all the power of the SOL is not reported on the wall, the part of missing power reaching more than 80% of the total SOL power in worst cases. This paper will present why some power is missing in this case, and different ways to rescale the heat load results and recover all the power of the SOL. The maximum heat load on the limiter can vary between 3.5 MW/m^2 to more than 20 MW/m^2 in function of the rescaling method.

Keywords: Plasma Facing Components (PFC), charged particles heat load, ray-tracing code, DEMO, limiter, PFCFlux

1. Introduction

The shaping of the Plasma Facing Components (PFCs) is a fundamental challenge for future fusion reactors like DEMO. The First-Wall (FW) shape has to be adapted to some steady state scenarii and be enough protected to ensure that the PFCs will not reach their thermal limits during trancient perturbation (minor disruption, Vertical Displacement Events...). The EUROFusion program WPLSI is in charge of designing the FW of DEMO [1] [2].

Finding an optimized number of limiters is a key issue for the design of a tokamak [3]. Too many limiters lead to a more complex design and increase the cost and maintenance time. On the contrary, too few limiters can cause too much heat load on them or not enough protection of the FW. Thus, simulation are needed to optimize the number of limiters.

The core heat load source on PFCs is caused by charged particles circulating in the SOL, following the magnetic field lines and impacting the PFCs. Design studies need the use of simplified models for fast simulations (couple of minutes) of the heat load, allowing for numerous go and back between CAD office and physic simulations. The simplest way to model the charged particles heat load is to assume that it comes from the Outer Mid Plane (OMP), is conducted parallel to the magnetic field lines and decreases exponentially (decay length λ_q) in the SOL from the Last Closed Flux Surface (LCFS). Effects of Larmor radius or electrostatic sheath are thus not taken into account. Codes like PFCFlux [4] or SMARDDA [5] use ray-tracing techniques to estimate the heat load deposited on PFCs on 3D CAD models with this approach and are used to design of DEMO FW.

This paper will present firstly the principle of a PFCFlux calculation and a result obtained on a limited equilibrium, then explaining why limited cases presents some missing power and how to understand it. Several ways to rescale the heat fluxes in limited cases will be introduced with their hypothesis and limits in a third part. Therefore finally applied the rescale of the heat flux on DEMO limiter for the previous limited equilibrium.

2. Charged particles heat load modeling

PFCFlux works in a two-step calculation.

2.1. Backward magnetic shadowing calculation

For a design calculation, the need is concentrated on what is the heat flux on the first wall or the limiter. It is thus of importance to model with a thin mesh the geometry and determine if particles can hit those locations. Thus, a *backward* calculation is more convenient in this case, allowing to calculate at each position of the wall if a magnetic shadowing is possible or not. The principle of the magnetic shadowing calculation is to start from any location of the First Wall and to follow the magnetic field line in the *backward* direction.

- If this magnetic field line reaches the OMP first, this location of the FW can receive particles from the OMP and thus charged particle heat load ($S = 1$).

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- If the magnetic field line is intersected by an object before reaching the OMP, this location of the FW is magnetically shadowed and can't receive heat load ($S = 0$).

The figure 1 gives a 2D representation of the magnetic shadowing calculation, with on the left a point of the FW which reaches the OMP and on the right another point from the FW which intersects a wall. A PFCFlux calculation is done in 3D.

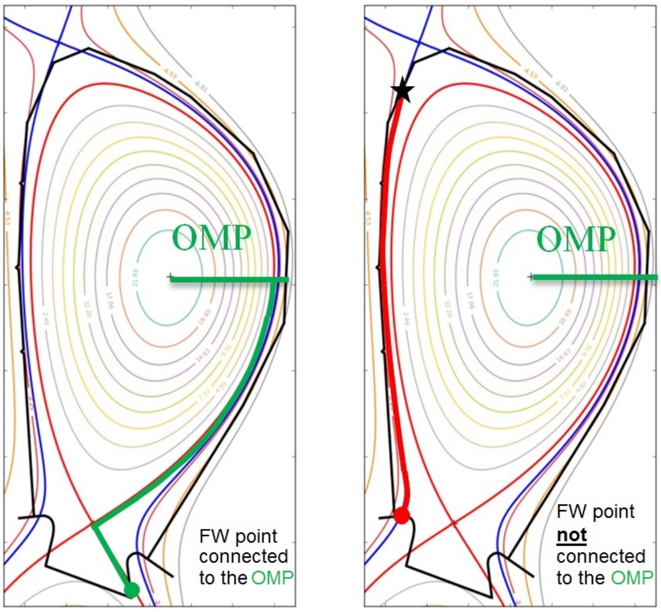

Figure 1: 2D repesentation of the magnetic shadowing calculation with PFCFlux

2.2. Heat load calculation

The parallel flux conducted by the particles is maximum located at the LCFS and decreases exponentially in the SOL as function of a decay length λ_q (from 6mm to 50mm in function of the equilibrium considered [1]). The expression of the parallel flux at a given position on the OMP is given in equation (1)

$$\phi(d) = \phi_0 \times e^{-d/\lambda_q} \tag{1}$$

where d is the geometric distance at the OMP between the LCFS and the magnetic field line at given ψ value. The maximum parallel flux value ϕ_0 is fixed so that the integration of the parallel flux on the OMP matches the total power conducted by the particles inside the SOL.

$$\int_{OMP} \phi dS = P_{cond} \tag{2}$$

The heat load on the wall is calculated by the following equation:

$$\varphi(\vec{r}, d) = \phi(d) \times sin(\alpha(\vec{r})) \times f_x(\vec{r}) \times S(\vec{r}) \tag{3}$$

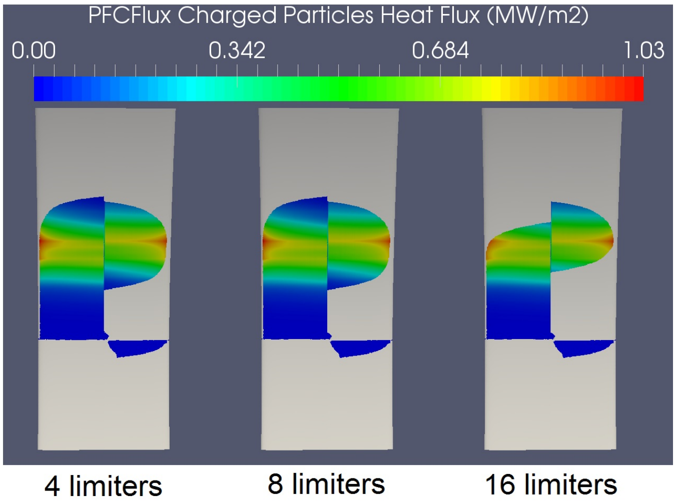

Figure 2: Heat load on a limiter for different number of limiters

where $\alpha(\vec{r})$ is the incident angle of the magnetic field line on the wall at the position $\vec{r}$, $f_x(\vec{r})$ the magnetic expansion of the field line between the OMP and the position $\vec{r}$ and $S(\vec{r})$ the result of the shadowing calculation.

2.3. Power ratio ρ

After each PFCFlux calculation, a power ratio ρ is calculated between the integration of the heat flux on walls and the total power inside the SOL.

$$\rho = \frac{\int_{wall} \varphi dS}{\int_{OMP} \phi dS} \tag{4}$$

In almost all cases, a point from the wall is paired with one point from the OMP, leading to a power ratio ρ close to 1, ensuring good energy conservation.

However, in limited equilibria and with discrete objects on 3D geometry, this power ratio drops, up to 0.2, i.e. only 20% of the power conducted by the particles is distributed on the wall. The figure 2 shows the heat load on a DEMO limiter for different number of limiters (4-8-16) inside the tokamak and for those three *backward* calculations, the power ratio ρ is going from 0.29 with 4 limiters to 0.51 with 8 limiters and 0.8 with 16 limiters.

One can see that for the 4 and the 8 limiters cases, the wetted area given by the backward shadowing calculation is almost identical.

As the magnetic flux is assumed to be toroidally constant, the heat flux calculation on a limiter gives the same result in the 4 limiters case that in the 8 limiters case.

Thus, with the same wetted area and heat flux pattern for 4 and 8 limiters cases, this explain why the power ratio is almost two times lower in the 4 limiters case than in the 8 limiters case.

This missing power issue is explained by the fact that some points from the OMP are not directly paired with the wall and need more than one poloidal turn. The *backward*

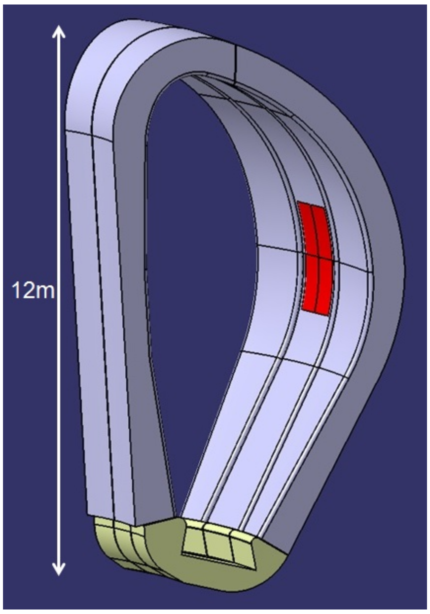

Figure 3: CAD geometry of a sector (22.5°) of DEMO - FW in blue - Outer limiter in red - Lower divertor in yellow

calculation can't allow to retrieve all the points from the OMP connected to the same point on the wall. Thus, wall heat fluxes are underestimated and a rescaling is needed to give more relevant heat flux values regarding to the energy conservation law.

3. Modeling of the missing power

3.1. Case studied

To understand the missing power in the previous case, a *forward* calculation is performed from the OMP. For each location on the OMP, we follow the magnetic field lines in the *forward* direction and see if this line hits a wall, a limiter, or the OMP itself. Calculation was done with the CAD geometry of DEMO (see Figure 3): 16 sectors of First Wall (FW) (height = 12m, minor radius = 6m, major radius = 12m) and a number of equatorial outer limiters between 2 and 16 (height=2.8m,width=1.1m, maximum protrusion to FW = 2cm) . The most representative part of the OMP was modeled (range of magnetic flux values between the LCFS one to a little further than the X-point one, involving a width of 20mm, see Figure 4).

Calculations was performed with PFCFlux with a magnetic equilibrium corresponding to a Ramp-Up case (figure 5), where the power conducted by the particles $P_{cond} = 6MW$ and the decay length $\lambda_q = 6mm$, based on the DEMO prediction in [1].

3.2. Area of missing power

The aim of this calculation is to detect the area where the OMP is paired with a wall or a limiter and where the OMP is connected to itself (leading to missing power in the *backward* calculation). The results shown in Figure 6

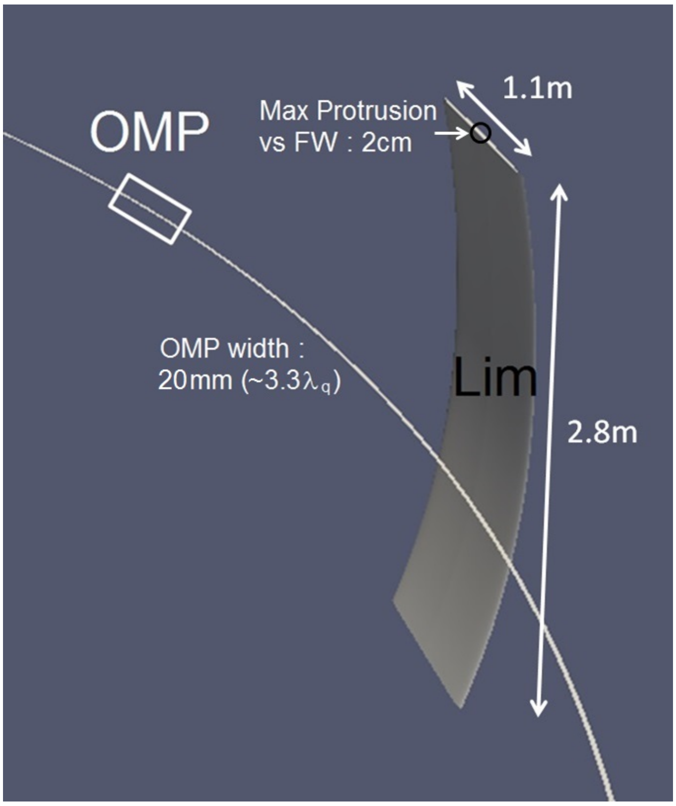

Figure 4: Outer mid plane modeled in front of an outer limiter

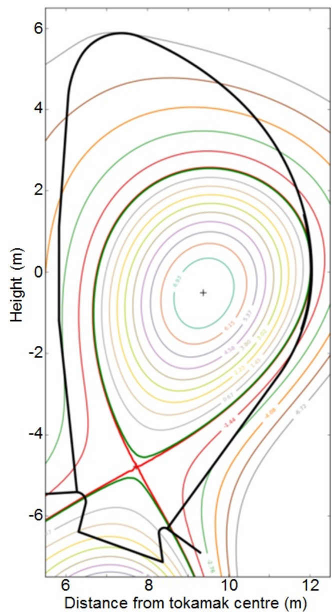

Figure 5: Ramp-Up equilibrium. Ip=6MA. Bold red line : X-Point. Bold green line : LCFS

illustrate a local zoom of the OMP (see rectangle on the figure 4) for calculations with different numbers of limiters inside the tokamak (from 2 limiters to 16 limiters).

In those figures, the green area represents all points from the OMP directly connected to the wall or to the lower divertor, as expected since these points got a magnetic flux value below the X-Point one. As those magnetic flux surfaces are open, a point from the wall can't perform more than one poloidal turn before touching another wall.

The red area indicates all points from the OMP not paired with the wall. A poloidal turn can be done without touching the FW or a limiter and thus this represents the missing power in *backward* calculation.

The white areas gives the link between the OMP and a limiter. On the 2 limiters case (left figure), one can see that the red area is very large, leading to a huge missing power issue.

This figure presents a local area of the OMP but the result is not toroidally symmetric. The connected areas are function of the distance to the limiter and the magnetic flux where the OMP is connected to a limiter is not constant toroidally. When the number of limiters increases (figure from left to right), the area where the OMP is connected to a limiter also increases, leading to a lower missing power issue, as seen in the *backward* calculation.

3.3. Quantification of the missing power

For each magnetic flux on the OMP, we compare the area of the OMP reaching an object to the one reaching the OMP itself. The operation was done for each limiter configuration (2 limiters to 16 limiters). Results are presented in the figure 7.

The missing power is mostly concentrated near the LCFS and all power is recovered when reaching the X-Point ψ. This figure shows that the missing power is not equally distributed. All walls spots below X-Point ψ don't need rescale and heat load on high ψ value are largely underestimated.

The figure 8 represents the heat load consumed on the OMP for different number of limiters inside the tokamak. Because of the missing power illustrated on figure 7, the heat flux shape is not an exponential decay as it should. The area ratio between a given curve and the expected one (red curve) represents the power ratio for this *forward* calculation. Those ratios (ρ in the legend) are very closed to the one observed after a *backward* calculation (see 2.3), meaning that the same phenomenon occurs in forward and backward calculation.

4. Rescaling of heat load calculations with missing power

4.1. Basic rescale

The easiest way to rescale the missing power is to divided all heat load on the wall by the power ratio ρ.

$$\varphi_{basic\ rescale} = \varphi \times \frac{\int_{OMP} \phi dS}{\int_{wall} \varphi dS} \tag{5}$$

This rescaling method implies that the missing power is equally distributed on the FW and limiters, although the figure 7 shows that it's not the case and this approach is surely not acceptable. With this rescaling, the heat flux shape at the OMP is not anymore in an exponential decay.

4.2. Rescaling for each ψ value

A second way to rescale the heat load is to quantify the missing power at the OMP for each distance to the LCFS.

$$\varphi_{PSI\ rescale}(d) = \varphi(d) \times \frac{\int_{OMP} \phi dS\big|_d}{\int_{wall} \varphi dS\big|_d} \tag{6}$$

The main hypothesis is that different spots on the walls or limiters with the same magnetic flux got the same missing power. The validity of this method is also discutable because of the toroidal asymmetry of the geometry as the result of the figure 6 is not toroidally constant.

4.3. Rescaling in function of the maximum number of poloidal turns

This third method relies on the fact that the application between the OMP and the wall is not bijective yet for limiter cases, but only surjective. To find all OMP points associated to one given wall point, the algorithm needs to continue following the field line even after reaching the OMP, until it hits another object. The number of particles coming from different spots of the OMP to the same location of an object is then equal to the number of poloidal turns made (see figure 9)

4.4. Effect of the different rescaling method on limiters

The different rescaling methods are tested on a 4 limiters case. The figure 10 shows the heat load on the front face of a limiter, after rescaling the flux by the different rescaling methods presented previously, even those with strong physics assumption.

When no rescale are done, the ratio of power recovered is about $\rho = 0.29$, with a maximum heat flux of $1.03MW/m^2$ on the limiter. The basic rescale doesn't modify the distribution of the heat load on the limiter, just forcing a ratio $\rho = 1$. This method gives thus a maximum heat load of $1.03/\rho = 3.54MW/m^2$.

The PSI rescale method creates higher heat load on the center of the limiter, where the highest ψ value are so where the most missing power is according to the figure 7. The maximum heat load in this case increases to $8.2MW/m^2$.

The rescaling by the number of OMP passages presents a more intriguing pattern, with very high heat load localized on some constant ψ values, reaching up to $21.7MW/m^2$. Those areas are positioned where the number of toroidal turns for each poloidal turns is almost rational, giving very

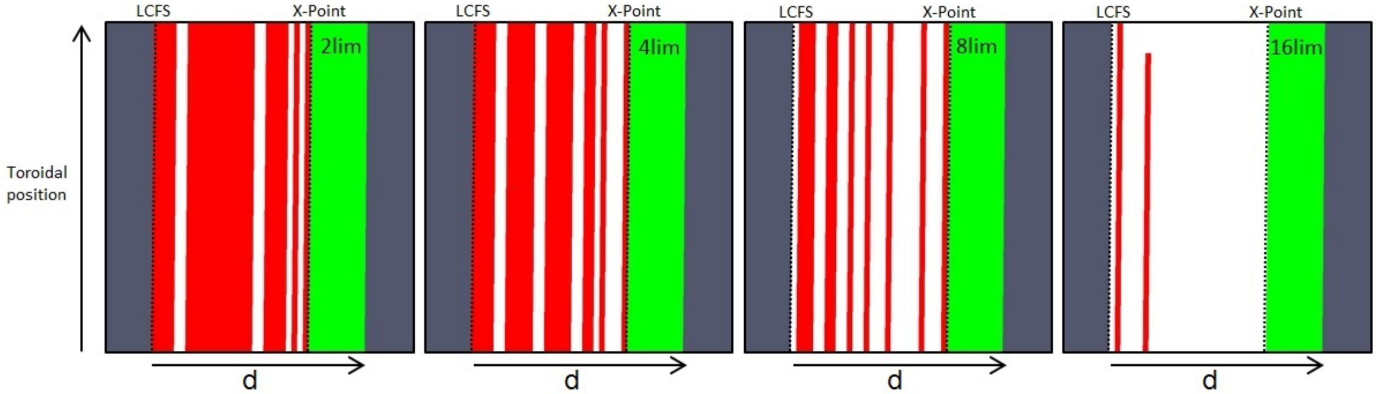

Figure 6: Field line tracing from the Outer Mid Plane for different number of limiters - Green : the OMP is connected to a wall - White : the OMP is connected to a limiter - Red : the OMP is not paired with the wall/limiters (connected to itself)

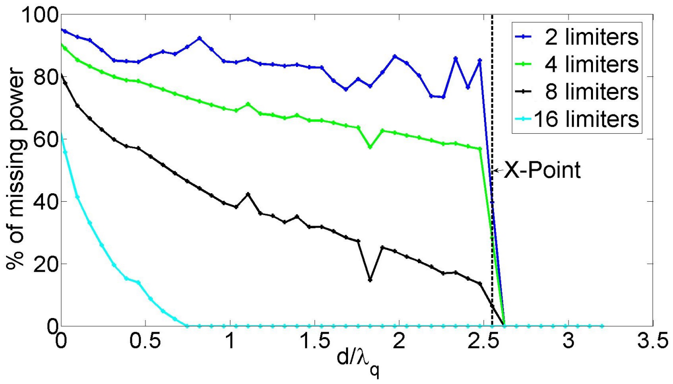

Figure 7: Pourcentage of missing power at the OMP. LCFS is at x=0. $\lambda_q = 6mm$. $P = 6MW$.

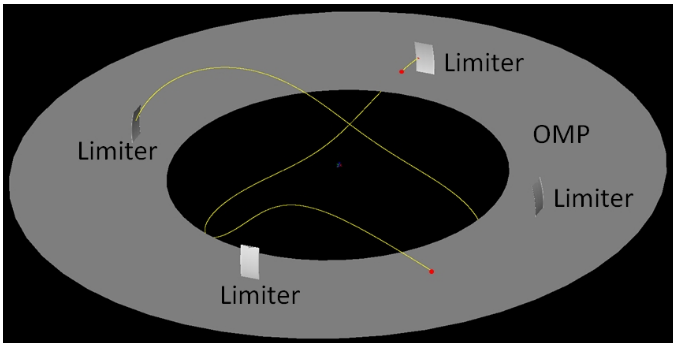

Figure 9: Simplified representation of a magnetic field line starting from a limiter and hitting two positions of the OMP (red dots) before hitting a limiter

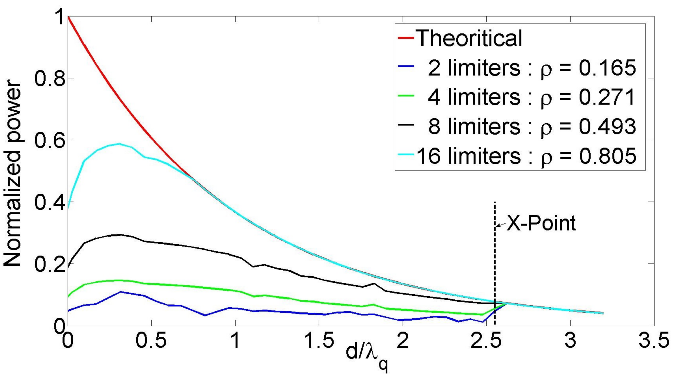

Figure 8: Heat flux shape on the OMP taking into account the missing power. $\lambda_q = 6mm$. $P = 6MW$.

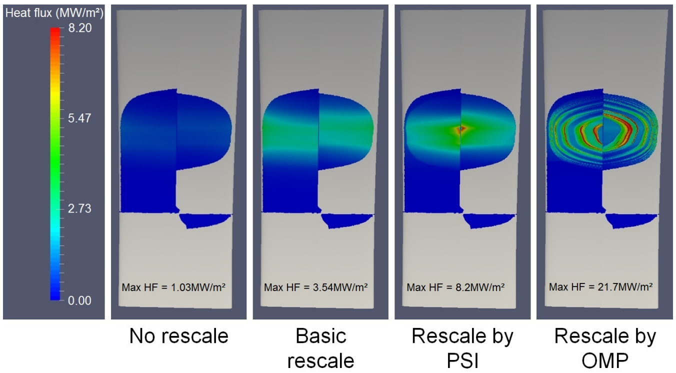

Figure 10: Heat load on a limiter for the different rescaling methods

few toroidal movement of the intersection point with the OMP and thus need a lot of poloidal turns before reaching another wall. The magnetic field lines are thus followed on a distance up to 7km.

5. Conclusion and prospects

Simplified models using 3D field line tracing are used to design the shaping of the PFCs on new tokamak. Those models allow fast simulations for optimizing the design of the FW or limiter protections. Limiter equilibrium studies are more difficult to model accurately with those simplified model, because they lead to some missing power, due to the fact that the link between the OMP and the FW becomes surjective instead of bijective. Several methods were discussed to rescale the heat load on limiters and FW to match the power balance. The rescaling is of importance since the resulting heat load on the limiter is multiplied by 3 to 21.

Some comparison with experiments and simulations carried with more physics complexity would help to quantify the errors of each rescaling method and improve the rescaling method, in particular the one consisting to count the number of passages at the OMP which could be improve with a parallel diffusion of the particules, especially for high connection length.

Acknowledgments

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References

[1] R. Wenninger et al. The DEMO wall load challenge. *Nuclear Fusion*, 57(046002), 2017.

[2] F. Maviglia et al. Wall protection strategies for DEMO plasma transients. *Fusion Engineering and Design*, 2018. https://doi.org/10.1016/j.fusengdes.2018.02.064.

[3] P.C. Stangeby. A three-dimensional analytic model for discrete limiters in ITER. *Nuclear Fusion*, 50(035013), 2010.

[4] M. Firdaouss et al. Modelling of power deposition on the JET ITER like wall using the code PFCFlux. *Journal of Nuclear Materials*, 348:536–539, 2013.

[5] W. Arter et al. The SMARDDA approach to ray-tracing and particle tracking. *IEEE Transaction on Plasma Science*, 43-9:3323–3331, 2015.