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Bi-level spatial subdivision based monte carlo ray tracing directly using CAD models

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ABSTRACT

To achieve fast Monte Carlo ray tracing on CAD models, a Bi-level Spatial Subdivision based ray tracing method (BSS) is proposed in this paper. This method was implemented and integrated in Super Monte Carlo Program for Nuclear and Radiation Simulation (SuperMC) and tested on ITER Benchmark and Force-Free Helical Reactor (FFHR) model. The testing results on ITER Benchmark model demonstrate the correctness of this method. The testing results on FFHR demonstrate that this method can save most of the preprocessing work to greatly improve the Monte Carlo analysis efficiency. Both results reveal that this method achieves applicable calculation speed comparing to the traditional Constructive Solid Geometry (CSG) broadly used in Monte Carlo codes.

1. Introduction

Monte Carlo (MC) method has been well applied to Fusion Neutronics analysis for it's convenient to describe complicated geometry [1]. To achieve fast Monte Carlo geometry modeling, geometry modeling methods based on CAD have been developed [7,14,15,21]. Using the CAD based method, great advances have been introduced, and promoted the development of fusion neutronics.

There are two major kinds of CAD based geometry modeling methods, the CAD to CSG conversion [7,13,16] and the direct CAD based ray tracing [4,6].

As revealed, the CAD to CSG conversion method is time consuming. CSG geometry cannot describe arbitrary solids, such as solids with twisted or curved high order surfaces that often used in CAD models. The CAD to CSG conversion relies on Boolean operations provided by CAD systems (such as ACIS and OpenCasCade), which is not stable to handle solids with intricate surfaces. Furthermore, time consuming preprocessing is needed to remove including those above before converting CAD solids to CSG description.

Currently, several works for direct ray tracing directly on CAD geometry have been implemented. MCNP6 adopts unstructured mesh [3] which can directly be generated from CAD models. Geant4 itself integrated a 2D mesh based ray tracing function [5]. The direct CAD based ray tracing is slow in computing speed. As a result, there's still space for these methods to be improved to achieve convenient application in Monte Carlo calculation. For example, the DAGMC adopts Oriented Bounding Box (OBB) to accelerate the ray tracing on 2D mesh [4], Geant4 redefines complex closed tessellated surfaces as tetrahedral meshes to accelerate the navigation process in Geant4 [5].

In order to achieve high calculation efficiency in geometry calculation, several methods have been developed in SuperMC, such as Optimal Spatial Subdivision (OSS) [22,12]. But it is designed for CSG based geometry, in which each solid is described by limited elements. It is not able to further accelerate the raytracing in a single solid that contains abundant geometry elements, such as facet based geometry, in which each solid is described by an enormous number of faces. This paper proposed a Bi-level Spatial Subdivision (BSS) based Monte Carlo ray tracing method directly on facet based CAD models for particle transport simulation and implemented it on Super Monte Carlo Program for Nuclear and Radiation Simulation (SuperMC) [8], which is a general, intelligent, accurate and precise simulation software system for the nuclear design and safety evaluation of nuclear systems [2,9,10,11,17–20].

2. Methodology

2.1. Generation of facet geometry

CAD models describe the accurate geometry of a solid. It forms solids with a topology structure consisting of face, edge and vertex, in

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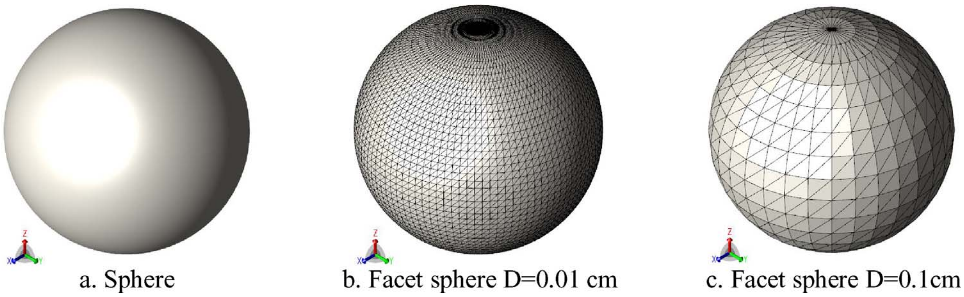


Fig. 1. Facet geometry with different Ds of a sphere with 10 cm radius.

which the face stands for the exact boundary shape of the solid.

A facet is a triangle associated to a direction parallel to its normal and to the outside of the solid. Facet based geometry describes solids using combined facets, where each edge of the facets connects two adjacent facets. Fig. 1 shows a sphere and corresponding sphere faceted in two different maximum deviations (referred to as parameter D in this paper), in which the maximum deviation means the maximum distance between the facets from the original solid boundary. As demonstrated in the figures, smaller deviation standing for higher accuracy, leads to more facets. A Bi-level Spatial Subdivision method which is described in Section 2.2 was proposed to accelerate the calculation with the large amount of facets.

On the basis of facet techniques supplied by the existing CAD engines, a facet based MC model generation procedure has been implemented in SuperMC. It stores the whole model in two files. One contains all the model setup information including IDs associated with the facet solids, material, tally, source and other calculation parameters; the other contains all the facet solids.

2.2. Bi-level spatial subdivision

In order to achieve efficient calculation on geometry with large amount of basic elements, the key point is to limit the number of basic elements in the ray tracing progress.

The ray-tracing method named BSS is based on two levels of spatial subdivision (Fig. 2): The solid level spatial subdivision divides the whole transport space into hierarchical tree, in which every leaf node contains a limited amount of solids, to make the solids involved in a single ray tracing step few. The facet level spatial subdivision divides the bounding box of each solid into a facet level spatial subdivision tree, in which every leaf node contains a limited number of facets, to restrict the amount of facets involved in a single ray-tracing step small. Both levels adopt BSP (binary space partition) method, which is widely used in computer graphic domain [23].

2.3. Ray tracing with BSS based facet model

For the particle transport, two key functions of the ray tracing module with geometry model are: 1. the function to search for a solid containing a given point, 2. the function to predict the distance of the point on the boundary of the current solid where the current particle is about to exit through or the point on the boundary of the next solid current particle is about to enter through.

To search for a solid containing a given point, the point is firstly located layer by layer to a leaf node in the solid level space subdivision tree. For each solid in the sub region, a ray starting from this point with arbitrary direction is tested, if the first facet intersect with the ray is with forward direction as the ray (the dot product of the direction of the ray and the facet is larger than 0), the point is then determined as inside the solid. If no such solid is found, the point is determined as outside of all the solids.

To predict the distance of a given point to the boundary in a given direction, if the point is inside a solid, the nearest facet with forward direction as the given direction would be found and the distance is calculated. Otherwise, the first intersecting facet to the ray starting from the point and the given direction with backward direction (the dot product of the direction of the ray and the facet is less than 0) in the sub regions is identified. The distance between the point and intersection point is obtained as the prediction.

Two functions all depend on locating the first intersecting facet to a ray. This facet is obtained through following steps. 1. The first intersection point to the sub regions is calculated layer by layer on the solid tree, until the leaf sub region. 2. Each facet in the sub region is tested with this ray for all the intersecting facets. If no facet in the sub region intersects with the given ray, the adjacent sub region intersect with the ray will be tested with the same steps.

3. Testing of BSS method

3.1. Testing on ITER benchmark model

To verify the correctness of BSS, ITER Benchmark model was adopted as the test case. In the previous work, SuperMC has been verified on the CSG model of ITER Benchmark, this work takes this CSG model as baseline (Fig. 3).

ITER Benchmark model was built by ITER International Organization to verify the CAD based modeling software, such as SuperMC/MCAM, McCad in 2006. It contains the main parts of the ITER tokamak machine, including blanket, divertor, vacuum vessel, cryostat, bioshield, central solenoid coils, TF coils, PFcoils, lower, upper, equatorial ports and et al.

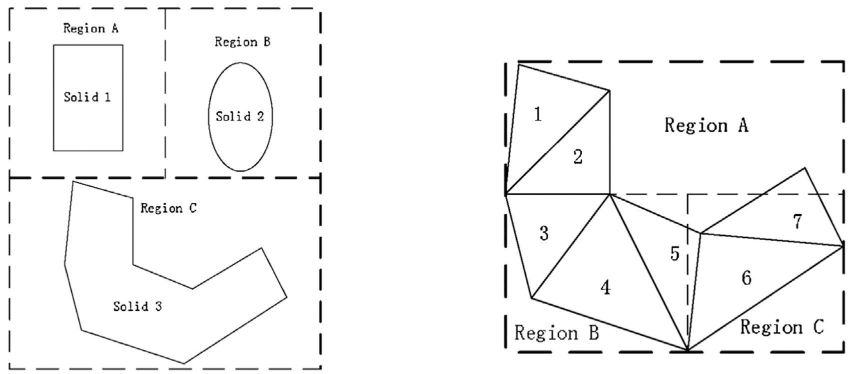
3.1.1. The analysis of the parameters in BSS method affecting the ray tracing speed

Two key parameters in BSS method directly determine the transport calculation speed and the accuracy. They are shown as follows.

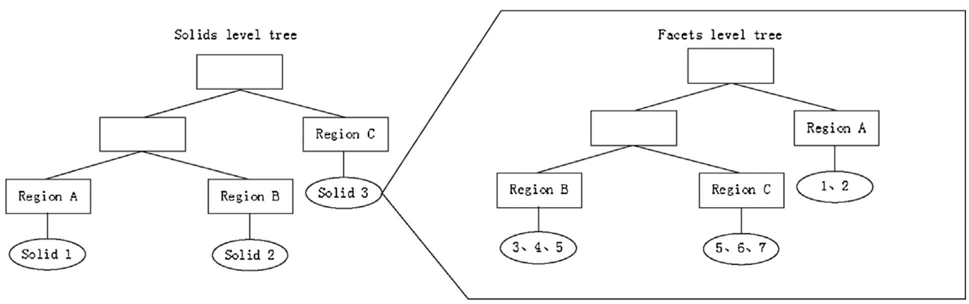
1. Min Facet Number in facet grids (MFN): During generating the second level tree for a facet solid, the parameter of min facet number in facet grids.
2. Deviation (D): The maximum deviation (in another word, the maximum distance) between the faceted surfaces and the original surfaces.

As the parameters can only influent the ray-tracing on geometry, several calculations on the model with void material were performed on the same computer. Multiple sets of parameters were tested on the viewpoint of both efficiency and accuracy. In each calculation, 10,000,000 histories were simulated, the source was the plasma source released with ITER Benchmark, and it was configured as with no reflecting surface or material.

To choose the valid D for faceting the models, comparison of the flux calculation results of all the void solids were compared. Fig. 4 compares the results of the flux calculation between two typical D parameters. The calculation results on CSG model were taken as the baseline. As the figure shows, the deviation increases linearly with the



a. Solid level spatial subdivision b. Facet level spatial subdivision



c. Bi-level Spatial Subdivision tree

Fig. 2. Example of Bi-level spatial Subdivision.

D. It can be concluded, convex surfaces shrink after converted to facets, and concave surfaces verse vise. On both kinds of surfaces, larger D would cause larger deviation, results the similarity between the deviations of models with different Ds. And it is shown that, with D = 0.01 cm, all the deviation falls under 1%. In the following test, 0.01 cm is selected as the D parameter in latter calculation on ITER Benchmark.

To get the representative MFN, different MFNs on facet models of different Ds were tested. As shown in Fig. 5, the best performance was achieved with a MFN = 10. Small MFN leads to less facets in the leaf node of facet level spatial subdivision tree, and increases the depth of the spatial subdivision tree. Less facets number increases the calculation speed in the leaf node. Larger tree depth costs more time in locating the leaf node. With MFN smaller than 10, the tree depth increases much faster than the decrease of the facet number, causes overall calculation speed slower. Also, from the study, it was learnt that the calculation efficiency varies little between geometry with different facet accuracy, in another word with different numbers of facets (The faceted models

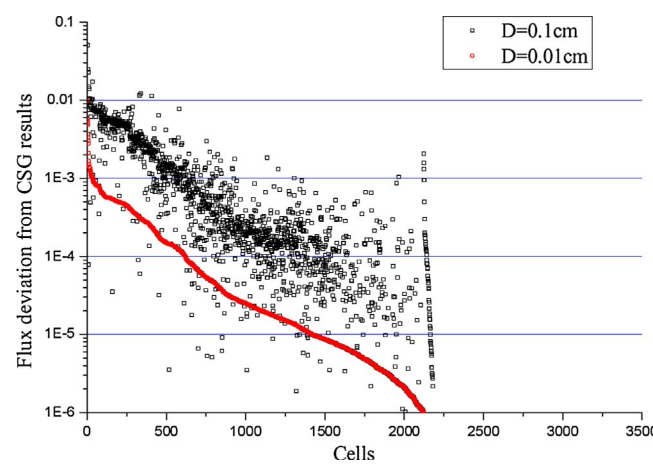
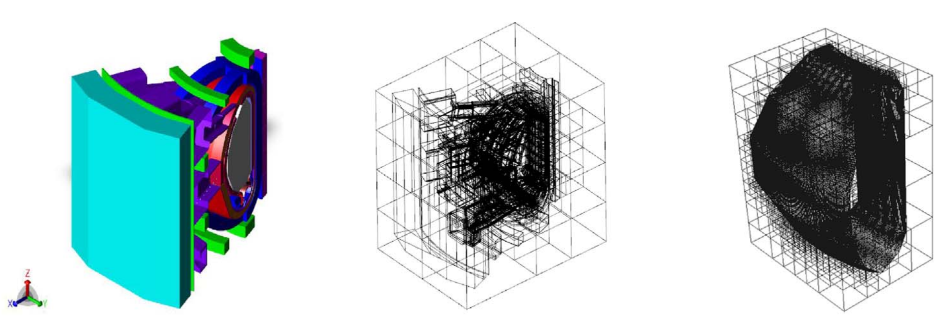


Fig. 4. Relative deviation of flux results between CSG and facet models with different accuracy.



a. ITER Benchmark model b. Solid Level Spatial Subdivision c. Facet Level Spatial Subdivision

Fig. 3. Bi-level Spatial Subdivision tree of ITER Benchmark.

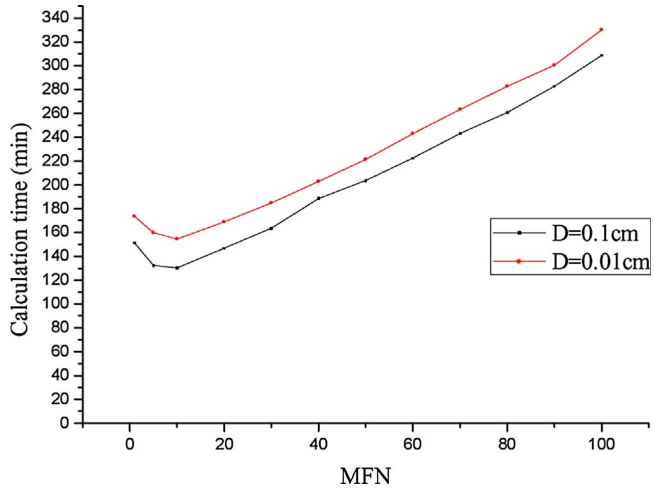


Fig. 5. Calculation time of different MFNs.

Table 1
Calculation time comparison between different configuration (minutes).

	BSS	facet level spatial subdivision off	BSS off
D = 0.1 cm	130	1500	13000
D = 0.01 cm	150	4400	16000

contain 139,336 and 362,982facets corresponding to D of 0.1 cm and 0.01 cm).

3.1.2. *The analysis of the improvements of the BSS method*

To demonstrate the total improvements brought by BSS, calculations without facet level spatial subdivision and solid level spatial subdivision were performed. The results are shown in Table 1. It can be concluded, that the BSS method accelerated the whole calculation by more than 100 times; the facet level spatial subdivision accelerated the calculation by 11–28 times corresponding to different facet accuracy. Because the solid level subdivision only accelerate the ray tracing when particle navigate into solids, while the facet level spatial subdivision works when particle go both in and out of solids, so the solid level spatial subdivision contribute less to the total acceleration in facet model in higher accuracy with more facets.

3.1.3. *Nuclear heat in the inboard TF coils*

In the first case with actual materials, the relative nuclear heat in TF coil was calculated on both CSG model and facet model (accuracy of 0.01 cm). The nuclear heat caused by the neutron and photon went through the blanket and vacuum vessel is one of the major engineering limitations of ITER. In this case, 1e8 histories of fusion neutron were simulated. The comparative results are shown in Fig. 6. The calculated value stands for nuclear heat caused per neutron. Due to large scale and thick shielding, the results converge differently in different part of the TF coil, however all the results on facet model fall in the statistic error region of the results on CSG model, shows good agreement with each other.

3.1.4. *Neutron flux in the equatorial ports*

The neutron fluxes in the void space in the equatorial ports involve deep penetration through complex material in another word involve many physics progresses. 7 groups of spheres for tally have been placed in the region for counting the neutron fluxes. In order to reach reasonable convergence, 5e8 histories of fusion neutron were simulated on both CSG and facet model. Fig. 7 shows the comparative results, from which the same consumption can be draw that the calculation results on both model agree well with each other.

3.2. *Testing on FFHR model*

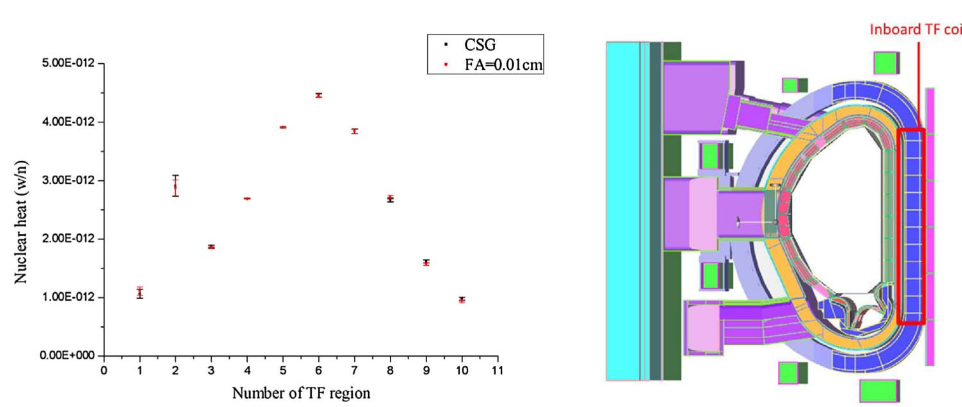
To verify the ability of dealing with geometry with complicated free surfaces, the BSS method was applied to a conceptual model of a helical-type fusion reactor FFHR [24]. In this fusion reactor, as shown in Fig. 8, the key parts, the blankets and their supporting parts are formed with free surfaces. Before this work, this model has been simplified to CSG model as baseline [25].

To demonstrate the advantages of the BSS based facet model. Fig. 9 shows the key parts in facet model and CSG model. The preprocessing of simplifying the whole model into CSG model costs 1 man-month while the facet model takes no manpower in preprocessing.

In this test, the neutron flux results were calculated on the two models. The calculation results are shown in Fig. 10. As shown in a) and b), the facet model preserved more details. As shown in c) and d), the simplification into CSG model caused observable difference of the calculated flux in this area from the facet model.

3.3. *Comparison of calculation efficiency*

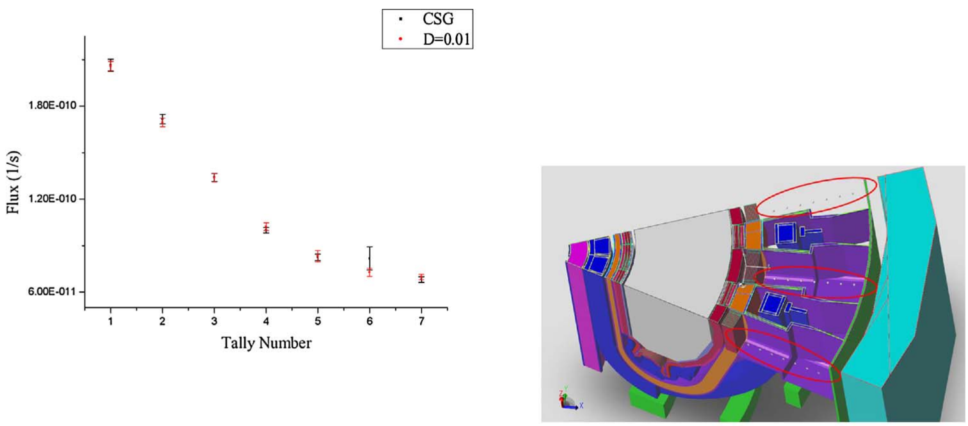
To get a full picture of the calculation efficiency of the BSS method, the CPU times of calculations on BSS based facet models and CSG models of ITER Benchmark and FFHR are listed in Table 2. The results shows that for void flux calculation associated with only geometry, BSS costs 2.53 times more than CSG model on ITER Benchmark model. For the cases considering actual physics processes, as geometry calculation no longer dominates the CPU time, BSS costs 1.50–2.00 times as long as



a) Comparative calculation results nuclear heat in in the inboard TF coils

b) The inboard TF coil in ITER Benchmark model

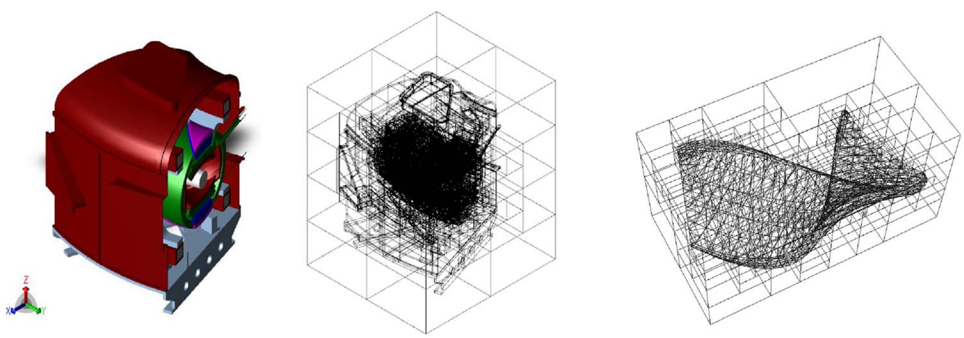
Fig. 6. Nuclear Heat in TF coil.



a) Comparative results on both CSG model and facet model

b) Tally location in the ITER Benchmark model

Fig. 7. Flux in the equatorial ports.

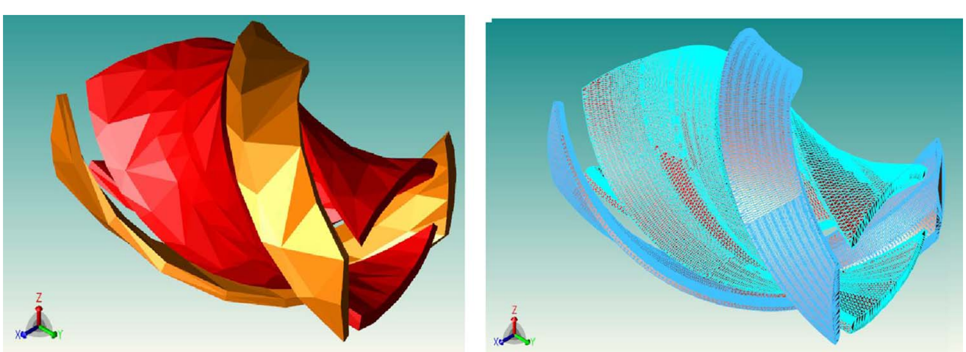


a. FFHR model

b. Solid level Spatial Subdivision

c. Facet level Spatial Subdivision

Fig. 8. Two level spatial subdivision tree of FFHR.



a) Key parts in CSG model

b) Key parts in facet model

Fig. 9. Comparing key parts in CSG model and fact model.

the CSG model. It can be concluded that BSS has achieved applicable calculation speed.

4. Conclusion

A fast Monte Carlo geometry describing method directly using CAD models has been developed based on SuperMC. It adopted the BSS method to avoid the low efficiency of introducing great number of facets for accurately describing complex models.

From the testing results on ITER Benchmark, it can be concluded that, the correctness of BSS based ray tracing has been verified. The testing results on FFHR show that, facet based geometry saves manpower that needs to be invested to build CSG model for complex models. From the detailed analysis, it can be concluded that the facet based method can achieve higher accuracy in modeling complex solids constructed with twisted surfaces.

By comparing the CPU time of calculations on BSS based facet models and CSG models, it is evident that the BSS method can accelerate the facet based ray tracing efficiently to the same order of magnitude of calculation speed as conventional CSG method.

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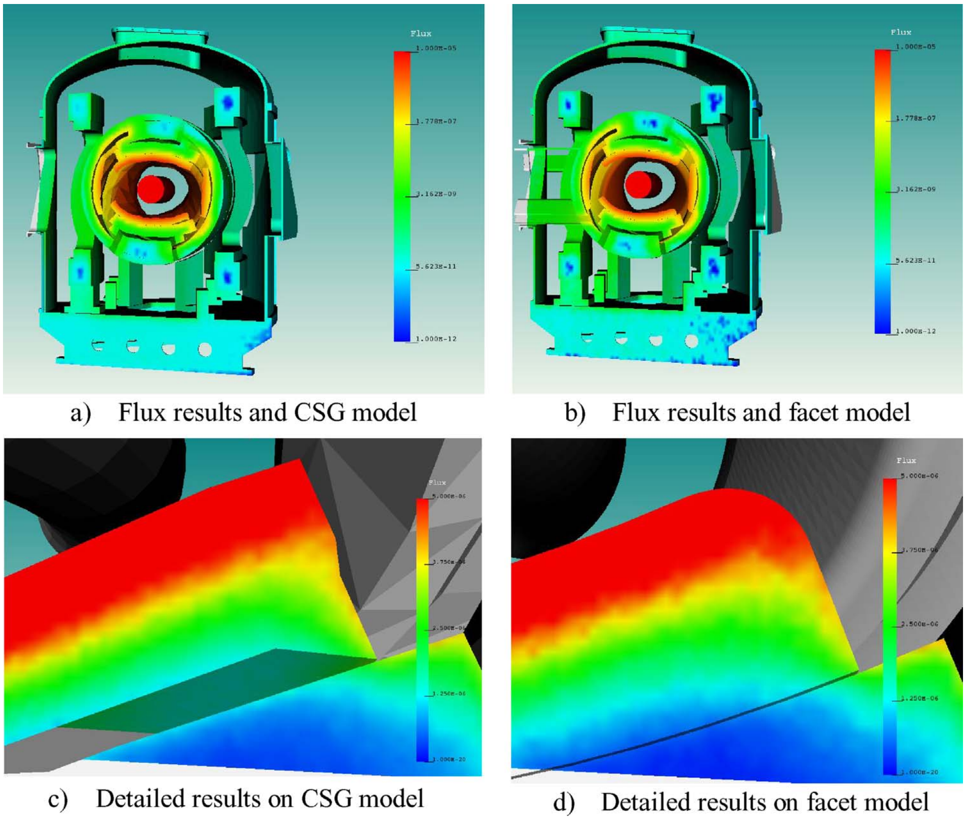

Fig. 10. Flux results calculated on both CSG and facet model of FFHR.

Table 2
Calculation time comparison between CSG models and facet models.

Model	Case	Configuration	CPU time (minutes)	Relative CPU time comparing to CSG
ITER Benchmark	Void flux, 1e7 neutron histories	CSG model	43.8	1
		BSS based facet model	154.6	3.53
	Nuclear heat in the inboard TF coils	CSG model	1340.62	1
	1e8 neutron histories	BSS based facet model	2524	1.88
	Neutron flux in the equatorial ports	CSG model	739.45	1
	1e8 neutron histories	BSS based facet model	1112.24	1.50
FFHR	Neutron flux map	CSG	7930.28	1
	1e9 neutron histories	BSS based facet model	15845.88	2.00

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