Summer student project

Radiation protection group

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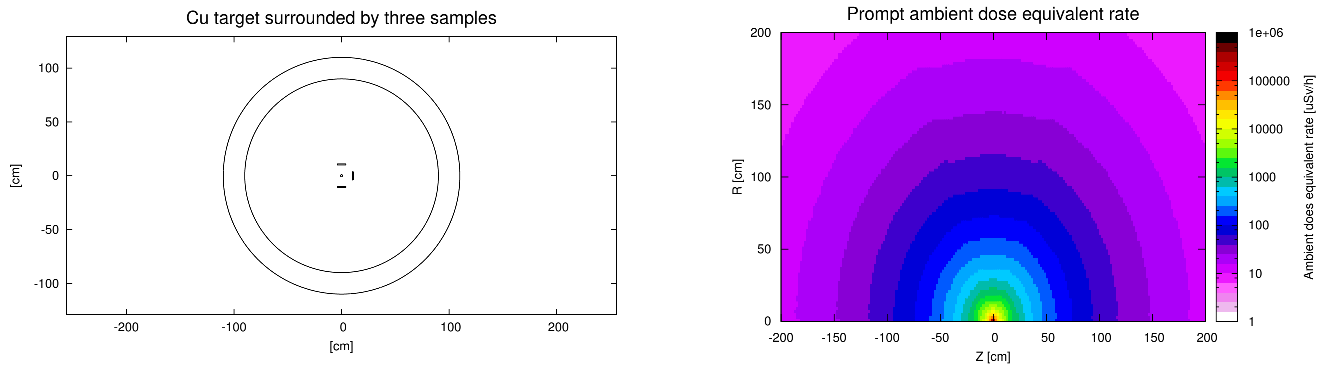
Abstract

The prediction of residual dose rates is an important task to insure proper radiation protection during maintenance and dismantling works.
During the summer student program the main project was writing a technical note (TN) about a simulation of an antiproton experiment. The TN has EDMS number 2011821. In the TN, an antimatter matter collision is simulated i.e. antiprotons are impinged on a Cu sphere surrounded by three cylindrical samples of Al, In and Bi. In a thin shell around the collision the flux of protons, neutrons, π^+, π^- and photons are logged alongside the prompt ambient dose equivalent rate around the Cu sphere and the residual radionuclides in the samples. The radionuclide production in the samples have been calculated from the neutron flux around the target as well as directly evaluated in FLUKA using RESNUCL and decay cards. These values are within a factor of two of each other.
The experiment described in the TN is performed in the Antiproton Decelerator (AD) experimental area. There are more details to take into account, such as the surroundings, beam line, etc. Here the activity of the Al, In and Bi samples are compared with the simulated ones.
In addition to the antiprotons study, a benchmark of FLUKA version 2011.2x.3 for the 14^{th} specialists' Workshop on Shielding Aspects of Accelerators, Targets, and Irradiation Facilities (SATIF), was conducted with a specific geometry. The results are used for intercomparison with other Monte Carlo codes.
Finally, the thermal neutron distribution in the CERN High energy AcceleRator Mixed field (CHARM) facility is investigated in collaboration with a radiation protection team from Japan. This is to characterize processes such as ^{40}Ar(n,γ)^{41}Ar.

1 Technical note

Using FLUKA [1, 2], one can perform Monte Carlo simulations of the stray radiation from particle beam collisions with various geometries. A GUI for FLUKA exist, which is called *flair* and is a convenient platform to setup the parameters to run the code and produce graphs.
The geometry of the experiment is: A Cu sphere with a diameter of 20 mm, that is surrounded by three cylindrical samples of Al, In and Bi with dimensions of 80 mm diameter x 10 mm height, each placed 10 cm away from the Cu sphere. The geometry is shown in Figure 1(a).
A 5.3 MeV antiproton beam with an average beam intensity of $3 \cdot 10^5$ antiprotons/s from the Antiproton Decelerator (AD) is set to collide with the Cu sphere.
At 1 m distance the prompt ambient dose equivalent rate around the collision point is around 100 uSv/h as can be see in Figure 1(b).



(a) (b)

Figure 1: (a) shows the geometry of the simulation. It is shown from above. In the middle there is a dot representing the Cu target. The two rings centered around the Cu target have a radius of 90 cm and 110 cm respectively and represent the scoring area for the particle flux. The Al (top), In (bottom) and Bi (right) cylinders are the three boxes. (b) shows the prompt ambient dose equivalent rate near the Cu target in uSv/h, with the samples in place. There is approximately 100 uSv/h one meter from the target after collision. Each bin have an area of 2 cm x 2 cm.

Al, In and Bi have important neutron reactions, which are going to be investigated. To find the yield of the created radionuclides, one can use the neutron flux $\Phi(E)$ simulated and logged in FLUKA.

$$Y = \frac{N_A}{M} \int \Phi(E)\sigma(E)\mathrm{d}E \approx \frac{N_A}{M} \sum_{\Delta E} \Phi(E)\sigma(E)\Delta E. \tag{1}$$

Y is the yield, N_A is Avogadro's number, M is the molar mass and σ is the cross section.
The activity is then found by solving the linear differential equation,

$$\frac{\mathrm{d}N(t)}{\mathrm{d}t} = -\lambda N(t) + P(t), \tag{2}$$

where $N(t)$ is the number of radioactive nuclei, λ is the decay constant and $P(t)$ is the production rate, which corresponds to the yield and it will be constant during irradiation and zero under cool down.

The solution with initial condition $A(t=0)=0$, where the cool down time is also included is,

$$A(T_{ir}, T_{cd}) = A_s(1 - \mathrm{e}^{-\lambda T_{ir}})\mathrm{e}^{-\lambda T_{cd}}, \tag{3}$$

where A is the activity, T_{ir} is the irradiation time, T_{cd} is the cool down time and A_s is the saturation activity. The saturation activity is given as $A_s = Y\, m$, where m is the mass of the sample.
The second method is using the RESNUCL and decay cards in FLUKA, which will find the activities directly.
The final data are shown in Table 1. The neutron flux calculation (analytical) and directly simulated yield in FLUKA (simulated) compare within a factor of two. The discrepancies may be on account of the cross sections FLUKA use and the ones that are used analytically [3].

	Analytical		Simulated			
Isotope	$A_{2h\ ir}$ [Bq/g]	$A_{8h\ ir}$ [Bq/g]	$A_{2h\ ir}$ [Bq/g]	$A_{8h\ ir}$ [Bq/g]	Ratio 2h in	Ratio 8h
Na-24	4.77E-4±0.042%	1.67E-3±0.042%	2.70E-4±0.52%	9.52E-4±0.53%	0.565±0.53%	0.570±0.53%
In-115m	2.90E-3±0.027%	7.73E-3±0.027%	4.59E-3±3.1%	1.24E-2±2.8%	1.59±3.1%	1.61±2.8%
Bi-201	8.10E-5±0.073%	1.44E-4±0.073%	1.48E-4±3.4%	2.60E-4±3.4%	1.82±3.4%	1.81±3.4%
Bi-202	2.93E-4±0.066%	5.08E-4±0.066%	3.17E-4±3.1%	5.25E-4±3.1%	1.08±3.1%	1.03±3.1%
Bi-203	1.28E-4±0.062%	4.31E-4±0.062%	1.31E-4±2.4%	4.44E-4±2.6%	1.02±2.4%	1.03±2.6%
Bi-204	1.78E-4±0.061%	5.98E-4±0.061%	1.55E-4±2.4%	5.39E-4±2.2%	0.870±2.4%	0.901±2.2%
Bi-205	9.77E-6±0.066%	3.89E-5±0.066%	8.11E-6±1.9%	3.41E-5±1.9%	0.830±1.9%	0.878±1.9%
Bi-206	2.95E-5±0.065%	1.16E-4±0.065%	2.22E-5±1.8%	9.05E-5±1.8%	0.754±1.8%	0.778±1.8%

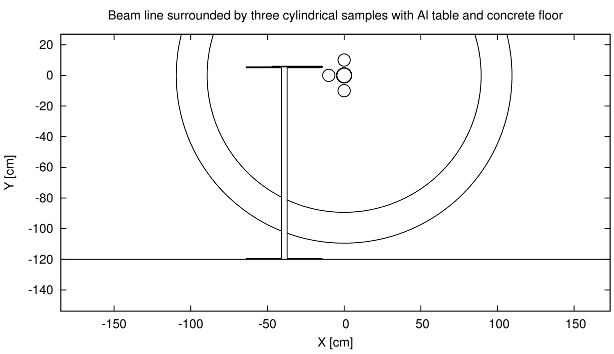
Table 1: In the analytical calculation of the activities, the attenuation length have not been taken into account. The ratio is [simulated/analytical] for 2 hours and 8 hours of irradiation, respectively. These numbers are from running the FLUKA code with 10 cycles with 10000 primaries on 40 different CPUs.

A gamma spectrometer will be used to measure the activity after irradiation. However, a gamma spectrometer has Minimum Detection Activity (MDA) depending on the gamma spectrometry setup, the mass of the sample and the measuring time. The radiation intensity is $\propto 1/r^2$, with this in mind, the distance the samples need to have to reach two times the MDA is found to be ten cm as mentioned in the geometry setup. This has been written in more detail in the technical note (TN) with EDMS number 2011821 [4].

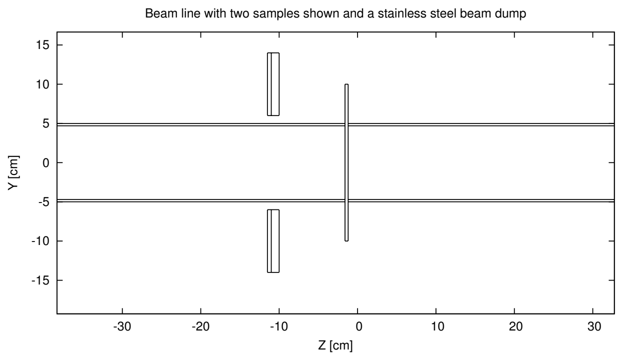
2 AD experiment

In Section 1 Figure 1(a) the FLUKA geometry is simple. To better match the conditions of the real experiment, which is based on the TN, the FLUKA geometry has been adjusted. The antiproton beam is defined to travel along the positive z-direction. Instead of the beam impinging on the Cu sphere there is a 4mm thick stainless steel vacuum windows that acts as a beam dump.. The samples have to be oriented differently to give each of them similar amounts of stray radiation, therefore they are mounted on a acrylic glass holder, which is fastened on an Al table. Along the z-axis the the distance from the beam dump to the samples are 8.4 cm for Al and In and 8.9 cm for Bi and they are all displaced 6 cm from the center of the 3 mm thick stainless steel vacuum beam line with an outer radius of 5 cm. The floor consists of concrete. This geometry is shown in Figure 2(a) and 2(b).
The new geometry will give the prompt ambient dose equivalent rate shown in Figure 3. The symmetry is distorted in Figure 3 compared to Figure 1(b). In comparison to the simulation in Section 1, the antiproton beam intensity is not constant. The beam intensity in the AD is logged and is delivered in spills every 100 s with a specific timestamp. With FLUKA the expected yield is found in nucl/prim. Instead of using Equation (3), the activity is found analytically. Every spill is assumed to react instantly and will produce a certain amount of radionuclides dependent on the beam

intensity, between the spills these are set to decay. When all the spills are delivered the produced radionuclides are multiplied with $\lambda e^{-\lambda T_{cd}}/m$ to get the activity after cool down in Bq/g.
After the experiment is performed the samples are transported to the gamma spectrometer lab, where they are analyzed. The results from the spectroscopy and FLUKA simulation will presented later in a publication that is under preparation.



(a)



(b)

Figure 2: (a) shows the three samples surrounding the beam line, Al (top), Bi (left) and In (bottom). The Al table is shown on the left and the two rings centered around the beam line have a radius of 90 cm and 110 cm respectively and represent the scoring area for the particle flux. The ground consists of concrete. (b) shows a cross section of the beam line with the beam dump inserted. The Al (top) and In (bottom) samples are also shown with the acrylic glass on the back.

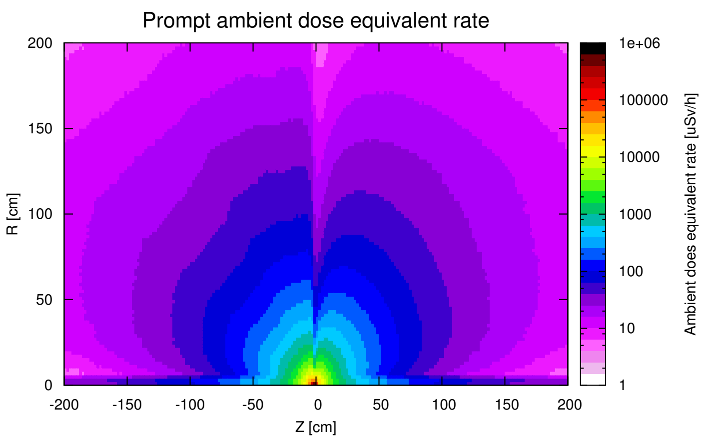


Figure 3: The prompt ambient dose equivalent rate around the collision point is shown in uSv/h with the geometry from Figure 2(a) and 2(b) and an assumed average beam intensity of $2.7{\cdot}10^5$ antiprotons/s.

3 FLUKA benchmark simulation

The Specialists' Workshop on Shielding Aspects of Accelerators, Targets, and Irradiation Facilities (SATIF) is a reoccurring event among radiation shielding experts. One of the things on the agenda is to see how the available Monte Carlo codes differ in their simulations. Therefore, a certain benchmark design has been specified, that the various Monte Carlo codes have to simulate, to test and compared them to each other. The specified design is: a proton pencil beam with an energy of 1, 10 and 100 GeV colliding with either an Al, a Cu or an Au cylinder target. This makes a total of nine scenarios. Then the scoring scheme is to measure different angular distributions of neutrons.
The specified design has been created in FLUKA version 2011.2x.3 and run on a computing cluster for 48 h on 20 CPUs for each scenario. This is done so the data can be presented in the upcoming 14^{th} SATIF workshop later in 2018.

4 Collaboration with colleagues from Japanese research institutes

Ar is the third most abundant gas in the earth's atmosphere and can make a neutron capture ^{40}Ar(n,γ)^{41}Ar. ^{41}Ar will β^--decay, so its concentration is important to predict for high energy accelerators. Therefore, the thermal neutron distribution is an essential quantity to know.
Au is a useful source to test the neutron flux in an area, because it has a high cross section with thermal neutrons ^{197}Au(n,γ)^{198}Au. Last year a Japanese radiation shielding team, in collaboration with the Radiation Protection (RP) group at CERN, performed a multitude of experiments. One of them took place in the CERN High energy AcceleRator Mixed field/facility (CHARM) in the Proton Synchrotron (PS) east area [5]. CHARM is an experimental area, where the proton beam from the PS is set to collide with a metal target to create stray radiation. This room contains some movable shielding walls in order to alter the radiation shielding for a given area. The momentum of the beam is 24 GeV/c. Around the room and in the hallway leading to the room, Au foils are placed. After 1.5 days of irradiation and 1.5 days of cool down their activity was measured with gamma spectrometers. With the FLUKA simulation the activity is also found by using USRBIN with a Au cross section script and by using USRTRACK and then using a Au cross sections.
This year the RP group collaborate with the Japanese team again and the last week of my stay I follow this collaboration to see, which methods are used and gain practical knowledge about operations at CERN in affiliation with the RP group.

5 Summary

The two methods, used for the TN Section 1, to find the activities of the samples are within a factor of two of each other. This is written in more detail in the TN [4].

In the AD experiment Section 2, the setup and expected prompt ambient dose equivalent rate are shown. The publication of these results are under preparation.

References

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[2] A. Fassò, A. Ferrari, J. Ranft and P.R. Sala. *FLUKA: a multi-particle transport code*. Technical Report CERN-2005-10 (2005), INFN/TC-05/11, SLAC-R-773.

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