

CONFERENCE PRE-PRINT**CFETR NEUTRONICS BENCHMARK CROSSCHECKING USING JMCT**

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Abstract

China Fusion Engineering Test Reactor (CFETR) is under engineering design, tritium self-sufficiency is one of its biggest challenges. In order to enhance confidence in tritium breeding ratio(TBR) calculation, Joint Monte Carlo neutron-photon-electron Transportation code(JMCT) is used to crosscheck blanket neutronics of CFETR. At the first stage, a 200MW CFETR neutronics benchmark in MCNP input format based on detailed CAD design are shared in China, the 25 blanket modules can be replaced to the five concept designs proposed by the corresponding institutes. The first three kinds are pure fusion concepts such as helium cooled pebble bed (HCPB), water-cooled pebble bed(WCPB), helium cooled lithium lead(HCLL) respectively. The other two kinds are fusion fission hybrid concepts as backup to achieve higher TBR and lower startup tritium inventory. The benchmark input file is converted to GDML format used in JMCT with the aid of JLAMT and several months manual work. At the second stage, a 1000MW CFETR HCPB benchmark model based on up to date CAD files in STP format is shared, it is converted automatically in 1255 seconds with the aid of CMGC and JLAMT. All the JMCT cross check results are in good agreement with those of MCNP and the relative error of calculated TBR(Tritium Breeding Ratio) are all within 0.5%. Simplification or ideal assumptions exist in all the blanket models, it may overestimate TBR and should be further investigated in future work.

1. BACKGROUND

A fusion reactor with 1GW nuclear power consumes about 152 g/day tritium and needs at least several kilograms startup tritium inventory. To suffice tritium self-sufficiency, the achievable tritium breeding ratio (TBR_{ach}) must be greater than the required tritium breeding ratio(TBR_{req}). According to Professor Abdou, the maximum value of TBR_{ach} is about 1.15, while the state of art TBR_{req} may be as high as 1.20[1]. Considering the about 10% uncertainties in nuclear data, detailed 3D modeling, fusion design elements and other factors, there must be a range of breeding margins in 3D TBR calculation of TBR_{3D} , which is used to evaluate TBR_{ach} to keep the Net TBR greater than TBR_{req} . During the design process of CFETR, three kinds of fusion blanket concepts such as HCPB from Southwestern Institute of Physics(SWIP)[2], WCPB from Institute of Plasma Physics(IPP)[3], HCLL from Fusion Driven System team (FDS) [4] are proposed, and the corresponding TBR_{3D} values are 1.18, 1.21 and 1.19, respectively. In order to enhance confidence in tritium breeding ratio(TBR) calculation, under support of national magnetic confinement fusion energy research project, it is suggested all the three concepts should be calculated in one independent, self-developed Monte Carlo transportation code, JMCT[5] is then selected as crosschecking tool. During the crosschecking, another two fusion fission hybrid blanket concepts from Institute of Applied Physics and Computational Mathematics (IAPCM) and Institute of Nuclear Physics and Chemistry (INPC) are proposed to achieve higher TBR and lower startup tritium inventory[6]. All the five blanket concepts are evaluated with a 200MW CFETR benchmark based on mcnp input file, which is called stage I. After that, HCPB is selected in CFETR engineering design, a 1000MW CFETR benchmark based on up to date CAD files is used in crosschecking, which is called stage II.

2. CHALLENGES / METHODS / IMPLEMENTATION**2.1. Challenges**

Fusion reactors are huge in size, complex in construction and contain many different materials. In order to accurately evaluate the TBR_{3D} , Monte Carlo particle transport code with powerful geometry modeling capability tools are of first priority. Since there are little margin in tritium self-sufficiency, it is necessary to model the detailed features that may influence TBR calculation as far as possible. In the first stage, the shared CFETR benchmark is a mcnp input file. All the five participants should add the blanket of their own into the framework

of the benchmark and finish TBR calculation using mcnp independently, IAPCM will convert the benchmark into GDML file and accomplish all the five calculations using JMCT.

2.2. Methods and Implementation

JMCT is self developed by IAPCM. JMCT1.0 was issued in 2013, the latest version is JMCT3.0 released in 2022. JMCT is different from MCNP in software infrastructure, geometry description and modeling, parallel computing, etc. It has various variance reduction techniques, powerful parallel computing capability and it is widely used in China's fission reactor projects, such as Pressurized Water Reactors in Dayabay, Qinshan-I, CAP1400 and design of Fast reactor CFR 600. CFETR is the first case study of JMCT in fusion area. It has two ways of geometry modeling, one is JLAMT and the other is a GMGC. JLAMT[7] is a CSG visualization modeling tool developed by IAPCM for large-scale problems. CMGC[8] is a CAD to Monte Carlo Geometry Converter tool jointly developed by Tsinghua University and IAPCM.

From the point view of neutronics simulation, the main difference between fusion reactor and fission reactor is geometry complexity. JLAMT allows users to create basic geometry elements such as box, sphere, cylinder, cone and torus to construct more complex geometry solids through Boolean operations. The created CSG model can then be exported as a Geometry Description Markup Language (GDML) file for JMCT simulations. For fission reactors, assemblies can be tailored and using repeated geometry rule to construct quickly. However, fusion reactors such as CFETR contains more irregular parts which need more effort to model one by one. It takes a few months to translate the 200MW benchmark from mcnp input file into GDML file in the first stage.

In the second stage, in order to save time in geometry modeling, we combine the BRep to CSG model conversion capability of CMGC with the visual CSG modeling capability of JLAMT. First of all, CMGC converts .stp file into a GDML file directly, JLAMT parses the information stored in the GDML file, and then converts it into a complete JLAMT project. Secondly, for non-convertible solids or solids failed to convert, CMGC will output parameters of them and incremental modeling is performed manually in JLAMT. Thirdly, JLAMT outputs the complete GDML file corresponding to the original CAD model including convertible and non-convertible geometry solids. Finally, JMCT read the GDML file and complete 3D neutronics calculation.

CFETR benchmark consists of blanket modules, divertor, vacuum chamber, upper port window, equatorial window, lower port window and other parts. More than 20,000 bodies are used to define CFETR framework. Blanket modules are replaced easily so as to compare different design concepts.

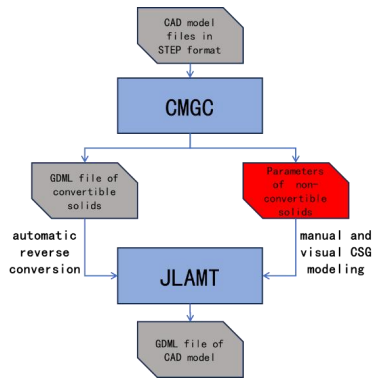


FIG. 1. Geometry modeling process

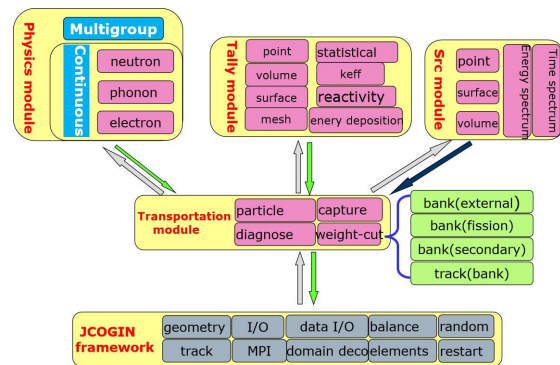


FIG. 2. JMCT structure

3. OUTCOME

3.1. The crosschecking shows good agreement with original concept design

All the JMCT crosschecking results are in good agreement with those of reference values and the relative error of global TBR are all within 0.5%.

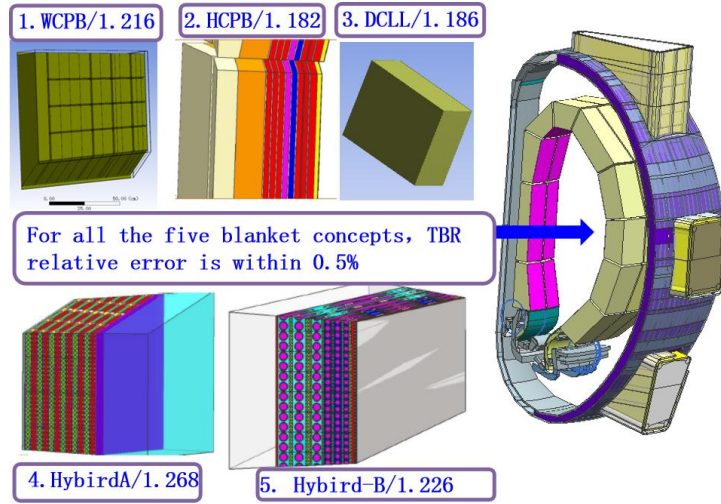


Fig.3 . CFETR neutronics benchmark crosschecking using JMCT

The relative error of local TBR also seems satisfying. There are 2283 cells in the WCPB blanket, and 707 of them are in tritium production zone. Among the tritium production cells, there are 546 with relative error less than 1%, which contributes 93.96% to TBR and 114 cells with relative error between 1%-2%, which contributes 5.57% to TBR. There are 47 cells with relative error bigger than 2%, which contributes 0.47% to TBR. In the HCPB blanket, there 500 cells and 100 of them are in tritium zone, and there are 4 cells with relative error bigger than 2%, which contributes 5.45% to TBR. In the HCLL blanket, there are 125 cells and 25 of them are in tritium zone, and all the relative error are within 2%. In the Hybrid-A blanket, there are 19991 cells and 861 of them are in tritium zone, 683 cells with relative error less than 1%, which contributes 87.35% to TBR and 106 cells with relative error between 1%-2%, which contributes 6.62% to TBR. In the Hybrid-B blanket, there are 27804 cells and 2816 of them are in tritium zone, 350 cells with relative error less than 1%, which contributes 32.96% to TBR and 323 cells with relative error between 1%-2%, which contributes 36.42% to TBR. It is easy to see that the more cells contained in the blanket, the bigger local deviation will appear, although the global TBR agrees well.

TABLE 1. RESULTS OF WCPB MODEL

Global TBR	JMCT(1.216)	MCNP(1.215)
deviation	number of lithium cells	tritium production rate
distribution	(% of total cells)	(% of contribution to TBR)
<1%	546(77.23%)	1.143(93.96%)
1%-2%	114(16.12%)	0.067(5.57%)
>2%	47(6.64%)	6.59E-3(0.47%)

3.2. The time consuming geometry conversion work are relieved

There are 2358 bodies in the framework of 1000MW CFETR benchmark, 2113 of them are converted by CMGC directly, 188 bodies contain overlap area fail to convert are fixed by adjust tolerance in UG, another 57 bodies contain ill torus face whose small radius is bigger than large radius are manually replaced by large sphere approximate to torus. All the 2358 bodies and related material are then combined in JLAMT to generate a JMCT input within 1255 seconds. The global TBR error between JMCT and reference value is 0.21%. There are 27 blanket modules in this benchmark, 24 modules with relative error less than 1%, 3 modules with relative error between 1%-2%.

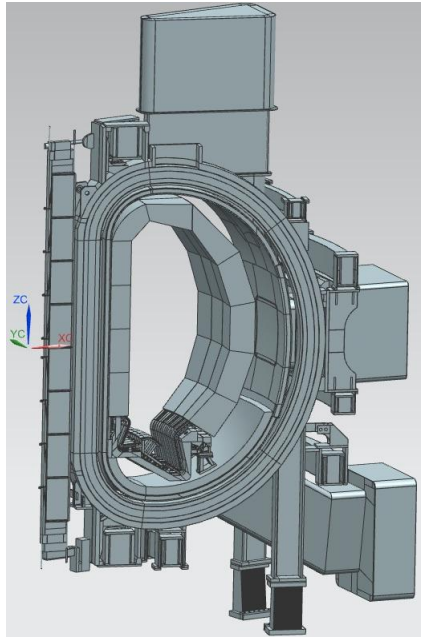


Fig.4 . 1000MW CFETR benchmark

3.3. There are ideal assumptions in all the five neutronics models

Homogenization is widely used. Although the whole benchmark framework is modeled in high accuracy, each cell in the blanket is either a plate or a wedge which is not consistent with the thermal hydraulic models. In the water-cooled ceramics model, the packing ratio in breeding zone is 80% (14.4% Li_2TiO_3 and 65.6% Be_{12}Ti). In the helium cooled ceramics blanket, only radial structural materials are considered. In the helium cooled lithium lead blanket, each blanket module has only one tritium zone. In the two hybrid blanket, the cooling tubes' joint parts are all simplified. These simplification or ideal assumptions may overestimate TBR and should be further investigated in future designs.

4. CONCLUSION

CMGC combine JLAMT can convert CAD files effectively to GDML input files for JMCT, it saves huge manual work. JMCT shows good agreement in global TBR with reference value, however, the local deviation may be as high as 2% for a few low tritium contribution cells. Simplification or ideal assumptions exist in all the 5 blanket models, it may overestimate TBR and should be further investigated in future designs.

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