GEANT4 STUDIES OF MAGNETS ACTIVATION IN THE HEBT LINE FOR THE EUROPEAN SPALLATION SOURCE

C. Bungau, R. Barlow, A. Bungau, R. Cywinski, T.R. Edgecock, University of Huddersfield, UK
P. Carlsson, H. Danared, F. Mezei, ESS, Lund, Sweden
A.I.S. Holm, S.P. Møller, H.D.Thomsen, Aarhus University, Denmark

Abstract

The High Energy Beam Transport (HEBT) line for the European Spallation Source is designed to transport the beam from the underground linac to the target at the surface level while keeping the beam losses small and providing the requested beam footprint and profile on the target. This paper presents activation studies of the magnets in the HEBT line due to the backscattered neutrons from the target and beam interactions inside the collimators producing unstable isotopes.

INTRODUCTION

The European Spallation Source (ESS) in Lund, Sweden, is a high power (5MW) proton accelerator which will produce high intensity neutron beams through spallation. The high-energy beam transport (HEBT) line will transport the 5 MeV, 2.5 GeV proton beam from the underground linac to the spallation tungsten target at surface level. The HEBT design used in this study is the one from the ESS Conceptual Design Report published in 2012. The HEBT line has four sections designed and optimised to obtain the desired beam sizes, phase advances and Twiss parameters at specific locations. The HEBT starts with a straight underground section (HEBT-S1) which accommodates a collimation system and space for additional cryo-modules for a power and energy upgrade followed by a semi-vertical bending section denoted HEBT-S2 bringing the beam from the underground linac tunnel to the target 1.6 m above ground level. The third horizontal section (HEBT-S3) includes the expansion system to provide the requested beam footprint. Finally the last section is a short horizontal section for a beam dump to be used for accelerator tuning and commissioning. Activation induced by particle nuclear interactions in beamline elements represents one of the main radiation hazards of high-energy accelerators. Exposure to radiation from induced activation can occur in connection with handling, transport, machining, welding, chemical treatment and storage of irradiated items. Because the accelerator components reveal high induced activation during normal operations and after accelerator shutdown, it is of primary importance to predict correctly their residual activity before any handling and maintenance procedures. The current paper studies the high radiation level of HEBT components from back-streaming neutrons coming from the target.

THE GEANT4 MODEL

GEANT4 [1] provides an extensive set of hadronic physics models for energies up to 10 - 15 GeV, both for the intra-nuclear cascade region and for modelling of evaporation. There are many different (data based, parameterized and theory-driven) models using different approximations and each has its own applicable energy range. Monte Carlo codes usually come with their own physics models and the user is offered default selections. Due to the vast range of applications, GEANT4 will not give the user any default physics models, the user themself has to work out what models to use for what processes. In order to model the proton and neutron inelastic interactions in the energy range relevant for this study, the best physics models available are the three theoretical intra-nuclear cascade models provided by GEANT4: INCL/ABLA (Liege) model, Binary cascade and the Bertini model. The Liege intranuclear cascade model together with the independent evaporation/fission code ABLA has been validated against experimental data for spallation processes in many different heavy elements [2]. However, the INCL/ABLA validation results presented at the IAEA benchmark for spallation reactions show that, for energies lower than 150 MeV, the results of the Liege model are not so good as above this energy [3]. This is because the model does not have preequilibrium: INCL cascade is directly "coupled" to equilibrium de-excitation handled by ABLA and therefore it does not describe well enough low energy reactions (where nuclear structure effects start to play their role). Above 150 MeV, INCL/ABLA works very nicely, being one of one of the best models available. On the other hand, the other two models available in GEANT4, Bertini and Binary cascade, do incorporate the pre-equilibrium model. The preequilibrium model in GEANT4 has been recently improved following a validation study against the TARC experiment data, in order to improve several shortcomings in applying this model to neutron spallation processes [4]. All these recent developments have been considered and implemented in our code.

In the simulations presented in this paper, the Bertini model was selected. For neutron energies below 20 MeV, the high-precision models were selected. These models use the ENDF/B-VII [5], JENDL [6], MENDL-2 [7] and other data libraries [8]. The S(α,β) coefficient which takes into account the corrected treatment for neutron scattering on chemically bound elements in the thermal region has also been implemented in the GEANT4 physics list used for this study.

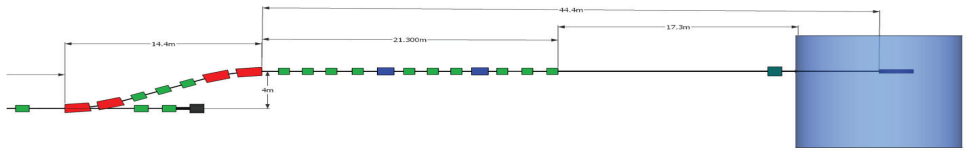

Figure 1: The HEBT-S3 - 2D layout which includes the magnets - quadrupoles (green), dipoles (red) and octupoles (blue), the fixed collimator (cyan) and the target monolith (including the proton beam window and the target wheel).

RESULTS

The geometry implemented into the code is shown in Fig. 1. For simplicity, the magnets were assumed to be made of a homogeneous mixture of Fe and Cu in equal proportions. The collimator is made of Cu and it is coated with W.

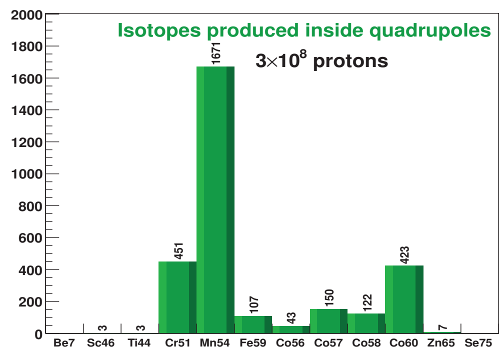

Figure 2: Isotopes produced inside the quadrupoles.

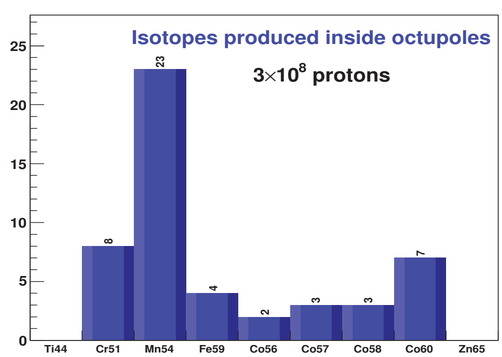

Figure 3: Isotopes produced inside the octupoles.

In order to study the beamline components activation, the code has been designed to register the production of any radioactive isotope which decays emitting gamma-rays and also which has a lifetime longer than 24 hours, since any isotope which decays in less than 24 hours can be considered as not posing a safety concern. These isotopes are: Be7, Sc46, Ti44, Cr51, Mn54, Fe59, Co56, Co57, Co58, Co60, Zn65, Se75, Rb84, Sr85, Y88, Zr95, Nb94, Nb95, Ru106, Cd109, In111, Sn113, Sn125, Sb124, Sb125, I125, Cs132, Cs134, Cs137, Ba133, Ce139, Ce141, Ce144, Eu152, Eu154, Gd153, Tb160, Tb161, Tm170, Yb169, Hf172, Ta182, Os185, Ir192, Au198, Au199, Hg203, Pb210, Bi207, Th228, Np239, Am241, Am243.

The radioactive decay processes have been added to the standard physics list provided by GEANT4, such that the production rate takes into account not only the isotopes produced by the direct impact of the backscattered neutrons on various accelerator components, but also the production of these isotopes following the decay of other isotopes produced in these interactions. While the accelerated proton beam is on, this production rates are constant in time, and for an isotope “i”, it is given by:

$$\frac{dN_i^{prod}}{dt} = \frac{N_{iso}}{\Delta t} = \frac{N_{iso} I}{N_p e} \qquad (1)$$

where N_{iso} is the number of isotopes produced in the simulation, I is the proton beam current from the accelerator, N_p is the number of protons simulated, and e is the proton electric charge. The number of isotopes produced inside the quadrupoles for 3×10^8 incident protons is shown in Fig. 2. The octupoles magnets are less affected, as shown in Fig. 3, because they are further away from the spallation target and hence they are hit by fewer backscattered neutrons. As expected, the worst affected is the proton beam collimator placed in front of the target monolith. The radioactive isotopes production is shown in Fig. 4 separately for the main copper volume and the tungsten coating.

Thus, during the beam-on period, the time evolution can be obtained by combining the production and decay rates:

$$\frac{dN_i}{dt}(t) = \frac{N_{iso} I}{N_p e} - \lambda_i N_i(t) \qquad (2)$$

where λ_i is the decay constant of isotope “i”.

The solution of Eq. 2, gives the number of isotopes at any time t during the beam exposure:

$$N_i(t) = \frac{N_{iso} I}{N_p e \lambda_i}(1 - exp(-\lambda_i t)) \qquad (3)$$

However, after the beam is switched off, following a continuous exposure for a given time t_1, the number of isotopes after a time t, which includes both the beam on period $t1$ as well as the beam off period, is given by:

$$N_i(t) = \frac{N_{iso} I}{N_p e \lambda_i}(1 - exp(-\lambda_i t_1)) exp(-\lambda_i (t - t_1)) \qquad (4)$$

ISBN 978-3-95450-122-9

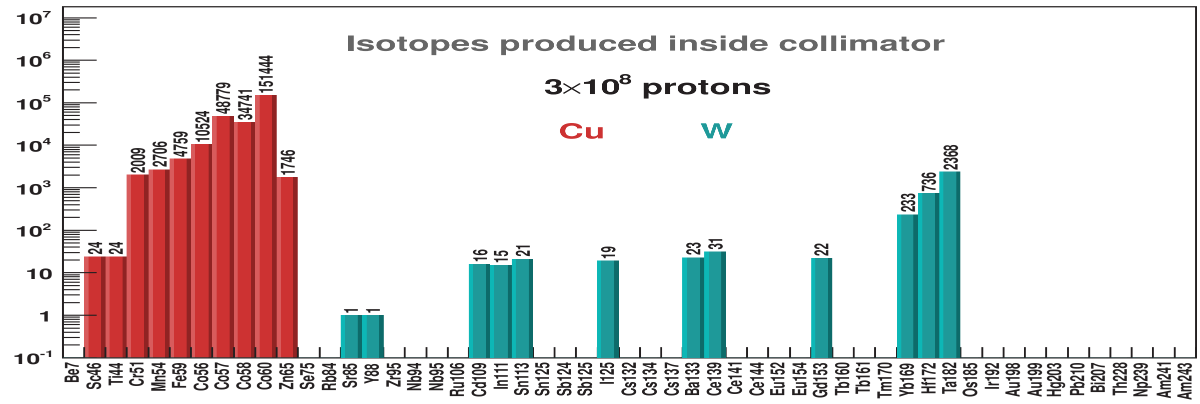

Figure 4: Isotopes produced inside the beam collimator.

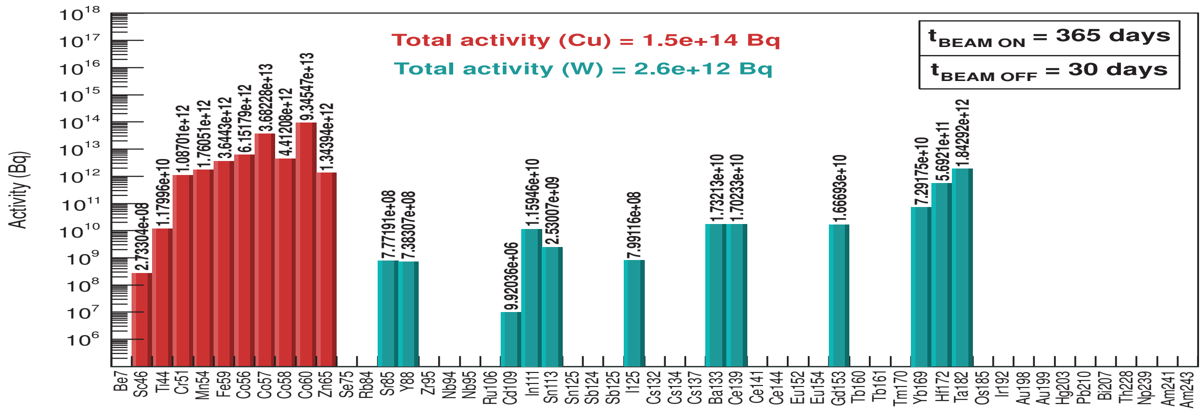

Figure 5: Activity inside the beam collimator.

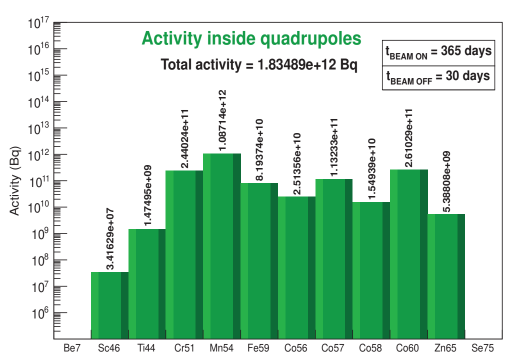

Figure 6: Activity inside the quadrupoles.

The induced activity inside the accelerator elements is given by Eq. 5.

$$A_i(t) = \lambda_i N_i(t) \tag{5}$$

Considering a beam exposure of 365 days, the induced activity inside the collimator is shown in Fig. 5 and inside the quadrupole magnets is shown in Fig. 6.

REFERENCES

[1] GEANT4 - a toolkit for particle passage through matter, version geant4.9.5.p01; http://geant4.web.cern.ch/geant4/

[2] A. Heikkinen *et al.*, "Implementation of INCL cascade and ABLA evaporation codes in Geant4," J. Phys., Conf. Ser. 119 (2008), 032024.

[3] IAEA benchmark for spallation reactions; http://nds121.iaea.org/alberto/mediawiki-1.6.10/index.php/Benchmark:2ndWorkProg

[4] A. Howard *et al.*, "Validation of Geant4 against the TARC benchmark and new developments in PreCompound/De-Excitation modelling," 1st Workshop on Accelerator Radiation Induced Activation, Paul Scherrer Institute, Switzerland, 2008.

[5] M. B. Chadwick *et al.*, "ENDF/B-VII.1 Nuclear Data for Science and Technology: Cross Sections, Covariances, Fission Product Yields and Decay Data," Nuclear Data Sheets, Volume 112, Issue 12, p. 28872996 (2011).

[6] T. Nakagawa *et al.*, J. Nucl. Sci. Technol. 32 (1995) 1259.

[7] Yu. N. Shubin *et al.*, "Cross section data library MENDL-2 to study activation and transmutation of materials irradiated by nucleons of intermed. energies," INDC(CCP)-385, International Atomic Energy Agency, 1995.

[8] J. P. Wellisch, Nucl. Inst. Meth. A 502 (2003) 669.