ISBN: 978-3-95450-208-0 doi:10.18429/JACoW-IPAC2019-WEPGW078

# DEVELOPMENT AND TEST OF A BEAM IMAGING SYSTEM BASED ON RADIATION TOLERANT OPTICAL FIBER BUNDLES

D. Celeste†, E. Bravin, S. Burger, F. Roncarolo, CERN, Geneva, Switzerland

*Abstract*

Many of the beam imaging systems at CERN are located in high radiation environments. In order to cope with this issue, VIDICON cameras are presently used, but their production has been discontinued worldwide. This paper presents the development of an alternative beam imaging system, based on radiation tolerant optical fibre bundles. The fibre bundle is used to relay the image of a scintillating screen to a standard CMOS camera, located away from the high radiation zone. A prototype system based on a 10m long bundle with $10^4$ fibres has been tested in the laboratory by simulating the beam profile using a laser spot. The light transmission through the system is rather low, but is compensated by the high sensitivity of the CMOS camera. The tested system had a field of view of 60 mm and a spatial resolution of ~1 mm. The radiation hardness of the fibre bundle was tested at the IRMA-CEA facility in Saclay, France. The bundle was irradiated at a rate of 3.6 kGy/h for 8 consecutive day. The total integrated dose achieved was ~700 kGy, which corresponds to about ten years of operation at the beam imaging station with the highest radiation dose at CERN. Although the light transmission was reduced by 50% after irradiation, this is still sufficient for our purpose.

## INTRODUCTION

An upgrade of the radiation hard beam imaging systems at CERN is needed to replace the obsolete VIDICON cameras currently used [1]. Even though the VIDICON cameras still fulfil our requirements, the production of VIDICON tubes has been discontinued and we only have spare tubes for a few years. This paper presents the concept and the first results of the alternative solution being investigated by the CERN Beam Instrumentation Group, based on imaging via radiation tolerant optical fibres.

The solution is based on an optical system that collects the light generated by the particle beam impinging on a scintillating screen, and relays the image away from the radiation area where it can be acquired using a standard CMOS camera. The optical system is based on a radiation-resistant, fused silica, fibre bundle.

This paper will give details of the setup and report on the optical performance obtained, including the radiation tests, and discuss the present, underlying limitations and plans to further improve the system.

## OPTICAL TESTS

### *Experimental Setup*

The principle of the technique is sketched in Fig.1. A calibration pattern is back-illuminated using a 5x7 cm$^2$ flat, "white" LED array. An objective lens of 9 mm focal length is placed 500 mm away from the test pattern to create an image of the reference pattern on the fibre bundle entrance face. The bundle used in this setup is a 10m-long, radiation-hard, Fujikura FIGR-10 bundle [3], which contains 10,000 ordered fibres of diameter 1100 ± 100 µm, arranged in a circular pattern.

A second lens, in this case of focal length 25 mm, is placed at the opposite end of the bundle in order to image the output face of the bundle onto a CMOS sensor.

The focal length of the lenses and the distances between fibre, lenses and camera have been optimised for the wanted field of view and magnification.

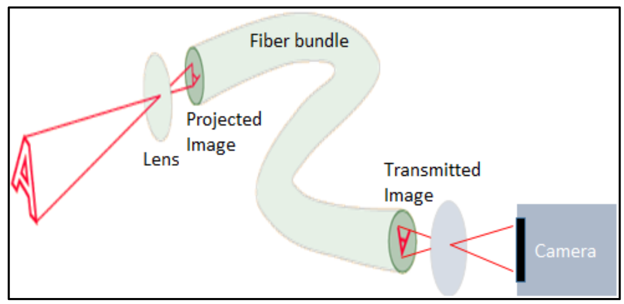


Figure 1: Sketch of the setup of the beam imaging system.

### *Optical Characterisation Results*

Initially we investigated the optical quality of the system for different lens combinations and different configurations. The two most important aspects in our case are the light transmission efficiency and the final optical resolution of the system. In order to identify the contributions of the different elements the following tests were performed:

1. Imaging using only one lens and the camera (Fig 2.)
2. Two stage imaging using two lenses and the camera, where the second lens re-images the real image of the first lens
3. Two stage imaging including the bundle. The bundle simply deports the real image of the first lens to a new location where the deported real image is re-imaged by the second lens onto the camera (Fig. 3)

These tests were performed for different lens combinations and for different lens-object distances. We have also compared a 2 m and a 10 m long bundles in the exact same conditions to study the losses in the fibre itself.

Comparing test 1 and test 3, with the lenses adjusted to obtain the same field of view and magnification, only 2.1% of the light that reaches the camera in the first case arrives on the camera in the second case. In test 2, with same conditions as test 3 but without the bundle, 26 % of the light reached the camera. In the central square of the target with

† damiano.celeste@cern.ch

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1 mm² gaps, the contrast when comparing tests 1 and 3 decreases from 0.9 to 0.16.

Despite the dramatic degradation of the image quality between test 1 and test 3, the results are still comparable with what we can obtain with the present radiation hard systems and this scheme would thus be suitable for monitoring the particle beams. Moreover further tuning of the parameters, adapting the field of view, magnification and exposure time could improve the quality of the images.

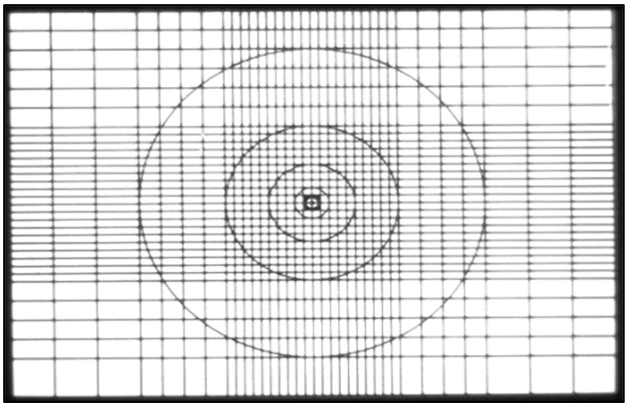

Figure 2: Reference image acquired with C-MOS camera with a 25 mm focal length lens.

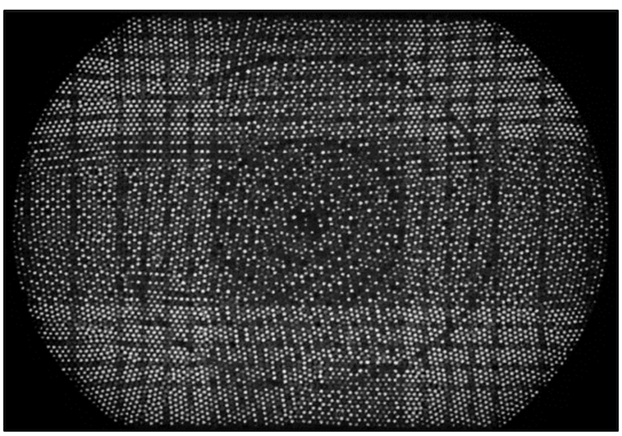

Figure 3: Acquired image with a 9 mm focal length lens (input), 10 m Fujikura FIGR-10 image fiber bundle, 25 mm focal length lens (output) and CMOS camera.

## RADIATION HARDNESS TESTS

### *Experimental Setup*

In order to address the second important aspect of the system, we performed an irradiation test that simulates ten years of operation in our accelerator environment, in order to quantify the degradation of the optical performances with the integrated dose. This test requires the uniform irradiation of a considerable portion of the fibre bundle up to a minimum of 500 kGy total absorbed dose.

This irradiation test was carried out in collaboration with the IRMA [4] irradiation facility in Saclay (France). A 2.2 m long segment of the FIGR-10 Fujikura fibre was wrapped with a 20 cm radius of curvature around a $^{60}$Co isotropic source, resulting in a dose rate of 3.6 kGy/h. The remaining length of the bundle was fed outside the irradiation cell where one end was used to image the test pattern light source and the other to relay the image to the camera, as in test 3. A sketch of the irradiation setup is shown in Fig. 4. This setup allowed a continuous monitoring of the optical system during the irradiation. The fibres were continuously irradiated for eight days and left in place without the source for one additional day to observe any annealing. Images were recorded every 15 minutes over the whole period.

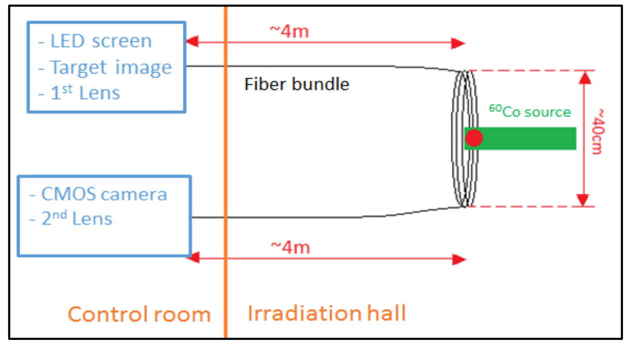


Figure 4: Sketch of the irradiation test set up.

### *Irradiation Results*

Figure 5 shows the images acquired before and after irradiation up to a 694 kGy total absorbed dose. The light transmission loss due to the irradiation is 48% (calculated as the difference in the light integral when comparing the two images). As expected an annealing effect occurs at the end of the irradiation with a recovery of 7% of transmission in the first hour and more than 10 % after 24 h. The annealing was re-measured four months later with the annealing reaching a saturation value of 15 %.

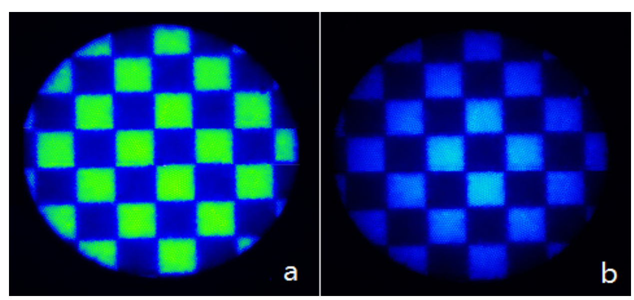


Figure 6: Test pattern image before irradiation (a) and after irradiation (b).

Looking more in detail it is possible to notice that the transmission loss is not uniform across the fibre bundle, with a higher loss on the outside fibres than the central fibres. This non-uniform behaviour has been quantified by normalizing all acquired images to the reference taken before irradiation and by evaluating the transmission loss across the diameter. The results are shown in Fig. 7. At 240 kGy the edges have lost more than 45% transmission while the loss in the centre is still less than 5%. From 240 kGy onward even the central area of the bundle starts quickly degrades, and by the end of the irradiation the central transmission has gone down to 63% of the initial value. For the

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outer part of the bundle, the transmission at the end of the irradiation is only 32% of the initial value. This difference along the diameter is probably due to production conditions that result in a larger number of structure defects towards the outside of the bundle. The annealing effect is also clearly visible in the graph.

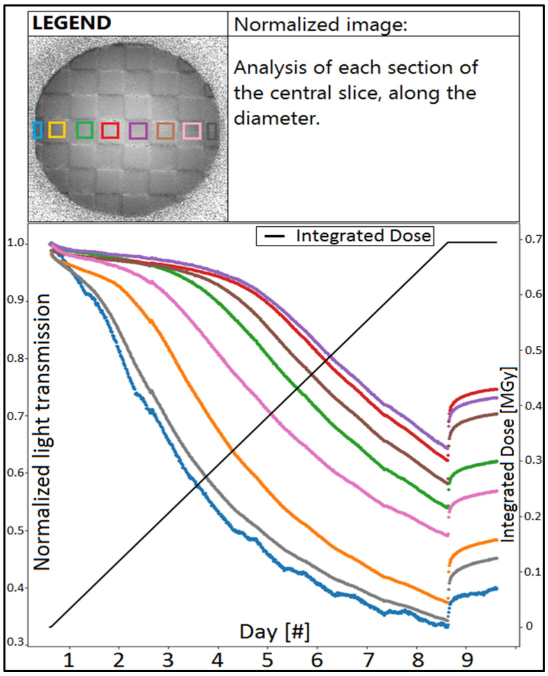


Figure 7: Transmission loss across the fibre bundle as a function of the total integrated dose.

## IMAGING TESTS

### *Experimental Setup*

To simulate the signal of a particle beam impinging on a scintillating screen a red laser (650 nm) on a white target was used. The laser spot has a quasi bi-Gaussian distribution with a width of the order of 1.6 mm which is a good representation of the real beams being measured. The first lens of the imaging setup under test sits 500 mm away from this target. Using the test bench, we compared a simple imaging system consisting solely of a lens and a camera (as in test 1of the original optical measurements) and a system based on the fiber bundle (test 3).

### *Results*

First of all, the magnification of the system was assessed by mean of a calibration pattern. After that, images of the laser spot were acquired with the projections onto both the vertical and horizontal axis calculated. The resulting profiles were fitted with a Gaussian function in which the center, amplitude and width were fit parameters. The results of these tests are shown in Fig. 8. The agreement is not good, with the ratio between the two measured widths being 1.23. We suspect light leakage and crosstalk between fibers to be the cause of this discrepancy. However, more investigations are needed to confirm this hypothesis.

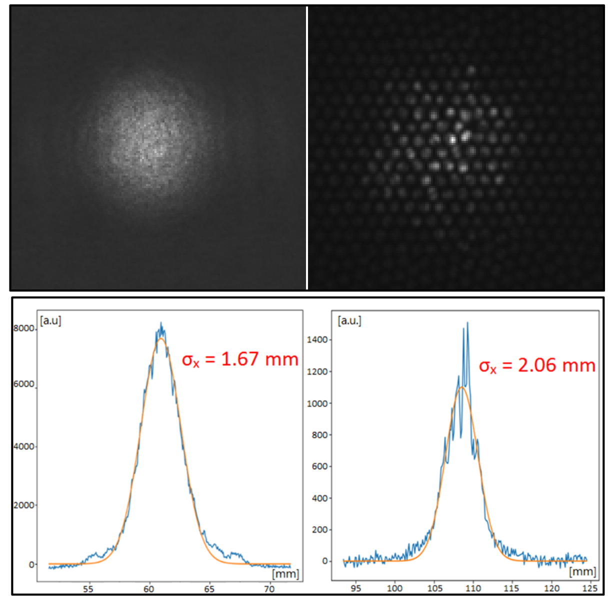


Figure 8: Laser spot image (top) and projection (bottom) without (left) and with imaging fibre bundle (right). The quoted sigma value corresponds to the width of the fitted Gaussian function.

## CONCLUSION

A radiation hard optical imaging setup based on imaging fiber bundles has been designed and characterized. Despite an overall low light collection efficiency of only 2% compared to a simple camera-lens system, the proposed scheme would still be competitive with the present VIDICON cameras.

Irradiation tests have shown that the degradation of the imaging fibers is acceptable, with 48% transmission loss after ~700kGy. However this is not uniform across the bundle and would therefore require post processing corrections. This could be done, for example, by normalizing images to a reference uniform light source.

The loss of optical resolution of the imaging system due to the limited number of fibers in the bundle would also be acceptable. However, imaging tests using a laser beam to mimic the particle beam, have shown that there is additional broadening. This is suspected to come from light leakage and cross-talk between the fibers, with further tests foreseen to confirm this.

## REFERENCES

[1] E. Bravin *et al.*, “A new TV beam observation system for CERN”, *DIPAC 2005,* Lyon, France, pp. 214.

[2] T. Lefevre *et al.*, “Profile monitors, injection matching monitor and synchrotron light monitors”, in Evian 2010 workshop on LHC commissioning, Evian-Les-Bains, France, Jan 2010, pp. 67-70.

[3] Fujikura Ltd., “Standard specification for imagefibers”, Jan. 28 2014, No.B-07D9045H, pp. 11.

[4] https://www.irsn.fr/EN/Research/publications-documentation/Publications/DSU/LPMAC/Pages/La-cellule-d-irradiation-IRMA-1437.aspx