TOOLKIT FOR HIGH PERFORMANCE MONTE CARLO RADIATION TRANSPORT AND ACTIVATION CALCULATIONS FOR SHIELDING APPLICATIONS IN ITER

A. Serikov, U. Fischer, D. Grosse, D. Leichtle, M. Majerle
Karlsruhe Institute of Technology (KIT)
Hermann-von-Helmholtz-Platz 1, 76344 Eggenstein-Leopoldshafen, Germany
arkady.serikov@kit.edu

ABSTRACT

The Monte Carlo (MC) method is the most suitable computational technique of radiation transport for shielding applications in fusion neutronics. This paper is intended for sharing the results of long term experience of the fusion neutronics group at Karlsruhe Institute of Technology (KIT) in radiation shielding calculations with the MCNP5 code for the ITER fusion reactor with emphasizing on the use of several ITER project-driven computer programs developed at KIT. Two of them, McCad and R2S, seem to be the most useful in radiation shielding analyses. The McCad computer graphical tool allows to perform automatic conversion of the MCNP models from the underlying CAD (CATIA) data files, while the R2S activation interface couples the MCNP radiation transport with the FISPACT activation allowing to estimate nuclear responses such as dose rate and nuclear heating after the ITER reactor shutdown. The cell-based R2S scheme was applied in shutdown photon dose analysis for the designing of the In-Vessel Viewing System (IVVS) and the Glow Discharge Cleaning (GDC) unit in ITER. Newly developed at KIT mesh-based R2S feature was successfully tested on the shutdown dose rate calculations for the upper port in the Neutral Beam (NB) cell of ITER. The merits of McCad graphical program were broadly acknowledged by the neutronic analysts and its continuous improvement at KIT has introduced its stable and more convenient run with its Graphical User Interface. Detailed 3D ITER neutronic modeling with the MCNP Monte Carlo method requires a lot of computation resources, inevitably leading to parallel calculations on clusters. Performance assessments of the MCNP5 parallel runs on the JUROPA/HPC-FF supercomputer cluster permitted to find the optimal number of processors for ITER-type runs.

Key Words: Monte Carlo MCNP5 parallel computations, R2S activation interface, McCad graphical tool, ITER upper port, IVVS/GDC plug, JUROPA/HPC-FF supercomputer.

1. INTRODUCTION

There is a high demand in radiation transport and activation calculations to support design activities for the ITER fusion reactor which is currently in phase of construction in Cadarache, France (its web-site is www.iter.org). For radiation transport calculations in the ITER tokamak geometry, the Monte Carlo (MC) method is the preferred one due to the geometry complexity with great part of heterogeneities encountered such as ports for plasma access, diagnostics channels, waveguide tubes for plasma heating, and its structural gaps and voids. The MC method allows describing neutrons interactions with matter by tracking individual particle histories, without any substantial limitations on the MC model geometry. The precision of the MC method depends on number of sampled particles according to statistical laws and on systematic uncertainties introduced by modeling assumptions. Due to the independence of particle histories,

their tracks can be processed in parallel. The use of parallel computation can substantially increase the number of sampling histories, improve by this way the MC statistics, and finally - increase calculation accuracy of the MC method. The systematic uncertainties are diminished by using state-of-the-art nuclear data libraries with continuous energy representation of nuclear cross-section data (FENDL-2.1 for radiation transport and EAF-2007 for activation calculations) and by reproduction with a reasonable and neutronically-relevant level of detailing in the MC geometry model description. In our practice of fusion devices modeling, we are using well validated Monte Carlo MCNP5 code [1] featured with its inherent Variance Reduction Techniques (VRTs) which are essentially speeding up the calculations. The geometry description of the MCNP5 models is produced automatically from the CAD (CATIA) files by means of the McCad interface program [2] developed at KIT which use was well tested and exemplified in fusion neutronic applications [3]. One of such applications, the Electron Cyclotron Heating (ECH) launcher, the important components of the ITER to be installed in its upper port shown in Fig. 1, was thoroughly investigated from neutronics point of view [4-7]. The purpose of the ECH launcher is to control Magneto-Hydrodynamic (MHD) instabilities in the ITER plasma [4-7]. Geometry of the ECH launcher was converted from CATIA files into the MCNP5 input deck using McCad. After that dummy shield plug inside the ITER upper port was replaced with the ECH launcher as depicted in Fig. 1. In the ITER-related neutronic works, the MCNP5 radiation transport computations have to be performed with the Alite standard ITER model [8] distributed by the ITER Organization (IO). The Alite MCNP5 model represents a 40^0 torus sector with all the ITER components inside, as shown in Fig. 1. It is a complex and large model, consisting of ~5000 cells defined with over 3050 surfaces. Its radius is 17 m and it has a height of 25.5 m. The ECH launcher calculations have been performed with Alite model ver. 003, while the newly completed analyses presented in Sections 3 and 4 are accomplished with updated Alite ver. 4.1.
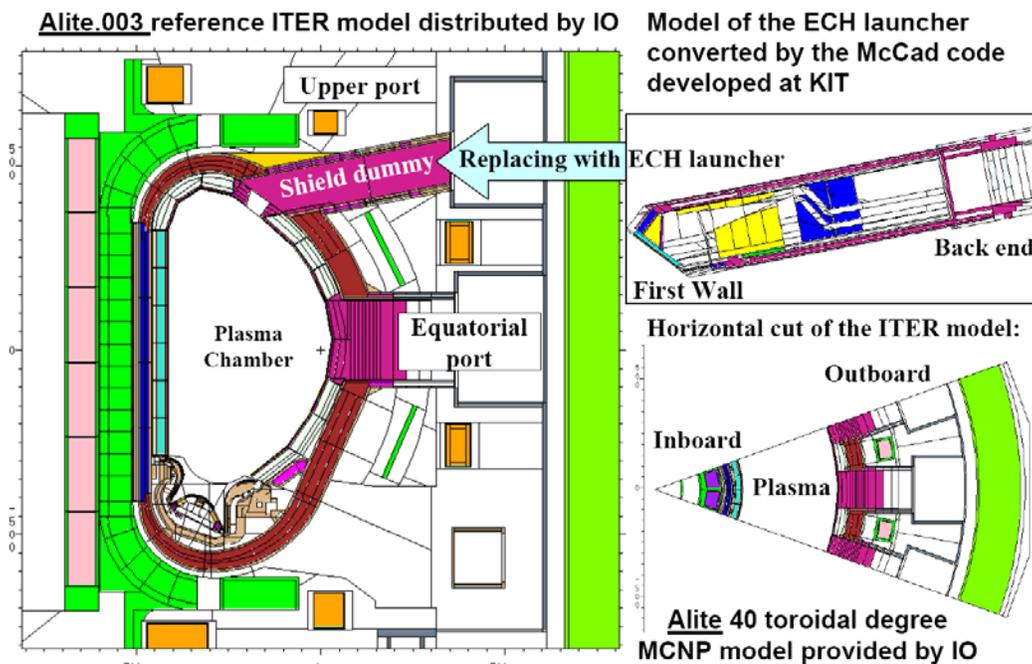

Figure 1. Integration of the McCad converted ECH launcher model inside Alite ITER model, with its vertical (left and right upper sides) and horizontal (right bottom side) cuts.

Activation calculations are very important for ITER because its materials are becoming radioactive under neutron irradiation emitted from D-T nuclear reaction in its plasma chamber shown in Fig.1. At ITER occupational radiation protection must be guaranteed for the protection of workers after the ITER shutdown for the reactor maintenance. This paper includes brief description of the computation kit of tools developed at KIT for activation calculations coupled with the MCNP5 radiation transport for shielding applications in ITER. Two applications have been considered in this paper: (1) In-Vessel Viewing System (IVVS) and the Glow Discharge Cleaning (GDC) unit – IVVS/GDC plug – in Section 3; (2) upper port in the Neutral Beam (NB) cell area – in Section 4. Instead of ECH launcher, the upper port in the NB cell was occupied with the structure consisted with shield block and a cap which are connected by the diagnostic tube shown in Fig. 2. This type of the upper port in the NB cell serves for diagnostics purposes of the ITER plasma, hence it must provide personnel access for maintenance inside the port extension at the port back side. The access must be possible after 10^6 s of shut-down time. Radiation shielding must be designed to ensure the dose is as low as reasonably achievable but, in any case, if the dose is estimated to be in excess of $100\mu Sv/h$ at 10^6 seconds after cessation of plasma operations, then further steps are considered to reduce the dose or to demonstrate that this is impracticable. A new design for the port internal shield structure was proposed by the ITER Organization and this paper together with more detailed work [9] confirm that it fulfills the ITER radiation design and nuclear safety requirements. In the new design the port plug is replaced by a cap and a shielding block connected by a diagnostic tube as shown in Fig. 2. This replacement with shorter shield block allows dismantling of the upper port insertions by remote handling from the side of the ITER plasma chamber. This shortage of the shield keeps nonetheless the ITER requirements as will be shown in Section 4.
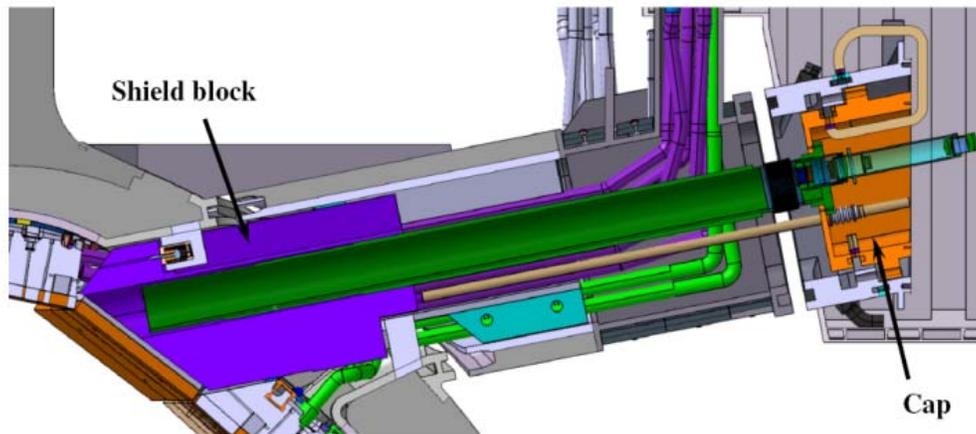

Figure 2. CAD model of the upper port in the Neutral Beam (NB) cell of ITER.

The next application for the computational kit of tools is the IVVS/GDC plug located as shown in Fig. 3 below the ITER equatorial port (see whole model of ITER in Fig. 1). The plug consists mainly of the IWS probe, capable of performing the laser-based in-vessel viewing and metrology, the GDC electrode, capable of producing glow discharge in the vacuum vessel during intermediate maintenance and wall conditioning periods, and their respective deployment systems to move the electrodes. The plug extends over a length of about 11 m from the GDC tip at the blanket level to the rear end at the bioshield level. At the present stage of the conceptual design of the IVVS/GDC plug [10], a neutronics analysis has been requested to provide initial

neutronic data for the design strategy. These data include assessments of neutron and photon operational fluxes and nuclear heating, as well as absorbed decay-photon dose and heating after the ITER shutdown. For the shutdown neutronic analyses we have used a dedicated computation kit of tools described in Section 2.
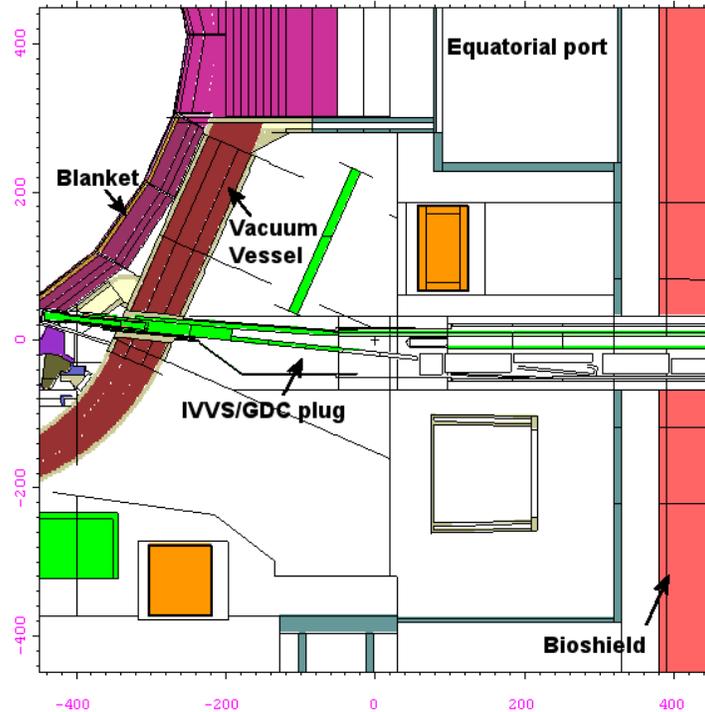

Figure 3. Vertical cut of the IVVS/GDC plug along its major axis integrated inside the Alite 4.1 ITER model.

2. COMPUTATION KIT OF TOOLS FOR TRANSPORT AND ACTIVATION CALCULATIONS

Logically, the computation kit of tools can be applied for solving many types of neutronic tasks we have encountered in the ITER project. Usually, the neutronic work-flow is conceived with given preliminary CAD (CATIA) files of the particular ITER component which is converted by the McCad code into Monte Carlo model. Then the model is passed through radiation transport and activation calculations using that model. Finally, the work ends with presentation of detailed maps of neutron responses and guidelines for the ITER designers how to arrange shielding of the component. Inevitably, the McCad conversion procedure implies some preparatory work on the original CAD files, keeping neutronically-important features of the CAD model and removing unnecessary, flooding details, such as connective holes, notches, and so on. The practical use of McCad is described in [3], while the mathematical background could be found in [2]. Also, the solids of the CAD model should include only those types of surfaces which are supported by both the MCNP code and the Open CASCADE (OCC) CAD kernel, which is a part of the McCad code. Free form surfaces (e.g. b-splines) must be substituted by the boundary representation (B-rep) algebraic boundaries such as planes or quadrics, which are MCNP- and

2011 International Conference on Mathematics and Computational Methods Applied to
Nuclear Science and Engineering (M&C 2011), Rio de Janeiro, RJ, Brazil, 2011

4/18

OCC CAD kernel-compatible. The McCad's graphical user interface (GUI), based on the Qt4 libraries, provides features for data exchange and visualization. The algorithmic limitations on the CAD model to be converted with McCad are explained in depth in [2]. Currently, in addition to MCNP, McCad can support other MC code –TRIPOLI-4 transport code [11]. The MCNP5 model segmentation is performed by McCad automatically depending on the material locations, hence some MCNP5 cells are rather large for the effective MC transport, and hence the MCNP5 mesh-based weight-window generator and mesh-tally [1] would be recommended to use.

In our practice we have provided neutronic service for the combining neutronic tasks which include deep-penetrating radiation transport in the complex ITER 3D geometry coupled with 3D activation analyses and shutdown dose rate calculations. Decay gamma transport in 3D ITER geometry is of primary importance for shutdown dose rate calculations due to the geometry complexity with many gaps and channels, and hence the possibility of gamma streaming. This aspect was taken into account in the Rigorous 2 Step method (R2S) [12] developed at KIT. The R2S automated interface has been developed at KIT to couple neutron transport with MCNP5, then activation and generation of decay gamma sources with the FISPACT-2007 code [13], and then arrangement of the decay-gamma source distributions and the decay-gamma transport calculations back in the original 3D MCNP geometry. All the data transfers are performed seamlessly by the R2S interface based on the interface settings and a user-defined set of MCNP geometry cells used for both tallying of neutron fluxes and sampling of decay-photon sources. This so called cell-based R2S interface has been experimentally benchmarked and validated on the 14-MeV Frascati Neutron Generator [14], the JET fusion reactor [15] and applied in many tasks for post-irradiated neutronic analyses [4-7, 12]. The cell-based R2S method was applied in Section 3 for decay-photon heating assessments for IVVS/GDC plug in ITER. Gamma sources were arranged in the MCNP cell with activated materials of the IVVS/GDC and its surrounding structures. The requested nuclear responses have been provided both in the IVVS/GDC cells and on a fine mesh grid superimposed to the IVVS/GDC plug and its surrounding as shown in Section 3.

The next generation of the R2S method has been recently developed at KIT, now in the R2S interface the possibility to couple the MCNP5 and FISPACT calculations through the MCNP5 superimposed mesh-tally (the card is called "FMESH" [1]) is appeared. In this new mesh-tally based R2S version, instead of the MCNP cells, the mesh-tally bins are used for both the MCNP5 neutron intensities and spectra calculation and for the FISPACT decay-gamma source calculations, returning back to MCNP5 the source distribution for decay-gamma transport. The mesh-based R2S method is an advanced version of the cell-based R2S. It is recommended to apply mesh-based R2S version in complicated geometries, where superimposed mesh grid is preferred to use. For effective MC radiation transport, the need for segmentation of the MCNP5 material cells is caused by two reasons: (1) particle weight should be changed in deep-penetrating calculations to keep the population of particles; (2) averaging the mean value of the response inside the tally region. The cells segmentation could be accomplished by introduction of additional splitting surfaces or by using the superimposed mesh keeping the original MCNP5 geometry, created e.g. by McCad from CAD (CATIA) files, untouched. Hence, the meshes can be used for MCNP5 tallying purposes and to apply for weight windows generation as Monte Carlo (MC) Variance Reduction Technique (VRT) [1]. In general, the mesh settings used for weight windows generation and for tallies are different. The MC statistics is affected strongly by the size and number of the calculation bins. The less the number and the bigger the size of the tally bins are, the more precise statistical results will be obtained. Therefore a coarse mesh is

used for neutron spectra calculations, and a fine mesh for total neutron intensities are introduced in the R2S mesh-based scheme. The spatial bins of both meshes should overlap, for easier use it is recommended that coarse mesh is by an integer factor divided fine mesh. The idea to use mesh-tally for the MCNP and FISPACT coupling in the R2S computational scheme was well recognized in fusion neutronic community, so that originated at KIT cell-based R2S method was enhanced independently at Culham Centre for Fusion Energy (CCFE) in Culham, UK with the MCR2S (Mesh-tally Coupled Rigorous 2 Step) program [16, 17]. Both programs, MCR2S and mesh-based R2S under development at KIT, follow the R2S formalism [12]. In both of them the spatial resolution of decay photon sources is treated with superimposed mesh-tally. One difference is found that instead of only one mesh in MCR2S mentioned in [16], in KIT's version there are two separate meshes: a fine one is to calculate neutron intensities and a coarse mesh to ascertain the neutron spectra. First time the programmed at KIT mesh-based R2S methodology was applied in neutronic analyses for the upper port in the Neutral Beam (NB) cell of ITER [9], and some outcomes of that work with new 3D visual post-processing with the VisIt graphical tool version 2.1.2 [18] are presented in Section 4.

The MCNP5 superimposed mesh tally comes with no information about the material composition of separate mesh tally cells which is necessary to set for the FISPACT activation calculations in the R2S mesh-based work-flow. For this purpose, the MCNP5 subroutine PTRAC should be called, which samples uniformly inside superimposed mesh tally and at each sampling point gives its cell number, three coordinates, and material number. In a general case, the mesh cells could share several materials, and the material sharing fraction can be found with the PTRAC card to specify the homogeneous material mixture for each cell. To write only start events in PTRAC we must provide that the generated particles are not transported after the start, which can be done by setting the energy cut-off higher than is the energy of the starting particle. To generate the PTRAC file, MCNP should sample enough histories to recognize materials inside a mesh bin, because the composition of the mesh tally bin is determined by the number of hits of different cells. Hence each mesh tally bin should be sampled several times. The PTRAC task is running only on a single processor and it is completed very fast, e.g. for the case of the ITER upper port, 4GB PTRAC files (10^7 particle histories) are processed without problems in ~5 minutes.

Considering the issue of computational performance of the codes incorporated in the scheme of the R2S activation interface, independently of its versions (cell- or mesh-based), the most computational time is spend for Monte Carlo MCNP5 computations of radiation (neutron and photon) transport. Due to the necessity to reach requested statistical accuracy in the MCNP5 calculations in ITER deep-penetrating shielding assessments, high demands for computations were requested. Hence, the computation performance is mostly dependant on the efficiency of the organization of the MCNP5 parallel computations on the cluster computers, and this issue is discussed in Section 2.1.

2.1. MCNP5 Parallel Performance Assessments

The MCNP5 code has been installed on the High Performance Computer dedicated For Fusion applications (HPC-FF). It is based on petaflop architectures of JUROPA/HPC-FF system currently in operation at Juelich Supercomputing Centre (JSC), Research Centre Juelich (FZJ) in Germany (http://www2.fz-juelich.de/jsc/juropa/). Performance assessments of the MCNP5 code

2011 International Conference on Mathematics and Computational Methods Applied to
Nuclear Science and Engineering (M&C 2011), Rio de Janeiro, RJ, Brazil, 2011

6/18

were carried out to find an efficient way to run the code in a parallel regime. The parallel version of the code has been compiled with the Intel Professional Fortran and C/C++ compilers, and the Message Passing Interface (MPI) libraries. In the MPI-connected MCNP5 parallel job, the master processor sends the instructions to trace the nuclear reactions with each particle and to do the necessary computations to a selected number of slave CPUs. The MCNP5 parallel performance had been estimated previously [19], reporting about achieving of 24 speed-up on 27 CPUs of he Opus[IB] Linux cluster at KIT (former CampusGrid cluster at FZK). Practice of the MCNP5 MPI-parallel computations [19, 20] shows that it is important to keep the master-slave communication as little as possible. This is achieved by setting the number of intermediate data exchange, called "rendezvous", to a minimum using the MCNP5 Print and Dump (PRDMP) card. The PRDMP card controls the intervals at which tallies are printed to the output file and calculation data are dumped in the RUNTPE file. The optimal number of CPUs used in MCNP5 parallel calculations is dependent on complexity of the model, physical process involved in particle tracks and particle histories longevity. Expressing in terms of the MCNP5 job settings, this optimal number of CPUs is dependent on the MCNP5 job size expressed in number of histories (parameter NPS in MCNP).

On the HPC-FF cluster there are 1080 compute nodes with 8 cores (8640 CPU cores in total) intended for batch parallel jobs. Each node includes 2 Intel Nehalem-EP quad-core processors (Xeon X5570 at 2.93 GHz) and 24 GB memory. The nodes are connected by means of the InfiniBand Mellanox ConnectX QDR network adapter cards and multiple-port switches in the InfiniBand topology. The operating system on HPC-FF is Linux SUSE SLES 11. The batch system is MOAB with underlying resource manager TORQUE. MOAB is a workload manager product of Cluster Resources, Inc. (www.clusterresources.com). The MOAB scheduler provides a utility to set polices for fair utilization of the available computational resources. By means of the MOAB scheduler commands, a user can submit parallel jobs and monitor their execution. The parallel file-system employed on HFC-FF is Lustre, which is optimized for large Input/Output requests. For the considered here test problem the size of file with dumped information (RUNTPE file) is ~1 GB, it is a binary file including information about nuclear cross-sections, MCNP model geometry, and the requested tallies. The parallel performance presented here was achieved for the problem of nuclear response (helium production and nuclear heating) calculations with use of the MCNP5 high-resolution mesh-tallies in the area of blanket shield module of the ITER Electron Cyclotron Heating (ECH) upper launcher [20, 21].

The results of the parallel performance and search for optimal number of CPUs are presented here in assumption of MCNP5 parallel run without intermediate rendezvous set by the PRDMP card. Values in the PRDMP card are equal to total number of histories set by NPS. When user sets certain number of CPUs in the MOAB script, then the MCNP5 NPS number is divided by this CPU number minus one. This is because in MPI-scheme one CPU is reserved for master process to control the MCNP job running on the slave CPUs. To do the MCNP5 parallel performance analysis, computational wall-clock times have been measured in dependence of number of used slave CPUs and size of the job. Results are presented in Figs. 4 and 5 in terms of speed-up and efficiency respectively. The speed-up (S_N) is defined as the ratio between the wall-time running on one processor (T_1) and the wall-time running on N slave processors (T_N), $S_N = T_1/T_N$. The efficiency (E_N) is estimated by the ratio between the speed-up (S_N) and the number of slave processors (N).

The bigger the job-size, the bigger the chunks of information are which will be processed by a single slave CPU, and the less the communications are between the master and the slave CPUs.

2011 International Conference on Mathematics and Computational Methods Applied to Nuclear Science and Engineering (M&C 2011), Rio de Janeiro, RJ, Brazil, 2011

7/18

As follows from Fig. 4, the speed-up peak and the number of utilized CPUs are shifted to higher values when increasing the number of sampled particles from 5e8 to 5e9. The MCNP5 parallel efficiency, plotted in Fig. 5, shows the same beneficial tendency of the job size increasing if many hundreds of CPUs are available. This plot allows judging a job from the comparison with a computational efficiency limit. In this case a limit of 60% was chosen as a good compromise between performance and availability of CPUs. The job size of 5e9 particles falls below this efficiency limit at about 1000 slave CPUs. That is, using more CPUs is getting less effective, and according to Fig. 4 it even spends more time to run the job if more than 1600 CPUs are used.

An important issue for scaling is keeping or increasing the calculation load on each processor: the higher ratio of computation per communication, the closer speed-up scaling to linear law. The short MCNP5 jobs assigned to parallel run have high overhead, hence use of many processors is inefficient. Parallel performance is sensitive to number of intermediate message exchanges between master and slaves (rendezvous). The rendezvous number should be reduced in compromise with fault tolerance. The best performance is achievable with only one rendezvous.

From the experience of the MCNP5 parallel runs for the ITER fusion neutronic applications, an optimal number of CPUs depends on size of the MCNP5 task and number of available processors on the cluster. In our practice, the averaged number of CPUs we have set on HPC-FF is ~800, while usual number of CPUs on HC3 (another cluster at KIT) and Opus^{IB} is ~96. These are rough number of CPUs which can be used without a long task queuing. The maximum speed-up was found on HPC-FF equaled ~700 with 1600 CPUs, this means that wall-clock time to run the same job on one CPU was 700 times longer than running on 1600 CPUs in parallel on the HPC-FF cluster at Juelich Supercomputing Centre (JSC).
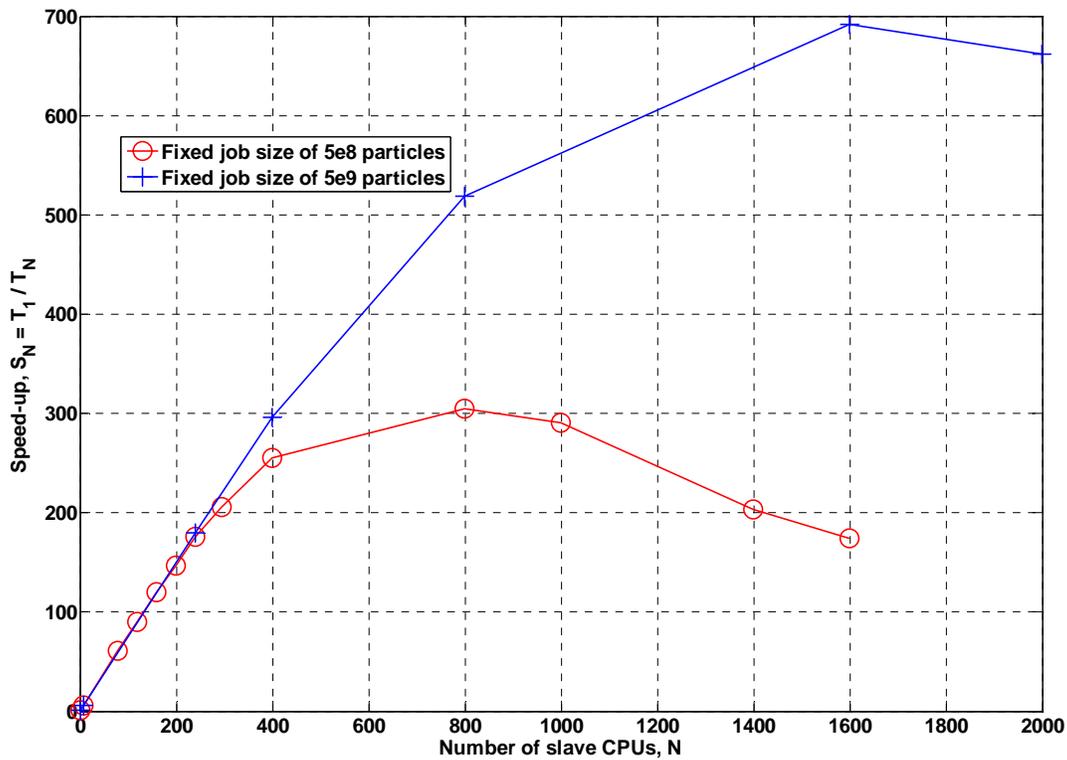

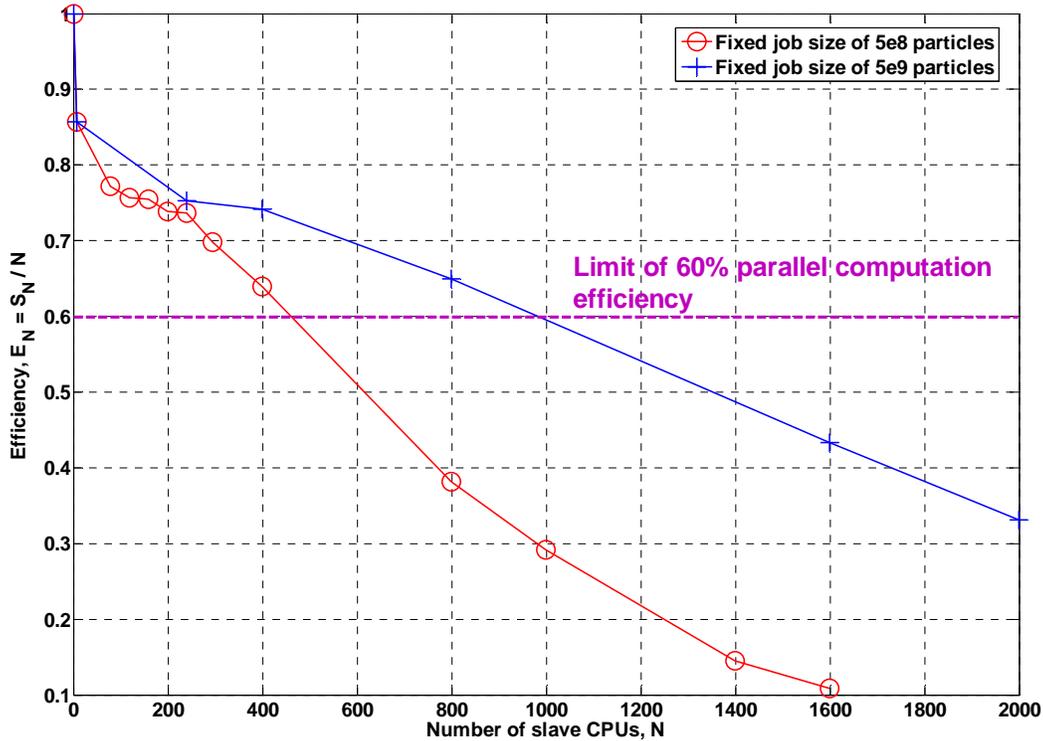**Figure 4. HPC-FF speed-up for two sizes of the MCNP jobs with 5e8 and 5e9 particles.**

Figure 5. HPC-FF efficiency for two fixed MCNP5 job sizes of 5e8 and 5e9 particles.

3. USE OF R2S CELL-BASED INTERFACE FOR DECAY–PHOTON HEATING ASSESSMENTS FOR THE IVVS/GDC PLUG

The cell-based R2S approach has been applied for decay-photon heating calculations of the In-Vessel Viewing System (IVVS) and the Glow Discharge Cleaning (GDC) unit assembled into the IVVS/GDC plug. The plug is located between two legs of the Toroidal Field Coils (TFC) shown in Fig. 6, below the ITER equatorial port and serves for plasma diagnostics and cleaning of the plasma chamber shown in Figs. 1 and 3 of Introduction. The plug extends over a length of ~11 m from the GDC tip at the blanket level to the rear end at the bioshield level. Additional segmentation of many radially-extended cells of the IVVS/GDC plug and large cells in its vicinity shown in Fig. 6 has been fulfilled manually.

According to the R2S cell-based methodology, decay-photon sources from activated materials of the IVVS/GDC plug and surrounding structures, such as blanket, vacuum vessel, toroidal and poloidal field coils, cryostat, and bioshield have been taken into account (see Fig. 6). Neutron spectra have been calculated in the manually segmented MCNP5 cells, and then the spectra have been supplied to FISPACT-2007 activation calculations to get the decay-photon sources at certain times after shutdown. A visualization of the decay-photon is plotted on the horizontal plane, which MCNP5 geometry is given in Fig.7 respectively to the map of decay-photon sources ($g/cm^3/s$) depicted in Fig. 8. The decay sources are mapped in Fig. 8 at zero cooling

2011 International Conference on Mathematics and Computational Methods Applied to
Nuclear Science and Engineering (M&C 2011), Rio de Janeiro, RJ, Brazil, 2011

9/18

time. It follows from Fig. 8 that gamma sources generated inside the Vacuum Vessel are five orders of magnitude higher than inside the back-end side of the IVVS/GDC plug.

At final step of the R2S work-flow, the decay-photon sources have been set in MCNP5 model, and photon transport has been accomplished for each shutdown time interval. The resulting assessments of the photon heating have indicated that even immediately after shutdown the maximum decay-photon heating is only about 4 mW/cm^3 at the copper layer located at the IVVS/GDC plug in front to the plasma (see Fig. 9). This value is less than 1% of the respective maximum operational heating. The maximum operational heating of about 0.6 W/cm^3 is observed for the copper cap (CuCrZr-IG alloy) of the GDC tip. This heating includes neutron and secondary photon heat depositions, and for the most IVVS/GDC heavy materials such as steel and copper, the photon contribution is dominated. With the exception of beryllium in which, as in a light mass element, neutron kinetic energy release creates the main contribution into the operational heating. The decay-photon heating decreases rapidly to ~10^{-8} W/cm^3 at the bioshield. As those values refer to the moment of ITER shutdown it can be stated that the heating due to decay-photons is insignificant compared to the nuclear heating during operation.

After 12 days of cooling time the decay-photon heat is reduced by two orders of magnitude (see Fig. 9) in front of the IVVS/GDC plug. At 100 days a further reduction of a factor of three is observed.
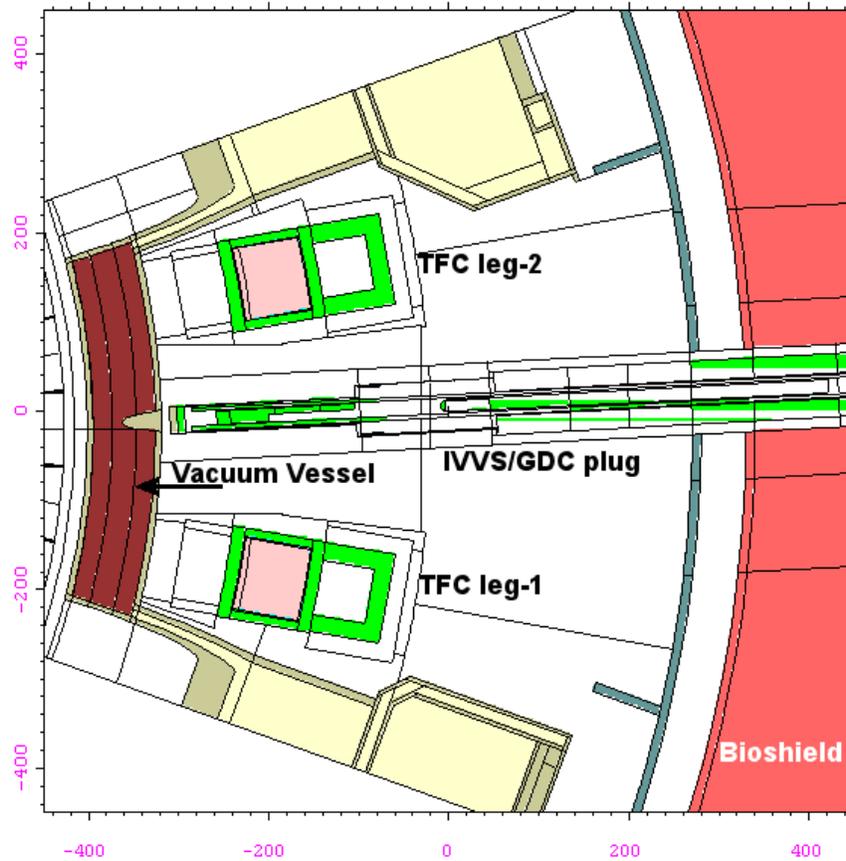

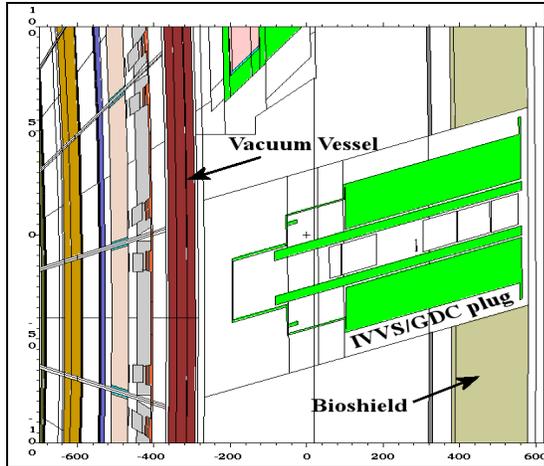**Figure 6. Horizontal cut of the IVVS/GDC plug in its radial-toroidal plane.**

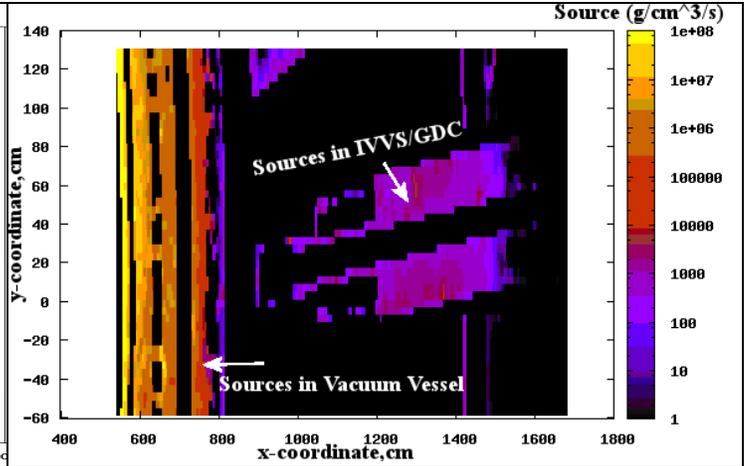**Figure 7. Horizontal cut (at z=-381 cm) of the MCNP model geometry through the IVVS/GDC plug.**

Figure 8. Map of decay-photon sources (g/cm^3/s) generated in materials of the IVVS/GDC plug at zero cooling time plotted on the horizontal plane corresponded to Fig. 7.
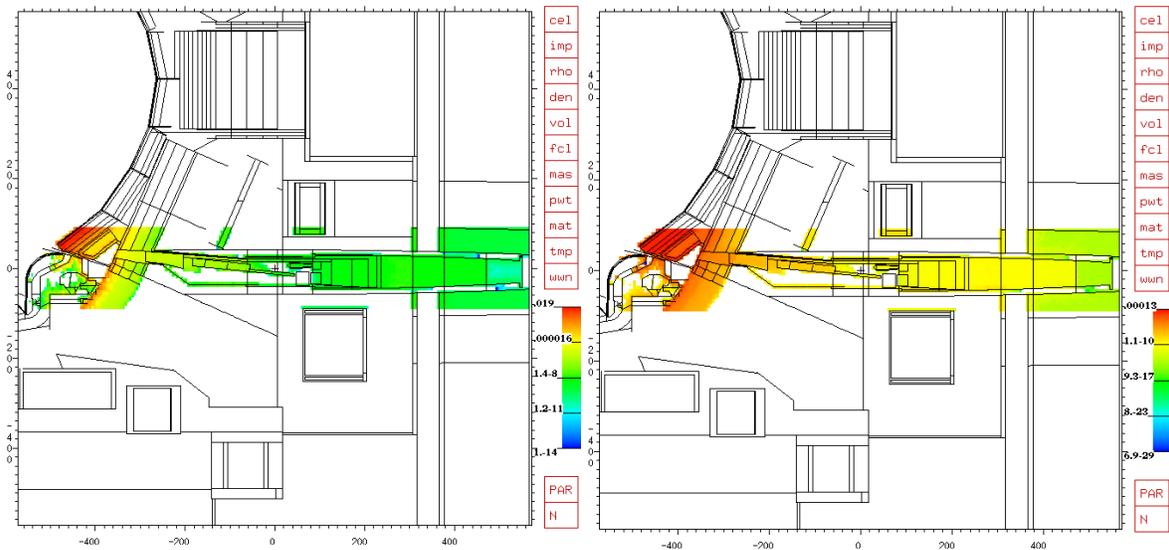

Figure 9. Map of decay-photon heating vertical distribution after 20 yr operation at cooling time 0 second (left) and 12 days (right), resp. [W/cm^3]

2011 International Conference on Mathematics and Computational Methods Applied to
Nuclear Science and Engineering (M&C 2011), Rio de Janeiro, RJ, Brazil, 2011

11/18

4. USE OF R2S MESH-BASED INTERFACE FOR PRODUCTION OF SHUTDOWN DOSE RATE MAPS AROUND THE UPPER PORT IN NEUTRAL BEAM CELL

Wide range of neutronic analyses has been performed in work [9] for assessment of the shielding performance of the newly proposed design of the upper ports in the Neutral Beam (NB) cell of ITER. In this paper we take interest in methodological part of work [9] related to first test of the mesh-based R2S method. It was shown that the R2S mesh-based method allowed the extension of shutdown dose rate calculations to non-segmented MCNP models which can be used with the mesh-based weight windows VRT.

The evaluations of shutdown dose rate distributions using the R2S mesh-based method are accomplished more efficiently by the combination of two types of neutron transport calculations: (1) neutron energy spectra calculations in larger spatial mesh than (2) total neutron flux calculations in fine mesh. The arguments for this combination are that the shapes of neutron spectra change slower than the neutron intensities by passing through the shielding materials such as steel and water. In the case of the R2S mesh-based application for the ITER upper port in the NB cell, two sets of mesh tallies have been applied, with two different sizes of the mesh cells: ~4 cm for the fine mesh to calculate total neutron fluxes and ~20 cm for the coarse mesh to obtain the neutron spectra with 175 energy groups in the VITAMIN-J structure. The outer boundaries of these fine and coarse meshes are chosen to coincide. According to the R2S calculation scheme, the total neutron fluxes and spectra obtained in each bin of the mesh tallies are used for the FISPACT-2007 activation calculations of decay gamma sources. As some cells of the meshes have shared different materials or void, the PTRAC card of MCNP5 was applied to provide the information about the volume fraction occupied by certain materials to be used in the FISPACT calculations. The main structural material of the port is the SS316L(N)-IG ITER-grade steel with the full list of constituent traced elements, which are important to activation calculations. The material compositions used in activation calculations have met the ITER nuclear requirements [8]. For decay gamma source calculations according to the mesh-based R2S approach, the space of the upper port in the NB cell was split by two areas of mesh-tallies: the Rear Mesh Area-I, and the Front Mesh Area-II, as shown in Fig. 10. The dose rate distribution from the dominant source area (Rear Mesh Area-I) at 10^6 s after shutdown is mapped in Fig. 11 using the MCNP standard 2D plot. The dose map in Fig. 11 includes only the far-back part of the Rear Mesh Area-I mesh plotted inside the box of upper port extension and its close vicinity. The dose results in spherical 10-cm radius detectors are presented selectively in Table I as partial contributions from areas I and II and as a sum. The shutdown dose rate inside the port extension is distributed in a range from 96 µSv/h to 10 µSv/hr after 10^6 seconds of cooling time. These shutdown dose rates are below 100 µSv/h inside the port extension area, as required to guarantee the personnel access.
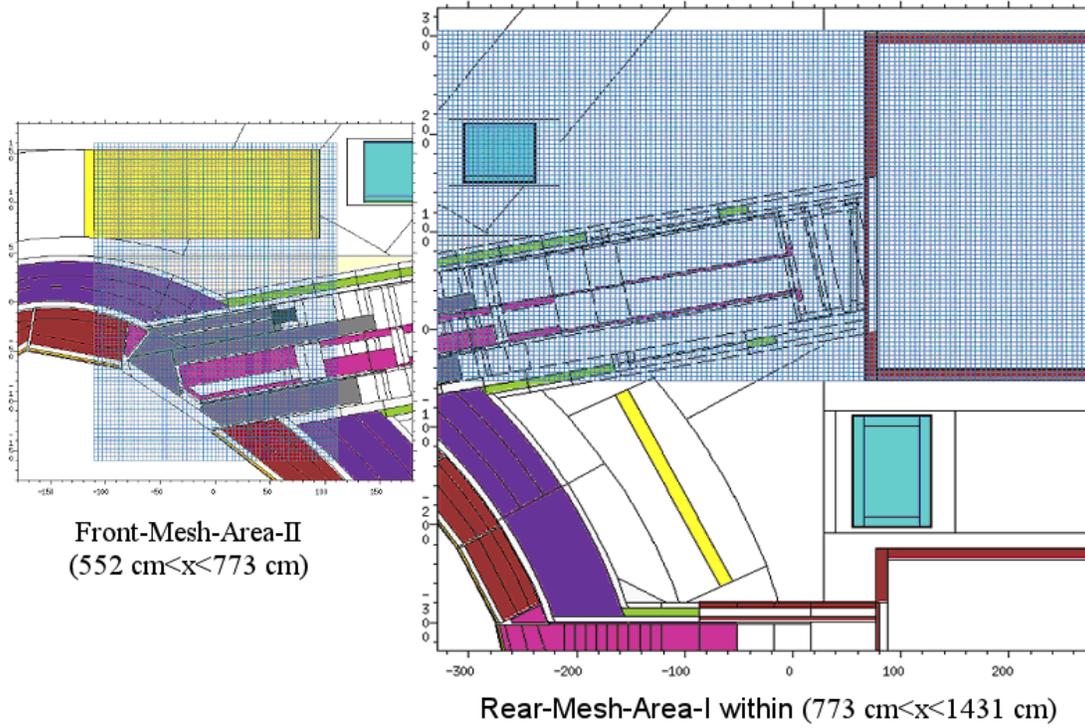
Figure 10. Arrangement of the two mesh tally areas used for the decay gamma source generation.
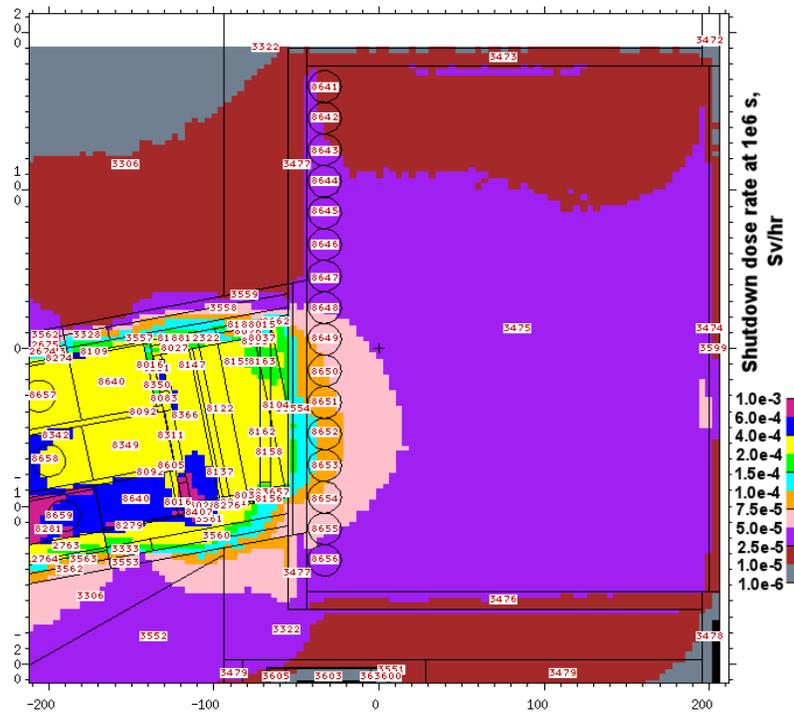

Figure 11. Map of shutdown dose rate (Sv/h) from sources inside the Rear Mesh Area I.

2011 International Conference on Mathematics and Computational Methods Applied to
Nuclear Science and Engineering (M&C 2011), Rio de Janeiro, RJ, Brazil, 2011

13/18

Table I. Shutdown dose rate estimates inside the selected sphere detectors distributed vertically at the beginning of the upper port extension (see Fig. 11)

MCNP sphere number	Shutdown dose rate from sources in area I, Sv/h	Shutdown dose rate from sources in area II, Sv/h	Shutdown dose rate from sum of sources in areas I+II, Sv/h
8647	3.69E-05	1.33E-07	3.70E-05
8648	4.81E-05	1.28E-06	4.94E-05
8649	6.51E-05	4.59E-06	6.96E-05
8650	7.64E-05	5.38E-06	8.18E-05
8651	8.42E-05	5.46E-06	8.97E-05
8652	9.12E-05	4.70E-06	9.59E-05
8653	8.86E-05	5.21E-06	9.38E-05
8654	6.98E-05	1.02E-06	7.08E-05
8655	5.34E-05	4.70E-07	5.38E-05

Valuable visual 3D information for the shutdown dose rate distributions is gained with the VisIt graphical tool version 2.1.2 [18] as shown in Figs. 12 and 13. The contributions to dose map from decay gamma sources are presented in these Figures separately. Particularly, in Fig. 12 the map is plotted with a contribution to dose from the sources generated inside the materials of Rear Mesh Area I only, while in Fig. 13 the sources inside the Front Mesh Area II are taken into account. The highest (red color) dose values are observed in front parts of dose distributions, which attenuated by passing through the port materials to relatively low (blue color) dose values at back sides. On the maps in Figs.12 and 13 the plane of the beginning of the port extension is drawn explicitly as a boundary behind which personnel access to the port should be provided to do its maintenance. The level of shutdown dose rate at 10^6 seconds after cessation of D-T plasma operations is one of many radiation design criteria considered in the neutronic analyses [9] performed for the upper port in the NB cell of ITER. By cutting out the low dose rates with setting in VisIt the dose rate threshold at 100 µSv/h, it was possible to visualize the area of the doses above 100 µSv/hr, the limit of personnel access in ITER. From Figs. 12 and 13 it is quite clear that shutdown dose rate is less 100 µSv/h behind the plane of the beginning of the upper port extension. Only few exceptional dose-lines pass behind the plane, but these lines are attributed for poor MC statistics and can be excluded from the reliable consideration.
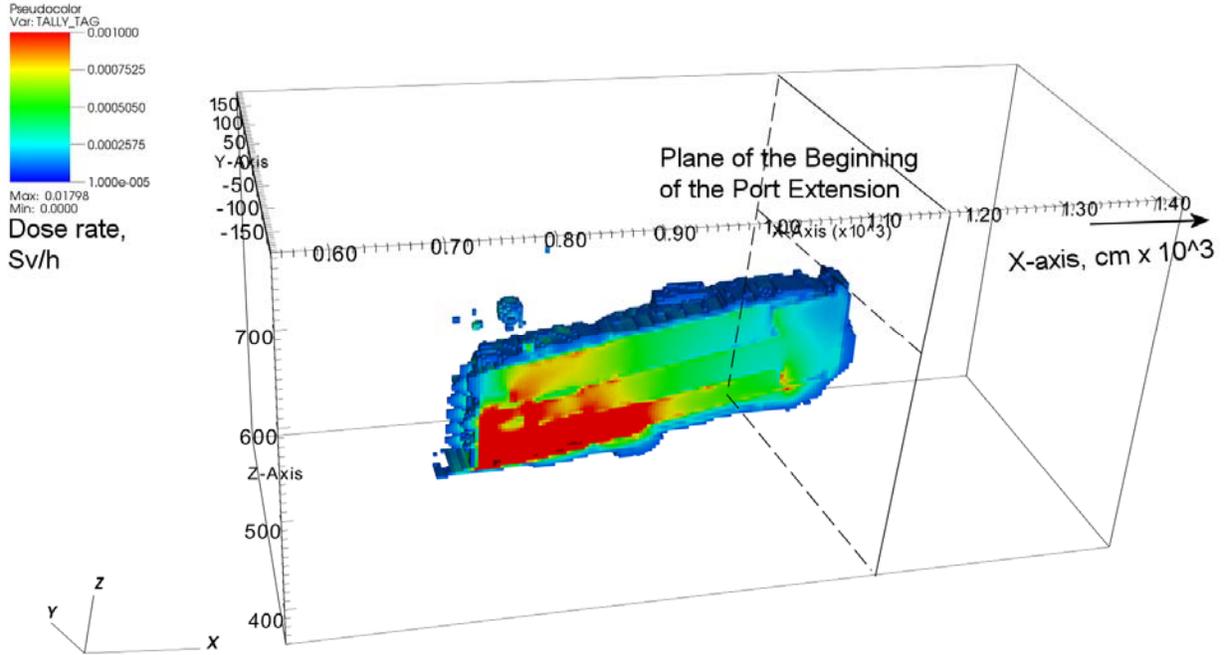
2011 International Conference on Mathematics and Computational Methods Applied to Nuclear Science and Engineering (M&C 2011), Rio de Janeiro, RJ, Brazil, 2011

14/18

Figure 12. Map of shutdown dose rate (Sv/h) from gamma sources located in Rear Mesh Area I (sources are in radial interval 773 cm <x< 1431 cm), produced with VisIt 3D tool.
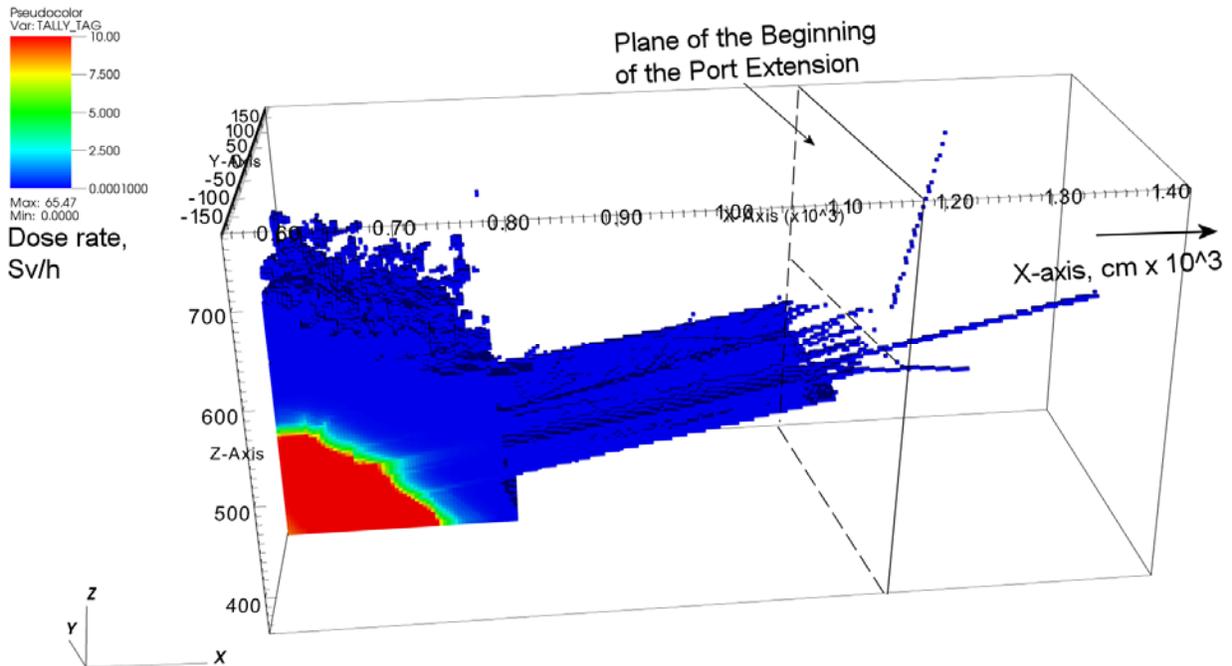

Figure 13. Map of shutdown dose rate (Sv/h) from gamma sources located in Front Mesh Area II (sources are in radial interval 552 cm <x< 773 cm), produced with VisIt 3D tool.

2011 International Conference on Mathematics and Computational Methods Applied to
Nuclear Science and Engineering (M&C 2011), Rio de Janeiro, RJ, Brazil, 2011

15/18

5. CONCLUSIONS

The computation kit of tools developed at KIT for a wide range of nuclear analyses has been presented and exemplified on several ITER components. This neutronic kit of tools is intended for shielding and activation analyses of fusion devices. Farther development of the R2S activation tool concerning its mesh-based version was tackled in the paper. The mesh-based R2S method allowed the extension of shutdown dose rate calculations to non-segmented MCNP models which was used together with the MCNP5 mesh-based weight windows generator as a Variance Reduction Technique (VRT). The use of superimposed meshes was beneficial to speed-up neutronic calculations during the design work of the ITER components, because the components were converted automatically with the McCad graphical tool from the CATIA files, and practically minimal amount of manual labor was used for the MCNP modeling and segmenting. The only great challenge was to integrate automatically created MCNP models of the components into the Alite general model of ITER.

The High Performance Computation (HPC) resources allocated at HPC-FF at Juelich Supercomputing Centre (JSC) in comparison with Opus[IB] and HC3 at KIT in Karlsruhe have been evaluated from the end-user's point of view assessing the parallel performance of the Monte Carlo MCNP5 radiation transport code. A considerable increase of number of CPUs exploiting the resources of the HPC-FF supercomputer at JSC makes available to accomplish shielding tasks for the ITER design development much faster than before at KIT, e.g. a job for one month running on 27 CPUs on the Opus[IB] cluster with speed-up of 24, now can be accomplished in one day on HPC-FF with speed-up of ~700 on ~1600 CPUs. This is evident benefit of evolution in speed-up of the MCNP5 radiation transport using HPC with massive parallel multiprocessing.

Applying the cell-based R2S methodology, the maps of decay-photon heating have been produced along ~11 m extension of the In-Vessel Viewing System (IVVS) and the Glow Discharge Cleaning (GDC) unit in ITER. The maximum absorbed decay-photon heating has been shown to be 4 mW/cm^3 at the copper layer located at IVVS/GDC in front to the plasma This maximum contributes less than 1 % of the nuclear heating released during the ITER D-T operation. Based on the work performed several indications for further improvements of the neutronics model have been envisaged, namely a precise definition of the plug insert at the vacuum vessel and specific material assignments for regions of interest.

The mesh-based R2S method was successfully applied for shutdown dose rate calculations of the upper port in the Neutral Beam (NB) cell in ITER. Its MCNP5 model was automatically converted by McCad and used in mesh-based R2S calculations without any manual segmentation together with the MCNP5 mesh-based weight windows VRT. This is beneficial to speed-up neutronic calculations during the ITER design work. The shutdown dose rate inside the port extension is distributed in a range from 96 µSv/hr to 10 µSv/hr after 10^6 s of cooling time. The dose rates are thus below the 100 µSv/hr design limit. Use of VisIt graphical tool is recommended for 3D visualization of the mesh-based results, such was demonstrated on the maps of shutdown dose rate distributions around the upper port in the NB cell. The distributions of nuclear heating obtained in the upper port internal structures indicate comparable values with other ITER systems such as the ECH upper launcher [6]. The scope of neutronic results provides a sound basis for the reliable operation of the whole ITER machine.

2011 International Conference on Mathematics and Computational Methods Applied to
Nuclear Science and Engineering (M&C 2011), Rio de Janeiro, RJ, Brazil, 2011

16/18

ACKNOWLEDGMENTS

REFERENCES

1. X-5 Monte Carlo Team, "MCNP — A General Monte Carlo N-Particle Transport Code, Version 5, Volume I, MCNP Overview and Theory," Los Alamos National Laboratory Report, LA-UR-03-1987, April 24, 2003 (Revised 10/3/05).
2. D. Grosse, H. Tsige-Tamirat, "Current Status of the CAD Interface Program McCad for MC Particle Transport Calculations," *Proc. M&C 2009*, Saratoga Springs, New York, May 3-7, 2009, American Nuclear Society (2009) [CD-ROM].
3. A. Serikov, U. Fischer, D. Grosse, et al., "Use of McCad for the generation of MCNP models in fusion neutronics," *Proc. M&C 2009*, Saratoga Springs, New York, May 3-7, 2009, American Nuclear Society (2009) [CD-ROM].
4. A. Serikov, U. Fischer, R. Heidinger, et al., "Radiation Shielding Analyses for the ITER Upper Port ECH Launcher," *Fusion Science and Technology,* **53** [1], pp.184-195 (2008).
5. A. Serikov, U. Fischer, R. Heidinger, et al., "Nuclear analyses for the ITER ECH launcher," *Nuclear Fusion*, **48**, 054016 (2008), doi: 10.1088/0029-5515/48/5/054016.
6. A. Serikov, U. Fischer, D. Grosse, et al., "Overview of recent nuclear analyses for the Upper ECH launcher in ITER," *Fusion Engineering and Design,* **85**, pp.1885-1895 (2010).
7. A. Serikov, U. Fischer, D. Grosse, et al., "Evolution of shielding computations for the ITER upper ECH launcher," *Proc. ANS RPSD-2010 Topical Meeting,* Las Vegas, April 18-23, 2010, submitted to *Nuclear Technology*.
8. M.J. Loughlin, et al., "ITER nuclear analysis strategy and requirements," *Fusion Science and Technology*, **56** [2], 566–572 (2009).
9. A. Serikov, U. Fischer, D. Grosse, et al., "Neutronic analyses for the upper ports in the Neutral Beam cell of ITER," *Proc. 19th Topical Meeting on the Technology of Fusion Energy (TOFE-19)*, Las Vegas, Nov. 7-11, 2010, accepted in *Fusion Science and Technology.*
10. D. Leichtle, A. Serikov, U. Fischer, "Absorbed decay-photon dose analysis of the IVVS/GDC plug in ITER," submitted to German Annual Meeting on Nuclear Technology (Jahrestagung Kerntechnik JK-2011), Berlin, Germany, May 17-19 (2011).
11. OECD/NEA Data Bank: http://www.oecd-nea.org/tools/abstract/detail/nea-1716.
12. Y. Chen, U. Fischer, "Rigorous MCNP based shutdown dose rate calculations: Computational scheme, verification calculations and applications to ITER," *Fusion Engineering and Design,* **63-64**, pp. 107-114 (2002).
13. R.A. Forrest, "FISPACT 2007 User Manual," UKAEA FUS 534 Report, March 2007.

14. P. Batistoni, M. Angelone, L. Petrizzi, "Benchmark experiment for the validation of shut down activation and dose rate in a fusion device," *Nuclear Science and Technology*, Supplement 2, pp. 974-977 (2002).

15. L. Petrizzi, M. Angelone, P. Batistoni, "Benchmarking of Monte Carlo based shutdown dose rate calculations applied in fusion technology: From the past experience a future proposal for JET 2005 operation," *Fusion Engineering and Design*, **81**, pp. 1417-1423 (2006).

16. A. Davis, R. Pampin, "Benchmarking the MCR2S system for high-resolution activation dose analysis in ITER," *Fusion Engineering and Design*, **85**, pp. 87-92 (2010).

17. R. Pampin, A. Davis, R.A. Forrest, "Status of novel tools for estimation of activation dose," *Fusion Engineering and Design*, **85**, pp. 2080-2085 (2010).

18. VisIt Tool version 2.1.2, updated in Dec. 2010: https://wci.llnl.gov/codes/visit/home.html.

19. A. Serikov et al., "Performance assessments of the MCNP5 parallel computations for the ITER ECRH launcher," *Proc. German Annual Meeting on Nuclear Technology (Jahrestagung Kerntechnik JK-2008)*, Hamburg, Germany, May 27-29 (2008).

20. A. Serikov et al., "MCNP5 parallel computations on JUROPA/HPC-FF supercomputer for ITER applications," *Proc. German Annual Meeting on Nuclear Technology (Jahrestagung Kerntechnik JK-2010)*, Berlin, Germany, May 4-6 (2010).

21. A. Serikov, U. Fischer, D. Grosse, "High Performance Parallel Monte Carlo Transport Computations for ITER Fusion Neutronics Applications," *Proc. of SNA + MC 2010,* Tokyo, Japan, October 17-20 (2010), accepted in *Progress in Nuclear Science and Technology*.

2011 International Conference on Mathematics and Computational Methods Applied to
Nuclear Science and Engineering (M&C 2011), Rio de Janeiro, RJ, Brazil, 2011

18/18