Activation of the ISIS muon beamline and corresponding gamma dose rates

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Abstract. The calculation of the activation of ISIS muon beamline components has been performed to predict the gamma dose rates and help in planning the replacement of the two quadrupole magnets during the first stage of the ISIS muon beamline upgrade project. The details about simulation procedure, obtained results and comparison with measurement results are presented in this paper.

1. Introduction
The ISIS muon beamline upgrade project has been recently successfully completed. The muon flux is now increased by about a factor of four with a significant improvement in reliability [1]. The first stage of this upgrade project was to replace the two quadrupole magnets near the production target with a new triplet. Those magnets were the parts of the original 1987 installation and over 25 years of operation they have been exposed to the particles produced in the interactions of proton beam with muon producing target.

2. Simulation procedure
The activation of the components of the muon beamline was calculated using the MCNPX Monte Carlo code [2] in association with the CINDER90 transmutation code [3]. The geometry of the model is based on the set of the engineering drawings [4] of the ISIS extracted proton beamline (EPB) section and the muon beamline. The CombLayer program [5] has been used then to build the corresponding MCNPX model. In addition to this, for the calculations described in this paper, the sub-set of C++ programs in the CombLayer was dedicated to prepare the neutron tallies and other files (and data) needed for subsequent run (using a set of in-house bash-shell scripts) of the transmutation code. In addition to the results on activation and inventory of radionuclides, CINDER90 is able to create gamma source definition to perform dose simulations. The set of in-house bash-shell scripts has been used to build gamma source terms for different cooling times using the results of the activation calculations. These, cell and energy dependent, gamma source terms have been used in a new MCNPX run to calculate the gamma flux [and

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the spectrum) at particular distance from the objects in the muon beamline model. Then, the energy dependent dose per flux factors [6] have been used to obtain the gamma dose rate.

2.1. Model geometry
The cross-section of the geometry implemented in MCNPX is shown in Figure 1. To illustrate the dimensions of the model, the distance between the origin of the coordinate system (coincides with the centre of mass of the intermediate target) and point 10 in Figure 1 is 290 cm, between points 10 and 11 is 57 cm, and between points 11 and 12 is 195 cm. The proton beam orientation is from the bottom upwards. The effective thickness of the intermediate graphite target (IT) is 10 mm.

Figure 1. The MCNPX geometry of the EPB section and the muon beamline. Looking at the muon beamline branch of the geometry (located on the right hand side), the intermediate graphite target is followed by the beam window and two quadrupole magnets (Q1 and Q2). The orange colour is used for iron/steel (mild steel for shielding and the XC-06 steel as a part of the quadrupole magnets) and green colour is used for copper.

Because the aim of this analysis is to estimate the radiation field as a function of cooling time\(^3\), the dose rates have been calculated (case A) at several positions denoted in Figure 1 with numbers 1 to 14. In addition, the gamma dose rates have been calculated for:

- the case where last part of shielding (between points 11 and 12) is removed. The results for this situation (case B) represent the dose rates expected at the beginning of the work in this area;
- the case where last part of shielding (between points 11 and 12) and the Q1 and Q2 magnets are removed. The results for this situation (case C) represent the dose rates that people would be exposed while installing the new quadrupoles;
- the case where only Q1 and Q2 quadrupole magnets contribute to the source term. The results for this situation (case D) represent the dose rates around Q1 and Q2 quadrupole magnets assuming they have been removed and are to be stored somewhere.

2.2. Beam and irradiation parameters
The incident beam is 800 MeV protons with Gaussian profile (both in x and y). The proton beam width at the IT position was assumed to be \(\sigma_x = \sigma_y = 5\) mm [7]. Estimated and simplified irradiation time profile has been used: 180 days per year with beam on over 25 years and then final irradiation of 2 months, with assumed proton beam current of 180 \(\mu\)A. It has to be noted that the total number of protons on target have been intentionally overestimated in the initial calculations in order to have a safety margin on estimated radiation field in the area.

\(^3\) To estimate the right time to begin with the process of removal of the magnets.
3. Results

As an illustration, Figures 2 and 3 show the calculated gamma dose rates for (case A) as a function of cooling time at the positions 1 – 11. The results for positions 12 – 14 are not shown because they are practically equal to zero (within statistical errors). Cooling time range of 7 months has been chosen expecting that work in this area will commence during such a time span after the last user cycle. As can be seen, the dose rates at these positions range from 10 to 5000 mSv/h depending on cooling time.

![Figure 2. Calculated gamma dose rate (case A) as a function of cooling time at the positions 1–5.](image)

![Figure 3. Calculated gamma dose rate (case A) as a function of cooling time at the positions 6–11.](image)

The gamma dose rates at different positions have been measured (see Table 1) approximately 2 months after the end of the last cycle, and then again during the staged process of removal of the two quadrupole magnets (approximately 4 months after the end of the last cycle). It has to be noted that measurement results for case C are obtained under different conditions than assumed in simulations (hence the symbol C* in Table 1). Also, post festum analysis of the simulation input factors showed that real integrated proton current was 30% lower so the scaled down dose rates are shown in last column in Table 1.

Visual inspection of Table 1 shows a very satisfactory agreement between calculated and measured dose rates, especially if we keep in mind the simplifications used in the simulations. For example, the material composition of some of the muon beamline components are poorly known (such as ‘mild’ steel) so they have been estimated, all the changes and improvements in the area over many decades have been ignored (including target thickness changes), simplified geometry of the components and irradiation time profile have been used, beam size/profile is known with uncertainty level of 20%. In addition, we have uncertainty of location where measurement is

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4 In addition to Q1 and Q2 magnets, the beam window assay (component between points 2 and 3 in Figure 1) has been removed as well.

5 Based on detailed record between 1999 and 2014.

6 Quick, first approximation of the corrected dose rate values.

7 The target effective thickness was different during the different stages of muon beamline operation: between 2.5 and 7 mm in the period 1987 - 1997, between 3 and 10 mm in the period 1997 - 2007 and 10 mm from late 2007 onwards.
performed compared with calculation, statistical uncertainty of calculated values, uncertainty of measured values, influence of physics model used in simulations (CEM03 model used here) on final results, etc.

Table 1. The comparison between calculated and measured gamma dose rates during staged process of upgrading the south side muon beamline at ISIS.

| Case | Position | Cooling time [days] | Measured dose rate [mSv/h] | Calculated dose rate [mSv/h] | Scaled calculated dose rate [mSv/h] |
|------|----------|---------------------|---------------------------|-----------------------------|----------------------------------|
| A    | 1        | 60                  | 2200                      | 2000                        | 1460                             |
| A    | 4b       | 60                  | 100                       | 800                         | 580                              |
| A    | 10       | 60                  | 8.7                       | 40                          | 29                               |
| B    | between 9 and 10 | 120              | 7                         | 30                          | 21                               |
| B    | 12       | 120                 | 5                         | 5                           | 3.7                              |
| C*   | between 12 and 13 | 120            | 1.5                       | 10                          | 7.2                              |
| C*   | between 6 and 11 | 120              | 15                        | 110                         | 80                               |
| C*   | 3        | 120                 | 200                       | 1100                        | 800                              |
| D    | 4a       | 120                 | 50                        | 55                          | 40                               |
| D    | 4b       | 120                 | 50                        | 52                          | 38                               |

4. Conclusions
The calculation of the activation of ISIS muon beamline components has been performed to predict the gamma dose rates and help in planning the replacement of the two quadrupole magnets during the first stage of the ISIS muon beamline upgrade project. The obtained results have been benchmarked against the measured dose rate values (during the staged process of removal of the magnets) and very satisfactory agreement has been found.

References
[1] Lord J S et al. 2017 Upgrading the south side muon beamline at ISIS, *Nuclear Instruments and Methods A* (to be published).
[2] MCNPX 2.7.0 - Monte Carlo N-Particle Transport Code System for Multiparticle and High Energy Applications, https://mcnpx.lanl.gov/.
[3] Wilson W L et al. 1998 *Proceedings of the SARE4 Workshop, Knoxville, USA*.
[4] Jones K and Russell R 2013 *private communication*.
[5] Ansell S 2014 https://github.com/SAnsell/CombLayer.
[6] International Commission on Radiological Protection 1987 *ICRP Report No. 51, Pergamon Press, New York*.
[7] Jones B and Adams D J 2013 "Design and Operational Experience of Delivering Beam to ISIS TS1" *ISIS Internal Report*. 