STUDIES OF INDUCED RADIOACTIVITY AND RESIDUAL DOSE RATES AROUND BEAM ABSORBERS OF DIFFERENT MATERIALS

M. Brugger, D. Forkel-Wirth, S. Roesler*, J. Vollaire, CERN, Geneva, Switzerland

Abstract

The FLUKA particle interaction and transport code is capable to calculate in one and the same simulation interactions at LHC energies as well as the associated hadronic and electromagnetic particle showers from TeV energies down to energies of thermal neutrons. Sophisticated models for nuclear interactions predict the production of radio-nuclides of which the built-up and decay, along with the associated electromagnetic cascade, can also be calculated in the same simulation. The paper summarizes applications of FLUKA to assess activation around LHC beam absorbers, such as the beam dumps, and presents results of measurements performed during LHC operation.

INTRODUCTION

Modern particle interaction and transport codes such as FLUKA [1,2] allow one to predict radioactivity and associated residual dose rates caused by high energy beam losses in accelerator components in great detail. Phenomenological models of high energy hadronic interactions linked to sophisticated generalized cascade, pre-equilibrium and fragmentation models are able to describe the production of individual radioactive nuclides with good accuracy (often within less than 20%), as comprehensive benchmark studies have demonstrated. The calculation of induced radioactivity has thus become an integral part of design studies for high energy beam absorbers. Results provide valuable information on material choices, handling constraints and waste disposal and allow an early optimization of components in order to increase the efficiency of the later operation of the facility while keeping doses to personnel as low as reasonably achievable. The present paper gives examples of both generic studies with FLUKA for different absorber materials as well as studies for collimators and absorbers of the Large Hadron Collider (LHC).

BENCHMARK STUDY

The unique features of FLUKA for the computation of induced radioactivity and residual dose rates were extensively benchmarked at the CERF facility. At this facility a positively charged hadron beam of 120 GeV interacts in a copper target creating a stray radiation field which can be used for a large variety of studies, among others the activation of material samples. Different materials commonly used for accelerator components and shielding (copper, iron, aluminum, *etc*.) were irradiated and their activation measured by gamma spectrometry and with dose rate instruments at different cooling times.

Furthermore, the irradiation as well as the radioactive build-up and decay were simulated with FLUKA and results compared to the experimental data [3,4]. The benchmark showed that FLUKA predicts specific activities of individual nuclides within 20-30% in many cases and is also able to reproduce residual dose equivalent rates. An example for the latter is given in Fig. 1 [4].

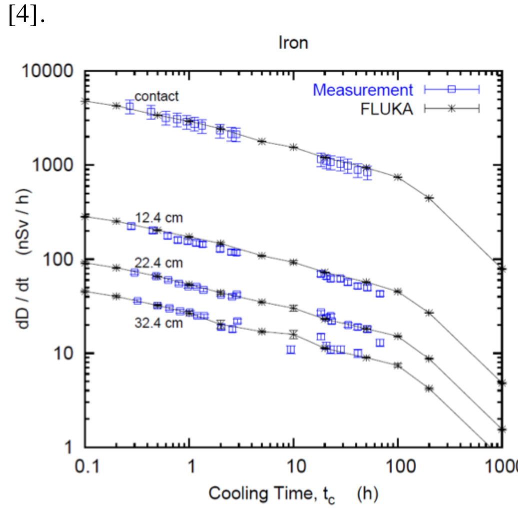

Figure 1: Residual dose equivalent rates as function of cooling time on contact to an iron sample and at three different distances as measured and as calculated with FLUKA [4].

GENERIC ACTIVATION STUDY

Calculations with a generic collimator allowed the assessment of different jaw materials on the activation properties of the entire assembly and the associated residual dose rates [5]. The geometry consists of two rectangular, vertical jaws of a length of 120 cm made of carbon, copper or tungsten. The cooling system is approximated by two copper plates with an artificially reduced density, in order to account for its actual design based on water-cooled pipes, fixed to the jaws with stainless steel clamps. The entire assembly is finally placed into a stainless steel tank. Figure 2 shows a cross sectional view through the geometry. While the jaws and copper plates are pure materials, the following elemental composition is used for all stainless steel components (given in percent by mass): Cr (15.0%), Ni (14.0%), Mn (2.0%), Mo (3.0%), Si (1.0%), P (0.045%), C (0.03%), S (0.03%), Fe (remaining fraction). The geometry also includes a tunnel wall which, however, is of minor importance due to its small contribution to the dose rate close to the absorber as well as to low-energy neutron activation of the absorber.

*Stefan.Roesler@cern.ch

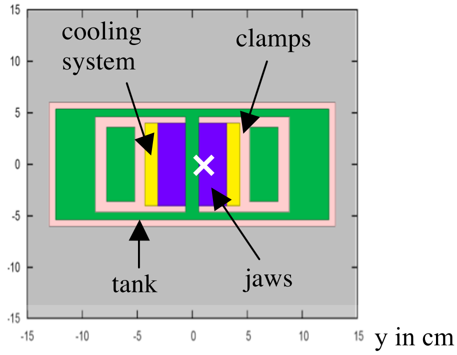

Figure 2: Cross sectional view of the absorber geometry. The beam impact point is indicated with a white cross.

For the calculations, a pencil beam of either protons (450 GeV and 7 TeV) or lead ions (2.6 TeV/nucleon) was assumed to hit one of the jaws at a distance of 4mm to its edge (see Fig. 2). While the simulation of the prompt radiation considered only hadronic cascades (activation by photo-production can be neglected at hadron accelerators) electrons/positrons and photons from radioactive decays were followed down to 100keV and 10keV, respectively.

Residual dose rates were calculated for a single LHC operational period of 180 days and nine cooling times between one hour and 10 years. Residual dose rates were calculated by folding fluence with ambient dose equivalent conversion coefficients in a one-dimensional, longitudinal binning (*i.e.*, in beam-direction) at 2cm above the absorber. As an example the results for a generic collimator with tungsten jaws is shown in Fig. 3.

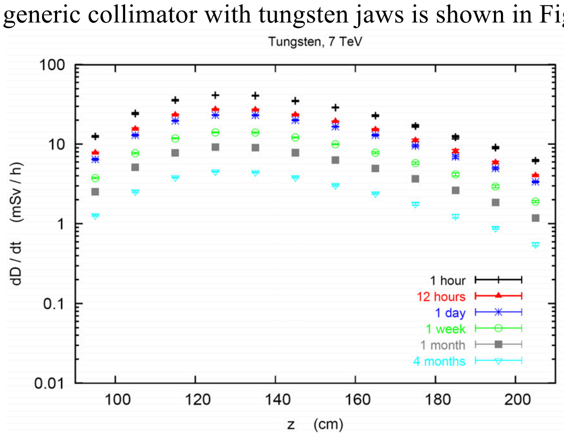

Figure 3: Residual dose rates close to the upper surface of the absorber for different cooling times and tungsten jaws.

Furthermore, the contributions of individual nuclides were also obtained which allowed for more detailed analyses of the results. Table 1 lists the contributions of different radio-nuclides to the total residual dose rate above a collimator with tungsten jaws (see Fig. 3, bin with maximum dose rate value). Only those nuclides are given that make up about 90% of the dose rates. Nuclides marked with "*" originate mainly from the activated jaws. In general, at short cooling times (up to a few days) many different nuclides contribute while at long cooling times only a few nuclides dominate. This makes dose rate results obtained with Monte Carlo codes for long cooling times very sensitive to how the particular nuclides are predicted by the implemented models.

Table 1: Contributions in percent of different radio-nuclides to the total residual dose rate above an absorber with tungsten jaws after 12hours, one week and four months of cooling. The last line gives the contribution to the total dose rates by the jaws.

	12h		1w		4m
^{171}Hf	20.40*	^{58}Co	26.24	^{54}Mn	30.20
^{58}Co	11.20	^{48}V	13.87	^{58}Co	26.56
^{48}V	7.22	^{56}Co	13.48	^{56}Co	16.43
^{52}Mn	6.84	^{54}Mn	12.96	^{182}Ta	8.36*
^{176}Ta	6.84*	^{52}Mn	8.18	^{172}Lu	6.54*
^{170}Lu	6.61*	^{182}Ta	5.48*	^{46}Sc	4.36
^{56}Co	6.49	^{46}Sc	3.82		
^{54}Mn	5.36	^{172}Lu	2.86*		
^{166}Tm	2.54*	^{170}Lu	2.24*		
^{175}Ta	2.28*	^{171}Lu	1.62*		
^{182}Ta	2.22*				
^{57}Ni	1.94				
^{46}Sc	1.65				
^{169}Lu	1.61*				
^{187}W	1.24*				
^{172}Lu	1.23*				
^{171}Lu	1.19*				
^{44}Sc	0.88				
^{158}Ho	0.67*				
^{88}Y	0.59				
^{90}Nb	0.53				
^{24}Na	0.50				
	54%		18%		18%

LHC BEAM DUMPS

The two LHC beam dumps (one for each counter-rotating beam) consist of air-cooled graphite cores which are surrounded by iron shielding. For the latter, old magnet yokes filled with concrete were used. Should a core degrade it has to be replaced which is evidently a delicate intervention as the interior of the shielding is strongly activated.

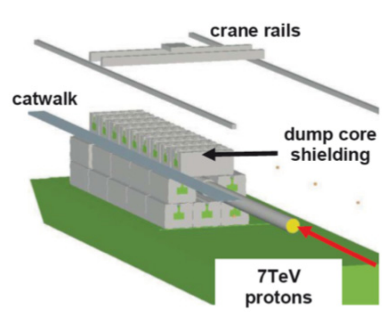

Figure 4: FLUKA geometry of a LHC beam dump. For clarity of the representation the walls of the cavern are not shown [6,7].

Thus, the core exchange has been studied during the design phase with FLUKA simulations [6,7]. The geometry included a very realistic representation of the dump structures in which the magnet yokes, as well as the air gaps in between them, were modelled in great detail. Figure 4 shows a three dimensional view of this geometry.

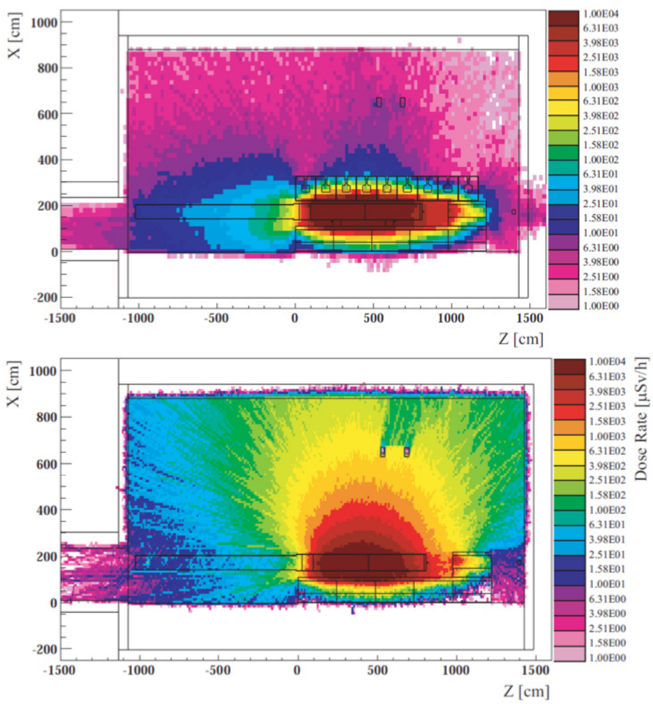

Figure 5: Spatial distributions of ambient dose equivalent rate after one year of operation and one month of cooling with the top shielding in place (top) and removed (bottom). Results are shown (in units of µSv/h) for a vertical section through the centre of the dump core [6,7].

For the estimation of doses received by personnel during the core replacement maps of residual ambient dose equivalent rate were computed assuming one year of operation and several cooling periods after the last beam dump. The exchange consists of several steps, such as disconnecting the core from the upstream beam pipe, removing the top-layer of the shielding with the overhead crane and lifting of the broken core assembly. During the work personnel is exposed to residual radiation also directly from the core and from the inside of the shielding. Thus, residual dose rates were calculated for different configurations, among others, with closed and open shielding. Figure 5 presents results for one month of cooling time [6,7]. The dose rate maps then served as basis for the estimation of job doses.

TED ABSORBER BENCHMARK

So-called RadMon detectors monitor the radiation fields around beam loss points and sensitive electronics at the LHC [8]. They consist of three units, which measure high-energy hadron fluence (static RAM), 1-MeV equivalent neutron fluence (PIN diode) and total ionizing dose (Radfet), respectively. Among other locations, RadMon detectors are installed downstream of the injection line beam absorbers (TED) used to setup the beam transport before injecting into the LHC.

The monitor readings served as benchmark of FLUKA calculations which were based on a detailed modelling of the TED absorber. Distributions of high-energy (E>20 MeV) hadron fluence, 1-MeV equivalent neutron fluence and absorbed dose around the absorber hit by a 450 GeV proton beam are shown in Fig. 6.

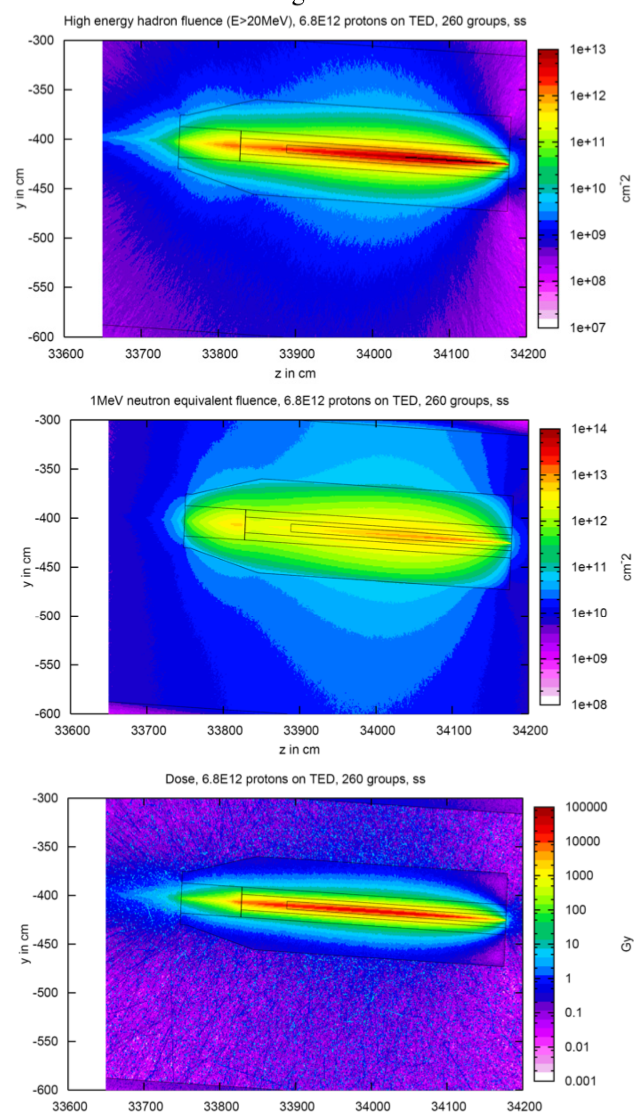

Figure 6: High energy hadron fluence (top), 1-MeV equivalent neutron fluence (center) and absorbed dose (bottom) around an LHC beam absorber. The beam hits the absorber from the right hand side.

The contour plots show horizontal sections through the TED at beam height, with the beam hitting the absorber from the right-hand-side and the RadMon response scored at (y,z)=(-401 cm, 33719 cm). Table 2 compares FLUKA predictions of the three, above mentioned quantities with the RadMon data. The last column demonstrates that FLUKA reproduces the radiation fields, including their particle type composition, within 20%.

Table 2: Comparison of measured values and FLUKA results for high-energy hadron fluence, 1-MeV equivalent neutron fluence and absorbed dose downstream of the TED absorber. The last column gives the ratio of measured and simulated values.

Quantity	RadMon [Error]	FLUKA [Error]	Ratio (R/F)
High-energy hadrons (cm^{-2})	1.2×10^{10} [20.0%]	0.96×10^{10} [3.2%]	0.80
1 MeV neutron equiv. (cm^{-2})	2×10^{10} [20.0%]	2.1×10^{10} [2.5%]	1.05
Dose (Gy)	4.73 [20.0%]	5.0 Gy [10%]	1.06

MEASUREMENTS IN THE LHC TUNNEL

The evolution of induced radioactivity around the LHC accelerator and experiments is monitored with air-filled plastic ionization chambers (so-called PMI monitors). These detectors are installed in locations where beam losses and, thus, considerable activation are expected in order to provide remote measurements of residual dose rates. They are connected to the general radiation protection monitoring system, called RASMES [9], which also includes other instruments monitoring, *e.g.,* dose equivalent in accessible areas and releases of radioactivity into the environment.

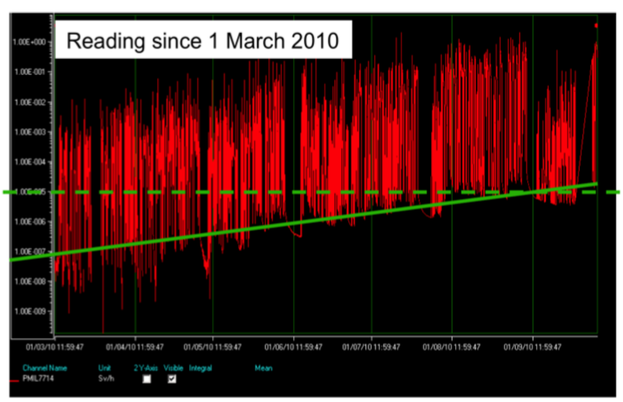

Figure 7: Reading of a PMI ionization chamber as function of time, installed downstream of a passive absorber in the LHC collimation region. The dashed horizontal line indicates 10µSv/h, the solid line shows the increasing residual dose rates (reading during beam-off periods).

Although the PMI chambers are designed to measure residual dose rates during beam-off periods, they take data continuously, *i.e.*, also during operation with beam. Of course, saturation effects may not be negligible in the latter case. As an example, the reading of the monitor installed close to a passive absorber in the LHC collimation region is shown in Fig. 7. The spikes indicate the prompt doses while the level of increasing residual dose rates during beam-off periods is indicated with a solid green line. At present, residual dose rates have reached about 30µSv/h after one day of cooling.

Assuming that losses in the collimation region scale with beam intensity and extrapolating the value to losses at nominal operational parameters yields about 1-2mSv/h, in agreement with the prediction by FLUKA for that location [10]. The latter is presented in Fig. 8, giving the dose rates around the absorber (center) and adjacent magnet (shown on the right) in a horizontal section at the height of the two beam-pipes.

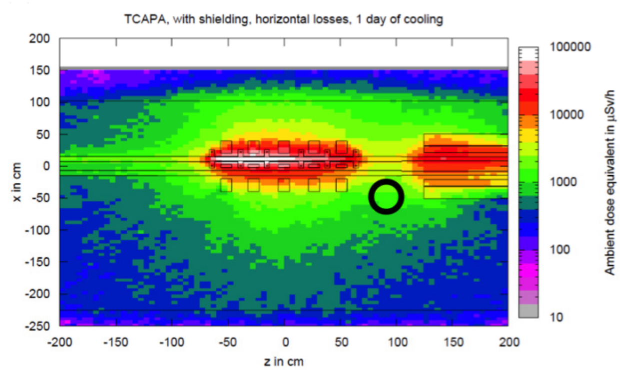

Figure 8: Ambient dose equivalent distribution around a passive absorber (in µSv/h) for losses at nominal LHC intensity. The location of the PMI monitor is indicated with a black circle [10].

SUMMARY

The paper summarizes applications of FLUKA to assess activation around LHC beam absorbers, such as the beam dumps, collimators and injection line absorbers. FLUKA is especially suitable for this type of application due to the fact that, among others, it allows a reliable simulation up to LHC energies and includes sophisticated nuclear models predicting the production of radio-nuclides at any energy. Beside these physics capabilities, radioactive decays as well as the electromagnetic shower associated with it can be simulated simultaneously with the high-energy cascade which is very convenient and user-friendly.

Throughout the design particular emphasis has been put on benchmarking results with measurements, both from dedicated activation studies as well as from radiation monitors installed around the LHC accelerator. In most cases, the results confirmed the reliability of the FLUKA calculations, the latter being capable of reproducing the measured data of specific activities and residual dose rates to within 20%.

With increasing power of the LHC beams and luminosity in the experiments activation of components will increase and provide further valuable benchmark data at energies which have never been reached before.

REFERENCES

[1] A. Fassò, A. Ferrari, J. Ranft and P.R. Sala, FLUKA: a multi-particle transport code, CERN-2005-10 (2005), INFN/TC_05/11, SLAC-R-773.

[2] G. Battistoni, S. Muraro, P.R. Sala, F. Cerutti, A. Ferrari, S. Roesler, A. Fassò and J. Ranft, "The FLUKA code: Description and benchmarking", Proceedings of the Hadronic Shower Simulation Workshop 2006, Fermilab 6-8 September 2006, M. Albrow, R. Raja eds., AIP Conference Proceeding 896, 31-49 (2007).

[3] M. Brugger, A. Ferrari, S. Roesler and L. Ulrici, "Validation of the FLUKA Monte Carlo code for predicting induced radioactivity at high-energy accelerators", Nucl. Instr. and Meth. A 562, p. 814 (2006).

[4] M. Brugger, H. Khater, S. Mayer, A. Prinz, S. Roesler, L. Ulrici and H. Vincke, "Benchmark studies of induced radioactivity produced in LHC materials, Part II: Remanent dose rates", Radiation Protection Dosimetry 116, p. 12 (2005).

[5] M. Brugger, D. Forkel-Wirth and S. Roesler, "Generic studies of radioactivity induced by high energy beams in different absorber materials", Nuclear Technology, 168, p.665 (2009).

[6] M. Brugger, A. Ferrari, D. Forkel-Wirth, M. Fürstner, E. Lebbos, M. Lorenzo-Sentis, S.Roesler, V. Vlachoudis and J. Vollaire, Predictions of residual dose rates with FLUKA for high energy accelerators at CERN, Proceedings of the 1st Workshop on Accelerator Radiation Induced Activation, PSI, 13-17 October 2008, PSI Proceedings 09-01, 194-205 (2009).

[7] J. Vollaire, D. Forkel-Wirth and S. Roesler, Calculation of remanent dose rate maps in the LHC beam dump caverns, Technical Note CERN-SC-2006-044-RP-TN (2007).

[8] T. Wijnands, C. Pignard and R. Tesarek, "An on line radiation monitoring system for the LHC machine and experimental caverns", Proceedings of the 12th Workshop on Electronics for LHC and Future Experiments, (2006).

[9] L. Scibile *et al.*, "The LHC Radiation Monitoring System for the Environment and Safety", Proceedings of the conference EPAC, 1903-1905 (2004).

[10] S. Roesler, M. Brugger and D. Forkel-Wirth, Radiological considerations for passive absorbers in the LHC betatron cleaning insertion, Technical Note CERN-SC-2007-056-RP-TN (2007).