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# Sensitivity of R2Smesh shutdown dose rate results on the mesh resolution

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## Abstract

R2Smesh is a Monte Carlo based computational interface developed at KIT for accurate shutdown dose rate (SDDR) analysis in fusion reactor. The superimposed mesh tally technology in MCNP has been introduced in its development effort for calculation of neutron intensity and multi-group spectra. The resulting neutron flux is averaged within each mesh element as its gradient is omitted. The accuracy of final SDDR thus relies heavily on mesh resolution. To evaluate the influence of mesh resolution on SDDR, the sensitivity analysis has been conducted on JET and EU DEMO by using series of fine and coarse mesh. The convergence of SDDR was achieved and the optimum size of mesh voxel for JET and DEMO SDDR calculation were determined after compromising between the precision of result and high computational cost. By employing the optimum mesh resolution, the R2Smesh interface was validated through comparison with JET measurements. Afterwards it was applied on DEMO for global SDDR analysis to provide support for neutron and gamma induced shielding design.

## Keywords

Shutdown dose rate, R2Smesh, convergence, JET, DEMO

# 1. Introduction

The decay gamma produced by radionuclides in a fusion reactor should be shielded in case of harm to workers for maintenance after shutdown. Shutdown dose rate (SDDR) estimation then is of great importance to the shielding design of fusion reactor. So far, there are two developed code systems for the SDDR prediction: one called rigorous-two-step (R2S) and another directed-one-step (D1S) method, both of which were initialized more than a decade ago [1]., [2].. The R2S method is a 3D simulation tool combining the Monte Carlo neutron photon transport and nuclides inventory calculation. It generally includes three calculation steps: first the neutron transport is performed in Monte Carlo code to obtain the space dependent neutron spectra and intensity; then nuclides inventory calculations is carried out by making use of resulting neutron spectra and intensity as input to obtain the time dependent decay gamma source; at last the gamma transport is run again in Monte Carlo code to get the gamma flux and be converted to the dose rate by using of flux-to-dose conversion factors [3]..

The R2Smesh interface code developed at KIT is one of several R2S codes [4].-[6]. combining Monte Carlo N-Particle code (MCNP) [7]. with inventory calculation code FISPACT [8].. In case of rapid attenuation of neutron flux within defined space, the fine mesh is employed for accurate neutron intensity calculation. A significant drawback of R2S method is the need for calculation of the multi-group neutron spectra resulting in high consumption of computer source. While, the shape of neutron spectra doesn't change as much as neutron intensity within a certain extent. Thus R2Smesh employs a coarse mesh for the calculation of neutron spectra. Only rectangular mesh type so far is available by R2Smesh for neutron flux tally.

For both fine and coarse mesh, the neutron flux is averaged over the volume of mesh voxel. This definitely results in averaged decay gamma distribution instead of pointing-wise distribution respect to real physics situation; moreover, it may cause overestimation of irradiation in space partially averaged over void. A finer mesh resolution can reduce this effect as it can depict more accurate distribution of neutron flux. However, it's still inevitable due to the defect of flattened neutron flux within mesh element. Thus the accuracy of calculated decay gamma source strongly depends on mesh resolution.

The aim of paper is to conduct sensitivity analyses of SDDR affected by the mesh resolution. The R2Smesh interface will be used and applied on fusion reactors JET and DEMO for that purpose.

JET is a fusion device which has Deuterium–Deuterium (DD) and Deuterium–Tritium (DT) operation scenario. The dose rate experiment at JET is an excellent benchmark for the validation of SDDR calculation codes. The SDDR benchmark experiment at JET was run since 2005 during Deuterium–Deuterium (DD) shutdown. The latest experiment during 2012-2013 DD shutdown has been conducted for the purpose to validate the simulation codes used in ITER relevant calculations [9]..

The European Demonstration Fusion Power Reactor (DEMO) is put forward in the frame of European Power Plant Physics and Technology (PPPT) programme towards the future commercial fusion reactor [10].. The Helium Cooled Pebble Bed (HCPB) is one of the blanket concepts tested in ITER also as a candidate for DEMO. The initial design and analysis of latest HCPB DEMO has been completed [11]..

The general method for this sensitivity study is to perform series of calculations on JET and DEMO mapped by fine and coarse mesh with different resolution; when the SDDR converges, the optimum mesh resolution can be determined. The R2Smesh code mapped with proper size of mesh was validated by comparison with JET measurements. The code has been applied on DEMO for global SDDR calculation later.

# 2. The advanced features of R2Smesh

The R2Smesh inherits many features of R2Scell [1].. Both of them follow the rigorous calculation steps described above. The R2Scell employs the cell tally technology in MCNP for neutron intensity and spectra calculation. Users have to adapt the cells by segmentation to describe the practical gradient of neutron flux especially at the positions where in case the neutron flux changes rapidly. While the R2Smesh takes advantages of mesh tally technology which the fictitious mesh is independent from the geometry. The size of mesh voxel can be simply adjusted to be adapted with the neutron attenuation without the modification of neutronics model.

The material composition is unknown inside this mesh element and should be detected in advance prior to the FISPACT run. The previous version R2Smesh uses the internal 'ptrac' function in MCNP to determine the material fraction in each fine mesh voxel [3]. This method has disadvantages as the 'ptrac' output file can become too large to handle. The latest R2Smesh has introduced parallel computation technology to facilitate the detection of material fraction by using random particles [12].. The generated random particle has its unique position and this can decide the material property at this point. Finally, the material fraction in each mesh element can be calculated by counting the random particles, which located in the same material zone. The accuracy of material detection depends on the density of random particles and up to 100 particles per cubic centimetre has been used.

After the prerequisite of neutron intensity and spectra in mesh elements, material composition, and provided irradiation scenario, the activation calculation then can be carried out by Fispact. The activation of each material inside a coarse mesh element is calculated separately but using the same neutron spectra. The decay gamma source in each fine mesh element can be obtained proportionally according to their calculated material fraction and is written into an external source file. A source subroutine has been developed to read the gamma source file and sample the gamma information such as energy, position, emitting direction, particle weight and so on in the later MCNP photon transport.

# 3. JET sensitivity of SDDR to mesh resolution

To evaluate the influence of SDDR affected by the variance of mesh voxel, a sensitivity study has been carried out. In the following, a brief introduction to the JET experiment and the neutronics model used in SDDR simulation will be presented; the general method for the sensitivity study and results will be described in details. At last, the R2Smesh interface has been validated through the calculation mapped by proper size of mesh and compared with JET measurements.

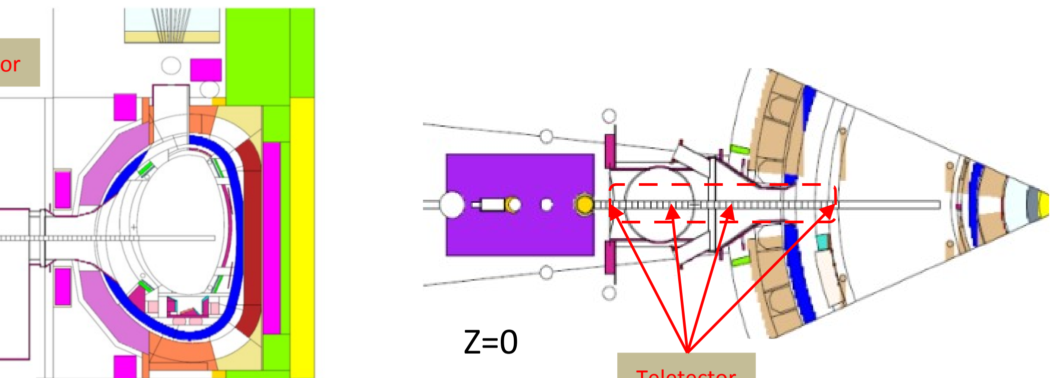
## 3.1. JET SDDR benchmark experiment

The SDDR benchmark experiment of JET has been conducted to validate the SDDR calculation codes for ITER related issues [9].. Several positions from JET plasma chamber at mid-port and side port have been measured using different dosimeters.

Three Geiger Müller (GM) type detectors, an ionization chamber monitor (STEP OD-2) and a NaI spectrometer (Georadis RT-30) has been used in this experiment. The GM Vacutec detector is installed at the side port and outside the main port; the GM Teletector and Mini Rad series 1000R have been used for the measurement at the mid-port along the port axis. Other positions close to side port and box port have been installed with Georadis RT-30, MiniRad and OD-2 meters for repeat measurements. Those dosimeters have been calibrated in advance by using Cs-137 and Co-60 gamma sources. The dose rates at these positions have been measured at different cooling time up to 186 days after JET shutdown. These results at different positions and cooling time contribute to the validation of SDDR simulation codes through a comprehensive comparison between measurements and calculation results.

## 3.2. JET neutronics model

The JET 3D neutronics model used in this SDDR calculation is a 45° segment of Octant 1 representing the full-scale model by inserting reflecting boundary on both lateral sides, shown in Error: Reference source not found. The material is elaborately described including impurities specified with chemical composition. Cells at the positions along mid-port axis and, at side port and box port which are corresponding to the measured sites have been constructed in this model for the purpose of gamma flux tally. Due to JET DD and DT operation scenario, the neutron source distribution has been described separately in MCNP input. Sample of neutron source during transport can be achieved by linking a source subroutine of internal MCNP function [13].. The total neutron yield of DD and DT from the starting run in 1983 to 2012 is $4.03 \times 10^{20}$ and $2.40 \times 10^{20}$ respectively. The irradiation



X=0 and z=0 section of JET neutronics model; position of mid-port
rt door

scenario for the inventory calculation by FISPACT is based on the neutron yield measured data of DD and DT operation.

## 3.3. JET sensitivity study and results

The coarse and fine mesh are introduced in R2Smesh for neutron spectra and intensity calculation respectively. Therefore, this sensitivity analysis includes the SDDR influence by both the fine and coarse mesh voxel.

*Table 1. A set of fixed fine mesh and varied coarse mesh*

| Fixed fine mesh (cm) | Varied coarse mesh (cm) |
|---|---|
| 2 × 2 × 2 | 10 × 10 × 10 |
| | 20 × 20 × 20 |
| | 30 × 30 × 30 |

*Table 2. A set of fixed coarse mesh and varied fine mesh*

| Fixed Coarse mesh (cm) | Varied fine mesh (cm) |
|---|---|
| 20 × 20 × 20 | 2 × 2 × 2 |
| | 5 × 5 × 5 |
| | 10 × 10 × 10 |
| | 20 × 20 × 20 |

First, the fine mesh voxel was fixed to 2 cm cubic for neutron intensity calculation, and the coarse mesh voxel was set to 10, 20 and 30 cm cubic respectively for neutron 175-energy group spectra calculation, shown in Table 1. Next, the coarse mesh voxel was fixed to 20 cm and the fine mesh voxel was set to 2, 5, 10 and 20 cm respectively for neutron intensity calculation, shown in Table 2. All the meshes have the same boundary covering the zones that have dose rate contribution to the tally cells. The calculated neutron intensity and spectra were fed to the FISPACT for inventory calculation. The decay gamma source was collected from the FISPACT output and transferred to MCNP for photon transport to get the SDDR results. The SDDR results of JET along the mid-port were collected, their difference due to variance of mesh resolution is discussed below.

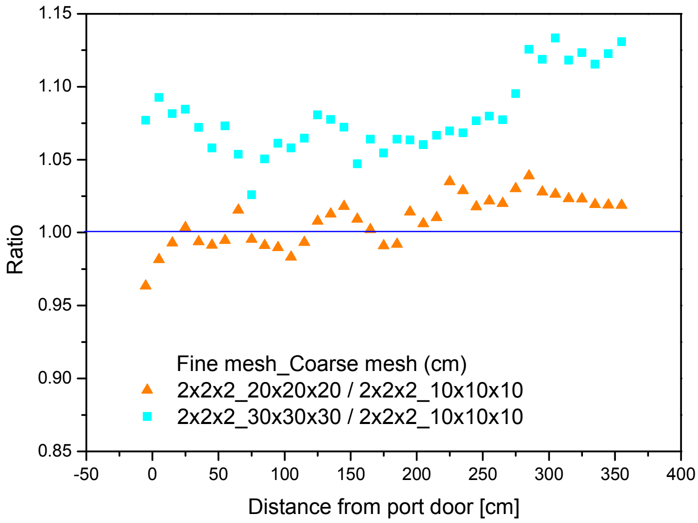



*Fig. 1. The ratio between the SDDR results calculated using different coarse mesh voxel of 10 × 10 × 10 cm, 20 × 20 × 20 cm and 30 × 30 × 30 cm and fixed fine mesh voxel of 2 × 2 × 2 cm.*

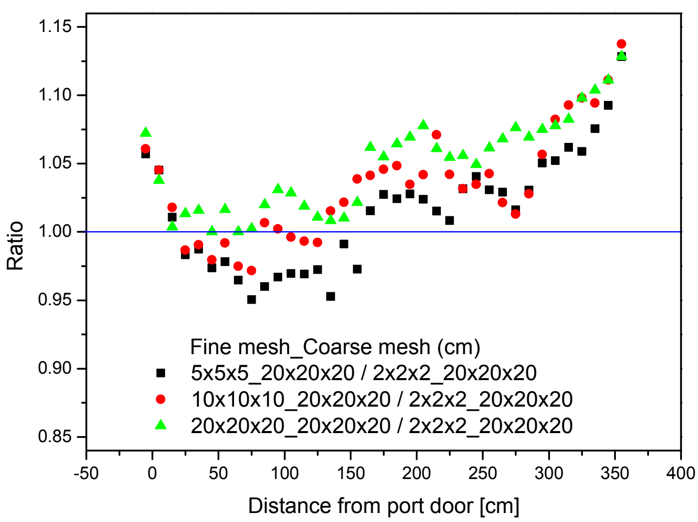



*Fig. 2. The ratio between the SDDR results calculated using different fine mesh voxel of 2 × 2 × 2 cm, 5 × 5 × 5 cm, 10 × 10 × 10 cm, 20 × 20 × 20 cm and fixed coarse mesh voxel of 20 × 20 × 20 cm.*

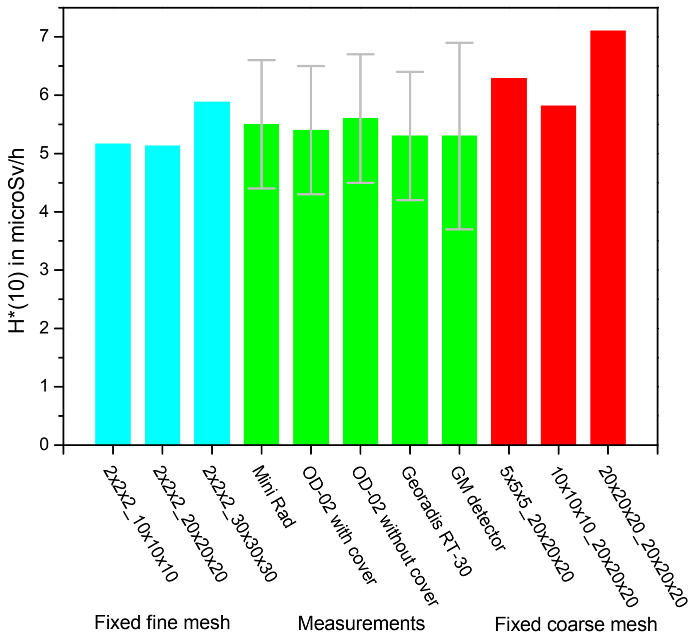



*Fig. 3. SDDR of jet at side port 7 days after shutdown by using different fine and coarse mesh and compared with measurements.*

When the fine mesh voxel is fixed to 2 cm, the result is converged after setting the coarse mesh voxel to 10 and 20 cm as the ratio is not more than 1.05; the SDDR ratio between them can be seen in Fig. 1. While, the difference becomes larger up to a factor of 1.14 and becomes unstable when the coarse mesh voxel expands to 30 cm. This reveals that the neutron spectra of JET don't change too much at the range up to 20 cm of coarse mesh voxel. When the coarse mesh voxel is larger as much as 30 cm, even the fine mesh voxel is as small as 2 cm, the difference of SDDR results gets bigger. When the coarse mesh voxel is fixed to 20 cm, the SDDR calculated with mesh voxel larger than 5 cm has high deviation up to a ratio of 1.13 compared with the use of 2 cm fine mesh voxel, shown in Fig. 2. The SDDR close to the center of reactor is much more sensitive to the variance of mesh voxel. This may be due to the gamma source at such positions mostly originating from the first wall components and is directly affected by the mesh resolution.

The SDDR at side port of JET calculated using different fine and coarse mesh resolution has same performance when compared with the experimental measurements, shown in Fig. 3. When the fine mesh voxel is fixed to 2 cm, their simulation results are closer to the measurements and actually have moderate variation even when the coarse mesh voxel changes from 10 cm to 30 cm. While they fluctuate obviously when the fine mesh voxel changes from 5 cm to 20 cm when the coarse mesh voxel is fixed to 20 cm.

There are many reasons for the presence of SDDR difference among a series of calculations using various mesh resolution. Generally, more accurate result can be obtained when setting finer mesh voxel as it represents the real situation of neutron flux. In fact, the neutron intensity and spectra is average inside each mesh element. Afterwards the gamma source distribution obtained by irradiation inventory calculation is not pointing-wise as natural situation. The decay gammas are sampled uniformly within mesh element according to the averaged gamma source and then are transported, which is also non-pointing-wise.

The convergence of SDDR calculation, which means the SDDR result doesn't change with the variance of mesh resolution, should be archived in case of big deviation of results. The choice of mesh resolution for specific model should be in a certain range that the simulation result is within tolerance. While, mesh resolution is not only the aspect for the SDDR calculation but other limitations like the computational cost should be considered. As an example of JET calculation using 2 × 2 × 2 cm for neutron intensity and 20 × 20 × 20 cm for neutron 175 energy groups spectra tally, it needs 256 cores on cluster more than two-day computer time to get an accurate result respectively. Accounting the subsequent inventory calculation of radionuclides, photon transport and data transfer to combine these calculation steps, the computational cost becomes much more expensive. At the same time, the storage capacity of computer should be feasible with the size of mesh. The final decision of mesh resolution should be a compromise among accuracy of result, time cost, power of computer, etc.

## 3.4. Validation of R2Smesh with JET measurements

The JET SDDR results using 2 × 2 × 2 cm of fine mesh voxel and 20 × 20 × 20 cm of coarse mesh voxel has been selected out and compared with the measurements as validation of R2Smesh code. The comparison of simulated SDDR (in terms of H*(10) rate) and measurements at equatorial port after 103 and 186 cooling days can be seen in Fig. 4 and Fig. 5. The simulation result has good agreement with measured data by detectors of Georadis, Minirad and Teletector after 103 cooling days at the beginning to 100 cm from port door. Higher deviation up to a factor of three between the simulated result and measurements has been detected after 186 cooling days at 200 cm to 350 cm from port door. This may be due to the uncertainty of measurements by Teletector including the uncertainty of detectors' position and direction to measure the dose rate. The map of JET SDDR and relative error after 103 cooling days can be seen in Fig. 6 and Fig. 7. The results show the high precision and robustness of R2Smesh interface for the SDDR simulation applied on fusion device.

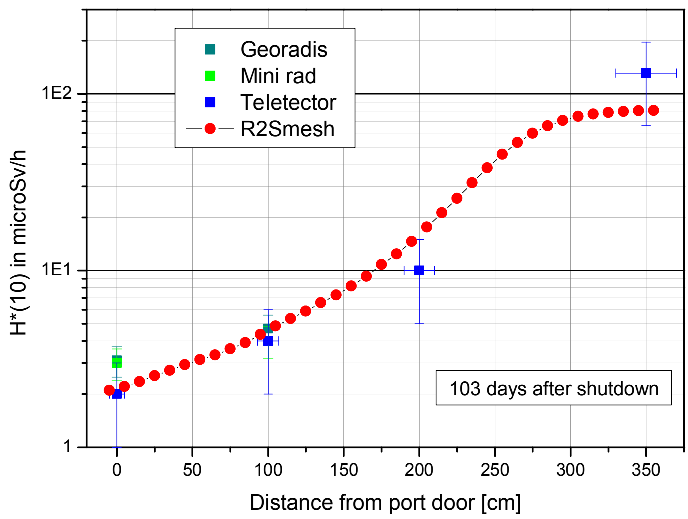



*Fig. 4. Comparison of SDDR 103 days after shutdown between R2Smesh simulation results and measurements.*

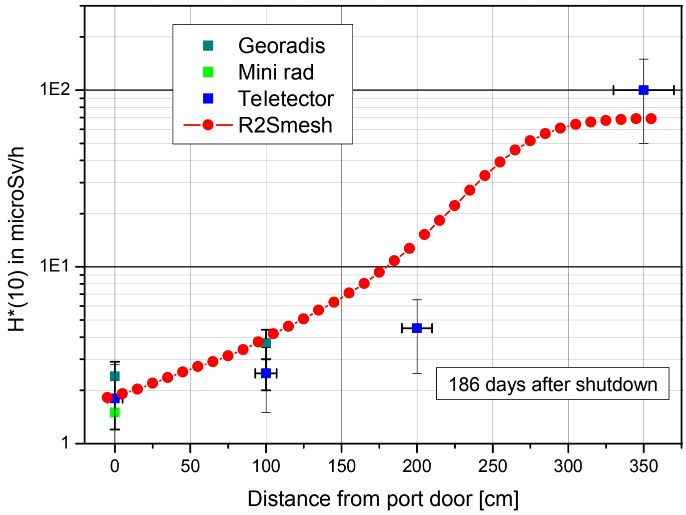



*Fig. 5. Comparison of SDDR 186 days after shutdown between R2Smesh simulation results and measurements.*

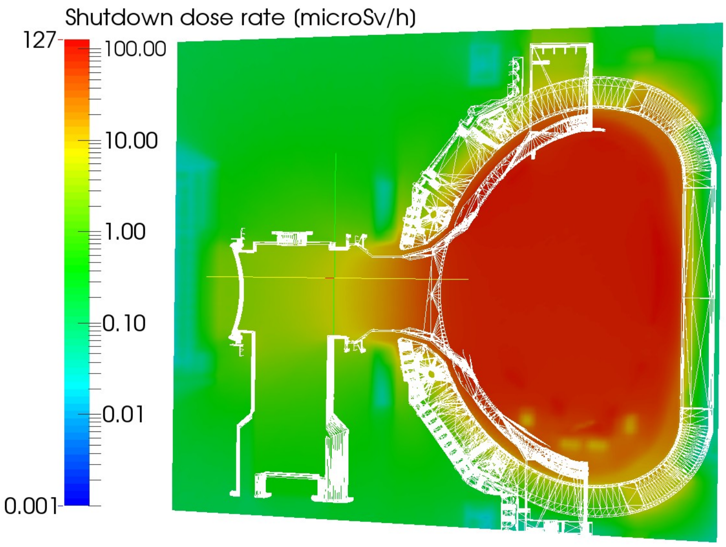



*Fig. 6. Shutdown dose rate map of JET 103 days after shutdown.*

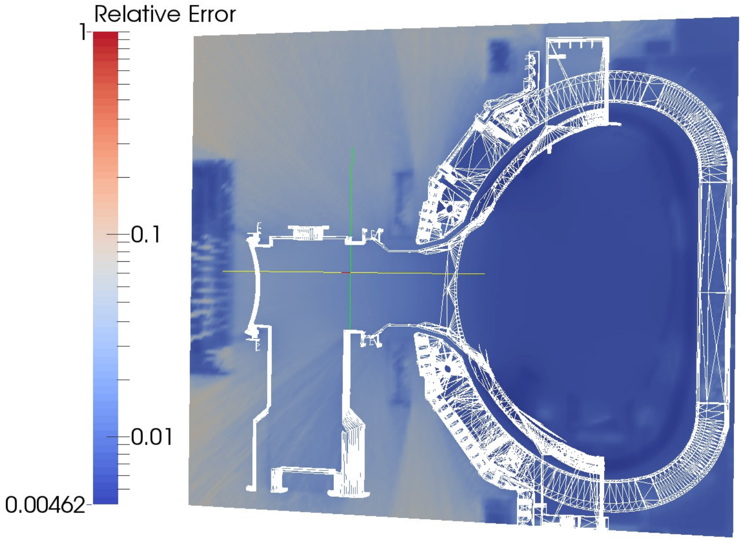



*Fig. 7. Relative error of JET SDDR 103 days after shutdown.*

# 4. SDDR calculation of HCPB DEMO

The R2Smesh code has been applied on HCPB DEMO for SDDR calculation to provide global SDDR data for the shielding design. The sensitivity study of SDDR to mesh resolution has been performed in advance to choose the optimum mesh resolution. The HCPB blankets in DEMO suffer the highest neutron irradiation directly from plasma that the neutron flux attenuates rapidly from first wall (FW) to back plate (BP). The result of neutron flux can be heavily affected by the mesh resolution. The HCPB component has been studied to assess the effect of mesh resolution to SDDR. The mesh resolution decided by this investigation has been used for its global SDDR calculation.

## 4.1. HCPB DEMO neutronics model

The neutronics model of DEMO used in SDDR calculation is shown in Fig. 8. It has been automatically generated by CAD to MCNP conversion tool McCad [14].. The model contains the main components of DEMO including central solenoids (CS), poloidal filed (PF) coils, toroidal field (TF) coils, thermal shields (TS), vacuum vessel (VV), inboard blankets (IB) and outboard blankets (OB), divertor and three (upper, equatorial and lower) ports. Most of these components have been simplified and filled with homogeneous material except the HCPB breeding zone for the need of accurate neutron response. The neutronics model has been manually filled with detailed HCPB structure with support of MCNP ‘fill’ and ‘universe’ card. The equatorial port has been filled with plug for neutron irradiation shielding to guarantee the safety of workers for maintenance. The plug is of 124 cm width radially and made of 80% steel and 20% water homogeneously. The SDDR in the equatorial port with plug will be studied as the safety need for maintenance.



E
q
u

TS

PFC

CS

HCPB

TFC

Divertor

*Fig. 8. Neutronics model of HCPB DEMO.*

The total fusion power of DEMO is 2037 MW and the intensity of 14.1 MeV neutrons is about $5.5\times10^{20}$ n/s. The irradiation scenario of DEMO for inventory calculation is assumed that the reactor runs 5.2 years and the first 5.2 years minus 10 days is assumed to run at an average level of 30% total fusion power. In the last 10 days before shutdown, the scenario is assumed to run 48 pulses and each pulse consists of 4-hour run at 100% fusion power and 1-hour dwell time. The SDDR at two weeks after shutdown will be studied to provide support for the maintenance and shielding design.

## 4.2. DEMO sensitivity study to mesh resolution

In the SDDR calculation of HCPB DEMO, it has been firstly focused on the SDDR sensitivity to mesh resolution in blanket zone where it suffers severe neutron irradiation. The neutron flux in the blanket has sharp gradient and the SDDR is much more sensitive to mesh voxel than other components. This investigation has been carried out in part of one blanket also using different fine and coarse mesh voxel. The fine and coarse mesh cover only part of blanket from FW to the manifold regardless of dose rate contribution from other parts to tell the difference due to the variance of mesh voxel.

*Table 3. A set of fixed coarse mesh and varied fine mesh*

| Fixed fine mesh (cm) | Varied coarse mesh (cm) |
|---|---|
| 3 × 3 × 3 | 6 × 6 × 6 |
| | 12 × 12 × 12 |
| | 15 × 15 × 15 |
| | 30 × 30 × 30 |

*Table 4. A set of fixed coarse mesh and varied fine mesh*

| Fixed Coarse mesh (cm) | Varied fine mesh (cm) |
|---|---|
| 30 × 30 × 30 | 1 × 1 × 1 |
| | 3 × 3 × 3 |
| | 5 × 5 × 5 |
| | 15 × 15 × 15 |

Firstly the fine mesh voxel is fixed to 3 cm and coarse mesh is set to 6, 12, 15 and 30 cm respectively, shown in Table 3. The map of SDDR can be seen in Error: Reference source not found. The SDDR among the four sets of SDDR data at the same positon near the FW varies from 653 Sv/h to 673 Sv/h, they are very close. The change of coarse mesh voxel does not have obvious impact to the SDDR because the neutron spectrum does not change significantly within the dimension up to 30 cm. Next, the coarse mesh voxel is fixed to 30 cm and the fine mesh voxel is set to 1, 3, 5 and 15 cm respectively. The map of SDDR can be seen in Error: Reference source not found. The SDDR results calculated using fine and coarse mesh voxel of 1 and 3 cm have little deviation (663 and 653 Sv/h respectively at the same position). While, when the fine mesh voxel expands to 5 and 15 cm, their results (552 and 434 Sv/h respectively) have big difference compared with that calculated using finer mesh voxel. The accuracy of neutron flux actually deteriorates due to low resolution of fine mesh in terms of this investigation.

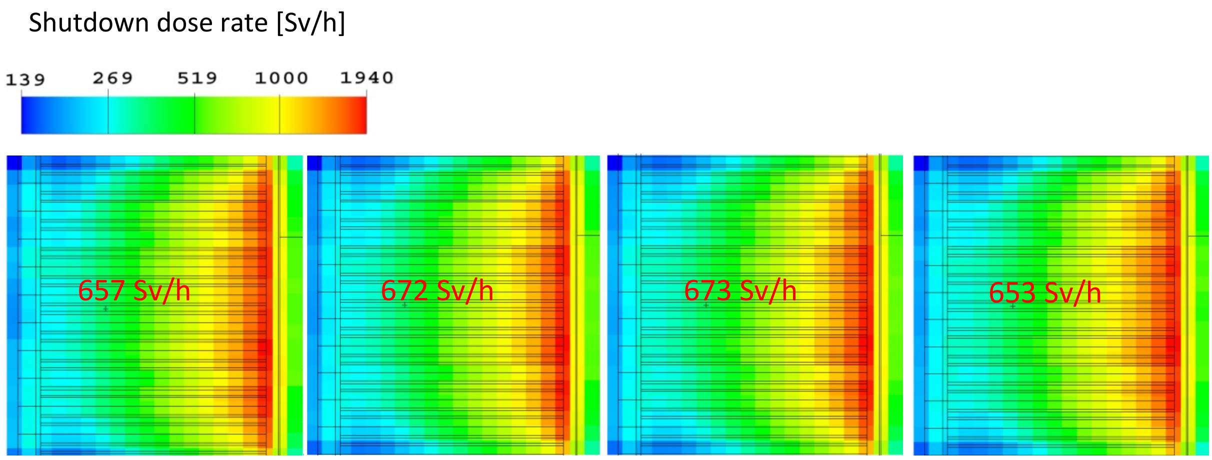



Fig. . The shutdown dose rate map using fixed fine mesh voxel 3 × 3 × 3 cm and coarse mesh voxel 6 × 6 × 6 cm, 12 × 12 × 12 cm, 15 × 15 × 15 cm and 30 × 30 × 30 cm respectively.

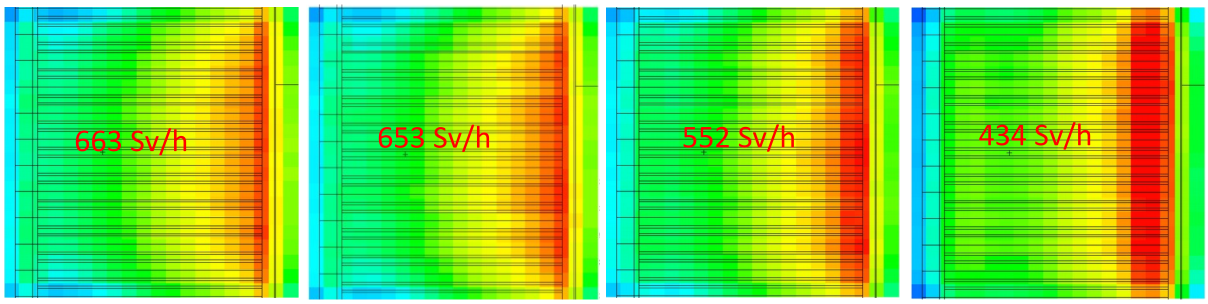



Fig. . The shutdown dose rate map (the same scale above) using fixed coarse mesh voxel 30 × 30 × 30 cm and fine mesh voxel 1 × 1 × 1 cm, 3 × 3 × 3 cm, 5 × 5 × 5 cm and 15 × 15 × 15 cm respectively.

For the fusion device DEMO, the recommended mesh size for global SDDR calculation is 1~3 cm of fine mesh voxel and 15~30 cm of coarse mesh voxel following the investigation analysis. Naturally, the finer mesh is possible based on the computer power and memory limitation. The mesh resolution used in next global calculation of DEMO SDDR is 3 cm for fine mesh voxel and 30 cm for coarse mesh voxel.

## 4.3. DEMO SDDR simulation

The DEMO SDDR calculation was carried out by using mesh resolution of 3 × 3 × 3 cm for neutron intensity and 30 × 30 × 30 cm for spectra calculation. The relative error of neutron flux can be guaranteed as high precision especially at some position that has large contribution to dose. The relative error in vacuum vessel (VV) is extremely high that it could hardly get accurate result inside such components.

The level of decay gamma at blanket FW is very high and neutrons penetrate through the gaps between blanket modules which results in higher activity at these positions. The decay gamma source distribution can be seen in Fig. 9. Neutrons from the lower port go into the space outside the VV and give rise to higher activity and decay gamma behind the VV. Higher level of SDDR has been detected at those positions and further extended to the equatorial port.

The SDDR at two weeks after shutdown and its relative error are shown in Fig. 10. The accuracy of SDDR has the same trend as neutron flux. It is still very hard for gammas to penetrate such thick VV and that gives a low statistic scores and high relative error. The relative error at other important zones such as ports and plug is less than 5%. The SDDR at FW is about $2.5\times10^{3}$ Sv/h; behind the equatorial port plug, it is about $2.8\times10^{-3}$ Sv/h two weeks after shutdown. As discussed above, the neutron leakage from lower port to the space outside the VV contributes to the dose at equatorial port. Obvious evidence about this leakage is that the SDDR in the space among the equatorial port, lower port and outside the VV is an order of magnitude larger than that in the space among upper port, equatorial port and outside the VV.

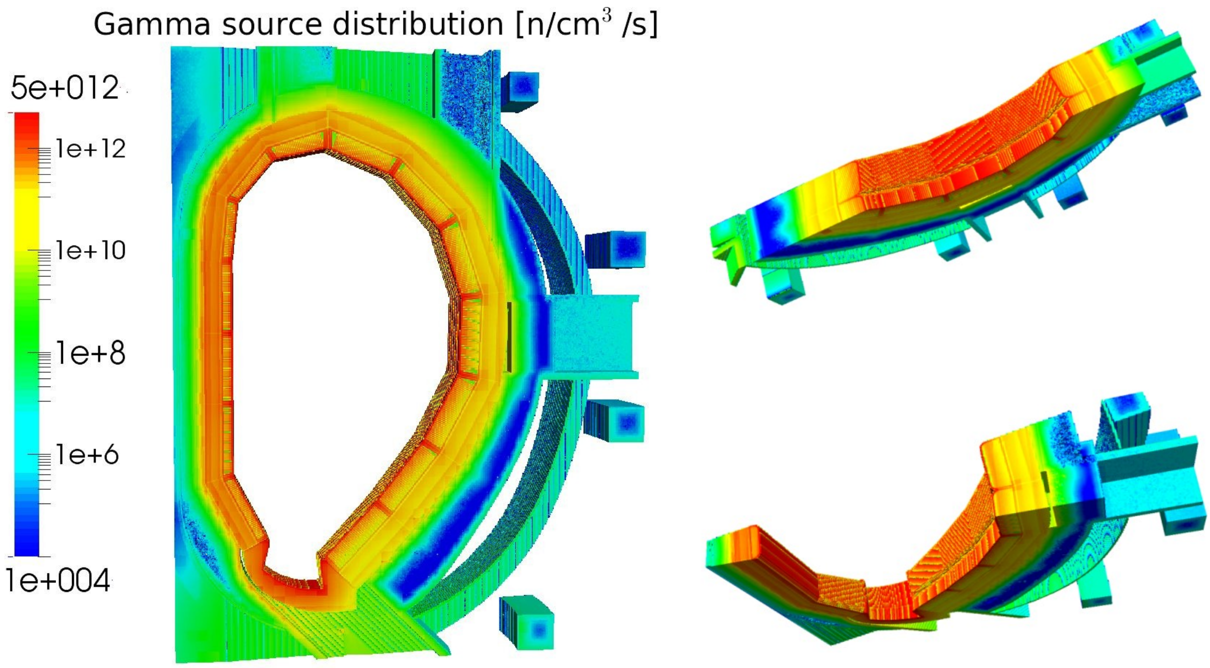



*Fig. 9. Gamma source distribution two weeks after shutdown; the upper right is plot of vertical section and lower right is plot of horizontal section.*

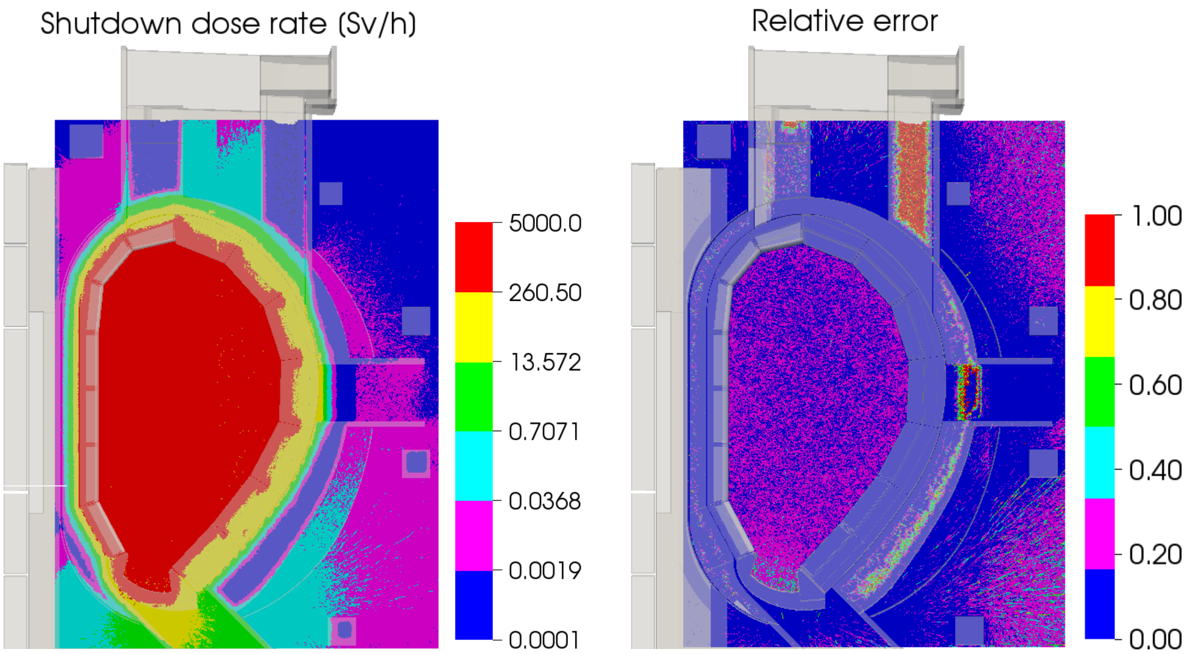


*Fig. 10. DEMO shutdown dose rate map two weeks after shutdown and relative error*

# 5. Summary

The R2Smesh interface developed at KIT has been proven as an accurate code for the calculation of shutdown dose rate in fusion reactor. The superimposed mesh tally technology of MCNP has been introduced in R2Smesh for neutron intensity and spectra calculation. The sensitivity of SDDR to the mesh resolution has been investigated in this paper. Convergence of SDDR has been achieved among series of calculation in JET and DEMO mapped by fine and coarse mesh with different resolution.

For the JET simulation, the investigation of SDDR sensitivity to mesh voxel showed when the fine mesh voxel was set up to 5 cm and coarse mesh voxel up to 20 cm that the SDDR converged. Within this limited range of mesh voxel, a general rule to determine the optimum mesh resolution has been put forward by compromising among the conditions of the result accuracy, computational cost. The simulation results obtained by setting of 2 × 2 × 2 cm fine mesh voxel and 20 × 20 × 20 cm coarse mesh voxel has been chosen to be compared with JET measurements to validate the R2Smesh code. Comparison shows they have good agreement. This approves the capability of R2Smesh to be applied on fusion reactor for accurate SDDR calculation.

R2Smesh has been applied on DEMO for global shutdown dose rate calculation. Likewise, a sensitivity study of DEMO SDDR to mesh voxel was carried out to determine fine and coarse mesh resolution. Around the blanket module it has large gradient of neutron flux from FW to back plate and these areas has been investigated. The sensitivity study shows the DEMO SDDR converged when setting 1~3 cm of fine mesh voxel and 15~30 cm of coarse mesh voxel. After applying the rule to determine the optimum mesh resolution, 3 × 3 × 3 cm fine mesh voxel and 30 × 30 × 30 cm coarse mesh voxel was used in the SDDR calculation. The SDDR behind the equatorial port is about $2.8\times10^{-3}$ Sv/h two weeks after shutdown; the neutron leakage from lower port to the space outside the VV contributes to higher gamma dose at equatorial port.

Both of the investigations on JET and DEMO show significant effect of mesh resolution to the final SDDR result. The mesh resolution for SDDR calculation should be carefully chosen when compromising among the limited conditions of the result accuracy, computational cost, etc.

# Acknowledgments

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