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Measurements and FLUKA Simulations of Bismuth, Aluminium and Indium Activation at the upgraded CERN Shielding Benchmark Facility (CSBF)

E. Iliopoulou[1,2], P. Bamidis[2], M. Brugger[1], R. Froeschl[1], A. Infantino[1], T. Kajimoto[3], N. Nakao[4], S. Roesler[1], T. Sanami[5], A. Siountas[2], H. Yashima[6]

[1] CERN, 1211 Geneva 23, Switzerland
[2] Medical Physics Laboratory, School of Medicine, Aristotle University of Thessaloniki, 54124 Thessaloniki, Greece
[3] Hiroshima University, 1-4-1 Kagamiyama, Higashi-Hiroshima 739-8527, Japan
[4] Shimizu Corporation, Etchujima 3-4-17, Koto-ku, Tokyo 135-8530, Japan
[5] High Energy Accelerator Research Organization-KEK, Oho, Tsukuba 305-0801, Japan
[6] Research Reactor Institute, Kyoto University, 2-1010 Asashiro-nishi, Kumatori, Sennan, Osaka 590-0494, Japan

E-mail: `elpida.iliopoulou@cern.ch`

Abstract. The CERN High energy AcceleRator Mixed field (CHARM) facility is situated in the CERN Proton Synchrotron (PS) East Experimental Area. The facility receives a pulsed proton beam from the CERN PS with a beam momentum of 24 GeV/c with $5{\cdot}10^{11}$ protons per pulse with a pulse length of 350 ms and with a maximum average beam intensity of $6.7{\cdot}10^{10}$ protons per second. The extracted proton beam impacts on a cylindrical copper target. The shielding of the CHARM facility includes the CERN Shielding Benchmark Facility (CSBF) situated laterally above the target that allows deep shielding penetration benchmark studies of various shielding materials. This facility has been significantly upgraded during the extended technical stop at the beginning of 2016. It consists now of 40 cm of cast iron shielding, a 200 cm long removable sample holder concrete block with 3 inserts for activation samples, a material test location that is used for the measurement of the attenuation length for different shielding materials as well as for sample activation at different thicknesses of the shielding materials. Activation samples of bismuth, aluminium and indium were placed in the CSBF in September 2016 to characterize the upgraded version of the CSBF. Monte Carlo simulations with the FLUKA code have been performed to estimate the specific production yields of bismuth isotopes (^{206}Bi, ^{205}Bi, ^{204}Bi, ^{203}Bi, ^{202}Bi, ^{201}Bi) from ^{209}Bi, ^{24}Na from ^{27}Al and ^{115m}I from ^{115}I for these samples. The production yields estimated by FLUKA Monte Carlo simulations are compared to the production yields obtained from γ-spectroscopy measurements of the samples taking the beam intensity profile into account. The agreement between FLUKA predictions and γ-spectroscopy measurements for the production yields is at a level of a factor of 2.

1. Introduction

The CERN High Energy AcceleRator Mixed field facility (denoted CHARM) has been constructed in the CERN Proton Synchrotron (PS) East Experimental Area in 2014 [1]. The facility receives a pulsed proton beam from the CERN PS with a beam momentum of 24 GeV/c with $5{\cdot}10^{11}$ protons per pulse with a pulse length of 350 ms and with a maximum average beam intensity of $6.7{\cdot}10^{10}$ p/s.

The extracted proton beam from the PS impacts on a cylindrical Copper or Aluminium target and the created secondary radiation field is used to test electronics equipment installed at predefined test positions.

The shielding of the CHARM facility [2] also includes the CERN Shielding Benchmark Facility (CSBF) situated laterally above the target [3]. This facility allows deep-penetration benchmark studies of various shielding materials [4, 5, 6, 7]. The CHARM facility at beam line level is illustrated in figure 1 indicating the direction of the beam coming from the Proton Synchrotron (PS), the CHARM target, the target alcove for storing the target during access and movable shielding walls.

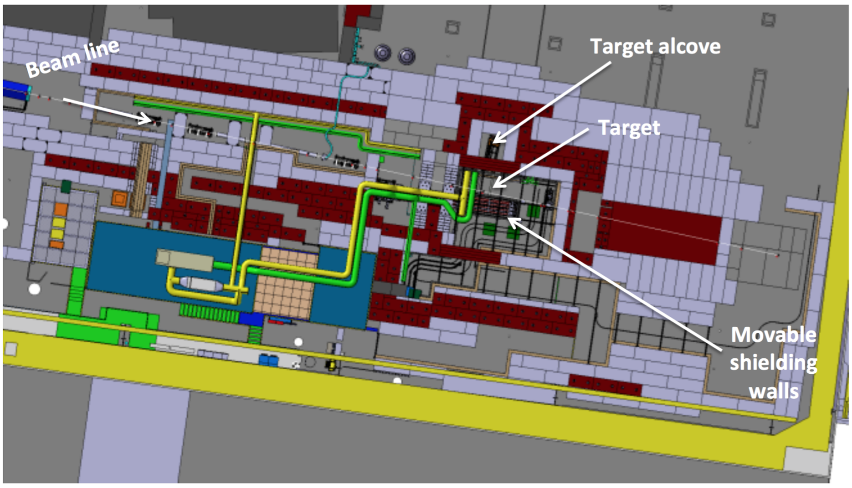

Figure 1. Horizontal integration drawing of the CHARM facility at beam line level. The CSBF is located laterally above the CHARM target.

An activation experiment campaign was performed in 2015 at the CSBF for the characterization of the facility [8, 9, 10] and, based on our experience, we decided to upgrade the CSBF in 2016 in order to simplify the exploitation of the facility and to integrate new functionalities. In order to understand and characterize the radiation fields in the upgraded CSBF, activation samples were placed in the CSBF in September 2016. Monte Carlo simulations with the FLUKA code [11, 12] have been performed to estimate the specific production yields of several bismuth isotopes,^{24}Na and ^{115m}I for these samples. This paper describes the comparison between the estimated values from FLUKA and the activation measurements performed in September 2016 with bismuth, aluminium and indium disk samples of different sizes in the upgraded CSBF.

2. Design of the CERN Shielding Benchmark Facility (CSBF)

The CERN Shielding Benchmark Facility (CSBF) has been significantly upgraded during the extended technical stop at the beginning of 2016. The CSBF upgrade allows for easier manipulation and for having more exploitation possibilities of the facility [10, 13]. The design of the upgraded CSBF was based on FLUKA simulations.

During the operational period of 2016, the CSBF consisted of 40 cm cast iron shielding, 360 cm of standard concrete, barite concrete and cast iron shielding that are part of the three main possible configurations of the CSBF. These three main possible configurations allow measurement at the removable sample holder concrete block (which is also the nominal configuration of the facility during the nominal CHARM facility operation), on the CSBF platform and in the shielding material test location.

2.1. Removable sample holder concrete block

The removable sample holder concrete block was needed for the facilitation of the handling procedure of the activation samples or passive dosimeters in order to place them deep inside the CSBF shielding and irradiate them. For this reason, the removable sample holder concrete block provides of 3 slots of 10 cm x 10 cm cross section that are centered along the vertical axis of the block, so that they can be filled with the samples. In figure 2 the recent layout of CSBF is presented when the removable sample holder concrete block is inserted. The position 1 is located at a height of 10.5 cm, measured from the bottom of the removable sample holder concrete block, the position 2 at 85.4 cm height and the position 3 at 160.35 cm height. There is also a possibility of placing samples on the top of the block, mentioned as position 4 at 200 cm height. The block is easily inserted in and extracted from the CSBF shielding in a specifically designed shaft, with dimensions 40 cm x 40 cm x 240 cm. The neutron spectra predicted by the Monte Carlo code FLUKA at the 4 positions of the removable sample holder concrete block are shown in the figure 3.

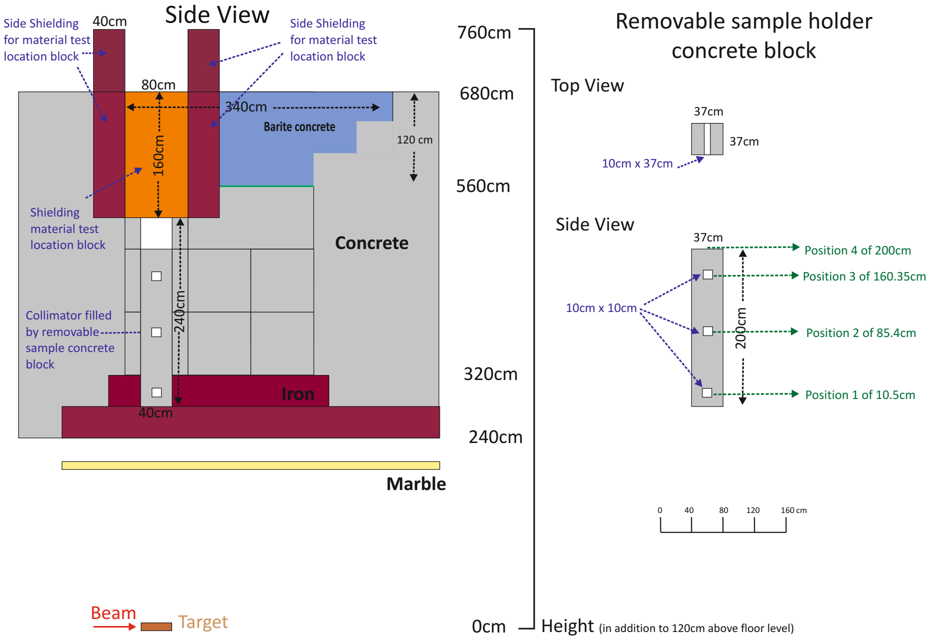

Figure 2. CSBF upgrade layout for measurements with the removable sample holder concrete block inserted in the facility.

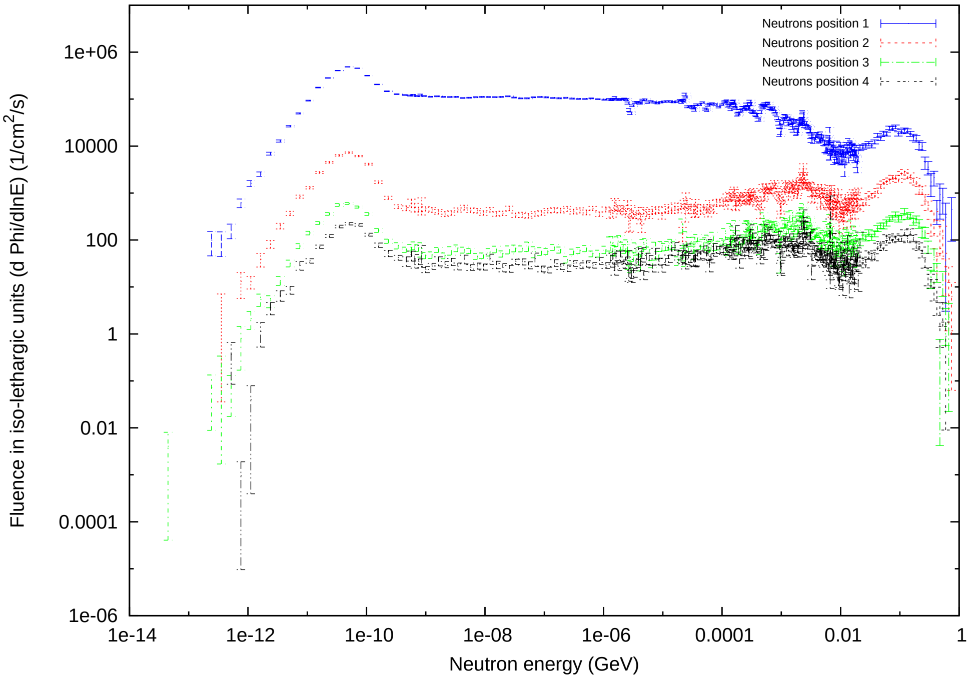

Figure 3. Neutron fluence spectra predicted by FLUKA at the 4 different positions on the removable sample holder concrete block for an average beam intensity of $6.7{\cdot}10^{10}$ protons per second.

2.2. CSBF platform

The CSBF platform was created at 560 cm above beam line level, indicated in figure 2, and allows placing active detectors or dosimeters attached to phantoms on the top of the shielding, for measuring their response to a deep penetration neutron spectrum. In order to use the platform, two barite concrete blocks of 120 cm height have to be removed. The CSBF platform measurements can be performed in parallel to activation measurements at the removable sample holder concrete block activation measurements.

2.3. Shielding material test location

The shielding material test location was designed for measuring the spectrum averaged attenuation length (λ) of various shielding materials (e.g. standard concrete, barite concrete, hematite concrete, colemanite concrete, magnetite concrete and cast iron). The available blocks are of 20, 40 and 80 cm thickness and for each material the ambient dose equivalent rate can be measured up to a shielding thickness corresponding to approximately 4λ or 5λ (depending on the material). The spectrum averaged attenuation length can then be determined by a second ambient dose equivalent rate measurement with an additional shielding layer, ideally with a thickness of the order of 1λ. To perform these measurements the removable sample holder concrete block has to be removed from the shaft so that there is a collimated radiation field heading directly to the shielding material test location. FLUKA simulations have been performed and have shown that the contributions from neutrons scattered on the side walls of the shaft and the surrounding shielding structure are less than 3% of the ambient dose equivalent rate.

3. Beam parameters and configurations

This section presents the beam parameters and the facility configurations that were used during the activation experiments in September 2016. The beam intensity was measured with a Secondary Emission Chamber, whose measurement values are logged in the CERN measurement database. An intensity calibration factor was applied to the counts per pulse to obtain the number of protons per pulse. This calibration factor had been previously obtained with aluminium foil activation measurements using sodium isotopes with a statistical uncertainty of 7% of the γ-spectrometry analysis [14].

A beam size of 1.2 cm x 1.2 cm Full Width at Half Maximum (FWHM) was used for the FLUKA simulations as specified in the layout of the beam line and confirmed by online beam profile measurements [14].

The average beam intensity of CHARM, binned in 5 minutes long intervals, from July 6 to July 12 and from September 16 to September 22, 2016 when the experiments were conducted, is shown in the figure 4 and figure 5 respectively. The first irradiation period corresponds to the irradiation of the aluminum samples, the second to the irradiation of the bismuth samples and the third to the irradiation of the indium samples.

The beam passes through the upstream Proton Irradiation facility (IRRAD) before impacting on the CHARM target. During the period of the experiment, Silicon samples with a total thickness of 0.2 cm were placed into the beam in IRRAD and these samples were also taken properly into account in the FLUKA simulations.

The shielding layout of the CSBF as implemented in the FLUKA simulations is shown in figure 2. The chemical composition of the concrete, the barite concrete and the cast iron implemented in the FLUKA Monte Carlo simulations for the shielding with their respective densities are listed in table 1 and in table 2.

During the activation experiment, the copper target of 8 cm diameter and 50 cm length has been used inside the CHARM facility. Inside the target room, there are four movable shielding walls, each of 20 cm thickness and made out of concrete or iron. They can be placed between the target and the irradiation positions for electronics components inside the CHARM facility in different combinations, so that the irradiation spectra are adjusted to the desired radiation field (energy and intensity) during the tests. The movable shielding walls are also indicated in the figure 1. For this activation experiment, only one configuration of the four movable shielding walls was used during the different irradiation periods, namely all movable shielding walls retracted from the facility. The configuration has been properly taken into account in the FLUKA Monte Carlo simulations.

Table 1. Chemical composition [7] and density of concrete.

Concrete	Density 2.4 g/cm^3		
Element	Weight fraction (%)	Element	Weight fraction (%)
Hydrogen	0.561	Silicon	16.175
Carbon	4.377	Sulfur	0.414
Oxygen	48.204	Potassium	0.833
Sodium	0.446	Calcium	23.929
Magnesium	1.512	Titanium	0.173
Aluminium	2.113	Iron	1.263

Table 2. Chemical composition [15] and density of cast iron [7].

Cast Iron	Density 7.2 g/cm^3
Element	Weight fraction (%)
Iron	92.3
Carbon	3.85
Manganese	0.3
Silicon	3.4
Phosphorus	0.08
Sulfur	0.02
Cobalt	0.05

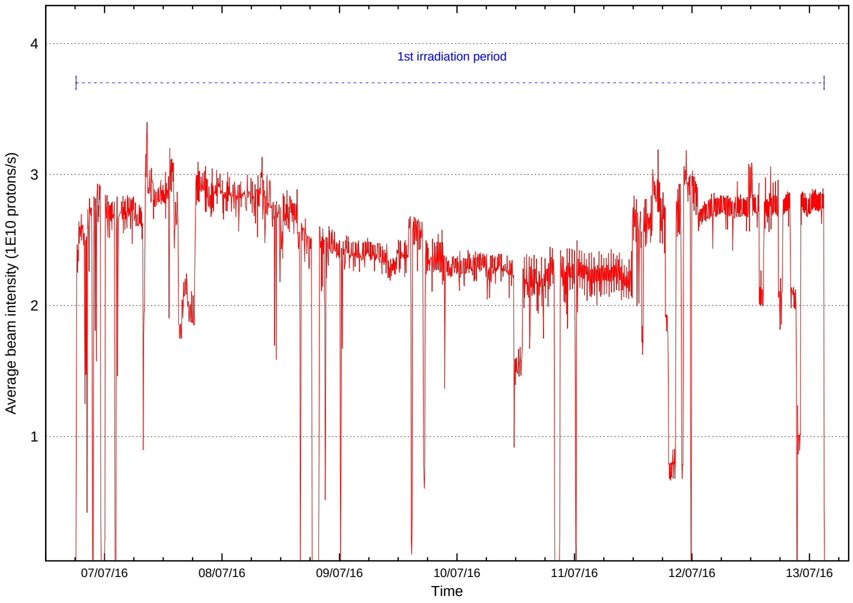

Figure 4. Average beam intensity of the CHARM facility during the activation experiments in July 2016 binned in 5 minutes long intervals.

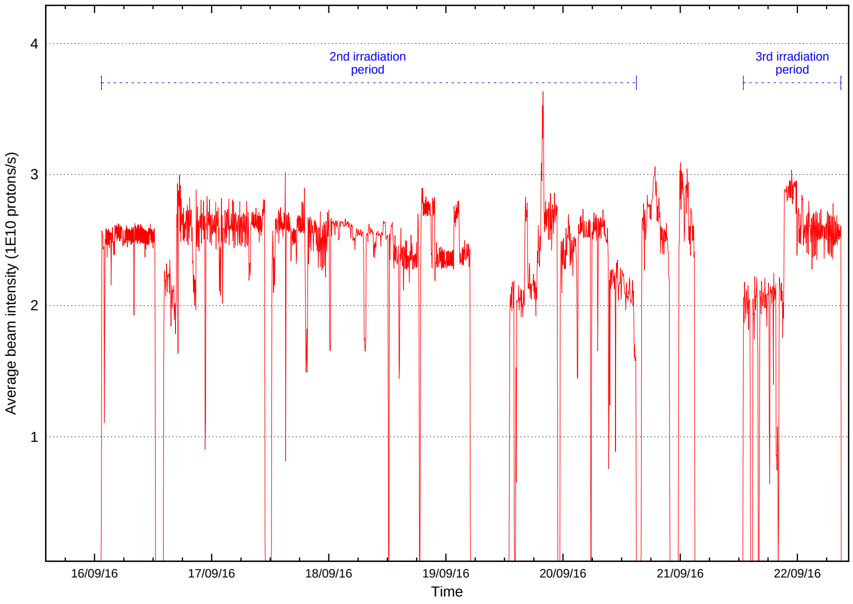

Figure 5. Average beam intensity of the CHARM facility during the activation experiments in September 2016 binned in 5 minutes long intervals.

4. Activation samples and their irradiation

Fourteen disk samples in total, five bismuth samples, five aluminium samples and four indium samples, have been irradiated. These samples were placed in the removable concrete sample holder block of the CSBF at the 4 positions as indicated in figure 2. All the details of the samples including their location, irradiation time, dimensions, weight, cooling time and duration of γ-spectrometry measurements are presented in table 3.

Table 3. Description of the irradiated samples and details of the γ-spectrometry measurements.

Sample Material	Irradiation Location	Duration of irradiation (h)	Start of irradiation (date and time)	Dimensions (mm)	Weight (g)	Cooling time (h)	γ-spectrometry measurement duration (h)
Al	Position 1	149.3	06/07/2016, 18:12 PM	40(diam.)×3	10.4	7	3
Al	Position 2	149.3	06/07/2016, 18:12 PM	40(diam.)×3	10.4	7	3
Al	Position 3	149.3	06/07/2016, 18:12 PM	40(diam.)×3	10.4	7	3
Al	Position 3	149.3	06/07/2016, 18:12 PM	60(diam.)×15	116.9	7	3
Al	Position 4	149.3	06/07/2016, 18:12 PM	60(diam.)×15	116.9	7	3
Bi	Position 1	109.6	16/09/2016, 01:25 AM	20(diam.)×2	6.23	2	3
Bi	Position 2	109.6	16/09/2016, 01:25 AM	40(diam.)×4	49.5	2 5 26 240	3 12 16 48
Bi	Position 3	109.6	16/09/2016, 01:25 AM	40(diam.)×4	49.52	2 4.5 25.5 187	3 12 16 48
Bi	Position 3	109.6	16/09/2016, 01:25 AM	80(diam.)×10	523.5	2	3
Bi	Position 4	109.6	16/09/2016, 01:25 AM	80(diam.)×10	540.34	2 5 26	3 12 16
In	Position 1	20	21/09/2016, 12:55 PM	20(diam.)×2	4.59	6	8
In	Position 2	20	21/09/2016, 12:55 PM	40(diam.)×4	36.38	6.5	8
In	Position 3	20	21/09/2016, 12:55 PM	80(diam.)×10	375.49	1	3
In	Position 4	20	21/09/2016, 12:55 PM	80(diam.)×10	384.77	1.5	3

5. Comparison of FLUKA simulation results to measured production yields

The simulation results were obtained by first scoring the neutron fluence spectra with FLUKA. Then, the neutron fluence was folded with cross section data for the bismuth isotopes, ^{24}Na and ^{115m}I [16], shown in figure 6, to obtain the predicted production yields per atom per primary proton on the target.

The activities of the bismuth isotopes,^{24}Na and ^{115m}I were measured for the bismuth, aluminum and indium samples respectively using γ-spectrometry, sometimes even at different cool-down times. In case of multiple samples for the same materials at the same position or multiple γ-spectrometry measurements of the same sample, the activities selected were the ones with the lowest uncertainty of the γ-spectrometry measurements. These activities have been converted to the production yields by taking into account the corresponding irradiation profiles with 5 minutes long binning and the corresponding cool-down times.

The production yields predicted by FLUKA and measured by γ-spectrometry are presented in figure 7 and in table 4. The agreement between FLUKA predictions and γ-spectrometry measurements for the production yields is generally better than a factor of 2.

The contributions that have been taken into account for the uncertainty estimation are shown in table 5. The uncertainty of the beam size has negligible impact on the results as verified by FLUKA simulations. The materials placed in IRRAD during the period of the experiment were taken into account in the simulations. The uncertainty of the production yields coming from the uncertainty of the materials placed in IRRAD is far below 1%. A hypothetical change in the concrete density would provoke a change on the slope of the dependence of the yields on the depth of the shielding plotted in figure 7 and the effect of the change would increase with increased shielding thickness.

The cumulative distribution to the production yields as function of the neutron energy is presented in figure 8 for the sample placed at a concrete shielding thickness of 160.35 cm in the CSBF. From this figure it can be seen that for sodium-24, the neutron energy range contributing to the production yield is quite large whereas for the bismuth isotopes the energy ranges are narrower and located around the respective cross section peaks. The 10%, 25%, 75% and 90% quantiles of the production yield distribution for the various radionuclides, are presented in table 6, quantifying this effect.

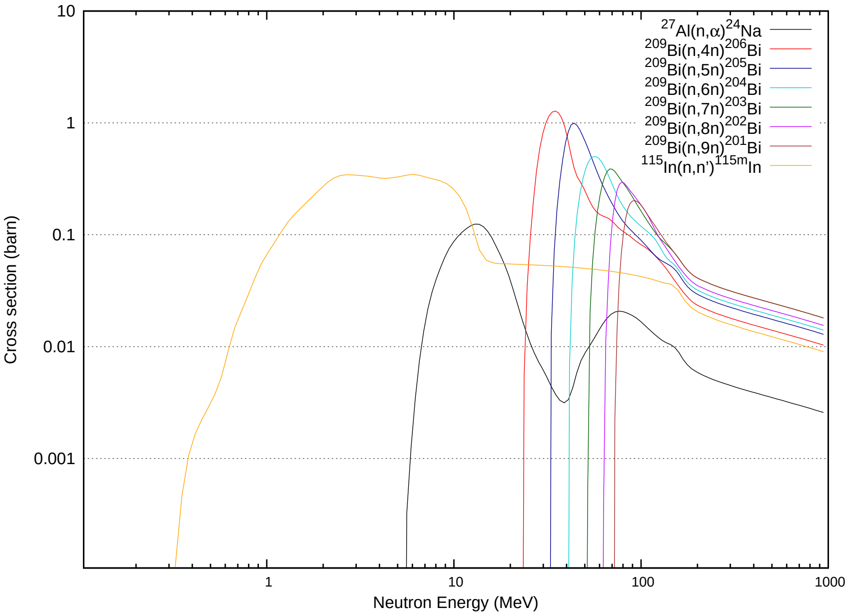

Figure 6. Production cross sections of the bismuth isotopes,^{24}Na and ^{115m}I as a function of the neutron energy [16].

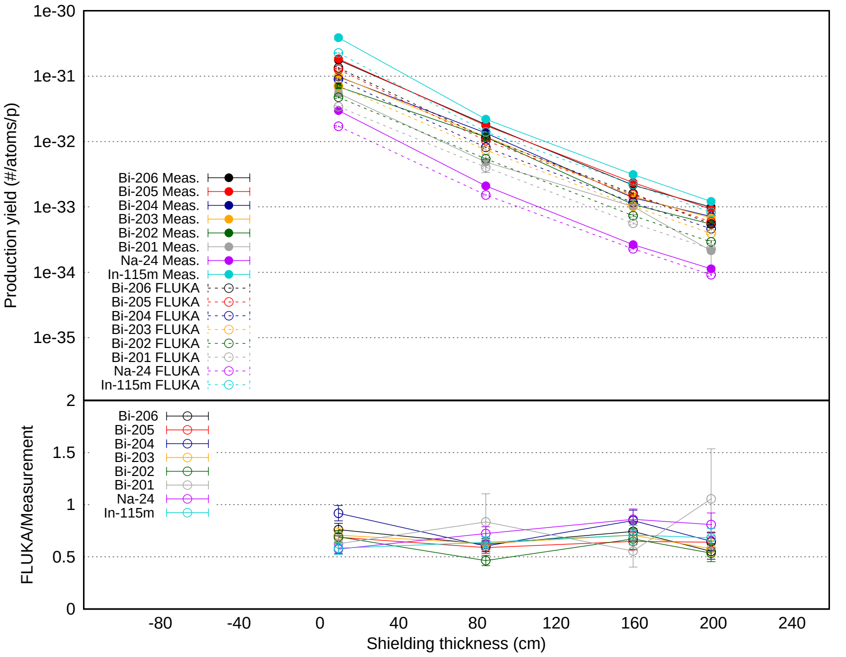

Figure 7. Comparison of the predicted production yields by FLUKA and the measured production yields by γ-spectrometry for bismuth, sodium and indium radionuclides as function of shielding thickness.

Table 4. Predicted production yields by FLUKA and measured production yields by γ-spectrometry.

Radionuclide	**Position / Height (cm)**	**Predicted Production yield by FLUKA (number/atom/p)**	**Uncertainties FLUKA (%)**	**Measured Production yield from γ-spect analysis (number/atom/p)**	**Uncertainties of γ-spect analysis (%)**	**Ratio Predicted/ Measured**	**Uncertainties Ratio (%)**
Bi-206	1 / 10.5	1.34E-031	±3.48	1.76E-031	±7.14	0.74	±7.94
	2 / 85.4	1.13E-032	±5.56	1.82E-032	±7.25	0.62	±9.14
	3 / 160.35	1.60E-033	±9.50	2.15E-033	±7.50	0.74	±12.11
	4 / 200	5.48E-034	±11.38	9.91E-034	±7.25	0.55	±13.49
Bi-205	1 / 10.5	1.26E-031	±3.47	1.83E-031	±7.58	0.69	±8.33
	2 / 85.4	1.03E-032	±5.28	1.75E-032	±7.92	0.59	±9.52
	3 / 160.35	1.53E-033	±9.19	2.36E-033	±8.72	0.65	±12.67
	4 / 200	5.89E-034	±11.29	9.2E-034	±7.96	0.64	±13.81
Bi-204	1 / 10.5	8.99E-032	±3.40	9.78E-032	±7.25	0.92	±8.01
	2 / 85.4	8.14E-033	±5.16	1.35E-032	±7.20	0.60	±8.86
	3 / 160.35	1.17E-033	±9.09	1.38E-033	±7.50	0.85	±11.79
	4 / 200	4.62E-034	±11.27	7.11E-034	±7.20	0.65	±13.38
Bi-203	1 / 10.5	7.08E-032	±3.59	1.00E-031	±8.78	0.71	±9.48
	2 / 85.4	7.42E-033	±5.21	1.18E-032	±8.54	0.63	±10.01
	3 / 160.35	1.02E-033	±9.15	1.44E-033	±9.76	0.71	±13.38
	4 / 200	3.93E-034	±10.89	6.79E-034	±8.38	0.58	±13.74
Bi-202	1 / 10.5	4.76E-032	±4.00	6.78E-032	±8.01	0.69	±8.96
	2 / 85.4	5.44E-033	±5.35	1.17E-032	±9.09	0.47	±10.55
	3 / 160.35	7.33E-034	±9.47	1.09E-033	±11.32	0.67	±14.76
	4 / 200	2.92E-034	±11.10	5.45E-034	±10.41	0.54	±15.21
Bi-201	1 / 10.5	3.41E-032	±4.19	5.45E-032	±13.72	0.63	±14.35
	2 / 85.4	4.05E-033	±5.42	4.85E-033	±31.88	0.83	±32.34
	3 / 160.35	5.61E-034	±9.72	1.01E-033	±25.77	0.56	±27.54
	4 / 200	2.26E-034	±11.16	2.19E-034	±44.16	1.06	±45.55
Na-24	1 / 10.5	1.71E-032	±2.62	2.98E-032	±7.14	0.57	±7.61
	2 / 85.4	1.52E-033	±5.15	2.10E-033	±7.47	0.72	±9.07
	3 / 160.35	2.28E-034	±9.01	2.65E-034	±7.31	0.86	±11.60
	4 / 200	9.16E-035	±11.01	1.13E-034	±7.96	0.81	±13.59
In-115m	1 / 10.5	2.26E-031	±1.48	3.87E-031	±10.04	0.58	±10.15
	2 / 85.4	1.40E-032	±4.68	2.19E-032	±7.12	0.64	±8.52
	3 / 160.35	2.22E-033	±8.81	3.13E-033	±9.90	0.71	±13.25
	4 / 200	8.26E-034	±10.39	1.21E-033	±8.32	0.68	±13.31

Table 5. Uncertainties taken into account for the uncertainty estimation of the production yields.

	Source of uncertainty	**Uncertainty on production yield**
Simulations	Statistical uncertainty	1.4-5.4 %
	Concrete density*	0.5-10 % **
Measurements	γ-spectrometry	1.3-14 % ***
	sample weights	1 %
	beam intensity	7 %
	beam momentum	< 1 %
	beam position and profile	< 1 %
	target density	< 1 %
	target dimensions	< 1 %

* Uncertainty of the concrete density is 0.05 g/cm^3.

** The concrete density uncertainty leads to an uncertainty of the production yield of 0.5% for 10.5 cm of concrete and of up to 10% for 200 cm of concrete.

*** Except for ^{201}Bi at 85.4 cm, 160.35 cm, 200 cm, see table 4.

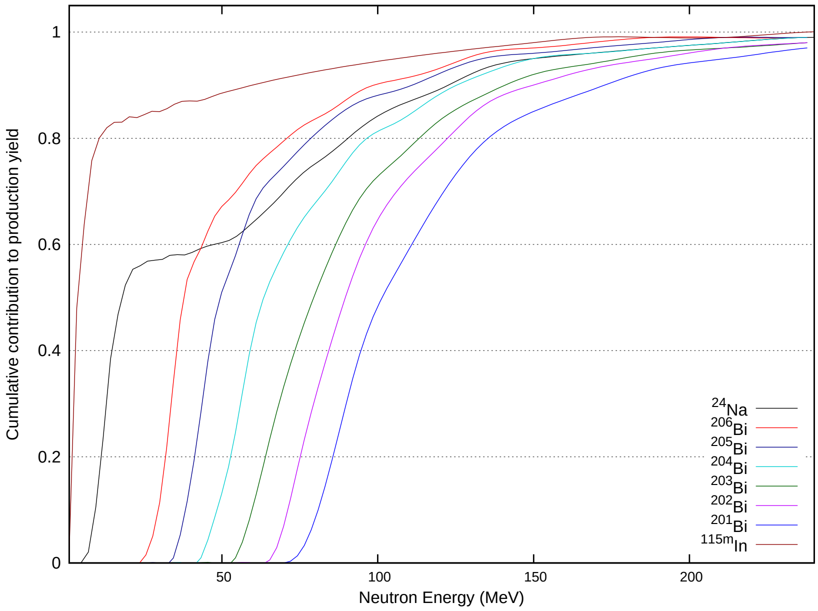

Figure 8. Cumulative contribution to the production yields at a concrete shielding thickness of 160.35 cm as a function of the neutron energy.

Table 6. The 10%, 25%, 75% and 90% quantiles of the production yield distribution for the various radionuclides at a concrete shielding thickness of 160.35 cm.

	Neutron Energy [MeV]			
Radionuclide	$\mathbf{q_{0.1}}$	$\mathbf{q_{0.25}}$	$\mathbf{q_{0.75}}$	$\mathbf{q_{0.9}}$
Bi-201	79.9	87.8	128	173
Bi-202	70.6	77.4	114	149
Bi-203	59.7	66.1	104	141
Bi-204	48.3	54.4	89.4	126
Bi-205	38.2	42.5	70.2	110
Bi-206	29.5	32.7	61.5	100
Na-24	9.39	12.2	79.7	122
In-115m	1.63	2.33	7.99	59.7

6. Summary & Conclusions

The CERN High Energy Accelerator Mixed Field facility (CHARM) has been constructed in the CERN PS East Experimental Area. The facility receives a pulsed proton beam from the CERN PS with a beam momentum of 24 GeV/c with $5{\cdot}10^{11}$ protons per pulse with a pulse length of 350 ms. The maximum average beam intensity is $6.7{\cdot}10^{10}$ p/s.

The shielding of the CHARM facility also includes the CERN Shielding Benchmark Facility (CSBF) situated laterally above the target. This facility allows deep-penetration benchmark studies of various shielding materials.

From our experience gained through a previous activation campaign in July 2015, we decided to upgrade the CSBF in 2016 in order to facilitate the procedure of sample placement and to add more functionalities in the facility. Based on the results mentioned above [8, 9], FLUKA was used for the design of the upgrade in CSBF (as a reliable Monte Carlo simulation tool).

An activation foil experiment has been conducted at the upgraded CSBF from September 21 to September 28, 2016. Bismuth, Aluminium and Indium cylindrical samples were placed in the removable concrete sample holder block of the CSBF at different heights. The production rates computed from the activities of the irradiated samples measured by γ-spectrometry have been compared to the estimated production rates from FLUKA Monte Carlo simulations. The agreement is at a level of a factor of 2.

This agreement is good for deep shielding penetration studies and is consistent with previous similar studies at the CERN-EU High Energy Reference Field facility (CERF) [7].

Acknowledgments

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References

[1] Mekki J, Brugger M, Alia R G, Thornton A, Dos Santos Mota N C and Danzeca S 2016 CHARM: A Mixed Field Facility at CERN for Radiation Tests in Ground, Atmospheric, Space and Accelerator Representative Environments, *IEEE TRANSACTIONS ON NUCLEAR SCIENCE*, **VOL. 63, NO. 4** p 2106-2114

[2] Froeschl R 2014 Radiation Protection Assessment of the Proton Irradiation facility and the CHARM facility in the East Area, Tech. Rep. CERN-RP-2014-008-REPORTS-TN, EDMS 1355933

[3] Froeschl R, Brugger M, Roesler S 2014 The CERN High Energy Accelerator Mixed Field (CHARM) facility in the CERN PS East Experimental Area *Proceedings of SATIF12, NEA/NSC/R(2015)3, Batavia, Illinois, United States* p 14-25

[4] Adorisio C and Roesler S 2011 Attenuation of high-energy neutrons in different shielding materials. A FLUKA benchmark for an intercomparison study, Tech. Rep. CERN-DGS-2011-035-RP-TN, EDMS 1139144

[5] Agosteo S, Birattari C, Para A F et al. 2001 Neutron measurements around a beam dump bombarded by high energy protons and lead ions *Nuclear Instruments and Methods in Physics Research A* **459** p 58-65

[6] Agosteo S, Pozzi F, Silari M et al. 2013 Attenuation in iron of neutrons produced by 120 GeV/c positive hadrons on a thick copper target *Nuclear Instruments and Methods in Physics Research B* **312** p 36-41

[7] Nakao N, Taniguchi S, Roesler S et al. 2008 Measurement and calculation of high-energy neutron spectra behind shielding at the CERF 120 GeV/c hadron beam facility *Nuclear Instruments and Methods in Physics Research B* **266** p 93-106

[8] Iliopoulou E et al. 2015 Measurements and FLUKA Simulations of Bismuth and Aluminium Activation at the CSBF, Tech. Rep. CERN-RP-2015-118-REPORTS-TN, EDMS 1566978

[9] Iliopoulou E et al. 2016 Measurements and FLUKA Simulations of Bismuth and Aluminum Activation at the CERN Shielding Benchmark Facility (CSBF) *Proceedings of SATIF 13, Dresden, Germany*

[10] Iliopoulou E et al. 2017 Measurements and FLUKA Simulations of Bismuth and Aluminum Activation at the CERN Shielding Benchmark Facility (CSBF) *submitted to Nuclear Instruments and Methods in Physics Research A*

[11] Böhlen T T et al. 2014 The FLUKA Code: Developments and Challenges for High Energy and Medical Applications, *Nuclear Data Sheets* **120** p 211-214

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

[13] Froeschl R et al. 2016 Radiation Protection Aspects of the Commissioning and Operation of the CHARM facility *Proceedings of SATIF 13, Dresden, Germany*

[14] Curioni A, Froeschl R, Glaser M, Iliopoulou E, La Torre F P, Pozzi F, Ravotti F and Silari M 2017 Single- and multi-foils ^{27}Al (p,3pn) ^{24}Na activation technique for monitoring the intensity of high-energy beams *Nuclear Instruments and Methods in Physics Research A* **858** p 101-105

[15] Lazzaroni M 2015 Personal Communication

[16] Maekawa F et al, 2001 Production of a Dosimetry Cross Section Set Up to 50 MeV *Proc. 10th International Symposium on Reactor Dosimetry, Sep. 12-17, 1999, Osaka, Japan, American Society for Testing and Materials* p 417