The induced radioactivity in the forward shielding and semiconductor tracker of the ATLAS detector

I. Bědajánek[1, 2], V. Linhart[1], I. Štekl[1], S.Pospíšil[1], A. Kolros[2], V. Kovalenko[3],
[1]Institute of Experimental and Applied Physics, Horská 3a/22, CZ-128 00, Prague 2
[2]Faculty of Nuclear Sciences and Physical Engineering, Břehová 7, CZ-115 19, Prague 1
[3]Joint Institute for Nuclear Research, Joliot-Curie 6, Dubna, 141980, Russia

ABSTRACT

The induced radioactivity in the forward shielding, copper collimator, and semiconductor tracker modules of the ATLAS detector has been studied. The ATLAS detector is a long-term experiment which during operation will require to have service and access to all of its parts and components. The induced radioactivity of the forward shielding was calculated by Monte Carlo methods based on GEANT3 software tool. The results show that the equivalent dose rates on the outer surface of the forward shielding are very low (at most 0.038 μSv/h). On the other hand, the equivalent dose rates are significantly higher on the inner surface of the forward shielding (up to 661 μSv/h) and especially at the copper collimator (up to 60 mSv/h) close to the beampipe. The induced radioactivity of the semiconductor tracker modules was studied experimentally. The module was activated by neutrons in a training nuclear reactor and the delayed γ-ray spectra were measured. The equivalent dose rate on the surface of the semiconductor tracker module was determined at less than 100 μSv/h.

INTRODUCTION

The ATLAS detector [1], which is now under construction at CERN on the LHC accelerator [2], will operate in a rather hard radiation environment. During running of the LHC, components of the ATLAS detector will become activated. In the period of operation of the ATLAS experiment (ten years and more) several parts of the detector will have to be dismounted for maintenance and repairs. Knowledge of the amount of induced radioactivity is important namely for two reasons: to insure personnel's safety against ionizing radiation during manipulation of components and parts and to calculate the level of background in the ATLAS detector subsystems (e.g., muon chambers, inner detector). The induced radioactivity for the forward shielding (JF) as well as for the copper collimator (TAS) has been calculated using Monte Carlo methods. The induced radioactivity of the semiconductor tracker (SCT) module has been determined experimentally after thermal neutron irradiation in a training nuclear reactor.

THE INDUCED RADIOACTIVITY IN THE JF SHIELDING AND TAS

The JF shielding and TAS are placed behind the end-cap toroids close to the end of the experimental hall. The length of the front part of the JF shielding is 6.5 m and its distance from the interaction point is approximately 13 m. The JF shielding protects the muon spectrometer chambers against neutrons and photons which are mainly produced in the copper collimators and surrounding material of the vacuum beam pipe. The TAS is located behind the JF shielding closely surrounding the beam pipe.

The JF shielding is made of ductile iron (DI), borated polyethylene (BPE), and steel cladding. It is composed of two main parts as seen in Fig. 1. The front section has a cylindrical shape and consists of the DI core with radius 147 cm. A polyethylene layer (5 cm thick) with 5 %wt of Boron (compound H_3BO_3+CH_2) surrounds the DI core. The BPE is covered by a 3 cm thick steel cladding to shield against γ-rays originated from neutron absorption by Boron. The back section has an octagonal shape and similar composition: a DI core (the diameter of the inner surface is 300 cm with the maximal dimension 420 cm) which is again coated by 8 cm thick BPE and 3 cm thick steel cladding. DI was proposed [3] and finally selected to absorb hadronic cascades due to its rather high content of Carbon (3.5 %wt) which contributes to the slowing down of neutrons in this material and their subsequent absorption in the DI itself. The TAS is made mainly from Copper (Cu 85%, Zn 5%, Pb 5%, and Sn 5%).

In the first step the material composition and geometry of the JF shielding and TAS according manufacturing drawing design were added to GEANT3 [4]. About 2000 p-p collisions were simulated. The program stores the types, positions and products of the reactions inside the JF shielding and TAS. The important reactions mostly responsible for activation are hadronic reactions and neutron capture. The numbers of radioactive nuclei (j) generated in the JF shielding and TAS per second (q_j) were obtained. Their activities were calculated using the expression $A(t) = \sum_j q_j (1 - \exp^{-l_j t_i}) \exp^{-l_j t_c}$, where t_i is the running time of the LHC (100 running days of the LHC per year are expected) and t_c is the „cooling time“ of the ATLAS detector (the time elapsed after the end of the LHC period of operation). The disintegration of radioactive nuclei generated in the JF shielding and TAS was calculated. Special attention was given to γ-ray production. From the positions of activated nuclei the GEANT3 program calculated self-absorption of all delayed γ-rays. Delayed γ-rays were assumed to be emitted isotropically. As a result we obtained the photon spectra on the surface of the JF shielding and TAS as well as the photon spectra at a distances of 20, 50, and 100 cm from the outer surface of the JF shielding and TAS. Finally, the equivalent dose rates were calculated from these spectra.

More than 100 isotopes were investigated in the JF shielding and TAS. However only few radioisotopes contribute significantly to the total equivalent dose rates (see Table 1). The map of equivalent dose rates after 100 days of operation in the first year of LHC running and after 10 days of cooling is given in Fig. 1.

DETERMINATION OF NEUTRON INDUCED RADIOACTIVITY OF THE SCT FORWARD MODULE

The purpose of the experimental tests was to identify radioisotopes generated in the SCT module after irradiation by neutrons. The module was inserted into the moderator in the vicinity of the active zone of a training nuclear reactor [5] in order to estimate its activation by thermal neutrons. Subsequently, the delayed γ-rays induced by neutron reactions with nuclei of SCT module were measured. Neutron radiative capture contributes most significantly to the material activation. Two gold foils with mass 128 mg were used as neutron flux monitors. The irradiation was carried under full reactor power (the neutron flux was determined at $(7.2 \pm 0.2) \times 10^8$ $cm^{-2}s^{-1}$) for 165 minutes. Spectra of delayed γ-rays were measured with a HPGe detector. Data were repeatedly collected in time periods in the increasing sequence of 1, 2, 4, ... minutes of real time. Within four days thirty spectra were accumulated. The full process (irradiation, γ-ray spectra measurement) was repeated three times to verify obtained results.

Radioisotope identification was based on the determination of energies and decay half-lives of observed γ-ray lines. Analysis of all 30 spectra resulted in the unambiguous identification of 26 radioisotopes. The 15 isotopes with highest activity are listed in Table 2. The dominant lines of measured spectra were 411 keV, 511 keV and 1779 keV. The first line belongs to Gold. Annihilation process (511 kev line) mostly follows the β^+-decay of ^{64}Cu. The third line is from ^{28}Al which has a short half-life (2.2 m) and gradually disappeared from the spectra. From the measured activity of isotopes the activity after 100 days of LHC running was calculated. Given the irradiation time of 165 minutes, some isotopes were observed only with small activity (e.g., A(^{110m}Ag)=318 Bq, A(^{117m}Sn)=59 Bq, A(^{123}Sn)=2 kBq) due to their longer half-lives, some isotopes were not seen at all (e.g., ^{119m}Sn, ^{114m}In, ^{113}Sn). Nevertheless, these isotopes were also taken into account for estimation of equivalent dose rates of SCT module. Based on known spectral and isotopic compositions the equivalent dose rates caused by γ radiation and β particles close to the surface of the SCT module were estimated. The maximal equivalent dose rate on the surface after 10 days of cooling is less than 100 µSv/h and is mostly caused by β particles.

CONCLUSION

The induced radioactivity was estimated in the JF shielding and TAS by Monte Carlo methods. For the assembled JF shielding, equivalent dose rates after 10 days of cooling are low (lower than 0.038 µSv/h). The situation changes dramatically when the JF shielding is disassembled. The inner surface of the JF shielding (the surface close to the vacuum beampipe) acquires much larger values (up to 661 µSv/h). The situation becomes even worse close to the TAS region where the equivalent dose rates reach the level of 11 mSv/h on the front side which is open during manipulation. Finally, the TAS itself becomes very radioactive (up to 60 mSv/h).

For the SCT module the induced radioactivity was studied experimentally by thermal neutron irradiation. The maximal equivalent dose rate was estimated less than 100 µSv/h.

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JF shielding

Cooling time [d]	10	150	250
Radioisotope	%	%	%
$^{54}_{25}$Mn	50.2	91.4	95.0
$^{52}_{25}$Mn	23.8	0.0	0.0
$^{46}_{21}$Sc	8.9	7.0	4.0
$^{48}_{23}$V	13.4	0.1	0.0

TAS

Cooling time [d]	10	150	250
Radioisotope	%	%	%
$^{58}_{27}$Co	38.0	34.8	27.8
$^{56}_{27}$Co	20.4	17.0	11.8
$^{60}_{27}$Co	8.6	22.4	36.3
$^{54}_{25}$Mn	6.5	10.8	14.4
$^{57}_{27}$Co	2.5	5.0	6.6

Table 1: Percentage contribution of different radioisotopes to the total equivalent dose rate on the inner surface of the JF shielding (left) and TAS (right) for various cooling times.

Radioisotope	Process	$T_{1/2}$ [h]	Activity [Bq]
^{24}Na	β^-	15.00	$3.7(5)\times10^4$
^{27}Mg	β^-	0.16	$7.9(8)\times10^4$
^{28}Al	β^-	0.04	$5.2(5)\times10^6$
^{42}K	β^-	12.40	$5.5(6)\times10^3$
^{51}Ti	β^-	0.10	$4.8(7)\times10^3$
^{56}Mn	β^-	2.60	$7.1(9)\times10^3$
^{64}Cu	EC, $\beta^{+/-}$	12.70	$2.0(2)\times10^6$
^{66}Cu	β^-	0.09	$3.8(5)\times10^6$
^{108}Ag	EC, $\beta^{+/-}$	0.04	$4.3(4)\times10^6$
^{116m}In	β^-	0.91	$4.2(4)\times10^3$
^{125m}Sn	β^-	0.16	$1.1(1)\times10^4$
^{124}Sb	β^-	1444.80	$7.3(7)\times10^4$
^{137m}Ba	IT	0.04	$1.0(2)\times10^4$
^{139}Ba	β^-	1.39	$7.9(8)\times10^4$
^{198}Au	β^-	64.80	$3.5(4)\times10^4$

Table 2: Radioisotopes observed after 165 minutes of SCT module neutron irradiation with measured activity higher than 3 kBq.

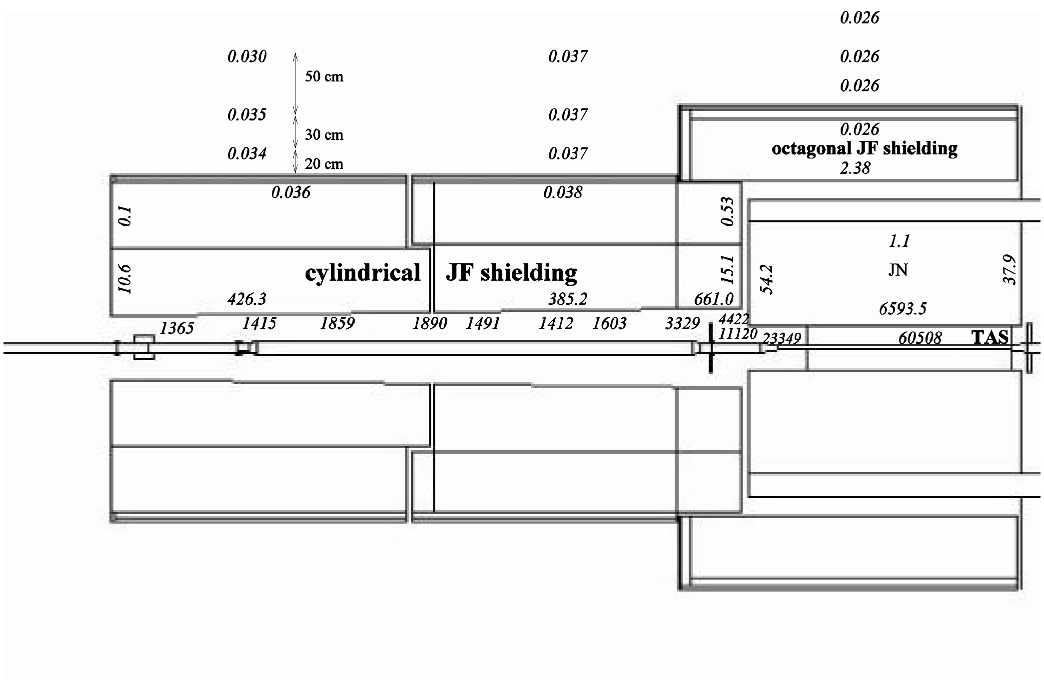

Fig. 1: Equivalent dose rates [μSv/h] expected after 100 days of ATLAS running and 10 days of cooling in the region of the JF shielding and TAS.