PUBLICATION VIII

Calculating the neutron current emerging through the beam tubes in IFMIF

(EFDA Task TW6-TTMI-001-D3a).
VTT Research Report 2006. 9 p.
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Calculating the neutron current emerging through the beam tubes in IFMIF (EFDA Task TW6-TTMI-001-D3a)

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Confidentiality: Public

Report's title

Calculating the neutron current emerging through the beam tubes in IFMIF

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Project name Neutroniikkalaskut IFMIF/ITER	Project number /Short name 3074 / NEUT06
Author(s) Petri Kotiluoto, Frej Wasastjerna	Pages 7
Key words fusion, IFMIF, neutronics, beam tubes	Report identification code VTT-R-06720-06

Summary

This is a report on behalf of the Association Tekes for the EFDA task **TTMI-001-D3**, sub-deliverable 3a “Neutron field and dose rate evaluation in the components of the raster beam scanner system (mainly magnets) as a function of their distance to the Target. Neutron field evaluation.” This task is in connection with further analysis of the raster beam scanning of the IFMIF accelerator facilities. The work has been carried out in collaboration with Association UKAEA, whom will be responsible for the deliverable 3b “Dose rate evaluation.”

In this work we have aimed at calculating the neutron current in the form of a surface source at the outer surface of the IFMIF “near wall”, the wall containing the beam tubes. This surface source can then be utilised by UKAEA to calculate the neutron flux and activation in the accelerators and their surroundings, using MCNP. Our calculations have been based on earlier McDeLicious model md34 of the IFMIF, which is not the latest model, but differences were estimated to have only marginal and at least conservative effect to the neutron field distribution along the beam tubes. The results and a data path to the created surface source file have been delivered to UKAEA.

Confidentiality: Public

Espoo 06.09.2006
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Introduction

This work is part of the effort to determine the activation of the accelerators and adjacent structures in IFMIF. One source of activation will be the neutrons emerging from the test cell, mainly along the beam tubes. Thus we aimed at calculating the neutron current in the form of a surface source at the outer surface of the “near wall”, the wall containing the beam tubes. This surface source can then be utilised to calculate the neutron flux and activation in the accelerators and their surroundings, using MCNP.

The source was accumulated at surface 8099, defined as pz -453.0 in the model.

For reasons which will be described below, two series of calculations were performed, which we will call the full geometry and reduced geometry calculations. In the former, most of the test cell was included, with neutrons killed only in the outer parts of the floor, cover and the walls other than the near wall. In the latter, only a small part of the geometry was included, consisting mainly of portions of the target and the beam tubes, with neutrons killed everywhere else.

All tallies were normalized to a beam current of 250 mA using an fm card, but the surface sources are normalized to a single incident deuteron.

Model

Our calculations were performed using the program McDeLicious, a variant of MCNP4C developed at FZK with a source routine capable of calculating the neutrons emerging from the interaction of deuterium beams with a lithium target.

The geometry model we used was that contained in the McDeLicious input file md34. This is not the latest model for IFMIF, but the only respect in which it is not up to date is that certain dimensions of the shield blocks in the cover have been modified since md34 was prepared. This cannot influence the current emerging through the beam tubes significantly. Since the later models have a different cell structure at the edges where the cover meets the walls, a cell structure that is more appropriate for shielding calculations on the cover but less appropriate for calculations on the walls, we decided that md34 was more suitable for this work.

The horseshoe shield is present in md34. It is not known to us whether it will actually be included in IFMIF, so we could either have kept it in the model or omitted it. Keeping it was adjudged to be the more conservative assumption, since this was expected to reflect slightly more neutrons in the direction of the near wall. Therefore we kept it, using a design with 30 cm W and 10 cm B-Cd mixture. In any case, the presence or absence of the horseshoe shield is unlikely to make a significant difference (it makes none at all in the reduced geometry calculations).

For this work, the details of the beam tubes are much more important. In md34, the beam tubes are assumed to be rectangular in cross section, with an inside height of 7.5 cm and an inside width of 28 cm. The walls are modelled as 3 cm thick Eurofer steel, with a density of 2/3 of nominal. This is a homogenized version of an assumed structure of 1 cm steel + 1 cm void + 1 cm steel. The tube walls are surrounded by heavy concrete.

The homogenization of the tube walls ignores the possibility of neutrons streaming along the gap between the two wall layers. However, this streaming is bound to be a minor effect compared to the streaming through the tube. A much more important question than this gap streaming is the accuracy of the underlying assumptions about the beam tube geometry. We have not succeeded in obtaining reliable information about this, which probably reflects the fact that the IFMIF design is not final but may still change. Thus we have to base our calculations on what seems plausible, and this rectangular beam tube geometry does seem plausible. In any case it makes much better sense from a neutronics viewpoint than a circular cross section, since it’s important to minimize neutron streaming by making the beam tube walls fit as snugly around the beams as possible.

The input files used in this work (having names beginning with nw34, nw standing for “near wall”) specify that a surface source be written at the outer surface of the near wall. The tallies include two current tallies at the same surface. One is segmented to separate the current emerging from the beam tubes from that emerging from their surroundings and is also subdivided into 211 energy bins and 5 cosine bins. The other lacks cosine bins and has only 3 energy bins, but all neutrons entering the tube walls are flagged. There is also a volume flux tally showing the flux in the beam tubes themselves as a function of position.

Full Geometry: Variance Reduction

We have two straight beam tubes, pointing directly at the neutron source. Moreover, they are large enough that every point in the beam footprint in the lithium jet can see the outer end of the tube directly, without intervening material. Thus one can expect neutrons coming directly from the source and streaming through the beam tubes to be the dominant component of the outgoing current. Other contributions will come from neutrons scattered in the test modules or other components, neutrons hitting the beam tube walls and scattering in the outgoing direction, and neutrons passing through the concrete wall (at least partway, perhaps also streaming along the beam tubes for part of their trajectory).

Accordingly, we needed to emphasize transport through the beam tubes. Angular biasing of the source or DXTRAN might have been the most effective ways of doing this, but both would have required modification of McDeLicious, so we preferred to try other means. Thus we had to rely mainly on importances.

Since MCNP, and consequently McDeLicious, doesn’t split particles in voids (which would be pointless), importances could not be used to emphasize uncollided transport through the beam tubes directly, only indirectly by rouletting neutrons in regions far from the near wall. Consequently we used decreasing importances with increasing distance from the near wall: 1 in the source region and High-Flux Test Module, 0.5 in the Universal Testing Machine, 0.25 in the Spectral Shifter, 0.125 in the In-Situ Tritium Release Experiment and the low-flux and very low flux module and 0.025 on the insides of the walls and cover, other than the near wall. Neutrons venturing more than a short distance into the walls and cover (about 20 to 40 cm, depending on location) were killed.

In addition, importances increasing in the outward direction were used in the tube walls to ensure that neutrons colliding in them would contribute to the surface source and tallies. In the concrete surrounding the beam tubes we sometimes used importances lower than in the tube walls, typically by a factor of 4, but also increasing outward. At the edges where the walls join the cover, the neutrons were mostly killed, since in this area it is especially difficult to devise satisfactory importance schemes, and these neutrons do not make a significant contribution.

In short test runs (60 minutes CPU time), several different importance schemes worked, and the differences in efficiency were fairly small. The best schemes increased the figure of merit by about a factor of 2.5 over setting the importance to 1 everywhere.

Full Geometry: Runs

When we tried to perform production runs, we kept encountering a situation where the program hangs, running for hours or days without producing any output, including dumps. We have encountered such behavior many times before and attributed it to “long histories”, in which a single history can sometimes proliferate into a very large number of tracks, taking essentially unlimited amounts of time. We initially assumed that that was the cause in this case too, though we did have some doubts.

In an attempt to avoid occurrence of long histories, cell-by-cell energy cut-offs with the ELPT card were tried, in order to kill those thermal or epithermal neutrons further away from the region of interest with no probability to contribute to the tallies. Also analog capture was tried instead of implicit capture. However, neither of these methods solved the problem and they were therefore abandoned.

Shorter runs worked in some cases. One run with 7,500,000 histories gave a surface source file containing 127,338 tracks, but we suspect that most of these are low-weight tracks, due to neutrons splitting in the tube walls or concrete. Probably the most important component is neutrons coming directly from the source or colliding near it and then flying out through the beam tubes without further collisions. Both analytical estimates and an investigation of the tally probability density function plot for tally 1 suggest that there may have been about 1,200 to 1,500 of these tracks, with the remaining 99% of the tracks giving just a minor contribution.

A new run was made with the importances adjusted to minimize this worthless fuzz. 7,104,165 histories gave 3,073 tracks, probably a more useful source file in spite of the small number of tracks.

The statistics of these semi-successful runs are fairly decent, with the results in the tally fluctuation chart bins passing most statistical tests. However, a much larger number of high-weight tracks in the surface source file would be desirable.

Reduced Geometry

In the full geometry calculations, many histories waste a lot of time wandering around in the complicated geometry of the test modules, and these make a relatively modest contribution to the emerging current, while the most important contribution comes from the source neutrons emerging directly through the beam tubes. This had already been taken into account to some extent in the choice of importances, but Dr Ulrich Fischer proposed something more radical: including only this direct source contribution and ignoring the scattered neutrons, for the sake of getting as many histories as possible in reasonable time. Consequently we prepared an input file with the importances set to zero – killing all neutrons – everywhere except in the target, the beam tubes and a few cells between and around these.

In such a geometry, with all importances set to 0 or 1, there was no way of getting the proliferation of tracks we had assumed to be the cause of hanging runs. Nonetheless we were plagued by hanging runs, even worse than before. Dr Stanislav Simakov found that the cause lay in the source subroutine of McDeLicious. He then corrected this subroutine and kindly performed a run with 10^9 histories, resulting in a surface source of 122,836 tracks.

Summary of Results

We believe that the surface source file resulting from Dr Simakov's calculation is the most useful one. 122,836 high-weight tracks may be sufficient to provide useful results, while 3,073 would most likely be too few and the original 127,338 track file is believed to contain mostly useless low-weight tracks. However, we must take into account that the reduced geometry calculation accounts for only the unscattered, direct contribution from the source plus neutrons scattered in the target or beam tube walls but not elsewhere.

We recommend applying two correction factors to the results obtained using Simakov's surface source. These factors are based on a comparison of tallied currents emerging from the near wall in the full geometry and reduced geometry cases. Even in the full geometry case, the statistics of this tally were good enough to permit reasonably accurate calculations of such correction factors.

The <u>scattering factor</u> accounts for the contribution from neutrons scattered both in the test cell internals (test modules etc.) and in the near wall outside the beam tubes. This is calculated as the ratio of the average outgoing current at the mouth of the beam tubes as calculated in a full geometry run (row 3 of Table 1) to that from a reduced geometry run (row 4). The appropriate value to use is that for the average of both beam tubes, 1.81442.

Table 1: Outgoing neutron current ($cm^{-2}s^{-1}$) at the mouth of the beam tubes, cosine bin -1 to -0.879, all energies

	Left beam tube	fsd	Right beam tube	fsd	Average
Analytical estimate					5.14125E+10
Full geometry, run 1	6.72721E+10	0.0369	6.80305E+10	0.0369	6.76513E+10
Reduced geometry	3.71981E+10	0.0042	3.73725E+10	0.0042	3.72853E+10
Ratio full / reduced	1.80848		1.82034		1.81442

Note that, although the currents in Table 1 are totals over energy, only one cosine bin, from -1 to -0.879 (-1 is the outgoing surface normal for the near wall) is included. However, the contributions from other bins are small, totaling about 2% of the contribution from the -1 to -0.879 bin.

Table 1 also shows an analytical estimate of the current, as a sanity check. This is based on the assumption that the source is isotropic and no neutron scattering occurs. The latter assumption also applies in the reduced geometry calculation, so we can see that the anisotropy of the source reduces the current by somewhat more than a quarter. The presence of scattering more than compensates for this.

The other correction factor is the <u>wall penetration factor</u>, which accounts for the fact that some neutrons emerge elsewhere than the beam tube mouths. Transforming the currents from tally 1 in the full geometry case into integrals rather than averages over the spatial segments and dividing the sum of these integrals by the sum over the beam tube mouths gives a factor of 1.11475.

Multiplying these two correction factors together gives a factor of **2.02263** which should be applied to responses calculated using Simakov's surface source. Multiplying this by the beam current factor, $1.56055*10^{18}$ deuterons per second, gives a total normalization factor of $3.15641*10^{18}$.

These correction factors only account for the difference in the total current, they do not consider the differences in the spectrum or angular or spatial distribution, which would be more difficult to take into account. The true spectrum is softer than in the reduced geometry case, due to scattering. (In the full geometry calculation, 89% of the outgoing neutrons had energies above 0.1 MeV vs. 97% for the reduced geometry case. In both cases, neutrons above 20 MeV were rare.) The true angular distribution is likely to be slightly more spread out. So is the spatial distribution of the points where the neutrons emerge from the wall. Whether these effects will increase or decrease the responses to be calculated can be estimated only with knowledge of the accelerator design, the reactions of interest and the energy dependence of their cross sections, and other matters which we do not know. It may be advisable to carry out a calculation with the 3,073-history full geometry surface source as well as Simakov's reduced geometry source and compare the two.

Experience from ITER calculations suggests that in order to keep the dose rate 10^6 seconds (about 11.5 days) after shutdown below the limit of 100 μSv/h the flux above 0.1 MeV should not exceed about 10^7 n/cm^2s during operation. The flux at the outer ends of the beam tubes is about 4 orders of magnitude higher, suggesting a dose rate of **1 Sv/h**, 10,000 times what is considered permissible for hands-on maintenance in ITER. However, it must be realized that this dose rate would apply only at local hot spots. The dose rate averaged over some large volume will be substantially lower, and it may be possible to shield workers from the radiation emitted by the hot spots.

Conclusions

We have attempted to provide a surface source for calculations of activation and other phenomena caused by neutrons exiting the IFMIF test cell through the beam tubes. These attempts have been plagued by difficulties that we first believed to be caused by long histories. However, it was finally realised that there seemed to be a bug in McDeLicious, related to a problem of neutron birthplace identification. This bug was fixed by Dr. Stanislav Simakov, who also performed the final reduced geometry production run with $1.0*10^9$ deuteron histories, producing 122,836 neutron tracks for the surface source file. Results derived using this file need to be corrected by a factor of about 2.02, however. Moreover, a comparison of results obtained with the reduced geometry surface source file (with the correction factor) and one or more of the full geometry source files (without a correction factor) is desirable, although the full geometry sources have poor statistics.

While calculating dose rates falls outside the scope of the work reported here, the high flux at the outer ends of the beam tubes is a cause for concern.

Acknowledgements

We are very grateful for the prompt and competent measures taken by Dr. Simakov to correct the bug found in McDeLicious. He also kindly performed the final production run for us.

This work, supported by the European Communities under the contract of Association between EURATOM/Tekes, was carried out within the framework of the European Fusion Development Agreement. The views and opinions expressed herein do not necessarily reflect those of the European Commission.