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JMCT Monte Carlo Simulation Analysis of BEAVRS and SG-III Shielding

Li D[1,2*], Gang L[1,2], Baoyin Z[1,2], Danhua S[1,2], Yan M[1,2], Zehua H[1,2], Yuanguang F[2], Rui L[2], Dunfu S[2], Xiaoli H[2] and Wei W[1,2]

[1]*Institute of Applied Physics and Computational Mathematics (IAPCM), Beijing, China*
[2]*CAEP Software Centre for High Performance Numerical Simulation (CAEP-SCNS), Beijing, China*

[*]**Corresponding author:** Li D, Institute of Applied Physics and Computational Mathematics (IAPCM), Beijing, China, Tel: 86-10-61935644, E-mail: deng_li@iapcm.ac.cn

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Abstract

JMCT is a general purpose Mont Carlo neutron-photon-electron or coupled neutron/photon/electron transport code with a continuous energy and multigroup. The code has almost all functions of a general Monte Carlo code which include the various variance reduction techniques, the multi-level parallel computation of MPI and Open MP, the domain decomposition and on-fly Doppler broadening, etc. Especially, JMCT supports the depletion calculation with TTA and CRAM methods. The input uses the CAD modelling and the calculated results use the visual output. The geometry zones, materials, tallies, depletion zones, memories and the period of random number are enough big for suit of various problems. This paper describes the application of the JMCT Monte Carlo code to the simulation of BEAVRS and SG-III shielding model. For BEAVRS model, the JMCT results of HZP status are almost the same with MC21, OpenMC and experiment. Also, we performed the coupled calculation of neutron transport, depletion and thermal-hydraulics in HFP status. The results of twenty four depletion steps are obtained, where the depletion regions exceed 1.5 million and 120 thousand processors to be used. Finally, we performed the detail modelling for Chinese SG-III laser facility, where the anomalistic geometry bodies exceed 10 thousands. The flux distribution of the radiation shielding is obtained based on the mesh tally in case of Deuterium-Tritium fusion reaction. The high fidelity of JMCT has been shown.

Keywords: Monte Carlo; Coupled of multi-physics; JMCT; BEAVRS; SG-III

Introduction

The high fidelity particle transport system JPTS (J Particle Transport System) has been developed for simulation of reactor full-core and shielding. This package is developed based on the three support framework JASMIN, JAUMIN and JCOGIN, where JASMIN is an adaptive structured mesh infrastructure, JAUMIN is an adaptive unstructured mesh infrastructure and JCOGIN is a parallel combinatorial geometry infrastructure. The JPTS package can do large scale parallel computation. Here, we mainly introduce a general purpose 3-D Monte Carlo transport code JMCT (J Monte Carlo Transport) [1-3]. Two models are chosen as test examples, where model one is the BEAVRS which is permitted by MIT Computational Reactor Physics Group in M&C2013 conference [4]. Another model is from the Chinese SG-III laser facility.

For BEAVRS model, we finish the detail modelling and simulation for the full core in hot zero power (HZP) status. 95% pins have less 1% standard deviation. The detailed pin-power density distribution, standard deviation etc. are shown. Then, we make the coupled calculation of neutron transport and depletion in full power status. Due to the memory resume too large, the simulation is done in case of 30/398 axial plane, where the depletion regions exceed 1.5 million. The simulation uses 120 thousand processors in Chinese TianHe-II supercomputer. Since the BEAVRS model involves the coupled with thermal hydraulics. At present, JMCT isn't coupled with thermal dynamic (being done), so the result is only for reference.

For SG-III model, the geometry is very complicated and irregular; the total geometry bodies exceed ten thousand. We order built some special body, such as optical instrument. The neutron and photon flux distributions of all building are given in case of the deuterium-tritium fusion reaction. The result has been used for the theory evidence of shielding design.

Introduce of JPTS Package and JMCT Monte Carlo Code

JPTS Package: JPTS package is developed by IAPCM. It contains the four applied codes JNuDa, JSNT, JMCT, JBURN and a suit of data libratory NuDa. Furthermore, the CAD pre-processor JLAMT and view post-processor TeraVAP are equipped (Figure 1).

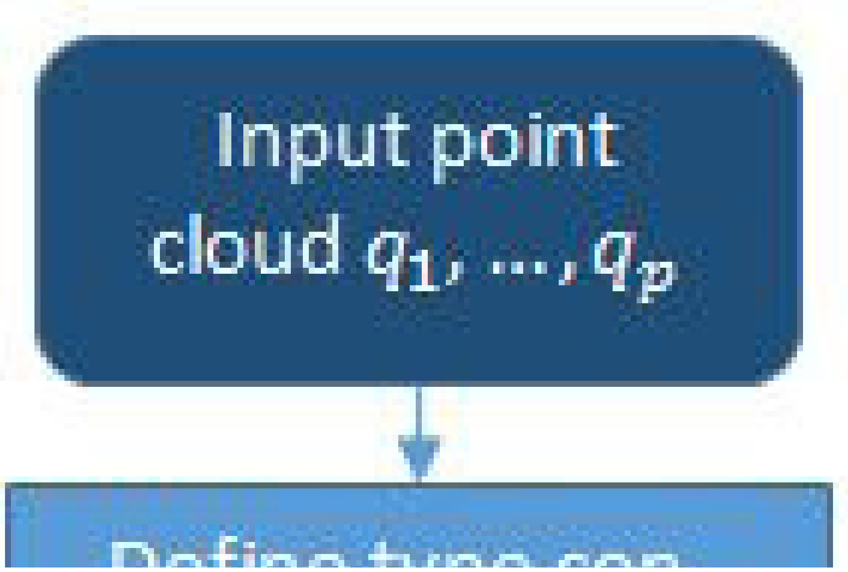


Figure 1: JPTS Package Flow

Currently, JSNT S_N Code Support [5,6]

1) **Particle type:** neutron, photon or coupled of neutron and photon.
2) **Mode:** forward/adjoint.
3) **Problem:** fixed-source/criticality.
4) **Space:** 3D/2D, Cartesian /cylindrical geometry.
5) **Mesh:** non-uniform structured (JSNT-S)/unstructured mesh (JSNT-U).
6) **Energy:** multigroup, anisotropic P_N scattering (N=1, 3, 5).
7) **Parallelization:** massive parallel computing (space- angle parallelization).
8) **Algorithm:** acceleration algorithms (rebalance methods, multigrid methods).
9) **Input:** visualization modelling and automatic mesh generation, multiple choice of spatial discretion (TWD, DFEM ...).
10) **Output:** visualization analysis.
11) **Support Framework:** JASMIN [1].

Currently, JBURN Depletion Code Support

1) **Analysis**: Transmutation Trajectory Analysis (TTA).
2) **Numerical:** Chebyshev Rational Approximation Method (CRAM).
3) **Mode:** inner coupled with JMCT.
4) **Depletion regions:** >1millions.
5) **Support Framework:** JCOGIN [2].

Currently, JTH Thermal-Hydraulics Code Support

1) Sub-channel analysis tight coupled with JMCT.
2) CFD simulation.
3) Two phase flow model.
4) CHF and DNBR are calculated.

Currently, NuDa Cross-Section Library

Continuous point-wise/Multigroup/Decay Data which is produced by NJOY code [7]. where

1) Point-wise cross-section about 450 nucleus.
2) Multigroup library of 47/172 group for neutron and 20 groups for gamma.
3) Decay data (>1500 elements).

Currently, JLAMT Pre-processor Support [8]

1) **Geometry:** sphere, cylinder, rectangle, et al., some special geometrical body can be ordered.
2) **Repeat structure:** especial supporting the same geometry with the different material.

Currently, TeraVAP Post-processor Support

Scale: TB scale data and parallel visualization output.

JMCT Monte Carlo Code: JMCT is a general purpose 3-D Monte Carlo transport code of neutron, photon, electron or coupled neutron/photon/ electron with the combinatorial geometry. Currently, JMCT support [3].

1) **Particle type:** neutron, photon, electron and coupled neutron/photon/electron.
2) **Mode:** forward/adjoint/depletion.
3) **Problem:** fixed-source/criticality.
4) **Space:** 3D combinatorial geometry.
5) **Energy:** continuous/multigroup (P_5).
6) **Source:** standard source/pin-by-pin source/user defined source.
7) **Tally:** point/surface/cell/mesh.
8) **Algorithms:** domain decomposition/uniform tally density /mesh tally and mesh windows. Etc [9,10].
9) **Parallelization:** MPI (particle) + OpenMP (domain).
10) **Input/Output:** CAD modelling and visualization.
11) **Temperture:** on-fly Doppler broadening [11]
12) **Fast critical search of boron concentration:** only one step.
13) **Tally types:** keff, point/surface/volume flux, energy deposition, power and reactivity etc
14) **Support Framework:** JCOGIN [2].

At present, tightly coupling of the neutron transport (JMCT), depletion (JBURN) and thermal-hydraulics (JTH) has been developed for simulation of reactor operation.

Tests

BEAVRS Model

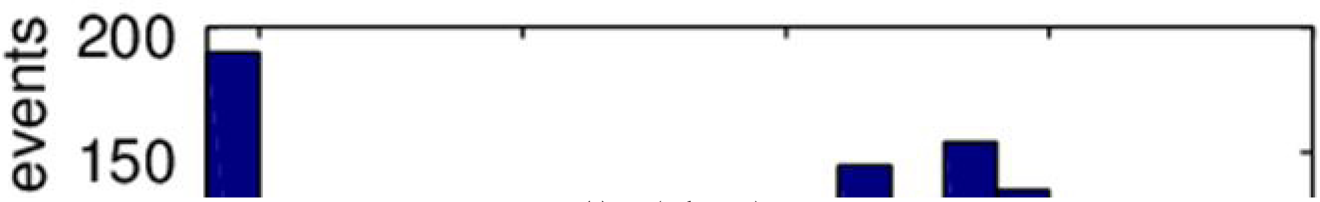
Introduction of Model: The BEAVRS model was released by MIT Computational Reactor Physics Group in July 7, 2013 (www.crpg.mit.edu). It includes detailed specification of operating 4-loop Westinghouse PWR (3411MW), two cycles of measured data, HZP/full power data, fuel loads by assembly as built, three enriched fuels (1.6%, 2.4% and 3.1%). The detailed data is in reference [4]. Two cycles of measured data can be used to validate high-fidelity core analysis codes. The basic data is as following:

Fuel assemblies: 193.
Axial planes: 398.
Pins/assembly: 289(17×17, where 264 fuel pins and 25 guide tubes).
Total tally regions: 22,199,246 (193×17×17×1×398).
Total regions: 44,398,492 (193×17×17×2×398).
Requirement: ≤1% standard deviation for 95% fuel pin-powers.
The part results of MC21 and OpenMC were presented in PHYSOR2014 [12-14]

Simulated Results:

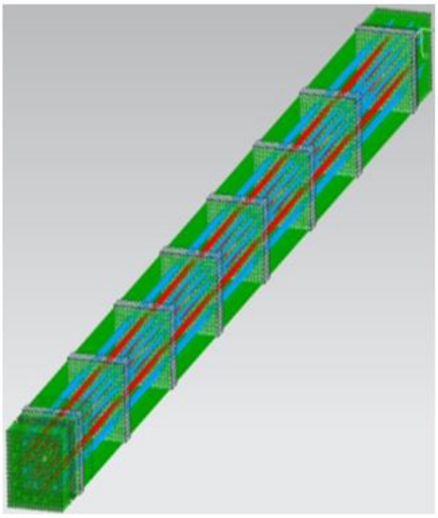
(1) Results in HZP status

HZP status is simulated in 398 layers in axial direction (Figure 2). Due to the memory exceeding the limit of single core, the space domain is decomposed into 8 parts (Figure 2(f)). Eight pin types (Figure 2(a)) and nine types of assembles (Figure 2(b)). The tally was for all pin fuel regions, the simulation tracks 4 million neutrons each cycle, it discards 400 cycles of 1000 cycles. Figure 1 shows the standard deviation distribution in 95% confidence level for all of pins. Table 2 shows the keff comparison of JMCT, Open MC and MC21 in different location of control rods and boron concentrations. Table 3 shows the reactivity worth of control rods in 556K. Figure 3 shows the comparison of pin-power distribution, difference at axial elevation of peak power and the comparisons of the MC21 and JMCT powers in axial. The maximal difference is 3.17%. Figure 4 shows the detectors tallies in meter pipes between JMCT and experiment. The maximal difference is -14.77% in B13 assemble and minimum power assemble is -5.648% in L15 assemble. Figure 5 shows the axial power shape of the B13 (maximal difference) and L15 (minimum power assembles) between MC21 and JMCT as compared to experiment.

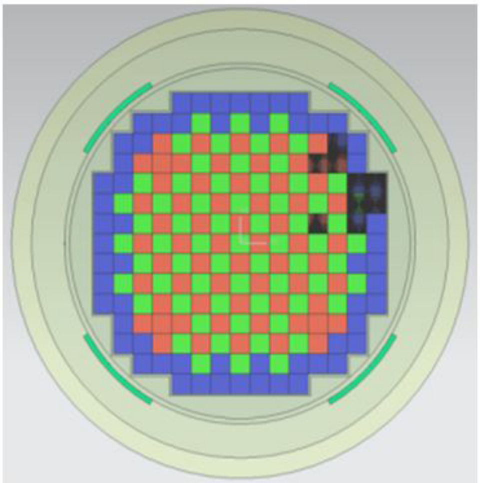


(a) Pins (eight types)

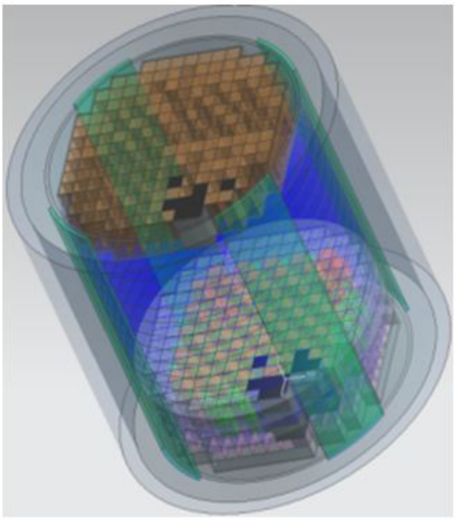
(b) Assembles (nine types)



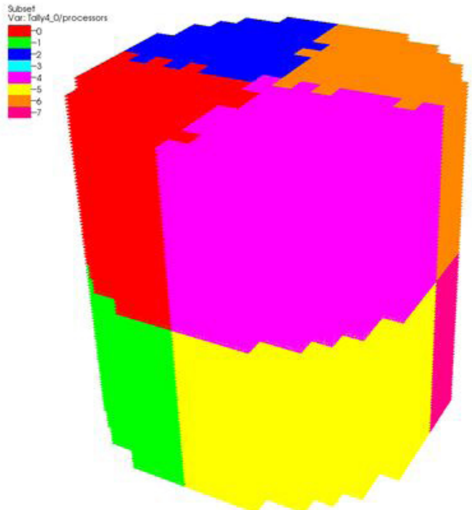
(c) Grid



(d) Core in Radial



(e) Full core



(f) 2×2×2 domain decomposition

Figure 2: BEAVRS modelling by JLAMT

Count	MAX	MIN	95%	99%
Flux	0.0091	0.00118	<0.00332	<0.00423
Energy deposition	0.01933	0.00254	<0.0075	<0.00955

Table 1: Max and min pin error of flux and energy deposition

HZP Critical Boron Evaluation	Boron Concentration	JMCT (95% confidence leave)	OpenMC (95% confidence leave)	MC21 (95% confidence leave)
ARO	975	1.000479±0.000030	0.99920±0.00004	0.9992614±0.000004
D in	902	1.002174±0.000030	1.00080±0.00004	
C,D in	810	1.001419±0.000032	1.00023±0.00005	
A,B,C,D in	686	0.9999172±0.000032	0.99884±0.00004	
A,B,C,D,SE,SD,SC in	508	0.9983806±0.000032	0.99725±0.00004	

Table 2: Keff comparison in different control rod statuses and boron concentration

HZP Bank worth	Boron	Measure	MC21	OpenMC	JMCT
D	938.5	788	773	771±6	770±6
C with D in	856	1203	1260	1234±7	1258±6
B with D,C in	748	1171	1172	1197±7	1162±6
A with D,C,B in	748	548	574	556±6	578±6
SE with D,C,B,A in	597	461	544	501±6	543±6
SD with D,C,B,A,SE in	597	772	786	844±6	781±6
SC with D,C,B,A,SE,SD in	597	1099	1122	1049±6	1107±6

Table 3: Comparison of reactivity worth of control rod in different statuses and boron concentration

HZP *MC21* results →
JMCT results →
% Diff (*JMCT* vs *MC21*) →

% The Max Diff: 3.173%
% The Min Diff: 0.000%

	R	P	N	M	L	K	J	H	G	F	E	D	C	B	A
1					0.734 0.754 2.725%	0.891 0.917 2.918%	1.010 1.040 2.970%	0.961 0.988 2.810%	1.023 1.046 2.248%	0.909 0.920 1.210%	0.745 0.760 2.013%				
2			0.889 0.896 0.787%	1.209 1.231 1.820%	1.137 1.168 2.726%	0.910 0.936 2.857%	1.105 1.132 2.443%	0.914 0.943 3.173%	1.112 1.136 2.158%	0.923 0.943 2.167%	1.153 1.179 2.255%	1.227 1.247 1.630%	0.900 0.912 1.333%		
3		0.885 0.897 1.356%	1.196 1.214 1.505%	1.150 1.175 2.174%	0.996 1.021 2.510%	0.991 1.016 2.523%	0.890 0.913 2.584%	0.957 0.980 2.403%	0.898 0.916 2.004%	1.004 1.021 1.693%	1.016 1.032 1.575%	1.172 1.189 1.451%	1.219 1.233 1.148%	0.902 0.909 0.776%	
4		1.209 1.222 1.075%	1.151 1.170 1.651%	1.392 1.419 1.940%	1.079 1.099 1.854%	0.909 0.928 2.090%	1.011 1.029 1.780%	0.876 0.895 2.169%	1.021 1.034 1.273%	0.924 0.935 1.190%	1.099 1.111 1.092%	1.429 1.439 0.700%	1.183 1.191 0.676%	1.243 1.246 0.241%	
5	0.742 0.748 0.809%	1.148 1.159 0.958%	1.000 1.016 1.600%	1.086 1.095 0.829%	0.953 0.963 1.049%	1.034 1.046 1.161%	0.889 0.895 0.675%	0.998 1.005 0.701%	0.895 0.898 0.335%	1.051 1.054 0.285%	0.972 0.974 0.206%	1.114 1.112 -0.180%	1.032 1.031 -0.097%	1.194 1.179 -1.256%	0.768 0.761 -0.911%
6	0.905 0.904 -0.110%	0.926 0.928 0.216%	1.004 1.006 0.199%	0.917 0.923 0.654%	1.039 1.043 0.385%	0.886 0.891 0.564%	0.974 0.972 -0.205%	0.836 0.836 0.000%	0.982 0.975 -0.713%	0.905 0.897 -0.884%	1.061 1.054 -0.660%	0.942 0.935 -0.743%	1.031 1.025 -0.582%	0.952 0.943 -0.945%	0.927 0.923 -0.431%
7	1.040 1.029 -1.058%	1.128 1.118 -0.887%	0.911 0.903 -0.878%	1.020 1.019 -0.098%	0.891 0.891 0.000%	0.971 0.969 -0.206%	0.800 0.797 -0.375%	0.841 0.834 -0.832%	0.807 0.801 -0.743%	0.983 0.973 -1.017%	0.905 0.899 -0.663%	1.049 1.034 -1.430%	0.921 0.916 -0.543%	1.152 1.137 -1.302%	1.058 1.046 -1.134%
8	0.985 0.970 -1.523%	0.944 0.931 -1.377%	0.981 0.968 -1.325%	0.896 0.887 -1.004%	1.000 0.994 -0.600%	0.835 0.833 -0.240%	0.834 0.830 -0.480%	0.738 0.734 -0.542%	0.843 0.834 -1.068%	0.843 0.836 -0.830%	1.022 1.006 -1.566%	0.909 0.896 -1.430%	0.998 0.982 -1.603%	0.952 0.943 -0.945%	1.001 0.987 -1.399%
9	1.049 1.030 -1.811%	1.145 1.116 -2.533%	0.920 0.903 -1.848%	1.032 1.021 -1.066%	0.900 0.890 -1.111%	0.974 0.967 -0.719%	0.800 0.796 -0.500%	0.837 0.831 -0.717%	0.801 0.797 -0.499%	0.988 0.973 -1.518%	0.911 0.896 -1.647%	1.050 1.031 -1.810%	0.933 0.914 -2.036%	1.157 1.132 -2.161%	1.062 1.040 -2.072%
10	0.916 0.908 -0.873%	0.939 0.929 -1.065%	1.021 1.009 -1.175%	0.931 0.923 -0.859%	1.049 1.039 -0.953%	0.894 0.889 -0.559%	0.975 0.965 -1.026%	0.838 0.833 -0.597%	0.979 0.969 -1.021%	0.906 0.893 -1.435%	1.068 1.047 -1.966%	0.948 0.928 -2.110%	1.044 1.017 -2.586%	0.960 0.938 -2.292%	0.938 0.916 -2.345%
11	0.750 0.747 -0.400%	1.165 1.161 -0.343%	1.022 1.017 -0.489%	1.103 1.096 -0.635%	0.961 0.962 0.104%	1.044 1.042 -0.192%	0.895 0.891 -0.447%	1.001 0.996 -0.500%	0.900 0.892 -0.889%	1.060 1.044 -1.509%	0.986 0.965 -2.130%	1.124 1.101 -2.046%	1.044 1.023 -2.011%	1.194 1.169 -2.094%	0.767 0.754 -1.695%
12		1.223 1.227 0.327%	1.171 1.174 0.256%	1.415 1.420 0.353%	1.096 1.097 0.091%	0.919 0.923 0.435%	1.022 1.023 0.098%	0.892 0.888 -0.448%	1.026 1.021 -0.487%	0.936 0.925 -1.175%	1.110 1.099 -0.991%	1.442 1.422 -1.387%	1.198 1.179 -1.586%	1.260 1.234 -2.063%	
13		0.892 0.898 0.673%	1.203 1.212 0.748%	1.168 1.174 0.514%	1.005 1.016 1.095%	0.999 1.010 1.101%	0.891 0.906 1.684%	0.967 0.971 0.414%	0.909 0.906 -0.330%	1.015 1.012 -0.296%	1.026 1.020 -0.585%	1.195 1.177 -1.506%	1.239 1.220 -1.533%	0.917 0.900 -1.854%	
14			0.888 0.896 0.901%	1.218 1.228 0.821%	1.148 1.161 1.132%	0.912 0.930 1.974%	1.108 1.119 0.993%	0.928 0.934 0.647%	1.126 1.124 -0.178%	0.934 0.932 -0.214%	1.172 1.165 -0.597%	1.241 1.228 -1.048%	0.918 0.901 -1.852%		
15					0.737 0.747 1.357%	0.895 0.909 1.564%	1.017 1.032 1.475%	0.970 0.974 0.412%	1.031 1.035 0.388%	0.914 0.912 -0.219%	0.754 0.752 -0.265%				

Figure 3: Comparison of pin power distribution and difference at axial elevation of peak power between MC21 and JMCT

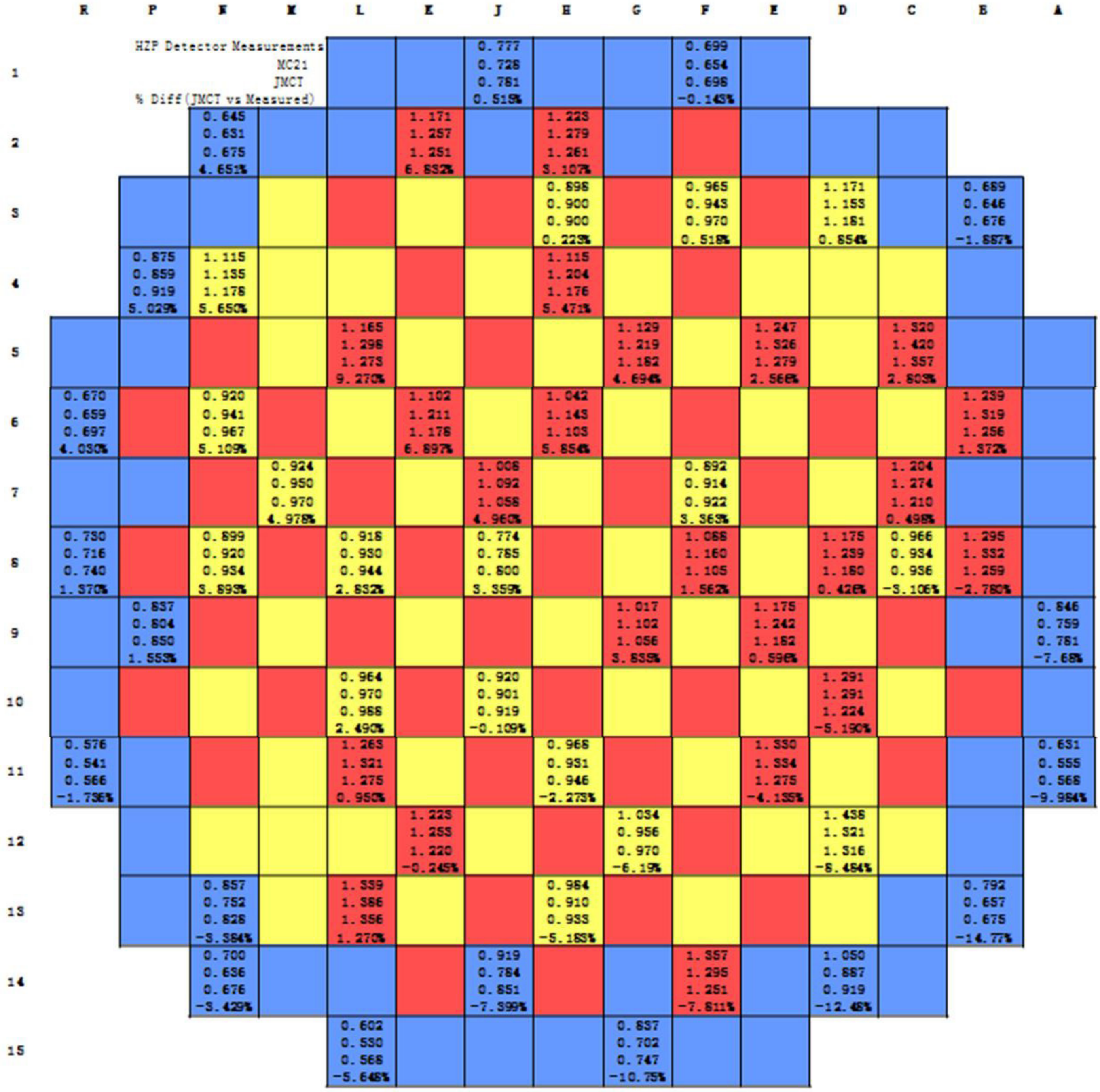
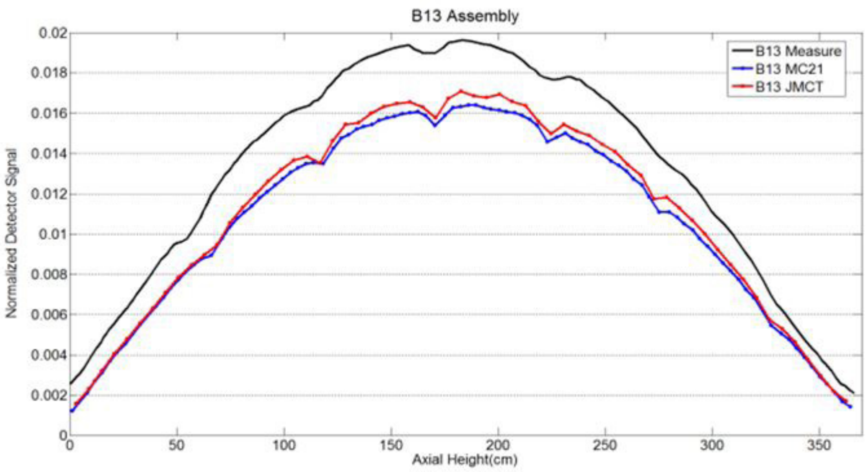
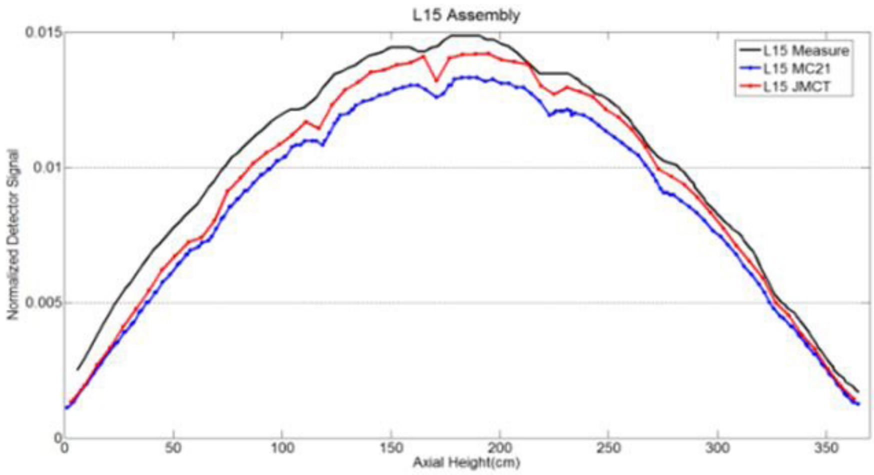


Figure 4: Comparison of the detectors tallies in meter pipes



(a) axial power shape in B13 assembly (with maximal difference)

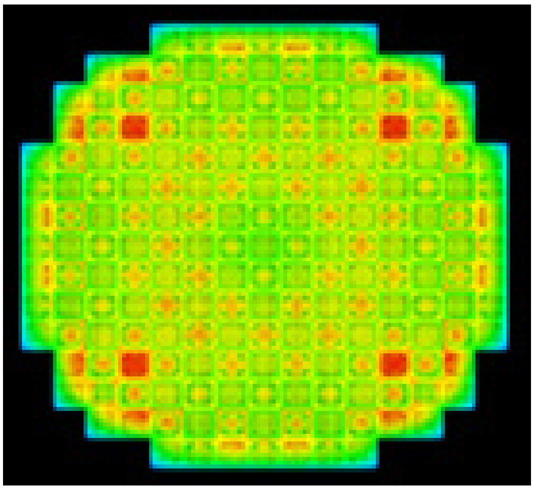


(b) Axial power shape in L15 assembly (with minimum power)

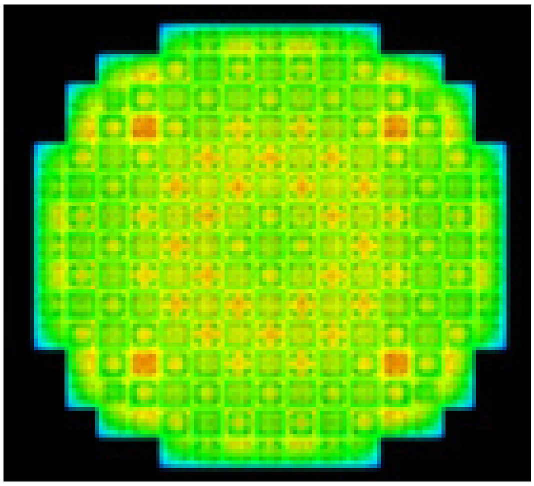
Figure 5: The axial power shape comparison of MC21, JMCT and experiment

(2) Result in Full Power Status

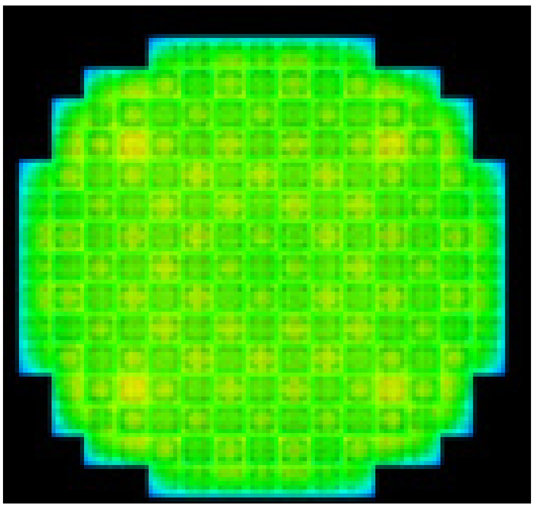
The coupled neutron transport, depletion and thermal-hydraulics is run in 30/398 axial planes for HFP status, where the depletion region is up to 1528560 (193×264×30). The space domain is also decomposed into 8 parts. It takes about one hour with 120,000 cores on Chinese TianHe-II supercomputer. The results of twenty four steps are obtained. Figure 6 shows the power distributions of 0 day, 4 day, 96 day and 190 day, respectively.



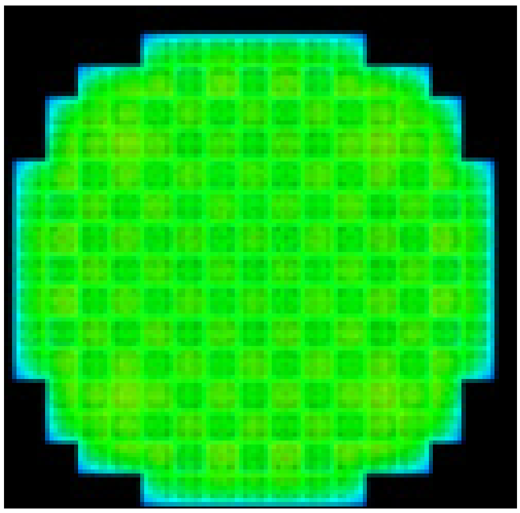
(a) 0 day



(b) 4 day



(c) 96 day

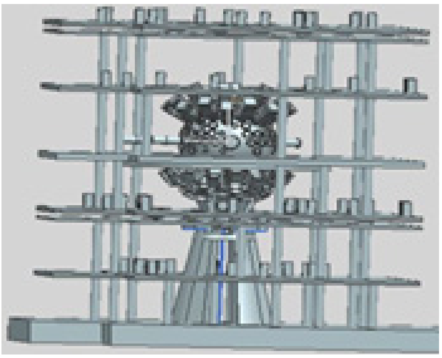


(d) 190 day

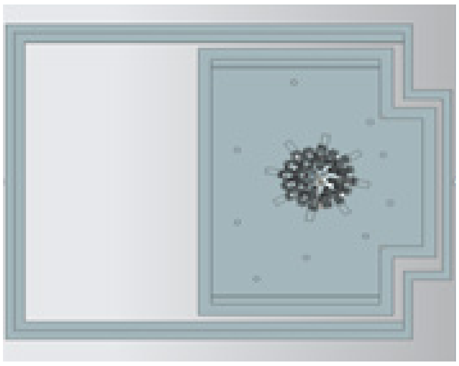
Figure 6: Pin power distributions in full power

Chinese SG-III Laser Model

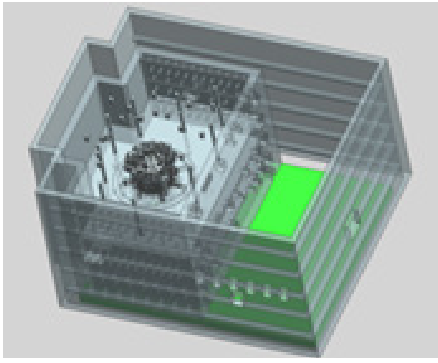
Chinese SG-III laser device is with 48 laser beams and size in 45m×45m×53m. Diameter of target chamber is 6 m. Power is 50 TW. It is applied to drive the nuclear fusion reaction by the laser energy. Figure 7 shows the modelling by JMCT pro-processor JLAMT, where Figure 7(a)(b) show the locations of tally floors and Figure 7(c) shows the building (six floors in ground). The tally is for all floors (seven floors in total). Mesh tally does and it has about 0.63 million meshes. The 0.4 billion neutron histories are simulated by 1024 cores. The 3.1 CPU hours are taken. Where the source is a 14.1 MeV deuterium and tritium (D-T) neutron point source. Figure 8(a)-(b) gives the neutron and photon flux distributions in the base of the fourth floor. Figure 8(c) gives the energy distributions of each floor. Figure 8(d) gives a part of flux distribution in the hall. The Figure 9 shows the comparison of flux between JMCT and MCNP. We can see some tiny difference existing between JMCT and MCNP. The high fidelity of JMCT is obvious.



(a) location of target

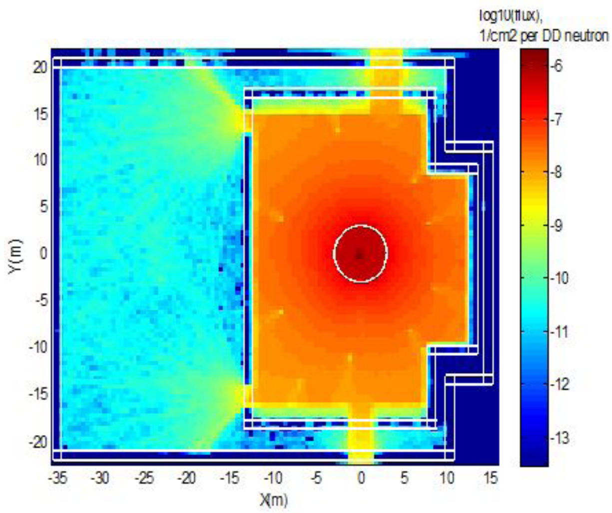


(b) section of tally floors

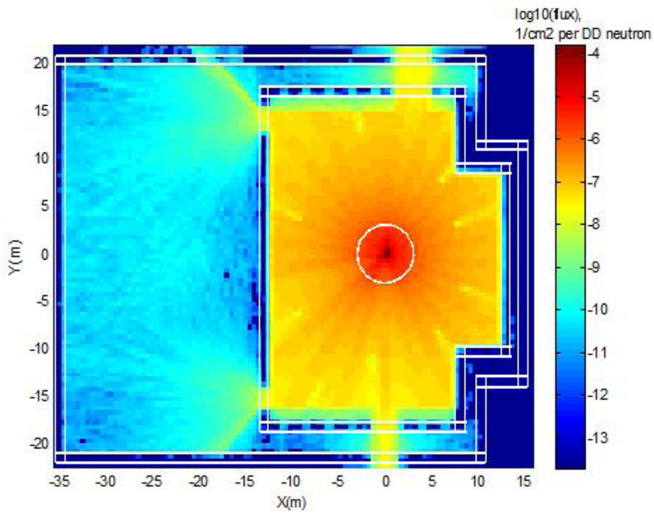


(c) hall of SG-III building

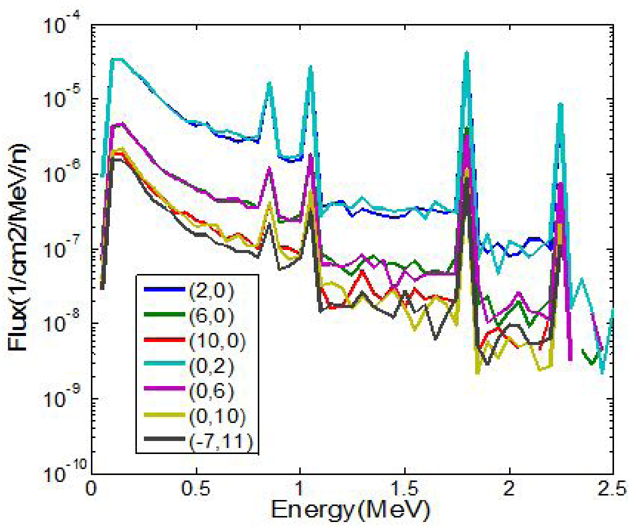
Figure 7 : Section of SG-III laser device



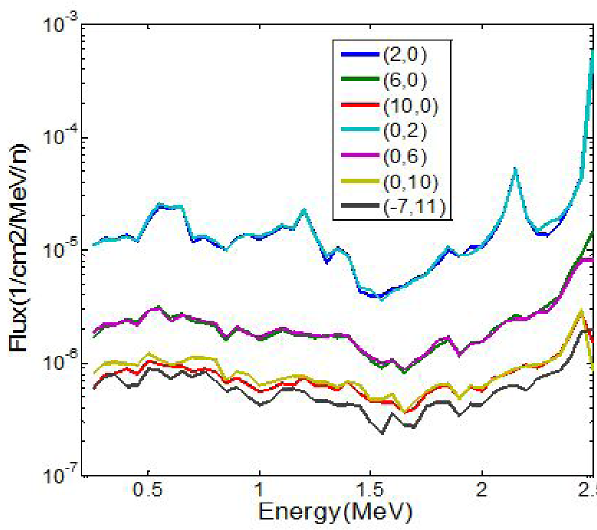
(a) Neutron flux in horizontal plane



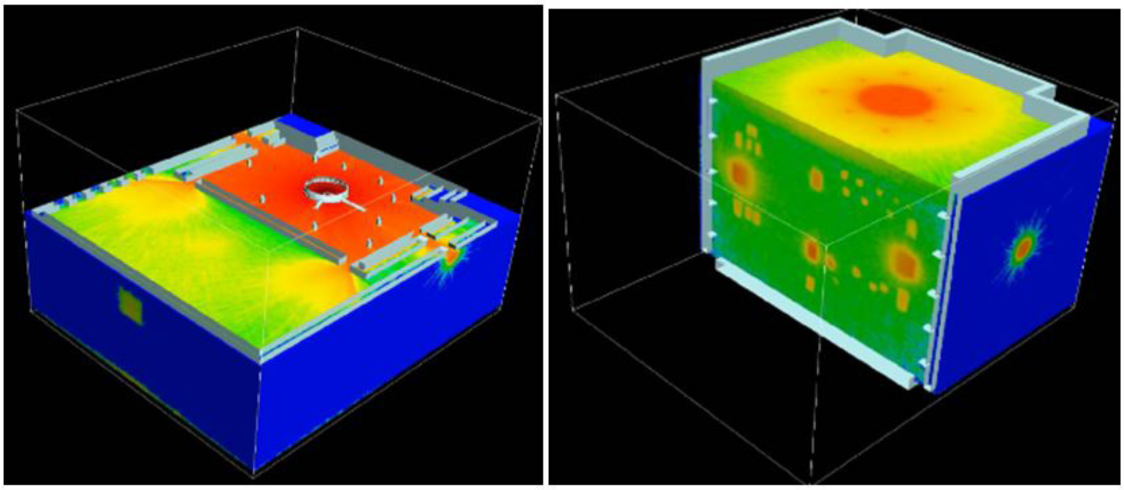
(b) Photon flux in horizontal plane



(c) Neutron energy spectrum in each floor

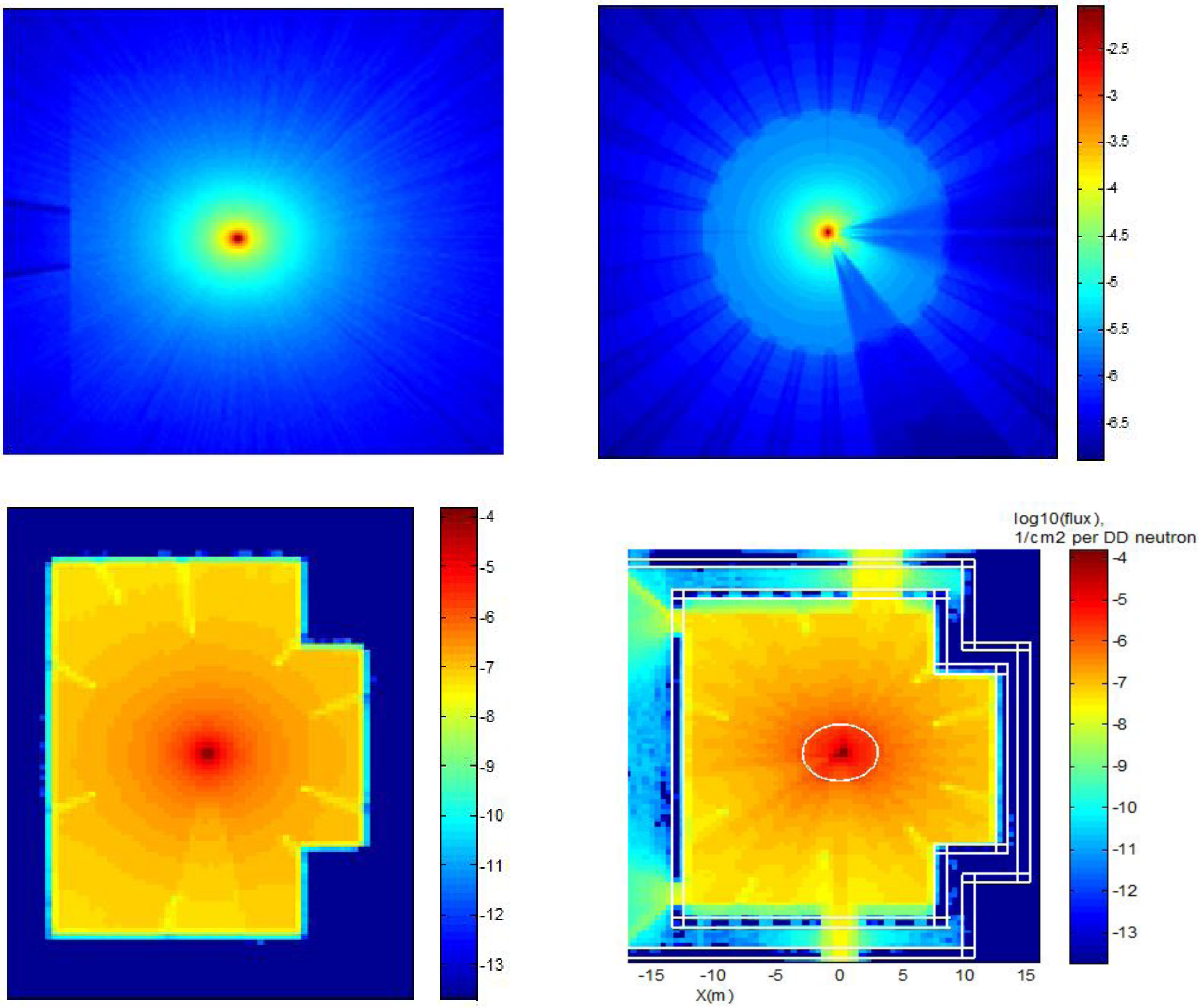


(d) Photon energy spectrum in each floor



(**e**) Flux distribution

Figure 8: Flux and energy spectrums in case of D-T reaction for SG-III laser model



(**a**) Flux distribution of MCNP

(**b**) Flux distribution of JMCT

Figure 9: Comparison of flux ditribution between MCNP and JMCT

Conclusion

A general-purpose Monte Carlo particle transport program JMCT has been developed for integrated simulation of nuclear system. It is designed for the simulation of the reactor full-core and radiation shielding. Advanced computer technologies, automatic geometry modelling and visualization make the code with high efficient. JMCT2.0, the latest version, has with the capability of core analysis.

Additional improvements in the analysis and simulation are necessary to attain desired accuracy for JMCT code. The future efforts will be forced on enhance of the computing efficiency. Some challenges still face for Monte Carlo simulation. The depletion complicating uncertainty quantification and propagation of error need to be considered. Furthermore, it needs to search some new algorithms to reduce the computing fee. JMCT is still in its evolution process toward this goal and all of the algorithms being actively developed at present.

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