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Penetration of ionizing radiation from ATLAS cavern into USA15 measured by MPX detectors

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Abstract: The attenuation of the ionizing radiation through a concrete wall between the ATLAS Cavern UX15 and Service Cavern USA15 was measured during LHC collisions in 2012 with two ATLAS-MPX detectors. The detectors were mounted on either side of the wall separating UX15 and USA15. The average cluster counts of photons and charged particles, and thermal neutron fluence per unit integrated luminosity were determined with both detectors. It was found that the cluster counts and thermal neutron fluence were attenuated by two orders of magnitude by the concrete wall. The cluster count on the USA15 side caused by LHC collisions reaches roughly 30% of the level of the natural radiation background at the same position, for a luminosity of 6×10^{33} cm^{-2}s^{-1}.

Keywords: Particle tracking detectors (Solid-state detectors); Dosimetry concepts and apparatus; Solid state detectors; Pixelated detectors and associated VLSI electronics

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Contents

1 Introduction

A network of MPX pixel detectors (ATLAS-MPX network) based on the Medipix2 chip [1] was installed within the ATLAS experiment at CERN. The network was in operation since 2008 up to first quarter of 2013. This article reports on the measurement of penetration of ionizing radiation through the ATLAS Cavern (UX15 cavern) wall into the service cavern (USA15 cavern) during the LHC collisions, as measured in 2012 with the detectors MPX11 and MPX17. These two detectors were mounted onto both sides of the wall. We focus primarily on the methods and results of measurements as a detailed description of the ATLAS-MPX detectors network and operation can be found in [2] and [3].

2 MPX detectors

The MPX device consists of a 300 µm thick silicon sensor matrix of 256×256 cells (pixel size $55{\times}55\ \mu m^2$, total sensor area $2\ cm^2$) bump-bonded to a pixelated Medipix2 read-out chip. Detectors in the network were operated in tracking mode (see ref. [2], page 5) with low threshold (8–10 keV). The signature of particles interacting in the silicon sensitive layer is seen as a cluster of adjoining activated pixels with different size and shape depending on the type of particles, their energies, incidence angles, and the nature of their interactions in the sensor. Besides photons and charged particles, the detectors are sensitive to neutrons as well because they are covered with a mask of converter materials made of ^{6}LiF layer and polyethylene foil, dividing the sensor into regions sensitive to thermal and fast neutrons, respectively [2]. The remotely settable integration time window (frame) of the MPX detectors was set short enough in order to visualize the tracks created by the individual particles without overlap of the tracks. Data collected in the tracking mode were analyzed with a pattern recognition algorithm [2] and subsequently stored for further evaluation.

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2.1 Location of MPX detectors

There were sixteen MPX detectors installed in ATLAS [2]. This report uses data acquired by MPX11 and MPX17. MPX17 device is positioned in USA15 directly opposite to MPX11 (see figure 1). The concrete wall between USA15 and ATLAS cavern is 2.0 m thick [4]. Table 1 presents the locations of the MPX detectors of interest for the purpose of this article.

Table 1. Locations and positions of MPX11 and MPX17 with respect to the central interaction point. X, Y and Z axes correspond to the Cartesian coordinate system: X pointing towards the center of LHC, Z pointing the beam direction, Y is perpendicular to the XY plane, $R = (X^2 + Y^2)^{1/2}$ is the distance from the beam axis at position Z.

Device	Location	X [m]	Y [m]	Z [m]	R [m]
MPX11	UX15 cavern wall, USA side	−16.69	0.05	4.86	16.69
MPX17	USA15, cavern wall	−18.90	0.05	4.86	18.90

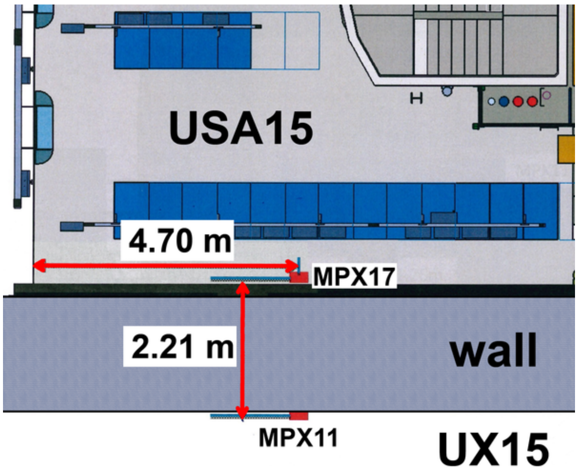

Figure 1. Location of MPX11 and MPX17. The wall is 2.0 m thick [4] and the distance between MPX11 and MPX17 sensors is 2.21 m.

2.2 Particle categorization

Data obtained from MPX measurements were analyzed with a pattern recognition algorithm according to the cluster shape and assigned into six categories corresponding roughly to the types of interacting particles and products of their interactions (see [2], pages 5, 6, 7, 38): *dots* — low energy X-rays and electrons, *small blob* — more energetic photons and electrons, *curly track* — energetic photons and electrons, *heavy blob* — heavy charged particles with short range, *heavy track* — energetic heavy charged particles, and *straight track* — highly energetic charged particles.

For further data interpretation, the clusters created by particles were grouped into the following categories [2]:

- Low Energy Transfer Particles (LETP):

  electrons and photons registered as dots, small blobs and curly tracks on the whole sensor, including other high energy particles which can be recognized also as small blobs;

- High Energy Transfer Particles (HETP):

  low energy protons (with high ionizing power, roughly below 80 MeV) and ions, fast neutrons effectively detected via recoiled protons or carbon ions from the polyethylene converter, energetic hadrons (including fast neutrons) interacting strongly in the silicon sensor, which are registered as heavy blobs and heavy tracks on the whole sensor except the ^{6}LiF region;

- Minimum Ionizing Particles (MIPs):

  muons and high energy charged hadrons registered as straight tracks on the whole sensor;

- Thermal neutrons:

  thermal neutrons detected via interactions in enriched ^{6}LiF (enrichment 89% of ^{6}Li) converter registered as heavy blobs in the ^{6}LiF region.

3 The method

3.1 The quantities

The quantities of interest for the comparison between MPX11 and MPX17 response were the LETP and HETP cluster counts and thermal neutron fluence per unit integrated luminosity. MIP cluster counts were not considered because the recognition of a MIP depends on the angle of incidence with the MPX sensor. Initially, for each LHC collision period, clusters sorted into the categories described in section 2.2 were summed from all frames recorded within each collision period. Mean radiation background measured before each collision period was subtracted from the data obtained during the collision periods. Then, the result was normalized to unit area of the sensor and unit integrated luminosity as measured by ATLAS [6]. For each MPX detector, the final value of the LETP and HETP cluster counts and thermal neutron fluence per unit integrated luminosity was calculated as a luminosity weighted mean of the values from all collision periods [2, 3].

3.2 The measurements

The data used were taken from measurements performed between 2 May and 24 June 2012 with roughly 50 LHC collision periods. Figure 2 visualizes an example of the cluster counts per frame recorded during a part of this period of time by MPX11 and MPX17. The penetration of the ionizing radiation through the USA15 wall was then estimated based on the ratio of quantities defined in section 3.1, obtained from MPX11 and MPX17 measurements. One can notice that the clusters of a curly track type are the most pronounced during the LHC collisions.

4 Results and discussion

Radiation background cluster rates and thermal neutron flux during periods in absence of LHC collisions are summarized in table 2. The LETP cluster rates could be converted into ambient dose equivalent rate, $\dot{H}^{*}(10)_{\mathrm{LETP}}$, using the method described in [2] and more thoroughly in [5]. Applying the conversion factor 2.0×10^{-10} Sv/cluster [5], the resulting $\dot{H}^{*}(10)_{\mathrm{LETP}}$ values were (0.050 ± 0.008) µSv/h and (0.075 ± 0.011) µSv/h measured with MPX11 and MPX17, respectively.

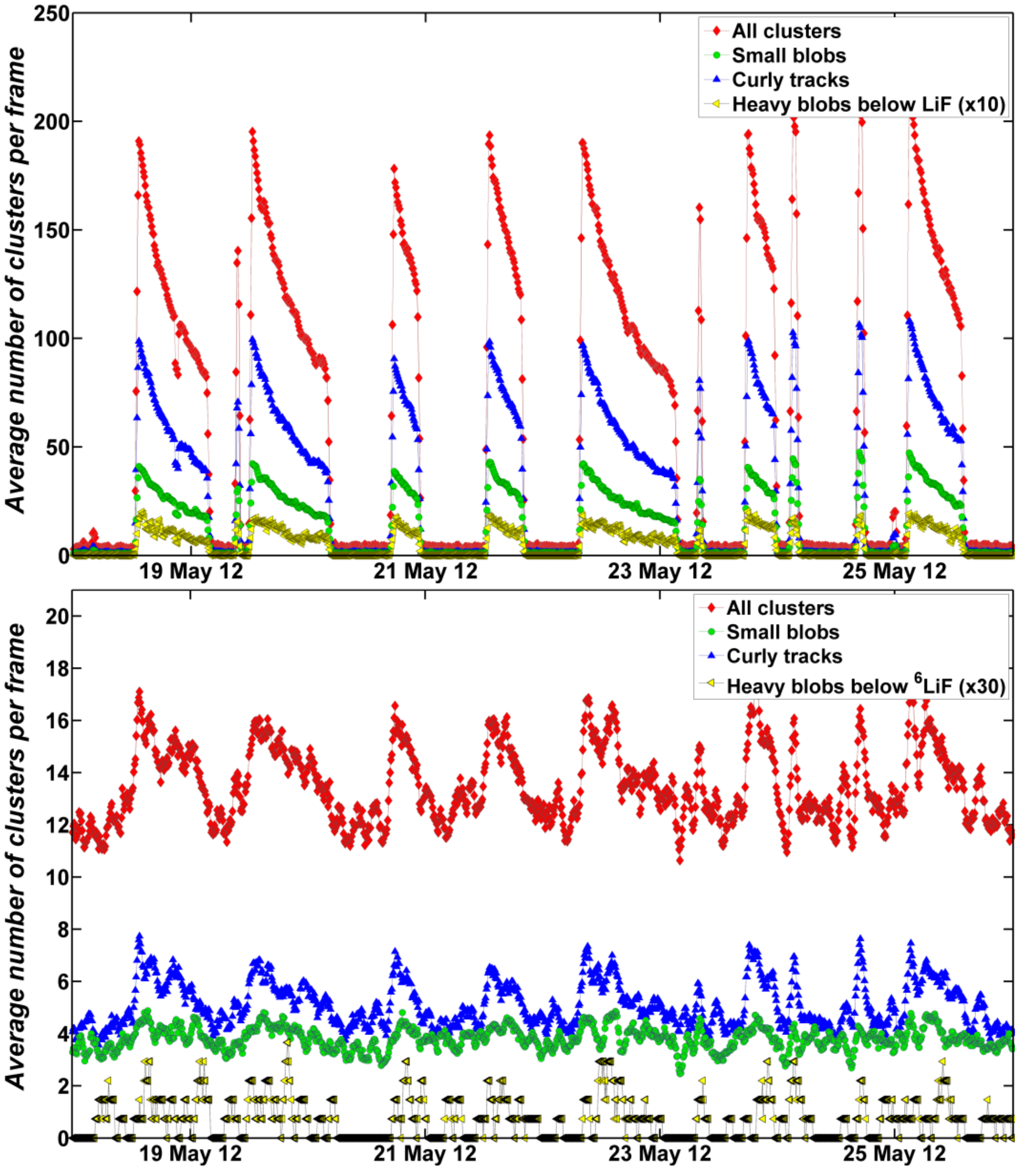

Figure 2. Response of MPX11 (above) and MPX17 (below) in the time period from 18 May to 26 May 2012. For MPX11, the LHC collision periods are clearly distinguishable from radiation background in absence of LHC collisions for all defined cluster categories. The increased cluster rate during the LHC collision periods, which characterizes the penetration through the wall is also measured by MPX17. Every data point represents the average over 40 and 80 min of data acquisition of MPX11 and MPX17, respectively.

As discussed in [5] most of the contribution to the $\dot{H}^*(10)_{\mathrm{LETP}}$ is caused by natural radiation coming from concrete of the wall itself and we can assume that $\dot{H}^*(10)_{\mathrm{LETP}} = \dot{H}^*(10)$.

MPX11 and MPX17 cluster counts and thermal neutron fluence per unit integrated luminosity during LHC collisions are compared in table 3. There is roughly a difference of a factor of 100 in the LETP cluster counts between both detectors and a factor of 130 in thermal neutron fluence.

Presented data show that the thermal neutron flux in absence of LHC collisions is below the detection sensitivity. On the other hand, during LHC collisions the thermal neutron fluences per

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Table 2. Average background HETP, LETP and MIP cluster rate and thermal neutron flux as measured by MPX11 and MPX17 in absence of LHC collision periods between 2 May and 24 June 2012. The uncertainties are composed of counting statistics only.

	Average background thermal neutron flux and HETP/LETP/MIP cluster rates [$cm^{-2}s^{-1}$]		
	MPX11	**MPX17**	**Ratio MPX11/MPX17**
Thermal neutrons	$(3.30 \pm 3.40) \times 10^{-3}$	$(0.58 \pm 3.78) \times 10^{-3}$	5.7 ± 38.1
HETP	$(4.25 \pm 0.08) \times 10^{-4}$	$(5.97 \pm 0.11) \times 10^{-4}$	0.71 ± 0.02
LETP	$(3.48 \pm 0.02) \times 10^{-2}$	$(5.21 \pm 0.01) \times 10^{-2}$	0.67 ± 0.01
MIP	$(6.21 \pm 0.28) \times 10^{-5}$	$(7.24 \pm 0.34) \times 10^{-5}$	0.86 ± 0.06

Table 3. Average HETP and LETP cluster counts and thermal neutron fluence per unit integrated luminosity as measured by MPX11 and MPX17 during LHC collisions between 2 May and 24 June 2012. The uncertainties are counting statistics.

	Average thermal neutron fluence and HETP/LETP cluster counts generated due to the LHC collisions only [cm^{-2}/nb^{-1}]		
	MPX11	**MPX17**	**Ratio MPX11 / MPX17**
Thermal neutrons	2.90 ± 0.28	$(2.18 \pm 0.39) \times 10^{-2}$	133 ± 27
HETP	$(6.24 \pm 0.38) \times 10^{-3}$	$(9.48 \pm 2.91) \times 10^{-5}$	66 ± 21
LETP	$(3.02 \pm 0.06) \times 10^{-1}$	$(2.77 \pm 0.44) \times 10^{-3}$	109 ± 17

unit integrated luminosity are reliably measurable with both MPX11 and MPX17 devices. It means that neutrons either penetrate into USA15 from UX15 or are produced in the concrete wall.

The peak luminosity per fill was around $6 \times 10^{33}\,cm^{-2}s^{-1}$ ($6\,nb^{-1}s^{-1}$) in June 2012 [6]. Using the MPX17 LETP cluster count presented in table 3 one can conclude that for this luminosity the LETP cluster rate reaches $1.7 \times 10^{-2}\,cm^{-2}s^{-1}$, i.e., roughly 30% of the LETP cluster rate of natural radioactivity background at the MPX17 position in USA15 on the wall between UX15 and USA15. After the LHC upgrade in 2013–2014 (called "Phase 0") the goal is to achieve the design luminosity of $10^{34}\,cm^{-2}s^{-1}$. The LHC upgrade in 2018 (called "Phase I") has the goal to bring the luminosity up to $2 \times 10^{34}\,cm^{-2}s^{-1}$ and Phase II in 2022–2023 aims at a luminosity of $5 \times 10^{34}\,cm^{-2}s^{-1}$ [7]. According to the presented results it can be expected that in Phase 0, Phase I and Phase II the total radiation background in USA15 during LHC collisions will be increased to 50%, 100% and 270%, respectively, above the natural background radiation in USA15 in absence of LHC collisions.

Quantities summarized in table 3 allow estimation of some components of total ambient dose equivalent $H^*(10) = H^*(10)_{\text{LETP}} + H^*(10)_{\text{N-TH}} + H^*(10)_{\text{HETP}}$ at the position of MPX17 in USA15 cavern. The photon and electron contribution can be calculated from LETP cluster rate. $\dot{H}^*(10)_{\text{LETP}}$ at USA15 wall neighboring the ATLAS UX15 cavern would reach $(0.11 \pm 0.01)\,\mu Sv/h$, $(0.15 \pm 0.02)\,\mu Sv/h$ and $(0.27 \pm 0.04)\,\mu Sv/h$ during LHC collisions in Phase 0, Phase I and Phase II, respectively. Similarly, the contribution from thermal neutrons [9] would reach $(0.008 \pm 0.002)\,\mu Sv/h$, $(0.017 \pm 0.003)\,\mu Sv/h$ and $(0.042 \pm 0.007)\,\mu Sv/h$. Evaluation of the contribution of HETP (fast neutrons and hadrons) to total ambient dose equivalent cannot be estimated mainly due to low statistics, low detection efficiency for fast neutrons and unknown hadron spectrum.

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5 Conclusions

Penetration of ionizing radiation caused by LHC collisions into USA15 cavern was measured utilizing the MPX11 and MPX17 detectors, which were mounted onto the walls of the ATLAS cavern and USA15, respectively. The total cluster rates measured by both detectors during LHC collisions show that the wall attenuates radiation roughly by a factor of 100. Hence, at $6 \times 10^{33}\,\mathrm{cm^{-2}s^{-1}}$ ($6\,\mathrm{nb^{-1}s^{-1}}$, the peak luminosity per fill) it reaches $1.7 \times 10^{-2}\,\mathrm{cm^{-2}s^{-1}}$, i.e., roughly 30% of the LETP cluster rate of natural radioactivity background at the MPX17 position. The value of thermal neutron fluence of $(2.18 \pm 0.39) \times 10^{-2}\,\mathrm{cm^{-2}}$ as measured with MPX17 per integrated luminosity of $1\,\mathrm{nb^{-1}}$ gives evidence of penetration of neutrons through 2.0 m thick concrete wall.

Based on the presented results it is estimated that after the LHC successive upgrades in Phase 0 ($10^{34}\,\mathrm{cm^{-2}s^{-1}}$), Phase I ($2 \times 10^{34}\,\mathrm{cm^{-2}s^{-1}}$) and Phase II ($5 \times 10^{34}\,\mathrm{cm^{-2}s^{-1}}$), the total radiation level in USA15 will be increased to 50%, 100% and 270%, respectively, above the natural background radiation level in absence of LHC collisions.

The use of pixelated detectors with the capability to differentiate individual components of complex radiation fields demonstrated, that the method applied in this article is exploitable for the evaluation of shielding effectiveness against impact of ionisation radiation on background radiation levels in specific areas of high-energy accelerators environment. In particular, in the case of ATLAS, it is expected that the use of pixelated detectors of new generation (such as Timepix3 [10]) can possibly improve the reliability of estimates of total radiation level in USA15, with new repartition of pixelated detectors network and shielding modifications occurring in the future.

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