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A setup to perform X-ray irradiation tests on scintillating fibres for the SciFi project

L. Gavardi[1], A.B. Cavalcante[2], C. Joram[3], R. Kristic[3]

[1] *Fakultät Physik, Technische Universität Dortmund, Dortmund, Germany*
[2] *Centro Brasileiro de Pesquisas Físicas (CBPF), Rio de Janeiro, Brazil*
[3] *European Organization for Nuclear Research (CERN), Geneva, Switzerland*

Abstract

An X-ray setup has been installed at CERN. The setup will serve for quality assurance purposes related to the acceptance of 11′000 km of scintillating plastic fibres for the SciFi detector of LHCb. The setup is intended to monitor the relative radiation response of the different fibre batches. The dose rate absorbed by the fibre under test can be tuned, adjusting the settings of the X-ray tube and adding aluminium filters of different thicknesses. When operating the X-ray tube without filters at a high voltage of 40 kV and an anode current of 30 mA, the dose rate is about 23 Gy/min. The maximum dose of about 35 kGy expected in the SciFi Tracker can be thus reached in about 1 day.

Contents

1 Introduction

1.1 The SciFi Tracker

A major upgrade for the LHCb detector will be installed during the Long Shutdown 2 of the LHC. The current trackers will be replaced by the SciFi tracker, a detector based on 250 µm diameter scintillating fibres [1]. The scintillating fibres will be arranged in mats of six layers of fibres of 2.5 m length. A mirror will be glued at one mat's end and the fibres will be read out by SiPMs at the other end. The SciFi detector will be composed by three tracking stations of 5 m length and 6 m width around the beampipe. Each station will consist of four stereo-layers in x-u-v-x configuration as sketched in Figure 1.
The SciFi detector is conceived to take physics data for an integrated luminosity of at least 50 fb^{-1}. FLUKA simulations [2, 3] have been used to model the absorbed dose in the tracking stations at the end of the SciFi tracker's lifetime (Figure 2). The absorbed dose varies by three orders of magnitude along the fibres length, from 35 kGy in the region close to the beam pipe, to 50 Gy at the outer edge where the SiPMs are located.

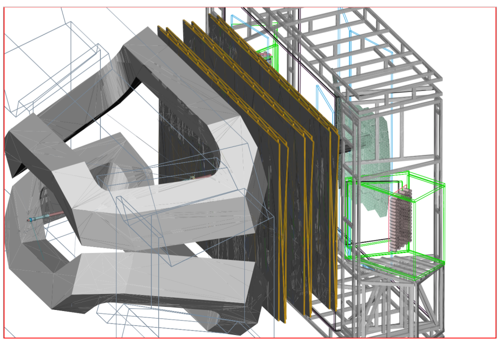

Figure 1: A sketch of the three SciFi tracking stations between the magnet and the RICH2 in the upgraded LHCb detector.

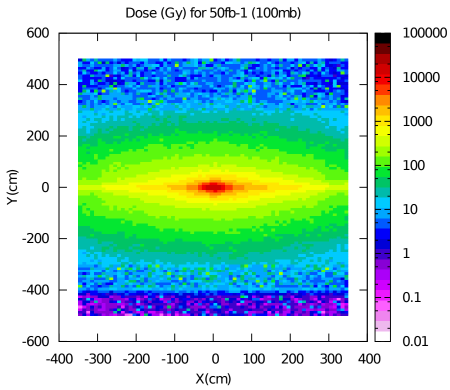

Figure 2: Absorbed dose in the first tracking station after an integrated luminosity of 50 fb^{-1} and for a pp cross-section of 100 mb. The point (0; 0) corresponds to the beam pipe. In the y-direction the SciFi extends only up to +/- 250 cm.

1.2 Motivation

Over 10′000 km of scintillating fibres are needed to build the SciFi detector. The fibres are produced by the Japanese company Kuraray and shipped to CERN. Here their mechanical and optical properties are inspected before they are dispatched to the institutes responsible for the fibre mats production. Scintillating fibres of a total length of 300 km are delivered to CERN every two weeks. The fibres quality assurance (QA) at CERN includes measurements of the attenuation length, light yield, diameter, cladding integrity

and radiation hardness. The setups are conceived for high throughput and run by a team of skilled operators.
The damage of ionizing radiation to plastic material is known to depend on radiation type, energy, rate and environmental parameters. X-ray irradiation in the lab can therefore not be used to validate the hardness of fibres in a high energy hadron radiation field. In the dose range relevant to the LHCb SciFi Tracker, ionising radiation reduces the attenuation length of the fibres while scintillation and wavelength shifting mechanisms appear unaffected. Possible anomalies in the degradation of the attenuation length, when exposed to X-ray irradiation, may hint to chemical or other problems (e.g. polluted ingredients). X-ray irradiation tests are therefore considered a useful complement to the optical QA tests.
We require that, after being exposed to X-rays to an ionizing dose of up to 1 kGy, the attenuation length of a 3 m long fibre shall not decrease to less than 40% of its original value. With the X-ray setup described in this note, an irradiation test of up to 1 kGy can be performed within 45 minutes.

2 Radiation hardness test

2.1 Experimental setup

The X-rays are generated by an XRD glass tube with a tungsten target produced by the company PANalytical[1]. It can be powered up to a maximum high voltage of 60 kV and a maximum power of 2.4 kW, so that the maximum anode current at 60 kV is 40 mA. The company GNR[2], who provided the power supply and the tube housing, suggested to operate the tube at a maximum setting of 40 kV, 30 mA to ensure a longer lifetime of the tube. The tube is positioned in a shielded housing, provided with two electromagnetic and mechanical safety shutters. When the shutters are closed, the radiation outside the tube shield is less than 1 mSv/year (full safety shielding according to the international guidelines) even when the X-ray tube is operated at its maximum power. Only one X-ray beam is used in this setup. Figure 3 shows the tube shield with the tube mounted inside. The tube shield is installed in a custom-made shielding box (see Figure 4). Its side walls, facing the X-ray outlets, are made of 5 mm thick lead plates, sandwiched between aluminium sheets. The top and bottom walls are fabricated from 6 mm thick copper sheets, while the back wall and front double doors are fabricated from 5 mm thick copper sheets. Structural stability is assured by a framework of Bosch profiles.
The high voltage is provided by a power supply of type GNR C3K6PC-RS232, located below the shielding box (Figure 4). The power supply can provide a maximum power of 3 kW and a maximum high voltage of 60 kV. The tube requires to be cooled by chilled water, which circulates in a closed loop with a refrigeration cooler (Julabo FL2503, Figure 5). The temperature of the water must be kept between 20°C and 26°C and the pressure

[1] http://www.panalytical.com
[2] http://www.gnr.it

between 4 and 8 bars.

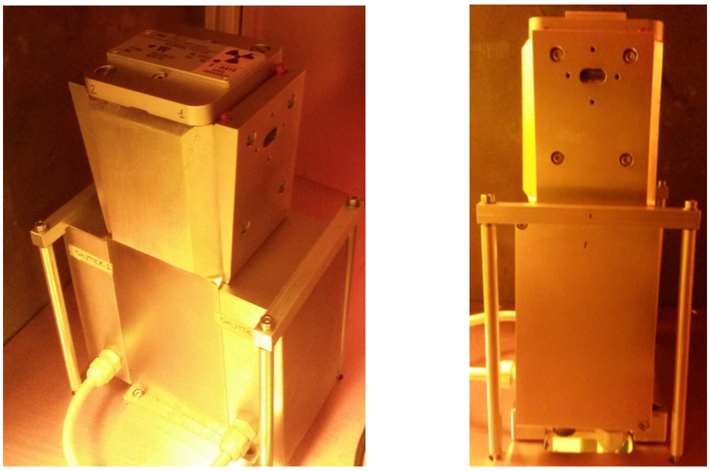

Figure 3: Side view (left) and front view (right) of the X-ray tube inside the tube shield.

2.2 Safety systems

The X-ray setup is equipped with several safety devices. The power supply is interlocked with two door switches on the shielding box (Figure 6), with a flow switch (Figure 5) and the X-ray warning lamp (Figure 4). The switches on the shielding box ensure that both shutters are closed if either of the two doors is open. The flow switch is mounted on the return line of the cooling system, approximately 1 m from the X-ray tube and would cause the high voltage to be switched off in case the water flow was too low. The

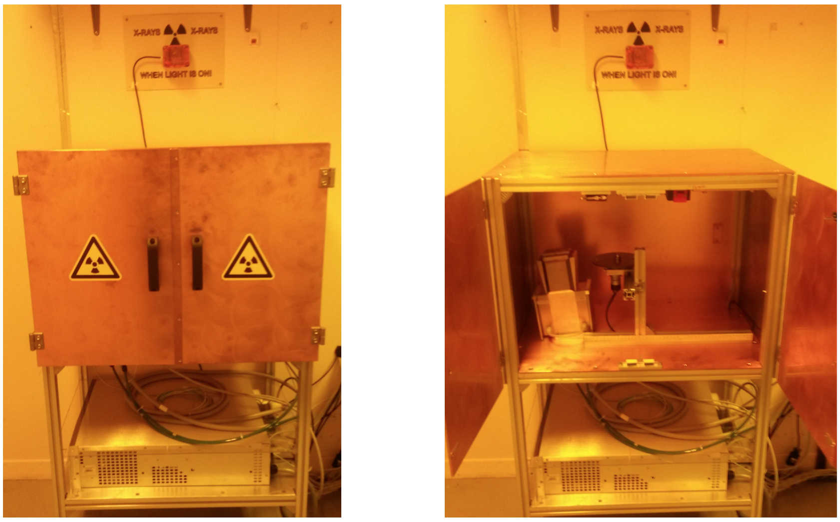

Figure 4: Custom-made shielding box containing the X-ray tube. The power supply is placed below the shielding box.

Figure 5: The chiller (left picture) and the flow switch (right picture).

warning lamp, placed just over the shielding box, is automatically switched on as soon as the X-ray tube is powered up. Furthermore the power supply is interlocked in case of overload, overvoltage or overcurrent.
The power supply, as well as all the safety devices, are connected to a wall-mounted control box. A picture of the control box can be seen in Figure 7. The LEDs on the control box indicate if the safety conditions, including water and interlocked doors, are fulfilled and if either of the two shutters is open.
The power supply, as well as the mechanical shutter in use, can only be operated via a GNR control software, which also shows the status of the safety devices. The software is installed on a dedicated laptop protected by a password. Figure 8 shows a screenshot of the software with all the security conditions fulfilled (green boxes), the tube powered to 40 kV, 30 mA and the shutter open (red box). The X-ray tube cannot be powered up manually and the software does not allow to power up the tube if any of the safety conditions is not fulfilled. The second shutter can only be opened with a key in custody of the Radiation Protection Group at CERN.
The Radiation Protection Group validated the safety of the setup, after testing the well functioning of the safety devices and measuring the dose outside the shielding box when the X-ray tube is powered up with the maximum high voltage and current allowed. As required by Swiss law, the dose rate was found to be less than 1 μSv/h at 10 cm distance for all the accessible surfaces of the shielding box.

2.3 X-rays emission spectrum

The emission spectrum is calculated with the commercial software *SpekCalc* [5]. The software allows to calculate the emission spectrum of an X-ray tube with tungsten target as a function of the applied high voltage and possible filter layers. The thickness and material of each layer is defined by the user. Figure 9 shows the emission spectra for a

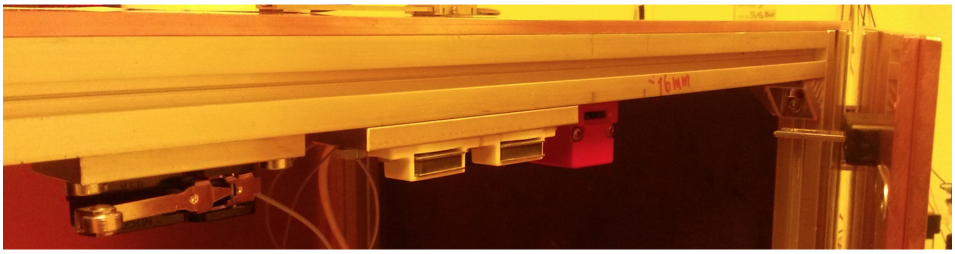

Figure 6: The two interlocks.

Figure 7: The control box.

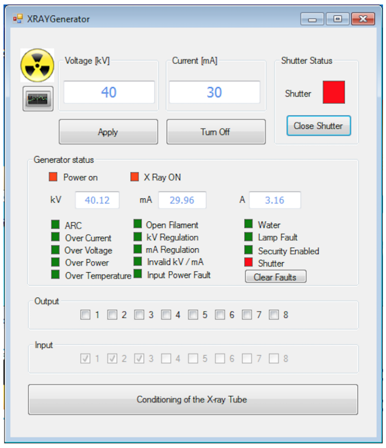

Figure 8: A screenshot of the software.

tungsten tube powered with a high voltage of 40 kV, after a layer of air of 45 mm thickness and layers of aluminium of different thicknesses. The typical spectrum of an X-ray tube shows spikes corresponding to the characteristic lines of the target atom and a continuous distribution due to bremstrahlung. A thin layer of aluminium can be used to absorb the low energetic X-rays and eventually remove the peak at < 10 keV.

2.4 Radiation tests and dosimetry

The scintillating fibre under test is typically $3 - 3.5$ m long. In this way its attenuation length can be measured as described in [4]. The fibre under test is wound on a 15 cm diameter and 5 mm height plastic wheel, equipped with a groove (Figures 11 and 12). The wheel can be placed in the setup so that the coiled fibre faces the beam outlet. The wheel is connected to a motor and rotates with constant speed, to ensure uniform irradiation over the whole fibre length. The setup inside the shielding box is shown in Figure 13.
Dosimetry is carried out with Gafchromic HD-810 dosimetric films[3]. They consist of an active layer, approximately 6.5 µm thick, coated on a clear, transparent 97 µm thick polyester sheet. When irradiated, the active component in the dosimetric film reacts to form

[3] http://www.gafchromic.com/

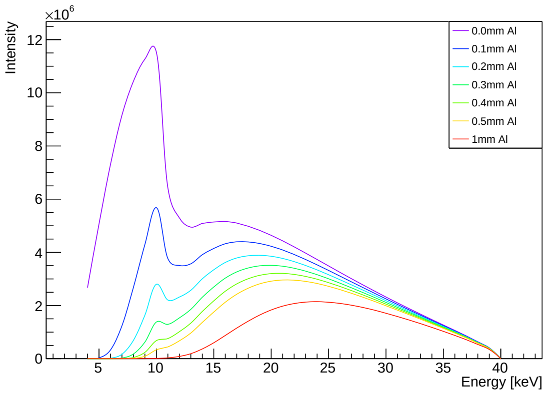

Figure 9: Emission spectra of an X-ray tube with tungsten target, powered with a high voltage of 40 kV, at a distance of 45 mm.

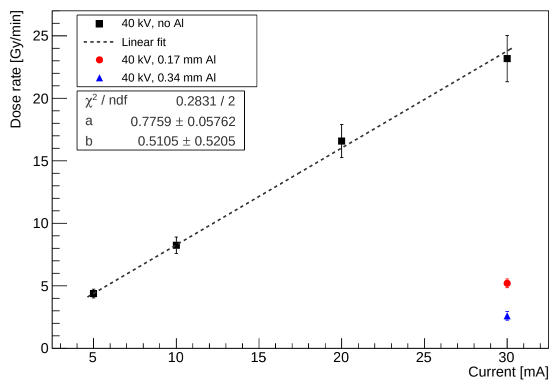

Figure 10: Measured dose rate at a distance of 4.5 cm from the beam outlet.

a blue coloured polymer and the optical density of the film is proportional to the absorbed dose. A dosimetric film is fixed to the rotating wheel before every irradiation as shown in Figure 14 and then measured with a Model 37-443 Nuclear Associates densitometer[4]. The uncertainties on the dose rate measurements are estimated to be 8%. A picture of a Gafchromic HD-810 film after irradiation is shown in Figure 15. The dose rate at a distance of 4.5 cm from the beam outlet has been measured with different tube settings and layers of aluminium. The measured dose rates are plotted in Figure 10.
At the present time 14 fibre samples have been tested for radiation hardness. The results are presented in the plot in Figure 16, where each spool lot number corresponds to a different fibre sample. All the samples have been irradiated to a dose of 1 kGy with the X-ray tube operated at 40 kV, 30 mA. For two of these samples (spool lot number CE160817-8 and CE160824-14) a 0.17 mm aluminium filter has been placed between the beam outlet and the fibre, while for all the other samples no filter has been used. All samples keep an attenuation length between 65% and 78% of the original value. Putting a 0.17 mm aluminium filter in front of the outlet and thus reducing the dose rate to 5 Gy/min, does not produce a different result. The results are very constant. The radiation hardness of the different fibre batches evaluated in this way has so far not changed. All the tested fibre samples are well above the limit of 40%.

3 Summary and conclusions

An X-ray setup has been installed at CERN. Its main purpose is the quality control of scintillating fibres for the SciFi detector of LHCb. The X-ray setup has been validated by the Radiation Protection department at CERN and is now fully operational. The dose rate absorbed by the fibre under test can be tuned adjusting the settings of the X-ray

[4] http://www.flukebiomedical.com

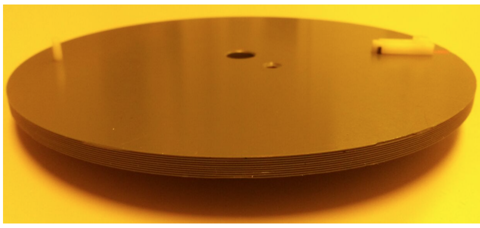

Figure 11: The plastic wheel.

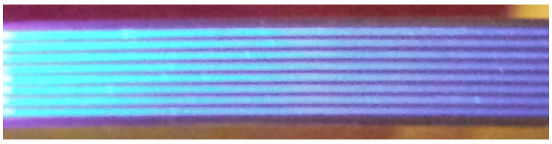

Figure 12: The fiber under test coiled around the plastic wheel. In this picture the fibre is excited with UV-light in order to improve visibility.

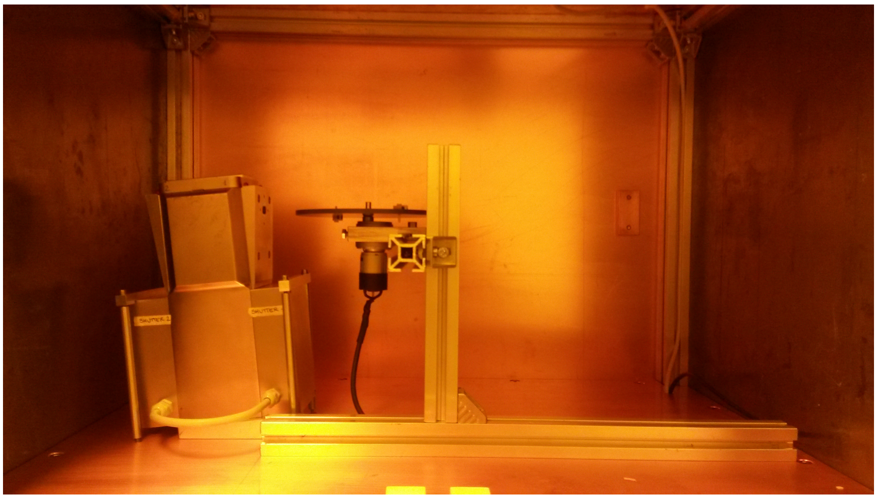

Figure 13: Setup inside the shielding box. The fibre under test is coiled around a plastic rotating wheel facing the X-ray beam.

tube. At the standard settings of 40 kV, 30 mA the dose rate is about 23 Gy/min. The time needed to irradiate a fibre sample to the maximum dose of about 35 kGy expected in the SciFi Tracker is about 1 day. The X-ray setup is being routinely used for QA purposes: 3 fibre samples from every 300 km are irradiated to a dose of 1 kGy with the standard settings of 40 kV, 30 mA.

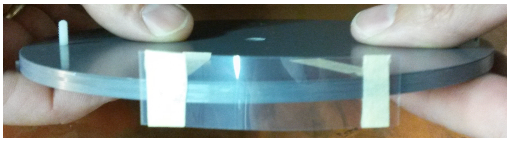

Figure 14: A transparent Gafchromic HD-810 dosimetric film fixed on the plastic wheel before irradiation.

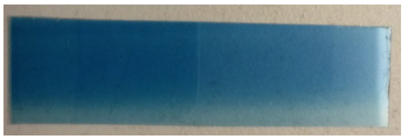

Figure 15: A Gafchromic HD-810 dosimetric film after irradiation: the active component reacted to form a blue polymer. The central region, where the fibres are located, has received a uniform dose.

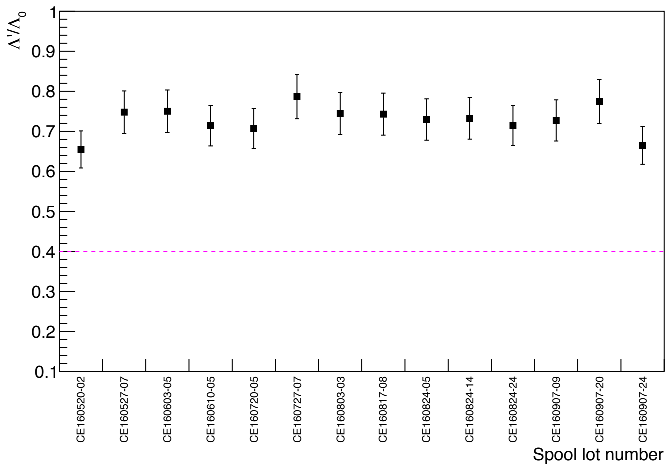

Figure 16: Results of the X-ray radiation test up to 1 kGy on 14 different fibre samples, where Λ_0 is the attenuation length before and Λ' is the attenuation length after irradiation. The magenta dashed line corresponds to the required limit of 40%. The error on the attenuation length measured with the setup described in [4] is 5%.

In parallel we perform other studies of more general interest. One example is the effect of X-ray irradiation on the spectral attenuation length of the fibres. Another field of interest is the annealing of the fibres after the irradiation as a function of the dose, dose rate and environmental conditions (fibre stored in air or in vacuum). These studies may shed light on the damage and annealing mechanisms of the fibres and complement the hadron irradiation studies performed previously with accelerator beams.

Acknowledgements

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