Research Article GU J Sci 36(4): 1786-1793 (2023) DOI: 10.35378/gujs.1018518

Gazi University

Journal of Science

http://dergipark.gov.tr/gujs

Radioactivation Measurement of a Protective Collimator and Comparisons with Simulation After METU-Defocusing Beamline Pretest Irradiation

Selcen UZUN DURAN[1,2*] M. Bilge DEMIRKOZ[2] Pelin USLU KICECI[2]

[1]*Program of Medical Imaging Techniques, Vocational School of Health Sciences, Karadeniz Technical University, Trabzon, Turkey*
[2]*The Research and Application Center for Space and Accelerator Technologies, Middle East Technical University, Ankara-Turkey*

Highlights

- Radioactivation analysis FLUKA and experiment comparison
- METU-DBL radioactivation analyses
- Space radiation environment

Article Info

Received: 3 Nov 2021
Accepted: 14 Oct 2022

Keywords

METU-DBL
FLUKA
Radioactivation

Abstract

Electronic components must be tested to allow for safe and reliable missions in radiation environments. The METU Defocusing Beamline (METU-DBL) was installed in the R&D room at the Particle Accelerator Facility (PAF) of Turkish Energy, Nuclear and Mineral Research Agency (TENMAK). This facility was established in accordance with the European Space Agency (ESA), European Space Components Coordination (ESCC), No: 25100 standard to conduct proton irradiation tests for electronic components and various materials to be used in the space environment. METU-DBL uses beam elements such as quadrupole magnets to amplify the beam and collimators to reduce the flux, as per the specifications of the standard.
A pretest setup was constructed, and this system was operated for a total of 17 hours for three months before the METU-DBL final design was assembled. The first protective collimator is made of stainless steel 316L and was used during the period of pretests. As a result of these irradiations, the emerged radioisotopes in the collimator were observed and measured in situ with a NaI detector. These measurements were compared with the FLUKA simulations 120 days after the last irradiation. Among fourteen radioisotopes, only six of them with activity above 1.0×10^{1} Bq/cm^3 were matched.

1. INTRODUCTION

The space environment has harsh and aggressive conditions due to the dominant cosmic rays which cause high radiation. Critical electronic components in satellites need to operate under this radiation environment. Therefore, newly developed electronic components should pass radiation tests and get qualified for missions before being deployed to space vehicles. The Proton Accelerator Facility (PAF) at TENMAK hosts a proton cyclotron which provides a proton beam with variable energy ranging from 15 to 30 MeV [1]. This facility has four rooms; three of them are used for production of radiopharmaceuticals and the fourth one is reserved for R&D experiments. Additionally, there is a five-port switching magnet in the R&D room that allows various experiments in the same room to users.

METU-DBL was built into the R&D room where one arm of the accelerator is located to operate Single Event Effect (SEE) tests in accordance with the ESA-ESCC No.25100 standard [2]. The parameters such as flux and current of the proton beam coming from the accelerator are not convenient for SEE tests. Therefore, the quadrupole magnets were used to enlarge the proton beam in both x and y axes. Thin defocusing films and collimators were employed to reduce the beam flux. Pretest setup consisted of a beam stopper and vacuum shutter. The former protects the METU-DBL from secondary radiation and the latter

*Corresponding author, e-mail: selcenduran@ktu.edu.tr

protects the vacuum of the accelerator in case of a problem. A protective collimator which decreases the flux and protects the magnets from secondaries was installed before two quadrupoles that allow the beam to be wider in the test area [3-4]. A pretest setup was designed to initiate some radiation tests using the existing beam elements of the METU-DBL due to the delivering problems of the five-port switch magnet. The photograph of pretest setup of METU-DBL are given in Figure 1.

Figure 1. *The photograph of pretest setup of METU-DBL*

In the simulation and experimental studies, it was observed that secondary particles emerge into the R&D room and these secondary particles increase the amount of radiation dose in the room while the METU-DBL is operating. Most of the secondary particles were detected to have come out from the first collimator. Only the first protective collimator is included in the pre-test design of METU-DBL. In order to reduce the dose in the R&D room, shielding studies were started with the shielding of this collimator. Radioactivation studies of this collimator are important in determining the source of the dose, as it has been determined that the secondary dose mostly originates from the first protective collimator in the R&D room. Figure 2 shows the technical drawing of the first protective collimator.

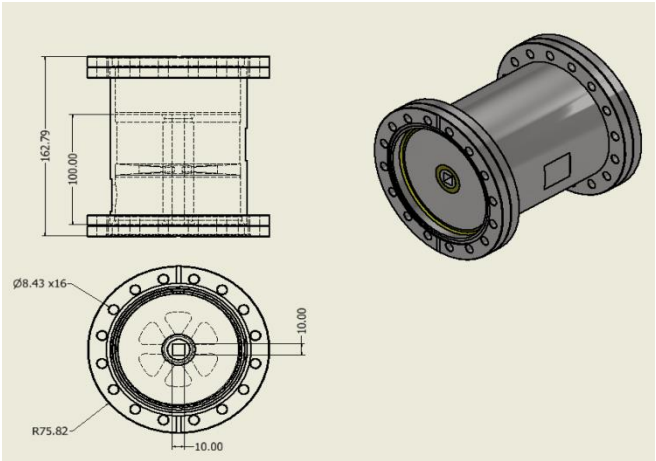

Figure 2. *Technical drawing of the first protective collimator*

The first collimator is made of stainless steel 316L. This alloy is frequently used in nuclear power plants and particle accelerators [5]. The outer part of the first protective collimator is shielded to reduce the radiation dose in the R&D room. The shield consists of layers of aluminum, lead and polyethylene (Al:0.5 cm-Pb:1.0 cm-PE: 5.0 cm-Al:0.5) from the inside to the outside, respectively. The type of aluminum is Al-6082 and the polyethylene is high density polyethylene. The mechanical design of collimator shield is shown in Figure 3. In Figure 4, pictures of the first protective collimator with and without shield are shown.

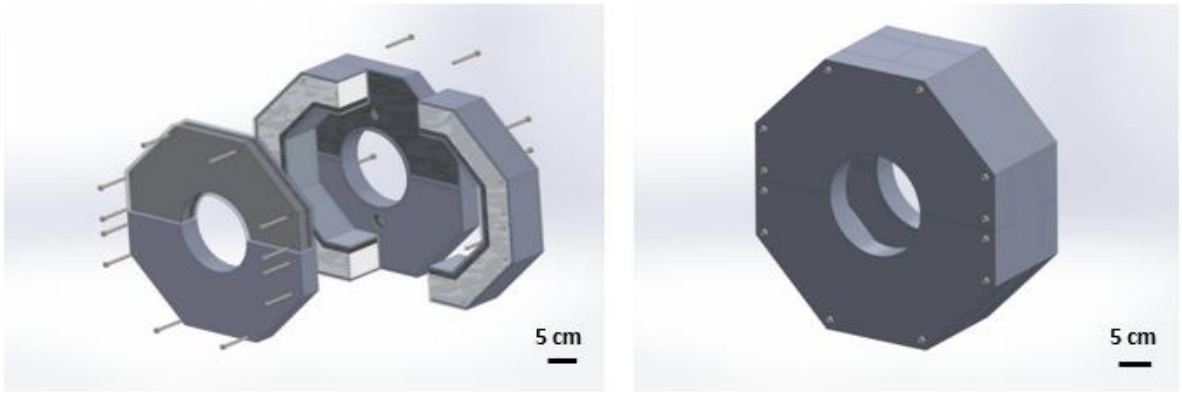

Figure 3. *The Mechanical Design of the Shield of the First Protective Collimator [6]*

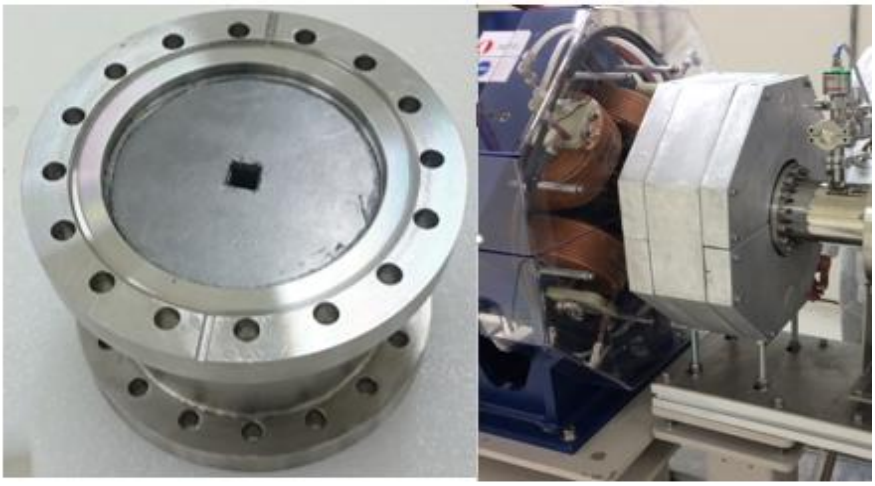

Figure 4. *On the left; unshielded collimator before integration. On the right, shielded collimator within the METU-DBL pretest installation [6]*

Radioactivation studies of the collimator was performed using FLUKA simulation program. This program is based on general purpose Monte Carlo software that records simulations of about sixty different particle/ray transports. [7-10]. It has dual capability: sided mode and full analog mode. The calculations of absorbed radiation dose, radiation cooling time and radioactivation can be done using FLUKA. This program can be used in many applications such as medical physics, radiobiology, nuclear physics due to its accurate results in 3D geometries [11].

The aim of this study is to determine the radioisotopes formed in the first protective collimator after irradiation. These experimental studies were conducted using Inspector 1000 portable gamma detector and the results were compared with FLUKA simulations. Performing radioactivation studies is important to determine the ambient dose and the source of the emitted secondary particles for the facility.

2. MATERIAL METHOD

2.1. Simulations

The FLUKA software was used to monitor the isotopes emitted by the first protective collimator during the METU-DBL pretest irradiation. Initially, METU-DBL beam elements were defined in FLUKA as follows. 30 MeV protons were defined as a radiation source using BEAM card. These protons were directed towards the beam line using BEAMPOS card. Beam elements of the METU-DBL such as collimators and quadrupole magnets were described with the BODIES card. The different materials that do not exist in the FLUKA database were specified using MATERIAL and COMPOUND cards. Then, materials were

designated to these bodies using the ASSIGNMA card. In the FLUKA simulation, the isotopes emitted in a single irradiation conducted for 1 hour at 0.1 μA current with 30 MeV protons were observed. The measurements were taken 120 days after the final irradiation using the RESNUCLEI with DCYSCORE cards. The RADDECAY card was added to the input for the request of radioactive decays.

Table 1. *Chemical composition of stainless steel 316L, aluminum-6082 and lead (wt %)*

Element	Stainless Steel 316	Al-6082	Lead
Carbon	Max 0.08	-	-
Manganese	Max 2.0	Max 1.00	-
Silicon	Max 0.75	Max 1.30	-
Chromium	16.0-18.0	Max 0.25	-
Nickel	10.00-14.0	-	Max 0.0020
Molybdenum	2.00-3.0	-	-
Phosphorus	Max 0.045	-	-
Sulfur	Max 0.03	-	-
Nitrogen	Max 0.1	-	-
Iron	Balance	Max 0.50	Max 0.0020
Magnesium	-	Max 1.00	-
Copper	-	Max 0.10	Max 0.005
Zinc	-	Max 0.20	Max 0.005
Titanium	-	Max 0.01	-
Aluminum	-	Balance	-
Tin	-	-	Max 0.005
Silver	-	-	Max 0.0080
Lead	-	-	Balance

The material of first protective collimator is stainless steel 316L. This collimator was shielded to reduce the dose emitting from the collimator since the proton beam hitting the collimator causes secondary particle production. Aluminum 6082 (Al-6082), lead and polyethylene were used in the shield of the collimator. Chemical composition of stainless steel 316L, aluminum-6082 and lead are presented in Table 1. The first protective collimator and its shield were defined in the FLUKA software with these compositions. Figure 4 indicates the shield and unshielded versions of the first collimator.

2.2. Experimental Method

The Inspector 1000 portable gamma detector manufactured by the Canberra corporation was used in this study. This device can measure the total gamma dose in situ and the total dose is presented both numerically and graphically on the device screen. During the data collection process, the graphical and digital presentations are updated in real time and the device issues warnings when the radiation level in the environment exceeds a certain value. With this device containing a multi-channel analyzer, on-site measurements could be conducted to obtain spectra and determine radionuclide concentrations.

It is necessary to know the corresponding energy for each channel to conduct spectrum analyses. This requires a standard source of radionuclides with known energy. The properties of the calibration sources that are used to calibrate the detector are presented in Table 2.

Table 2. *Calibration Source*

Isotopes	Gamma Energies (keV)	Gamma/s	Half-Life
^{137}Cs	662	2441	30.17 year

The analysis of the spectra was conducted with the Genie-2000 software [12]. The boundaries of the peaks in these spectra were determined by maximizing the area under the peaks and minimizing the errors. The channel corresponding to the center of these peaks was determined and the corresponding energy was

determined with calibration. Radionuclides corresponding to these energies were identified using the database.
The activity was obtained in microcurie (μCi) units with the Equation (1) [13].

$$\text{Activity}(\mu\text{Ci}) = (\text{Net Area})/((\text{Counting time})\text{x}(\text{Efficiency})\text{x}(\text{Branching Rate})\text{x}(37000)) \quad (1)$$

"Net Area" is the net counting rate of the gamma ray. "Efficiency" is the detector efficiency of the specific gamma ray. "Branching Rate" is the absolute transition probability of gamma decay. "Counting time" is the duration of the measurement. The spectrum count time was set to 83377 s. The detector counted during the selected time and a spectrum was obtained. This spectrum was stored for future analysis.

3. RESULTS & DISCUSSION

In this study, the radioactivation analysis of the first protective collimator used in the pretest setup of METU-DBL was performed. This analysis was performed via simulations and experiments. The detector's Nuclear Library within the user's manual and gamma energy lists were used to determine which radionuclides correspond to the determined energies [14-16]. ^{57}Co, ^{54}Mn, ^{56}Co, ^{109}Cd, ^{65}Zn and ^{55}Fe can be observed in this experiment.

Table 3. *The isotopes emitted from the first protective collimator based on Inspector 1000 portable detector and FLUKA measurements*

Radioisotopes	Half life	FLUKA	Inspector 1000	Decay Mode	Gamma Energies(keV)
		Activity (Bq/cm^3)	Activity (Bq/cm^3)		
^{56}Co	77.2 day	2.2×10^5	$1.9\times10^5\pm365$	β^+	846.7 & 1238.2
^{55}Fe	2.7 year	1.1×10^5	$1.36\times10^5\pm129$	EC	126.0
^{51}Cr	27.7 day	6.0×10^4	-	EC	320.0
^{57}Co	271.7 day	4.1×10^4	$3.9\times10^4\pm260$	EC	122.0
^{58}Co	70.9 day	1.4×10^4	-	β^+	810.7
^{54}Mn	312.2 day	1.0×10^4	$1.2\times10^4\pm150$	EC	834.8
$^{113(1)}$In	1.6 hour	6.8×10^3	-	IT	391.6
^{113}Sn	115.0 day	6.8 x10^3	-	β^+	391.6
^{109}Cd	1.2 year	8.3×10^2	$6.3\times10^2\pm250$	EC	88.03
^{48}V	16.0 day	6.3×10^2	-	β^+	983.5 &1312.1
^{65}Zn	243.9 day	6.1×10^2	$4.8\times10^2\pm108$	β^+	1115.5
^{60}Co	5.2 year	3.3×10^2	-	β^-	1173.2 & 1332.4
$^{119(1)}$Sn	293.1 day	5.4×10	-	IT	23.8
^{3}H	12.3 year	1.8×10	-	β^-	<25

In Table 3, the isotopes emitted by the first collimator and activities based on the Inspector 1000 portable detector data and FLUKA are presented (where EC is an electron capture, IT is an isomeric transition. Sn--113 decays by electron capture mainly to the In-113m isomer. Sb-119 decays by electron capture mainly to the Sn-119m isomer). The analysis of the radioisotopes formed in the collimator was measured in situ with a NaI detector and compared with FLUKA simulations 120 days after the last irradiation. Among fourteen radioisotopes only six of them with activity above 1.0×10^1 Bq/cm^3 were matched. Obtained radioisotopes with the experimental data and their possible production processes are presented in Table 4.

Table 4. *Possible production processes of radioisotopes determined with the Inspector-1000 portable detector and FLUKA simulations [17]*

Identified isotopes	Possible production processes
^{56}Co	^{56}Fe(p,n)^{56}Co; ^{58}Ni(n,p2n)^{56}Co
^{55}Fe	^{54}Fe(n,γ)^{55}Fe; ^{55}Mn(p,n)^{55}Fe
^{54}Mn	^{54}Fe(n,p)^{54}Mn; ^{54}Cr(p,n)^{54}Mn
^{57}Co	^{60}Ni(p,α)^{57}Co; ^{58}Ni(p,2p)^{57}Co; ^{58}Ni(n, pn)^{57}Co
^{109}Cd	^{108}Cd(n,γ)^{109}Cd; ^{109}Ag(p,n)^{109}Cd
^{65}Zn	^{64}Zn(n,γ)^{65}Zn; ^{65}Cu(p,n)^{65}Zn

^{56}Co radionuclide is produced following proton bombardment of the stainless steel via ^{56}Fe(p, n)^{56}Co nuclear reaction. Stainless steel 316L mainly consists of chrome, nickel and iron. As seen in Table 4, ^{57}Co, ^{54}Mn, ^{56}Co elements emerge as a result of the activation of chrome, nickel and iron. The results obtained with the radionuclide analysis of irradiated stainless steel 316L with a proton beam were consistent with the predicted values for iron, chrome and nickel activities. ^{109}Cd and ^{65}Zn are most likely due to the activation of the lead in the shield of the first protective collimator. As seen in Table 4, ^{109}Cd can be formed by ^{108}Cd and ^{109}Ag activation, while ^{65}Zn can be formed by ^{65}Cu and ^{64}Zn activation.

The other six radionuclides (^{60}Co, ^{113}Sn,$^{113(1)}$In, ^{48}V,$^{119(1)}$Sn, ^{3}H) could not be observed with the Inspector 1000 detector.^{113}Sn with $^{113(1)}$In (half-life: 1.6582 h) in equilibrium. ^{113}Sn is formed by the activation of tin [17], which indicates that the material does not contain tin. ^{48}V is formed by the activation of titanium (^{48}Ti (p, n)^{48}V) [18-19]. Titanium, defined as an impurity (Max. 0.01) in Al-6082 in the FLUKA, is therefore not present in the material. The Inspector 1000 detector can measure gammas in the range of 25 keV to 3 MeV [20]. The gamma energies emitted by $^{119(1)}$Sn and ^{3}H are outside of the energy range of the detector. In FLUKA, isotopes were observed in a single irradiation performed for 1.0 hour at 0.1 μA current with the 30 MeV proton beam. However, a total of 17 hours of irradiation was performed for 3 months. Radioactivation studies were carried out 120 days after the last irradiation. Consecutive irradiation at different currents and intervals during the pretests may have led to the difference between the two methods for ^{60}Co radioisotopes.

4. CONCLUSION

^{57}Co, ^{54}Mn, ^{56}Co, ^{109}Cd, ^{65}Zn and ^{55}Fe isotopes were observed in both FLUKA and the Inspector 1000 portable detector measurements on the first collimator and its shield. Furthermore, the possible nuclear reactions presented in Table 4 can be some of the reactions that produced the secondary neutrons observed during the METU-DBL study. These studies should be detailed to determine the source of secondary neutrons observed in METU-DBL.

ACKNOWLEDGMENT

This study was carried out within the scope of METU-SDH, financed by the Strategy and Budget Department (Grant no: 2015K121190). It is also supported by the Turkish Academy of Sciences. We thank the TENMAK Proton Accelerator Facility team. In addition, we want to thank the Physics Department of Karadeniz Technical University for the NaI detector.

CONFLICTS OF INTEREST

No conflict of interest was declared by the authors.

REFERENCES

[1] TAEA, “Proton Accelerator Facility Booklet”, TAEA SANAEM, (2012).

[2] ESA, "Single Event Effects Test Method and Guidelines, ESCC Basic Specification No. 25100", (2014).

[3] Demirkoz, M.B., Seckin, C., Avaroglu, A., Bulbul, B., Uslu, P., Kılıç, E., Orhan, Y., Akçelik, S., Saral, Ç., Uzun Duran, S., Kılıç,U., Efthymiopoulos, I.,Poyrazoglu, A.B., Albarodi, A., Celik, N., "Metu-Defocusing Beamline: A 15-30 MeV Proton Irradiation Facility and Beam Measurement System", EPJ Web of Conferences. EDP Sciences, 225: 01008, (2020).

[4] Demirkoz, M.B., Efthymiopoulos, I., Poyrazoglu, A.B., Seckin, C., Uslu, P., Celik, N., Bulbul, B., Albarodi, A., Akçelik, S., Orhan, Y., Avaroglu, A., Kılıç, E., Saral, Ç., Uzun Duran, S., Yiğitoğlu, M., "Installation of the METU Defocusing Beamline to Perform Space Radiation Tests", In 2019 9th International Conference on Recent Advances in Space Technologies, 355-361, (2019).

[5] Grégoire, O., Ladrière, J., "Activation of stainless steel with high energy neutrons", Journal of Nuclear Materials; 298(3): 309-315, (2001).

[6] Uzun Duran, S., Uslu Kiçeci, P., "Demirköz, B. Shield Design of the First Protective Collimator in the METU-Defocusing Beamline (DBL) Project", Nuclear Technology, 208(2): 364-370, (2022).

[7] Battistoni, G., Boehlen, T., Cerutti, F., Chin, P.W., Esposito, L.S, Fassò, A., FerrariA., Lechner A., Empl A., Mairani A., Mereghetti A., Ortega P.G., Ranft J., Roesler S., Sala P.R., VlachoudisV., Smirnov G., "Overview of the FLUKA code", Annals of Nuclear Energy, 82: 10-18, (2015).

[8] Ballarini, F., Battistoni, G., Brugger, M., Campanella, M., Carboni, M., Cerutti, F., Empl, A., Fasso, A., Ferrari, A., Gadioli, E., Garzelli, M.V., Lantz, M., Mairani, A., Mostacci, A., Muraro, S., Ottolenghi, A., Patera V., Pelliccioni, M., Pinsky, L.,Ranft, J., Roesler, S., Sala, P.R., Scannicchio, D., Smirnov, G., Sommerer, F., Trovati, S., Villari, R., Vlachoudis, V., Wilson, T., Zapp N., "The physics of the FLUKA code: recent developments", Advances in Space Research, (2007).

[9] Böhlen, T.T., Cerutti, F., Chin, M.P.W., Fassò, A., Ferrari, A., Ortega, P.G., Mairani, A., Sala, P.R., Smirnov, G., Vlachoudis, V., "The FLUKA Code: developments and challenges for high energy and medical applications", Nuclear Data Sheets, (2014).

[10] Collamati, F., An intraoperative Beta-Probe for Cancer Surgery, Switzerland: Springer International Publishing, (2016).

[11] Ferrari, A., Sala, P.R., Fasso, A., Ranft, J., FLUKA: A Multi-Particle Transport Code, CERN-2005-010, Geneva, (2011).

[12] Canberra Industries, Genie-2000 Spectroscopy System-operations manual, Meriden, USA, (1999).

[13] Dizman, S., "Measurement of natural radioactivity level in Rize-centre and towns of Rize", PhD, Karadeniz Technical University, Trabzon, TURKEY, (2006).

[14] https://www.cpp.edu/~pbsiegel/bio431/genergies.html Access date: 1.06.2020

[15] http://www.gammaexplorer.com/wp-content/uploads/2014/03/gammaenergies.pdf Access date: 10.06.2020

[16] http://www.nucleide.org/DDEP_WG/Nuclides/Sn-113_tables.pdf Access date: 10.06.2020

[17] http://www.nucleide.org/DDEP_WG/DDEPdata.htm Access date: 2.06.2020

[18] Sökmen, G., "Cross-Section Measurements of Sc-43 and V-48 Radioisotopes Produced via Bern Medical Cyclotron", PhD, Middle East Technical University, Ankara, TURKEY, (2017).

[19] Hichwa, R.D., Kadrmas, D., Watkins, G.L., Wollenwebe, S, Maniam, S., "Vanadium-48: A renewable source for transmission scanning with PET", Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms; 99(1-4): 804-806, (1995).

[20] http://www.old.slcj.uw.edu.pl/~agniecha/por/InSpector100UserManual.pdf. InSpector™ 1000 Digital Hand-Held MCA, User's Manual.