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Irradiation of a 2.5 m long SciFi module with 24 GeV/c protons to the dose profile expected in LHCb

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Abstract

A 2.5 m long and 13 cm wide SciFi module, made of a 6-layer single fibre mat, was irradiated with 24 GeV/c protons in the new CERN PS IRRAD facility. The module is equipped with an aluminised mylar mirror and was previously carefully characterised in a test beam experiment in the CERN H8 zone. For the irradiation the module was tilted by 7° w.r.t. the beam axis. A translation table allowed to move the module during the irradiation transverse to the beam in order to generate the dose distribution expected in LHCb after an integrated luminosity of 50 fb^{-1}, including the very sharp rise at the mirror end to 35 kGy. The dose distribution was derived from the generation of sodium isotopes in the aluminium strips placed in front of and behind the module. The dosimetry relies mainly on the activity of the long-lived Na-22 isotope, as the short-lived Na-24 gave in our specific case less precise results. The irradiated zone corresponds to an approximately 25 mm wide band running along the fibre mat, at 32 mm from its edge. The other part of the module are expected to have received a negligible amount of radiation and can be considered as reference zone. Within the uncertainty of the dosimetry, the dose distribution comes close to the targeted profile.

Contents

1 Introduction

1.1 SciFi detector

During the Long Shutdown 2 of the LHC, a large scintillating fiber (SciFi) Tracker [1] is going to replace the actual LHCb Inner and Outer Trackers. The SciFi detector will be built of 250 μm diameter scintillating fibres being readout by SiPMs at the top and bottom edges of the detector. The fibres are going to be processed to fibre mats of 2.4 m length, made from 6 staggered fibre layers with a thin mirror attached to the end. The detector is organised as 3 tracking stations (T1, T2, T3), each comprising 4 × 12 modules in x-u-v-x configuration and covering an area of about $6 \times 4.8\ m^2$. The total length of the needed fibres exceeds 10'000 km.

1.2 Motivation

The scintillating fibres are exposed to a field of ionising radiation which shows a steep radial growth towards the beam axis. Ionising radiation leads to a dose-dependent reduction of the optical transparency and hence the light output of the fibres. Previous radiation experiments, performed on individual fibres and fibre bundles, allowed to establish a dose-damage relation over the full dose range relevant for the SciFi detector. This made it possible to calculate the expected signal losses in the SciFi irradiation field as predicted by FLUKA calculations [2].

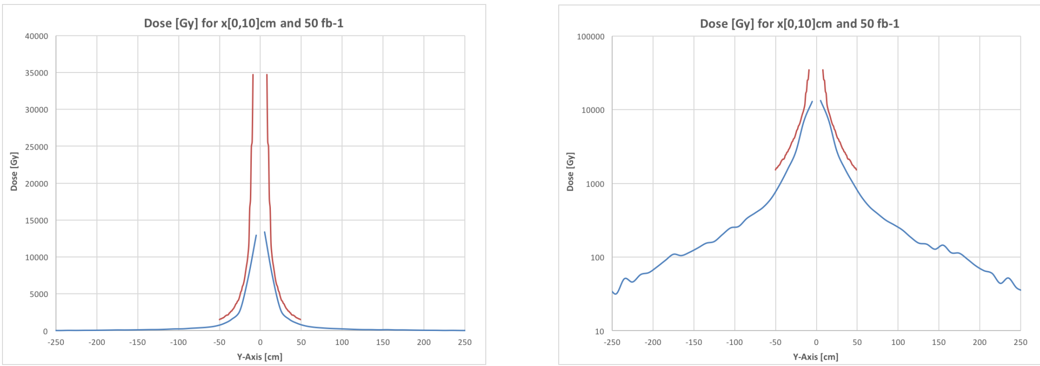
The aim of the irradiation experiment presented in this note is to expose a full SciFi fibre module of 2.5 m length to a dose profile which resembles as much as possible the one in the upgraded LHCb detector operating for 10 years (50 fb^{-1}). According to FLUKA simulation (see 1.3), the SciFi detector is going to be exposed to an ionizing dose ranging from 50 Gy in 2.5 m distance from the beam pipe up to 35 kGy in the innermost region. The majority of the particles crossing the SciFi detector will consist of multi-GeV charged hadrons. Irradiating the 6-layer mat module with the 24 GeV/c proton beam from the PS therefore provides the correct particle type and a similar energy range as in the real detector.

The 6-layer fibre mat was characterised in a test beam experiment in May 2015 (before the irradiation) and was re-tested in November 2015 (after the irradiation) in the beam. The results will be reported elsewhere [3]. A comparison of these measurements is expected to allow for significant verification of the SciFi radiation model.

1.3 The expected radiation field

We provide an estimate for the radiation levels in terms of total integrated dose for the position of T1 (z = 783 cm) of the future Fibre Tracker, which will receive the highest dose of all stations at its most central region. A dose profile along the y axis at this position is given to establish a proposal for the irradiation of the module. The FLUKA [4, 5] studies presented in this section concerning upgrade radiation levels at the Fibre Tracker stations were performed in 2012. They are calculated using a geometry description of the current LHCb experiment, which is a modified and improved version of an already very detailed model from 2003 [6].

Estimations for upgrade studies were calculated by simulating head-on proton-proton collisions with an energy of $\sqrt{s} = 14$ TeV using the current detector geometry (LHC Run1). Detailed magnetic field maps consisting of 4 sectors are integrated into the simulation. Apart from the collision energy, neither upgrade conditions nor changes to the layout of the detector were decided upon at the time of calculation. Since the Tracking stations were designed to consist of as little material as possible, in order to minimally interfere with particles of interest coming from the IP, an eventual upgrade to an equally light Fibre Tracker was considered to have only little influence on the deposited dose in that area. As it is now known, the upgrade of the whole detector will nonetheless introduce significant changes to the current geometry. In particular, the envisaged removal of the Muon detector M1, the Scintillating Pad Detector and the PreShower detector will influence the radiation field in front of the remaining calorimeter detectors. A FLUKA study has been performed recently where these subdetectors are replaced by empty airspace. According to this simulation, the modification of the geometry will greatly influence the neutron fluence around the Tracking stations. However the same results show that the dose values only increase by about 25% around the centre of T3 and by less than 10% at T1. Since simulations estimate that the maximum dose at the new tracking stations will be deposited in the most central region of T1, the results from the 2012 studies are still valid for this area.



(a) Linear scale

(b) Logarithmic scale

Figure 1: 1D projection of the dose along the y-axis for x [0,10] cm, fitting results of 10 x 10 x 10 cm^3 binning in the blue curve. The curve in red represents results obtained using cylindrical rings that increase by 1 cm steps in their radius up to 50 cm. All values correspond to an integrated luminosity of 50 fb^{-1} and a cross section of 100 mb.

The dose profile along the y-axis which is given in Fig. 1 shows an overlay of the results of 2 different scorings for total integrated dose. The blue curves are a fit of values from a Cartesian 3-dimensional binning with 10 x 10 x 10 cm^3 cubes. This rather large bin size is known to misrepresent dose values in the central regions, because the dose gradient within a bin rises steeply as it comes close to the beam, and in addition the innermost binning averages over an area with vacuum inside the beam pipe. In order to partially correct for these shortcomings, a scoring using cylindrical rings increasing by 1 cm steps in their radius around the beam pipe was introduced. It extends up to a radius of 50 cm in x and y and 1 cm in z. The result is represented by the red curve in the plot. This ring scoring averages over an asymmetric dose distribution which features higher values along the horizontal axis, because of the way the LHCb dipole deflects charged particles. Compared to the blue Cartesian scoring which only follows the vertical distribution, this leads to a display of higher values in the red ring scoring versus the lower end of r = 50 cm. As a pragmatic approach, an effective dose distribution has been defined, which transits at x = 5 cm from the Cartesian to the cylindrical system, as shown in Fig. 2. The data can be reasonably well described by a sum of 3 exponentials which facilitates its use for the irradiation planning. Although the ring scoring is averaging over an asymmetric distribution, it is considered sufficiently accurate to act as template for the irradiation described in this note.

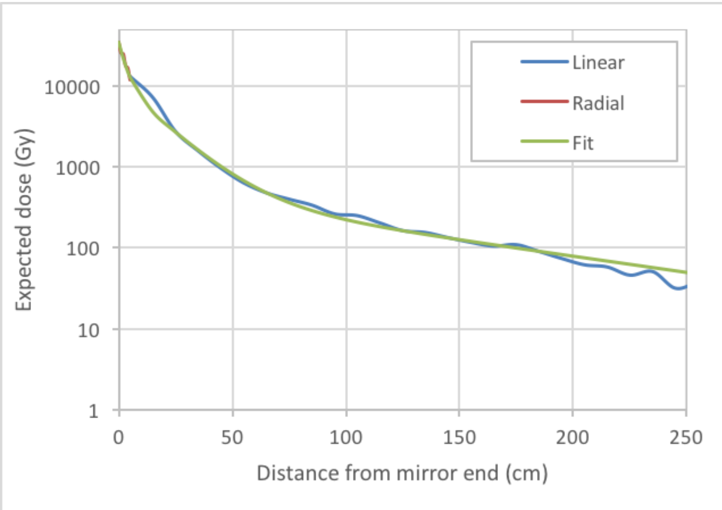


Figure 2: Fit with three exponentials of the combined (Cartesian and cylindrical) dose distribution from FLUKA. Fit function: $f(x) = 23875.03 \cdot e^{-x/3.04} + 10340.93 \cdot e^{-x/16.57} + 495.14 \cdot e^{-x/108.21}$

2 Methods and materials

2.1 The new CERN PS irradiation facility

Since end 2014, the new PS proton irradiation facility, named IRRAD [7], is operational. As shown in Fig.3, the 24 GeV/c proton beam traverses the various irradiation zones, in which the samples or Detectors Under Test (DUT) are mounted on translation tables which allow to position, move and rotate them, also during the irradiation. Given the size of the fibre module, the table IRRAD17 in zone 3 was identified as the most appropriate zone.

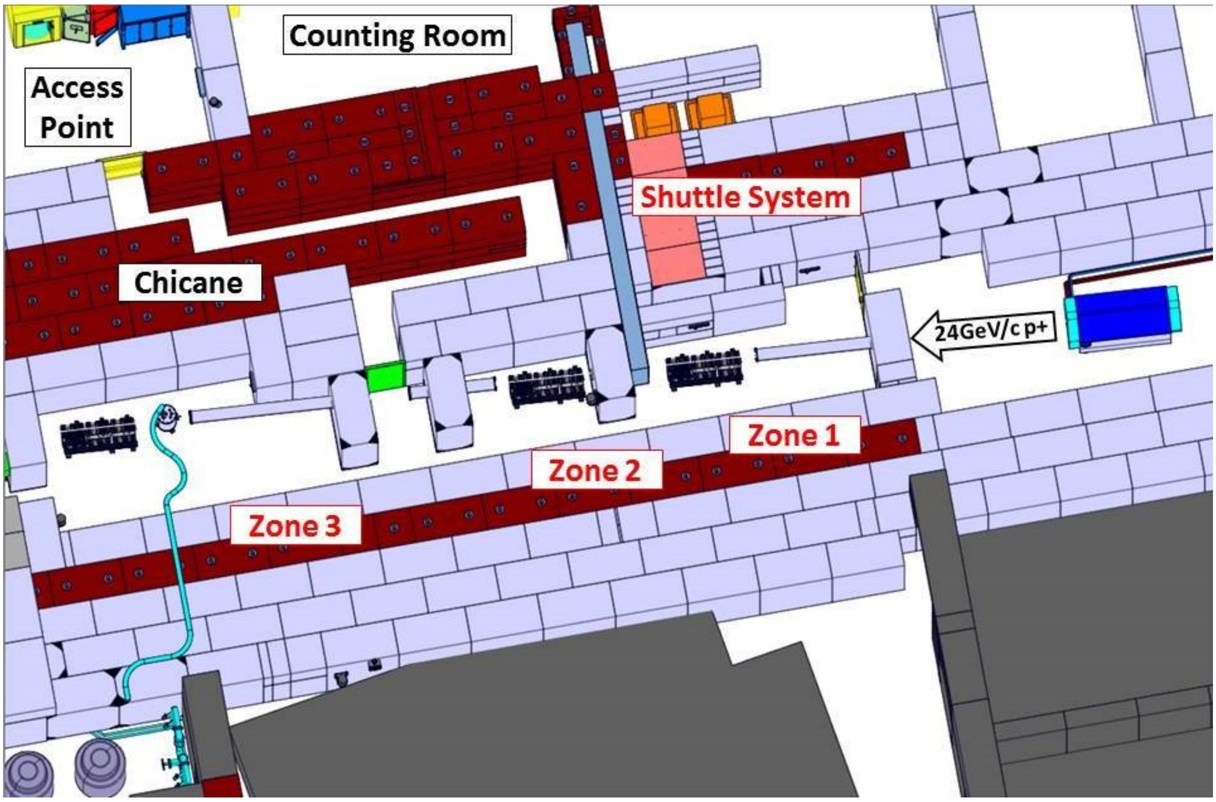


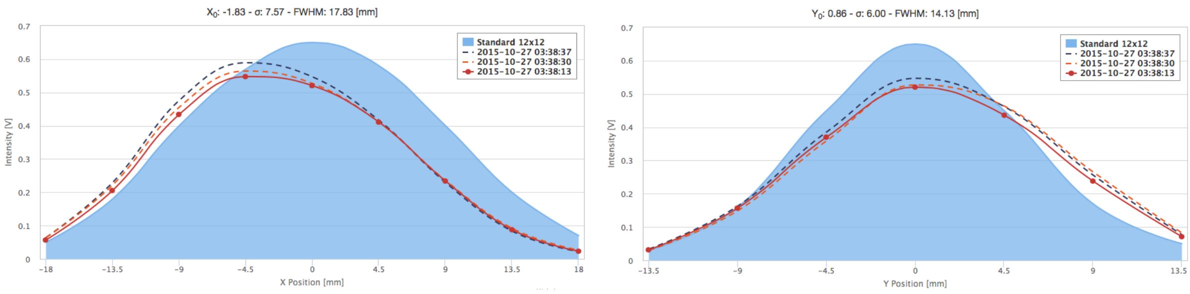
Figure 3: Layout of the new PS IRRAD zone.

The beam is extracted from the PS accelerator in spills containing typically 3.6 $\cdot 10^{11}$ protons, distributed over a roughly Gaussian beam spot, which has at the position of the IRRAD17 table a width of $\sigma_x \approx \sigma_y = 7 - 8$ mm. Depending on the operation mode of the PS, of the order of 200 spills per hour are directed towards the IRRAD facility.

The intensity of each extracted proton spill is monitored using a Secondary Emission Chamber (SEC) provided by the PS beam instrumentation team. It allows to determine the ionizing dose actually received by the DUT. The profile of the proton beam fluctuates in the range of a few mm in position and also in shape. A spill-by-spill recording of the profile is achieved by custom-made Beam Profile Monitors (BPM). BPM3 and BPM4 are installed up- and downstream of the IRRAD17 table. The distance between BPM3 (BPM4) and the table is about 4 m (2 m). Examples of beam profile in the horizontal and in the vertical direction as measured by BPM3 and BPM4 can be seen in Figs. 4 and 5.

2.2 The 6-layer single-mat module

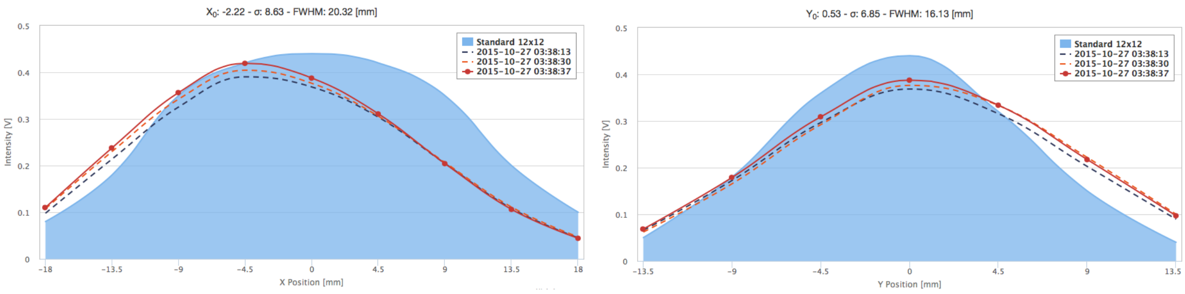
The DUT is a SciFi fibre module consisting of a single 6-layer fibre mat. It is identified as SciFi test beam module "4TSHEITBM00004". The module is approximately 2.5 m



(a) Horizontal beam profile

(b) Vertical beam profile

Figure 4: Beam profile measured by BPM3. The blue area in the plot shows the standard beam profile, while each line represent the actual beam profile measured by BPM3 for a specific spill.



(a) Horizontal beam profile

(b) Vertical beam profile

Figure 5: Beam profile measured by BPM4. The blue area in the plot shows the standard beam profile, while each line represent the actual beam profile measured by BPM4 for a specific spill.

long and 13 cm wide. The fibre mat is equipped with SCSF-78 fibres over full width. It is sandwiched between two honeycomb panels reinforced with 200 μm thick carbon fibre sheets. On the readout side, the fibres are glued between two polycarbonate end pieces, which are held by the two relatively massive endplugs which are made of aluminium. On the non-readout side, two small polycarbonate endpieces are mounted and an aluminised mylar mirror is attached to the fibre ends with EPOTEK H301 epoxy glue.

2.3 Installation and alignment of the DUT

The available space in the irradiation zone and the travel of the translation table would have not allowed to scan the 2.5 m long module transversally to the proton beam. In addition, *painting* the full length of the module with beam spots of 20 mm width would have required in this configuration more than 100 table positions. The module was therefore aligned under an angle of about 7° with respect to the beam axis, so that the full length of 2.5 m could be irradiated. A mechanical 50 cm long holder was designed and fabricated in plexiglass which allowed to tilt and maintain the detector in position.

This holder needed to be mounted off-centre on the table, such that the beam could reach the full detector length. The off-centre mounting slightly compromised the rigidity of the holder, resulting in light shaking at the moment when the table was moved to the next position. A further complication resulted form the fact that, due to the aluminium end plugs, the readout end of the module is significantly more heavy than the mirror end. The module had therefore to be supported asymmetrically by the holder.

A 3D LASER level was aligned with the beam coordinate system. The module was adjusted to coincide with the beam horizontally and adjusted in height so that the beam centre will hit 32 mm from the lower module edge. Fig. 6 illustrates the set-up. The zero of the transverse movement of the table was defined such, that the beam would be centred on the fibre layer on the mirror end. In order to produce the steep dose rise at the mirror end, the beam needed to be positioned at negative values, such that only the right half of the beam spot hit the fibres.

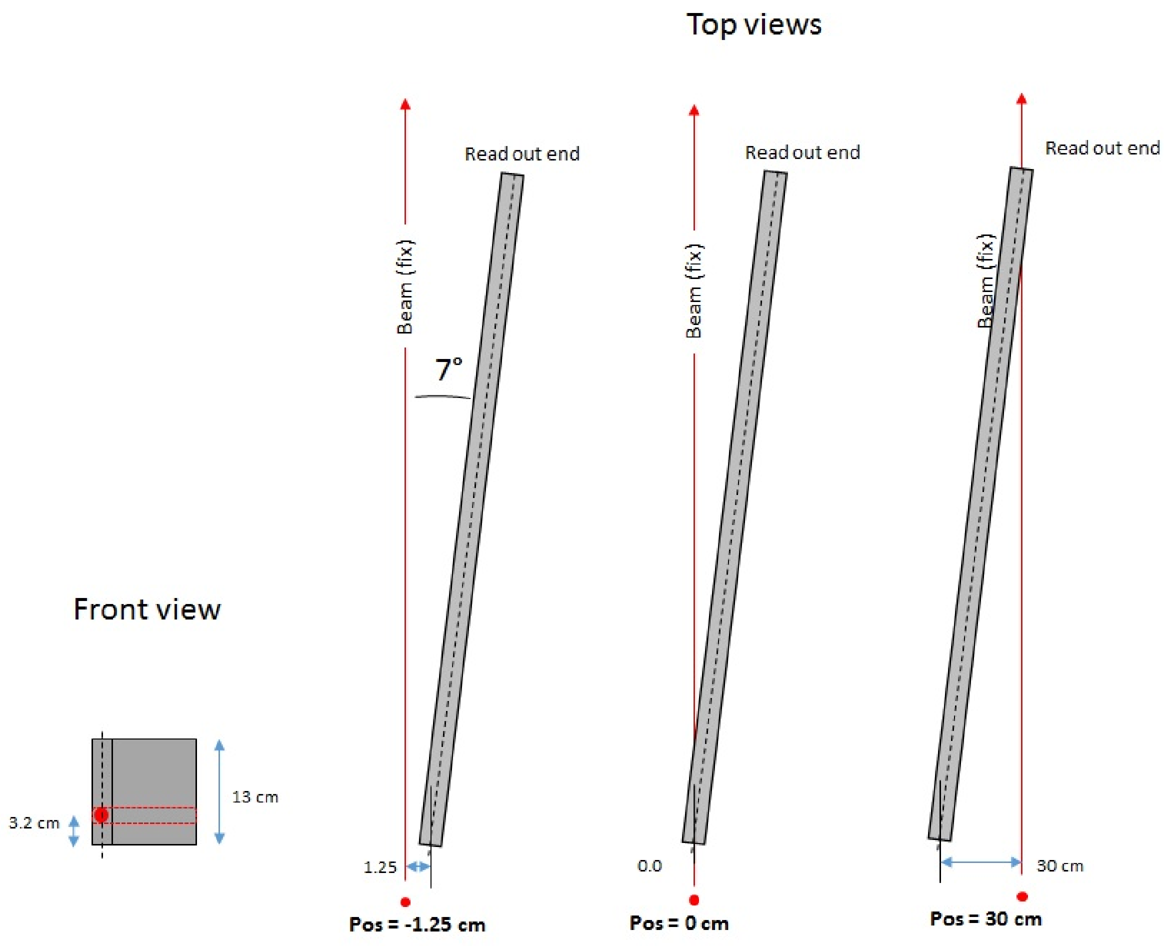


Figure 6: Principle of the positioning and alignment of the module in the PS beam.

2.4 Irradiation plan

As described above, in order to irradiate the 2.5 m long DUT over its full length, the detector needed to be inclined by 7° w.r.t. the beam axis. The linear translation table allows to move the module by up to approximately 32 cm transversely to the beam with a minimum step size of 0.1 mm in both axes.

The typical PS beam profile can be described by a Gaussian distribution with 10 mm width. The projected beam spot on the module has then a width of about (10 mm/sin(7°)) = 82 mm. Hence, by chosing for example a total of 30 steps, a fit of the expected dose profile using a superposition of Gaussian functions with $\sigma = 82$ mm is able to provide the number of protons which the module shall receive in each step position.

Estimation of the dose of 1 spill

Considering that one spill has roughly $3.6 \cdot 10^{11}$ protons and the energy loss of 1 proton in polystyrene[1] is 1.936 MeV cm ^{2}/g, the dose can be expressed as:

$$\mathcal{D} = \mathrm{N} \cdot \frac{\Delta \mathrm{E}}{M_p} = \mathrm{N} \cdot \frac{\left(\frac{dE}{\rho_p \; dx}_p\right) \cdot \rho_p \; dx_p}{\rho_p \cdot \mathrm{S} \cdot d_p} \tag{1}$$

where the p subscript refers to polysterene, N is the number of protons, $\rho_p = 1.06\,\mathrm{g/\,cm^3}$ is the polystyrene density, dx_p is the path length of the protons in polystyrene, d_p is the detector thickness and $S \approx \pi\sigma_y\sigma_z$ is the effective beam spot size (σ_y and σ_z are the gaussian RMS widths in the horizontal and vertical directions). If the module is tilted by an angle ϑ with respect to the beam, then $dx_p = d_p/\sin(\vartheta)$ and $\mathrm{S} = \pi \cdot 10\,\mathrm{mm} \cdot (10\,\mathrm{mm}/\sin(\vartheta))$. The $\sin(\vartheta)$ terms in equation (1) cancel out and therefore the total dose over the beam spot surface per spill is:

$$\mathcal{D} = \mathrm{N} \cdot \frac{\left(\frac{dE}{\rho_p \; dx}_p\right)}{\pi(10\,\mathrm{mm})^2} \approx 35.5 \text{ Gy} \tag{2}$$

However, taking into account the Gaussian profile of the beam, the corrected dose in the beam centre of one spill is $\frac{35.5 \text{ Gy} \cdot 20 \text{ mm}}{\sqrt{2\pi}\sigma} = \frac{35.5 \text{ Gy} \cdot 20 \text{ mm}}{\sqrt{2\pi} \cdot 10\,\mathrm{mm}} = 28.3$ Gy.

Evaluation of the number of spills at each table step

As a function of the distance along the module, a superposition of 31 Gaussians (8.5 cm wide) was fitted to the dose profile, as illustrated in Fig. 7. The start mean position was chosen to be -10 cm to achieve the steepness of the dose profile on the first 15 cm. The Gaussians were separated by 8.5 cm distance. Just a few of them were plotted to not overdraw the picture. The superposition of all Gaussians is represented by the red curve. A movement of 8.5 cm along the module corresponds to a $\approx$ 1 cm step of the table. The start position (-10 cm) corresponds to the table position -1.25 cm. The number of spills for

[1]Information obtained from PDG (Particle Data Group).

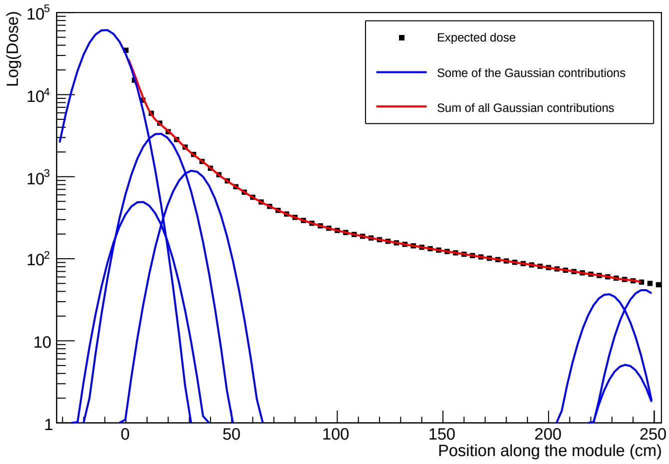


Figure 7: Fit of the simulated dose profile in the LHCb after 50 fb^{-1}. The fit function is a superposition of 31 Gaussians. The black data points are the expected distribution of the dose obtained by the 3 exponentials fit of FLUKA data (see Fig. 2). Only 7 of the 31 Gaussian functions were drawn (in blue).

a given position is obtained by dividing the peak value of each Gaussian in Fig. 7 by 28.3 Gy. Table 1 lists the number of spills for each table position.

2.5 Dosimetry

Activation of aluminium strips and colourisation of Gafchromic films are used in order to perform a dosimetric analysis after the irradiation. The position of the aluminium strips and dosimetric films can be seen in Fig. 8. Six aluminium strips were fixed on the module, orthogonally to the beam direction, three of them on the mirror end and three of them on the readout end. The aluminium strips were 25 mm wide and had a length of about 35 cm long in order to cover (in the projection) the full length along the module. The middle strips, both on the readout end and on the mirror end, were mounted on the height of the beam and will after the irradiation indicate the dose absorbed by the fibres. In order to obtain spatial information along the module, the aluminium strips were cut after the irradiation into pieces of 0.5, 1 or 2 cm length, which were then individually analysed. The strips on the top and bottom of the module can be used to estimate the background. Furthermore, one dosimetric film is fixed on each of the two middle aluminium strips. When exposed to radiation the films react to form a blue coloured polymer. They were not used for quantitative dosimetry but allow to check the correct alignment of the module with respect to the beam during the irradiation.

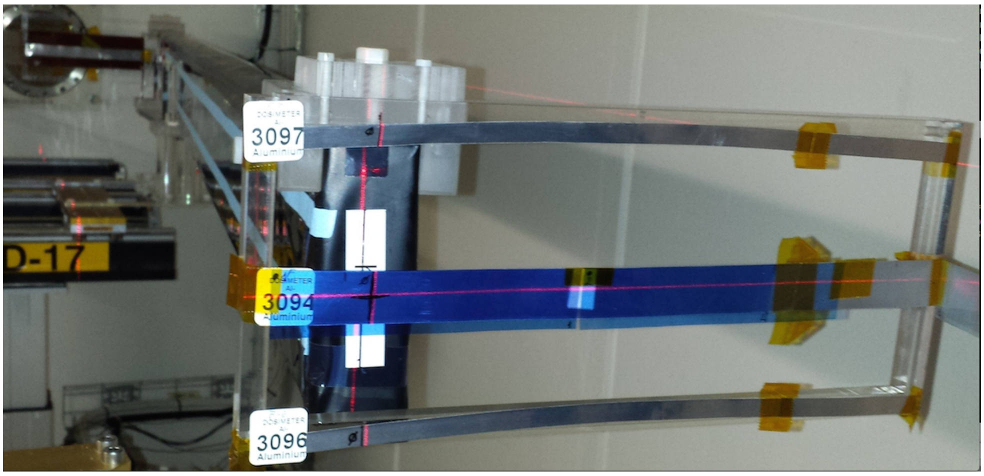


Figure 8: Picture of the module with the aluminium strips and dosimetric films for dosimetry. The photo was taken when another (5-layer) module was installed in the zone. The sample numbers visible on the photo do therefore not correspond to the irradiation described in this note. The middle aluminium strip (in this picture: sample number 3094) is aligned with the beam and will be used for dosimetry after the irradiation.

Position (cm)	# spills
-1.25	2313
-0.25	0
0.75	28.5
1.75	189
2.75	0
3.75	66
4.75	9
5.75	25
6.75	8
7.75	12
8.75	6
9.75	8
10.75	4.5
11.75	4.5
12.75	4.5
13.75	4.5

Position (cm)	# spills
14.75	3
15.75	3
16.75	3
17.75	3
18.75	3
19.75	1.5
20.75	3
21.75	1.5
22.75	1.5
23.75	1.5
24.75	1.5
25.75	1.5
26.75	1.5
27.75	0
28.75	3

Table 1: Number of spills applied for each table position. The number of spills for a given position is obtained by dividing the peak value of each Gaussian in Fig. 7 by 28.3 Gy.

2.6 Irradiation operation

The irradiation procedure started on 26th October 2015 at 16:48 and lasted for a total of 27 hours. It consisted of a fixed sequence which was repeated for every table position:

1. Remotely place the table in one of the positions shown in Table 1.
2. Note the starting time of the irradiation (time of first spill on the BPM3).
3. Wait until the required number of protons for this position is applied. The actual number of proton can be read on the display of the SEC.
4. Note the total number of protons and the time of the last spill.
5. Reset the display of the SEC.
6. Move the table to the next position.

Most of the regions irradiated in the module were exposed just to a few spills only, requiring the presence of more than one operator for a period of roughly 4h.

3 Results

3.1 Dosimetric analysis

Aluminium strips were fixed on the module as described in section 2.5. During the irradiation the nuclear reactions $^{27}\mathrm{Al(p,3p3n)}^{22}\mathrm{Na}$ and $^{27}\mathrm{Al(p,3pn)}^{24}\mathrm{Na}$ take place in the aluminium strips. The produced radioactive isotopes, ^{22}Na and ^{24}Na, decay with a half-life of 2.6 years and 15 hours respectively. The energy of the emitted photons is respectively 1274.54 keV and 1368.53 keV. Dosimetry is based on the determination of the number of protons which hit the aluminium by evaluating the ^{22}Na and ^{24}Na activity, which is measured after the irradiation with a germanium detector. The activity of ^{24}Na must be measured straight after irradiation, due to the short half-life of ^{24}Na. On the other hand, the activity of ^{22}Na can still be measured weeks after the irradiation.

The number of protons which hit the aluminium is related to the Na activity A_0 at the end of the irradiation by:

$$\mathrm{N} = \frac{A_0\ \Delta t}{\sigma\ \frac{N_{av}\rho}{m}\ d\,(1 - e^{\lambda\Delta t})} \tag{3}$$

where Δt the duration of the irradiation, $\sigma = 1.1 \cdot 10^{-26} b$ $(8.6 \cdot 10^{-27} b)$ is the cross-section for the reaction $^{27}\mathrm{Al(p,3p3n)}^{22}\mathrm{Na}$ (or respectively $^{27}\mathrm{Al(p,3pn)}^{24}\mathrm{Na}$), N_{av} is the Avogadro constant, $m = 26.98\,\mathrm{g/mol}$ is the molar mass of aluminium, $\rho = 2.7\,\mathrm{g/\,cm^3}$ the density, d is the Al thickness and λ is the inverse of the half-life of the considered Na isotope.

The dose $\mathcal{D}$ absorbed by polystyrene can then be calculated from the formula

$$\mathcal{D} = \frac{\mathrm{N}\left(\frac{\mathrm{dE}}{\rho\ \mathrm{dx}}\right)_p \rho_p\ d_p}{M_p} = \frac{\mathrm{N}\left(\frac{\mathrm{dE}}{\rho\ \mathrm{dx}}\right)_p \rho_p\ d_p}{\rho_p\ \mathrm{S}_p\ d_p} = \frac{\mathrm{N}\left(\frac{\mathrm{dE}}{\rho\ \mathrm{dx}}\right)_p}{\mathrm{S}_{Al}} = \frac{\mathrm{N}\left(\frac{\mathrm{dE}}{\rho\ \mathrm{dx}}\right)_p \rho_{Al}\ d_{Al}}{M_{Al}} \tag{4}$$

where the subscript p refers to polystyrene and the subscript Al refers to aluminium. In equation (4), N is the total number of protons that hit the aluminium strip during irradiation, $\mathrm{dE}/\rho\mathrm{dx} = 1.936\,\mathrm{MeV\,cm^2/\,g}$ is the mass stopping power for minimum ionizing protons in polystyrene, ρ is the density, S is the surface, M is the mass and d is the thickness of the considered material ($d_{Al} = 200\,\mu\mathrm{m}$).

In order to measure the dose profile along the panel only the two middle aluminium strips on the readout end and on the mirror end are considered (see Figure 8). Both strips are cut along the long side in pieces of 0.5 cm (in the hottest region), 1 or 2 cm (in the region corresponding to low dose irradiation). Each piece is weighed on a precision scale and the ^{24}Na and ^{22}Na activities of each piece are measured individually with a Germanium detector. While the ^{24}Na were determined within days after the irradiation, restrictions in the availability of appropriate Ge spectrometers delayed the completion of the ^{22}Na measurements until January 2016.

Equation (4) is then evaluated for each piece. The position along the aluminium strip is related to the position along the module by the relation $x_{module} = x_{strip}/\sin\vartheta$, where $\vartheta = 7°$ is the angle by which the module is tilted with respect to the beam.

Due to the short half-life of ^{24}Na, the precise knowledge of the irradiation time is crucial for a correct dose estimate. This is however difficult to achieve because a given aluminium sample can receive dose contributions from different table positions. Although the precision on the ^{24}Na activity is about 7% we observed point to point fluctuations which were significantly larger. We therefore concentrate the dosimetry on the ^{22}Na activities.

3.2 Corrections

The beam in the vertical direction has a Gaussian profile as shown in Figs. 4(b) and 5(b). The two middle aluminium strips used for dosimetry are 25 mm high and are aligned in a way that the center of the Gaussian coincide with the centre of the strip as illustrated in Figure 9. The calculation of the dose using equation (4) is the average of the dose along the 25 mm. In order to compare the absorbed dose with the expected dose (Fig. 7), the average dose in a smaller region around zero has to be evaluated. We chose the region of ± 5 mm around the centre of the Gaussian. From the profiles measures at BPM3 ($\sigma = 6.43$ mm) and BPM4 ($\sigma = 6.78$ mm) the beam appears to have widened up only slightly. A correction factor was derived from the ratio of the integrals under the Gaussian (averaged between BPM3 and BPM4) in the ranges [-5 mm,5 mm] and [-12.5 mm,12.5 mm].

A comparison of the respective aluminium strips on the mirror and readout side showed systematic discrepancies which could not be explained by the slight widening of the beam width over 2.5 m. It turned out that the discrepancies disappear if one assumes a small rotational misalignment of the module by 0.5° in the horizontal plane.

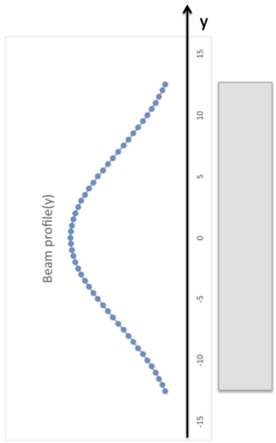


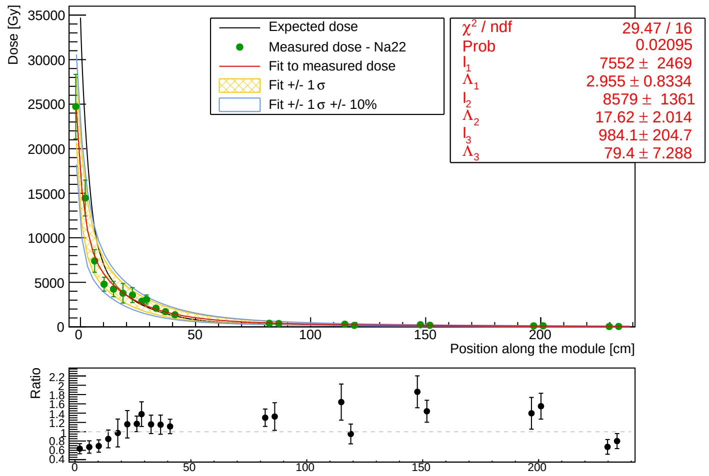
Figure 9: Alignment of the aluminium strip with the beam in the vertical direction.

As mentioned above, due to the CERN end-of-year closure and maintenance needs, not all aluminium strips could be analysed on the same Ge spectrometer. Cross comparisons of a few samples which were measured on both spectrometers revealed a systematic difference in the resulting activity of 20% which could neither be resolved nor attributed to one of them. As a pragmatic approach, it was decided to renormalise all measurements by plus or minus 10% to a virtual average spectrometer. To account for this additional uncertainty, the final dose results carry an additional uncertainty of ±10%.

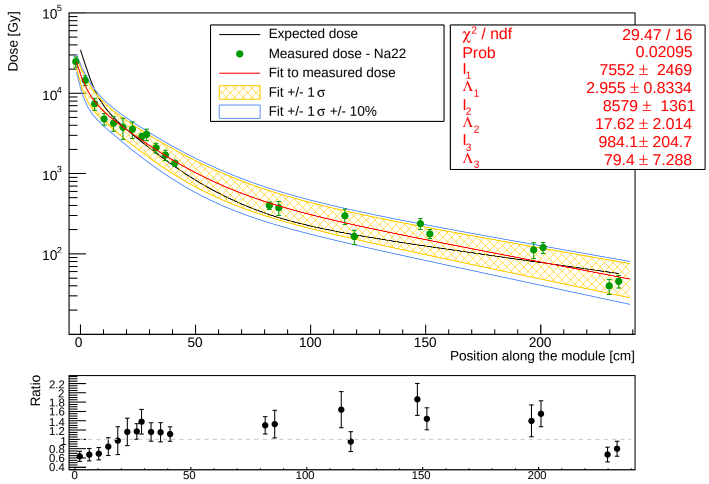
3.3 Dose profile

The plots in Figure 10 show the results of the dose calculations including all corrections and re-normalisations as a function of the position along the fibre module. The left edge (position = 0) corresponds to the mirror end. The data points are exclusively based on the analysis of the ^{22}Na activity. The data was fitted with a sum of three exponential functions (red line). The plots include also the targeted dose as predicted by the FLUKA calculations (black line). For positions up to 40 cm, the results of the front and back aluminium samples (0.5 and 1 cm wide) were averaged to a single value per position taking into account the 0.5° rotation. For larger positions the front and back results are plotted individually, with a separation of 4 cm which corresponds to the 0.5° rotation. The ratio plots show the ratio of the measured and target doses. The results in numerical form are summarised in Table 2.

Within the uncertainties, the measured dose profile matches well the targeted distribution. At positions below 20 cm, the module was under-irradiated by about 20-30% while for positions above 50 cm the measured results trend to a 30-40% overdose. The irradiation can be considered as successful in the sense that it has reproduced a dose distribution which comes very close to the one expected in the final SciFi detector.



(a) Linear scale



(b) Logarithmic scale

Figure 10: Comparison of the expected and measured dose along the module. The black line represents the targeted dose on the module. The data points are the values of the dose measured with ^{22}Na. The data points were fitted with a sum of three exponential functions. The $\pm 1\sigma$ envelope is drawn as a yellow shaded area. The blue lines represent the additional $\pm 10\%$ uncertainty.

3.4 Discussion

The main goal of this experiment was the irradiation of a 2.5 m long fibre module with a dose distribution which resembles as much as possible the expected distribution in LHCb after an integrated luminosity of 50 fb^{-1}. Constrained by geometrical and technical limitations,

Position [cm]	**Dose [Gy]**	**Err [Gy]**
-2.1	24727.6	3620.9
2.1	14460.5	2015.3
6.2	7397.8	1272.4
10.3	4786.1	784.5
14.4	4241.7	862.7
18.5	3773.8	1100.1
22.6	3567.2	832.9
26.7	2882.8	294.7
28.7	3074.4	506.1
32.8	2095.7	290.2
36.9	1702.5	253.6
41.0	1356.7	131.9
82.1	401.5	41.5
86.2	375.7	75.4
114.9	298.0	64.1
119.0	164.9	33.0
147.7	238.0	36.9
151.8	177.2	23.0
196.9	112.3	25.1
201.0	119.9	17.9
229.8	40.0	8.5
233.9	45.6	8.0

Table 2: Measured dose as a function of the position (from the mirror end). The first point at -2.1 cm lies outside the fibre mat. The errors reflect the statistical uncertainties of the activity measurements at the 1σ-level. The overall normalisation of the dataset has a $\pm 10\%$ uncertainty (see section 3.3).

the tilted mounting of the module was the only way to achieve such a profile. Installing and aligning such a relatively heavy object with an asymmetric weight distribution in the beam is challenging, when the radiation background (approx. 10 μSv/h) suggests to keep the presence of people in the zone as short as possible.

The design of the mechanical support provided the necessary flexibility and adjustability. Made from plexiglass to avoid activation, it also slightly deformed under the load which was however corrected in an ad-hoc way by using little shims. The instability of the PS beam width by several mm was found to be a limitation for the precision with which the steep dose profile could be reproduced. Variations of the beam in the mm-range transform to cm changes in the module coordinate system.

The chosen approach for the dosimetry, namely the use of Al-strips mounted orthogonally to the beam axis, proved to be an efficient way to assess the dose distribution along the mat. The strips could be cut in sufficiently small pieces, down to 5 mm width, which represent sections of about 4 cm length along the fibre module. The activity determination of the numerous Al pieces by means of a Germanium spectrometer is a tedious work, which for the short-lived ^{24}Na isotopes needs to be done within very few days after the irradiation. As explained in section 3.1, we obtained more reliable results by concentrating on the analysis of the longer-lived ^{22}Na isotope.

We encountered the unexpected problem of inconsistent results when using two different Ge spectrometers, which we could only work around by a re-normalisation of the data, which entailed however an increase of the uncertainty. Thanks to the long half-life of the ^{22}Na there is a chance to sort out this issue at a later stage when both spectrometers are operational again.

During the irradiation the module, presumably mainly the aluminium endplugs, was activated. A measurement performed by the CERN RadioProtection Group with a Ge spectrometer one month after the irradiation revealed the only presence of the unstable isotope ^{7}Be (half-life of 53 days), with an activity of $3.2 \cdot 10^4$ Bq. This value is below the CERN exemption limit, so that the module could be declared as non-radioactive.

In summary, the irradiation experiment was successful and it can be expected that the analysis of the test beam data will provide valuable information for a verification of the design parameters of the LHCb SciFi detector.

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