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Plasma power deposition to first wall of ITER reactor with focus on ray-tracing

The work by UL focuses on the optimization of ray-tracing techniques, commonly used in simulation of nuclear fusion phenomena, especially estimation of radiation on plasma facing surfaces, signal calculation of diagnostic systems to arrive at synthetic diagnostic signal. Our analysis presents a study in ITER tokamak, starting from magnetic equilibria of plasma to arrive at heat flux at plasma-facing components due to particles conducted along magnetic field lines using L2G code [1]. Then a thermal model is solved using OpenFOAM [2] to convert heat fluxes into temperatures. Finally a Monte Carl ray-tracing technique can be used to estimate radiation from plasma combined with radiation from plasma facing surfaces to assess total heat load on a specific surface. Optimization technique KD-tree partition is explored. Strong scaling and weak scaling study is presented for ray-tracing code Raysect [3].

Field line tracing

Main goal is to determine whether a field line intersects individual sections of plasma facing components Due to shaping of PFC tiles, field lines intersect some PFC surfaces but not all. L2G code solves the field-line equation.

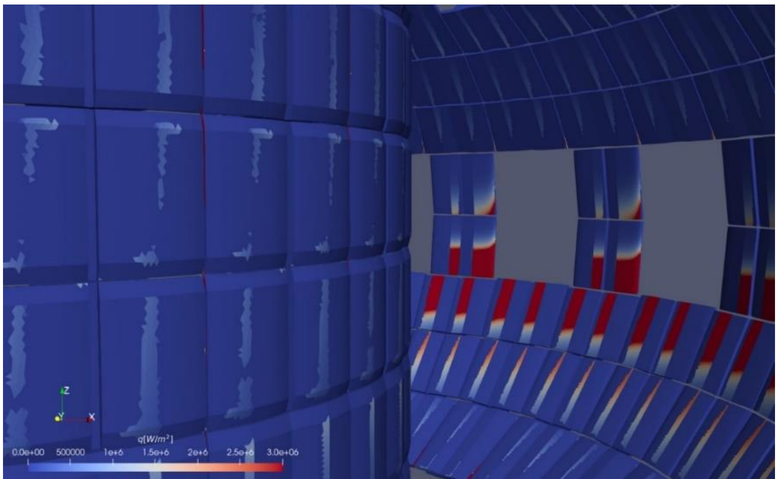
The standard field-line equation is given as

$$\dot{x} = \frac{dx}{dt} = B(x)$$

Heat flux is calculated through

$$Q = \frac{F P_{loss}}{2\pi R_m \lambda_m B_{pm}} \boldsymbol{B} \cdot \boldsymbol{n} \, exp\left(-\frac{(\psi - \psi_m)}{\lambda_m R_m B_{pm}}\right)$$

F is the fraction of power lost in the flux tube, $\boldsymbol{B} \cdot \boldsymbol{n}$ is dot product between normal and magnetic field, $P_{loss}$is power loss in scrape-off layer, λ_m is decay length, R_m is radial distance from separatrix and ψ is magnetic flux.



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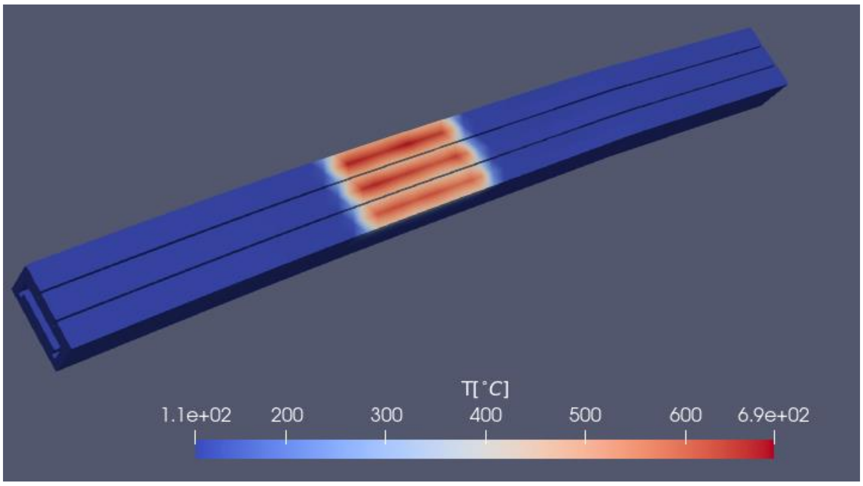
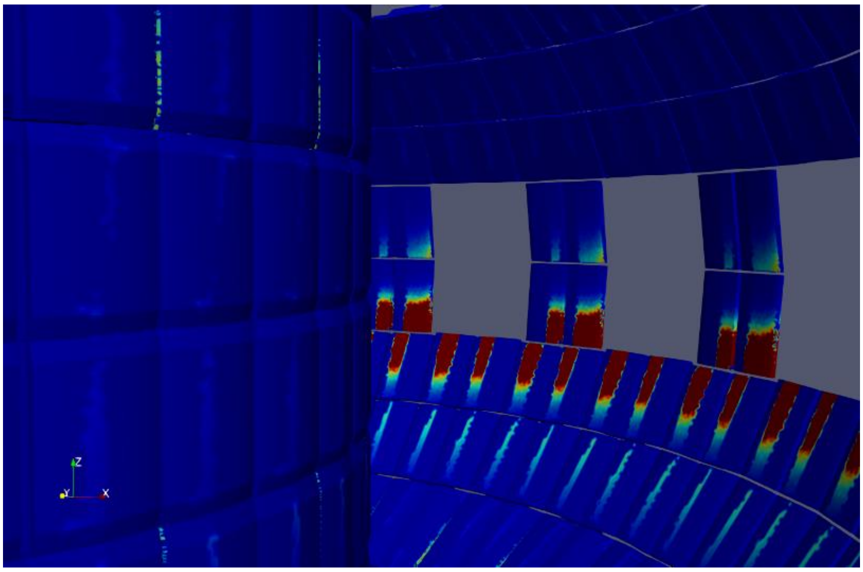
Heat transfer

Heat transfer is used to calculate temperature from plasma heat fluxes, which are prescribed on the surface as boundary condition. Temperature dependent material properties are taken into account (density $\rho[kg/m^3]$,heat capacity $c_p[J/(kg \cdot K)]$, heat conductivity $k[W/(m \cdot K)]$) to solve the diffusion equation of a 3D plasma-facing structure. At ITER, the first wall comprises of so-called fingers, made of beryllium or tungsten as being the first materials exposed to plasma. The diffusion equation is solved:

$$q = -\kappa(T)\nabla^2 T, \quad \text{with } \kappa(T) = \frac{k(T)}{\rho(T)c_p(T)}$$

Finger temperature distribution.





Temperature distribution on all blanket panels. Maximum temperature is around 1000°C.

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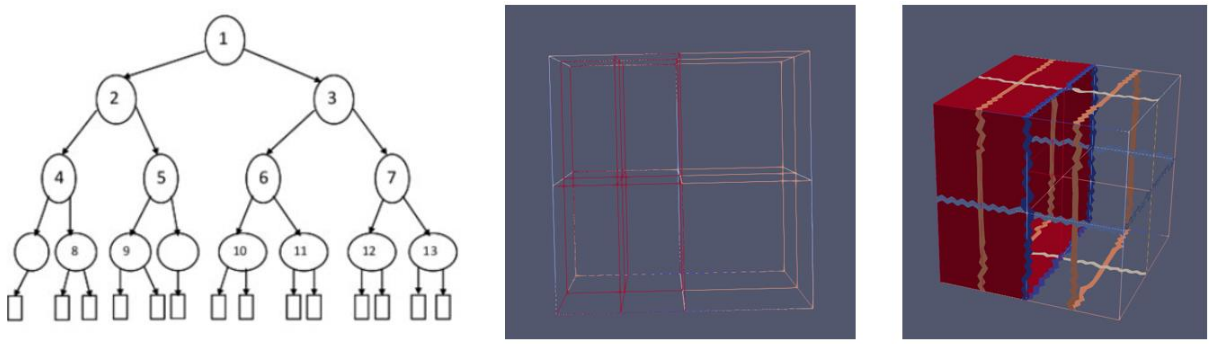
Ray-tracing

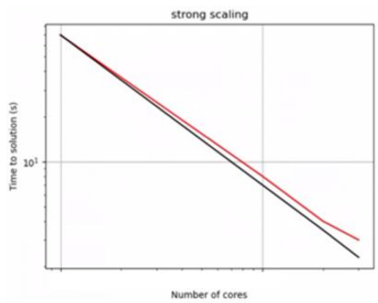
Performance of ray-tracing code Raysect

KD-tree partition is used to separate computational mesh into boxes that contain multiple sub-boxes (tree structure with multiple levels). The intersection of ray with computational mesh is done only for the box, thus speeding up the process.



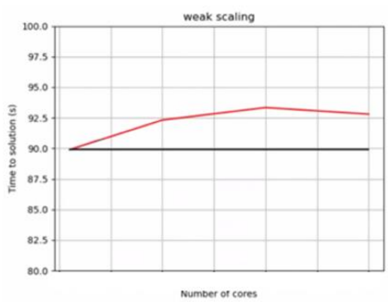
(left) KD-tree structure. Fig. courtesy [4] (middle) Partition into bounding boxes (right) Triangular mesh sorted into boxes.

In ray tracing, backwards ray-tracing is employed, meaning that rays are generated on the object of interest and projected into computational domain where their parameters are assessed. The case for both strong and weak scaling contains ~26k triangles. From each triangle 40 rays were launched randomly into space and checked for intersection with objects in the scene (in total ~1.41 million triangles). For weak scaling number of triangles is the same but number of rays on each triangle is reduced accordingly.



N proc	Actual time (s)	Ideal time (s)
1	70.7	70.7
10	8.4	7
20	4.7	3.5
30	3.9	2.33

Strong scaling for Raysect



N proc	Actual time (s)	Ideal time (s)
1	89.89	89.89
10	92.32	89.89
20	93.34	89.89
30	92.8	89.89

Weak scaling for Raysect

Scaling plots for Raysect.

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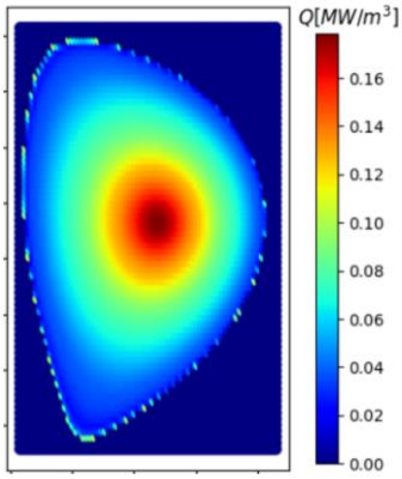
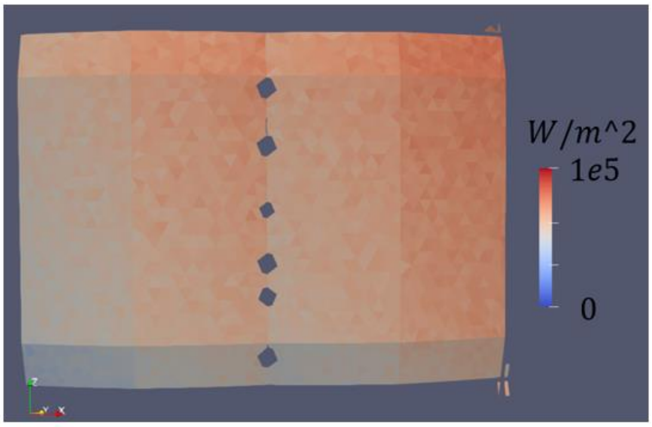
In the Monte Carlo Ray Tracing Method (MCRT) the radiative heat transfer is calculated by randomly releasing a statistically large number of energy bundles from observer geometry and tracking their progress through the scene. For a specific plasma configuration, a radiation profile is defined (either as power $P[W/m^3]$ or radiance $I[\frac{W}{m^3 sr}]$). From temperature on surface, radiance can be derived from Stefan-Boltzmann law. The total power P_i arriving at observing surface S_i is defined as integral of the incident radiance $L_i(\boldsymbol{r},\omega)$ over the collecting solid angle Ω and surface area A_i

$$\mathrm{P_i} = \int_{\mathrm{A_i}} \int_{\Omega} \mathrm{L_i}(\boldsymbol{r}, \omega) \cos\theta \, \mathrm{d}\omega \mathrm{d}A$$





(left) Example of plasma radiation at ITER (core plasma) (right) Example of photonic radiation on panel 4 at ITER (core plasma + surface temperatures)

Conclusion

In conclusion, this study addresses the procedure to arrive at calculating the radiation on the surface of nuclear devices. Some optimization of ray-tracing method is presented. In the future, the kernel of Raysect (ray-triangle intersection) is to be rewrittenCurrent algorithmic improvements are k-d tree partition and Russian roulette algorithm for terminating reflected rays. Importance sampling is also implemented to sample rays more effectively. Tracing of each ray can be executed concurrently i.e. tracing of individual field lines is independent of each other. The IO parameters needed for this particular simulation are plasma distribution (this is usually given from other plasma physics simulations which store results in integrated database at ITER – in binary hdf5 mode). Large number of meshes which describe the fusion reactor is currently supplied in ASCII VTK format.

References:

[1] Gregor Simic, "Enhancements and applications of the SMITER magnetic field line tracing and heat load mapping code package," presented at the 30th IEEE Symposium on Fusion Engineering, Oxford, UK, 7 2023

[2] T. Looby *et al.*, "A Software Package for Plasma-Facing Component Analysis and Design: The Heat Flux Engineering Analysis" *Fusion Sci. Technol.*, vol. 78, no. 1, pp. 10–27, Jan. 2022

[3] Carr Matthew and Alex Meakins, "Raysect Python Ray-tracing package." [Zenodo]. Available: https://doi.org/10.5281/zenodo.1205064

[4] Yiang, Xiaoqian & Cheng, Samuel & Ohno-Machado, Lucila. (2011). Quantifying fine-grained privacy risk and representativeness in medical data. Proceedings of the ACM SIGKDD International Conference on Knowledge Discovery and Data Mining.

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