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NOVEL HOLLOW CORE OPTICAL FIBRE-BASED RADIATION SENSING TECHNIQUE FOR MEDICAL APPLICATIONS AND EXTREME ENVIRONMENTS

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Abstract

As part of our search for radiation-hard techniques for beam profile monitoring, we tested a novel method based on hollow-core optical fibres. These fibres, filled with scintillating gases, combine exceptional radiation tolerance with the inherent radiation hardness of the gases. We tested this new technique at the CLEAR accelerator at CERN, demonstrating its potential for beam diagnostics. The standard deviation of the CLEAR electron beam transverse profile was successfully measured to be 1.15 mm ± 0.02 mm, close to the width of 1.30 mm ± 0.07 mm obtained from a YAG screen. No loss of signal was observed after the fibre received a dose of 0.915 MGy. The technique shows particular promise for FLASH therapy, where it could offer significant improvements in reliability and functionality compared to current instrumentation.

INTRODUCTION

Future needs for beam instrumentation to measure intense beams, with up to 10^{11} particles per second, have motivated a search for suitable techniques, for both research and medical purposes in radiation-hard environments. An overview of this research is presented at IBIC 2025 [1]. Previous work has studied the possibilities of using solid silica glass rods [2, 3] or glass capillary tubes filled with a liquid scintillator [4] coupled to a camera or other photo-sensor. Both of these techniques give a good signal, but suffer from degraded performance at high absorbed doses. The development of hollow core fibres (HCF), capable of guiding light in the visible spectrum [5, 6], presents new opportunities for radiation sensing techniques. HCFs do not suffer from the same radiation-induced attenuation that limits the lifetime of conventional optical fibres in environments with high radiation levels [7]. In this paper, we present work that combines the radiation-hard characteristics of the HCF with an intrinsically radiation-hard noble gas scintillator to obtain a novel radiation-hard beam-sensing technique.

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METHODS

A 200 MeV electron beam from the CLEAR accelerator [8] was used for the experiment. The intensity of the beam was varied in the range from 0 nC to 41.2 nC per bunch train, both by changing the charge per bunch and the total number of bunches in one shot from the accelerator. The irradiation was carried out with a repetition frequency of 0.833 Hz. The bunch length was 10 ps and the bunch spacing was 666 ps.

The key elements of the setup are sketched in Fig. 1. The HCF was placed horizontally in the plane perpendicular to the beam. On one end, the HCF was spliced to a Thorlabs SM450 fibre. The opposite end of the HCF was connected to a compression-based gas feed-through assembly, which interfaced it with a gas distribution pipe. Both the gas pipe and the SM450 fibre were routed to a barrack outside the beam area. The length of HCF between the beam impact point and the splice was 60 cm. The HCF was placed on a support structure holding it steady in the beam. This support was placed on top of a vertical motion stage, allowing the HCF to be scanned through the beam in the direction perpendicular to the beam and the HCF. Immediately upstream of the HCF, the electron beam passed through a beam charge monitor. A scintillating screen was placed downstream of the HCF at an angle of 45° to the beam, and a camera was pointed at the screen perpendicularly to the beam. The HCF used was a 7-tube single-cladding ring fibre, with 170 nm thick capillary membranes, capable of continuous guidance from 360-1100 nm, fabricated from fused silica glass [5, 6]. In the barrack, the SM optical fibre was routed to a black box and placed such that the light exiting the fibre impacted a Hamamatsu S13360-1350PE silicon photomultiplier (SiPM) sensitive to photons in the wavelength range of 300-900 nm. The output of the SiPM was connected to an oscilloscope, acting as a digitiser of the analogue signal from the SiPM. The oscilloscope was triggered by a signal from the accelerator. The digitised pulses from the SiPM were then sent via Ethernet to a PC and timestamped and saved for offline analysis. The gas transport pipe was connected to a custom gas panel, which was used to measure the pressure, p, of the gas in the system, as well as switch the connection between

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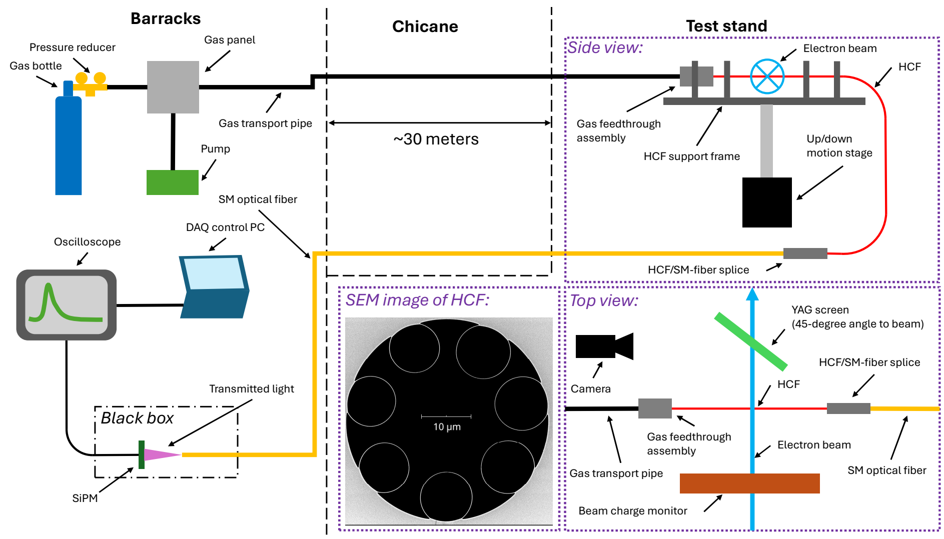

Figure 1: Sketch of key elements of experimental setup. HCF = hollow core fibre, YAG = Cerium(III)-doped Yttrium aluminium garnet [9], SEM = scanning electron microscope, DAQ = Data acquisition.

a gas bottle containing the scintillating gas and a pump used for extracting the atmospheric air out of the system.

The total charge of the beam was measured using the beam charge monitor upstream of the HCF, and in combination with the images of the YAG screen, the charge passing through the hollow core of the fibre, Q, was computed. The number of cells, N_{cells}, that fired in the SiPM was calculated by dividing the total SiPM current pulse integral by the current pulse integral corresponding to a single cell firing.

Measurements were carried out with two gases: a pure N_2 gas and a gas mixture containing 99 % Argon and 1 % N_2 by volume. The pressure was varied in the range 0 to 21 bars absolute using the reducer on the gas bottle and the pump connected to the gas panel. Argon is a well-known scintillator, which mostly generates photons in the UV, peaked at a wavelength of 128 nm [10]. The small N_2 component acts as a wavelength shifter, shifting a portion of the UV photons to a wavelength range to which the SiPM is sensitive [11, 12].

RESULTS

The energy deposited in the gas mixture is calculated as follows:

$$\Delta E = S(E) \frac{\pi r}{2} \frac{mp}{k_B T} \frac{Q}{e}, \tag{1}$$

with $S(E)$ being the stopping power of the gas mixture at the energy of the electrons in the beam, taken from [13], r =20 μm the radius of the hollow core, m the mean mass of one molecule in the gas mixtures, k_B Boltzmann's constant, T the absolute temperature of the gas, and e the electron charge. The factor of $\frac{\pi}{2}$ comes from the average path length of the beam electrons in the cylindrical fibre.

Using literature values for the light yield of Argon gas at different pressures [14] and assuming no saturation effects in the gas, the number of photons generated by the interaction of the beam with the gas, N, is simply the product of the deposited energy and the pressure-dependant light yield $L(p)$:

$$N = L(p) \cdot \Delta E. \tag{2}$$

The number of photons arriving at the SiPM that can trigger the detector, N_{obs}, can then be calculated by taking into account all the efficiencies of the transport, trapping, and the quantum efficiency of the SiPM. Here we take the product of these efficiencies as a single dimensionless fit parameter A. We also take the pressure dependence of the absorption of the gas mixture into account. We assume a linear relationship between pressure and absorbance, i.e. that the gas mixture follows the Beer–Lambert law [15]. We arrive at:

$$N_{obs} = A \cdot N \cdot e^{-p \cdot B \cdot d}, \tag{3}$$

where B is a fit parameter characterising the absorbance of the gas mixture in the relevant wavelength range and d the distance in the HCF from the interaction point to the splice. N_{cells} is then calculated with the following detector saturation model:

$$N_{cells} = N_{eff} \left(1 - \exp\left(-N_{obs}/N_{eff}\right)\right), \tag{4}$$

with N_{eff} being the number of cells in the SiPM that the light from the fibre is spread over, taken as a fit parameter. In summary, the 3 fit parameters of the model are A, B, and N_{eff}. Note that the distance between the SiPM and transport fibre was not well controlled or measured in the setup (but was kept constant), and we therefore have to take N_{eff} as a fit parameter.

The main observable, N_{cells}, is plotted as a function of Q in Fig. 2 for three data series: one with vacuum in the HCF, one with a 21 bar Ar N_2 gas mixture, and one with a 11 bar pure N_2 gas. We see an increase in N_{cells} as Q increases for all 3 cases. A linear fit was made to the vacuum data series, and taken as a background not related to the scintillation or Cherenkov light generated in the hollow core, and subtracted

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from the rest of the data in the analysis. The background signal could be due to beam losses generating Cherenkov light in the transport fibre. We see that the signal obtained from the pure N_2 gas is indistinguishable from background. We also see that there is a clear increase in signal over the background in the case of the Ar N_2 mixture, which we attribute to the scintillation of the Ar, since the measurements with pure N_2 yielded no boost to the signal compared to the background.

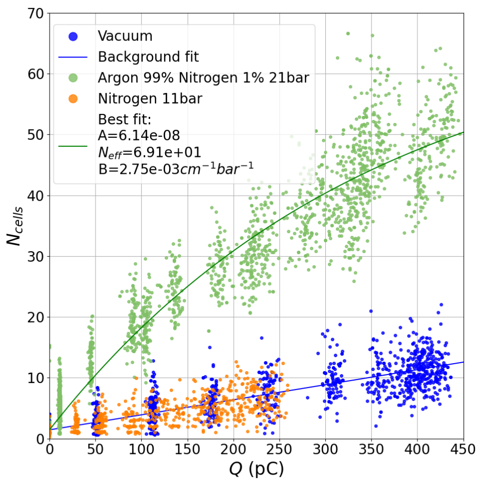

Figure 2: Number of cells fired in the SiPM as a function of the charge passing the hollow core of the fibre. Several data-series are shown for different gas mixtures and pressures. The blue line is a linear fit to the vacuum data. The green line is a fit of Eq. (4) to the 21 bar Ar N_2 mixture data.

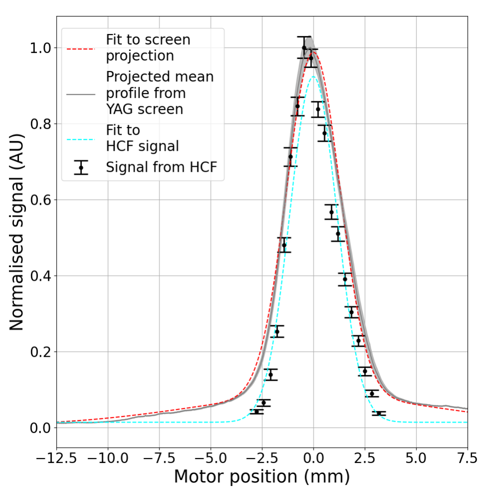

Figure 3: Profile of the beam obtained when scanning the HCF through the beam with the motorisation stage. The reference profile obtained from the camera (grey line) is the mean profile over the shots used to obtain the data points. The standard deviation is represented with a grey shaded area. Dotted lines show fits to the profiles.

Equation (4) was fitted to the obtained data with a standard least squares method. The fit is displayed in Fig. 2. The fit obtained was used to create a lookup table, with which Q could be inferred from a measured N_{cells}. This was used to reconstruct the mean profile of the beam, by inferring the mean charge passing the hollow core as a function of the motorisation stage position. The position scan was carried out with 2000 bunch trains from the accelerator. Figure 3 shows the results of this experiment compared to the mean profile obtained from the camera. The profile from the camera has been scaled using marks on the YAG screen. The profiles were fitted with a Gaussian function. The fit to the HCF data yields a standard deviation of 1.15 mm ± 0.02 mm, while the fit to the camera data yields a slightly larger standard deviation of 1.30 mm ± 0.07 mm. We believe that the broad Gaussian component of the signal obtained from the camera is due to Cherenkov light generated in the air being reflected by the YAG-screen. This could be removed in a future experiment with a blocking foil.

The total dose absorbed by the section of HCF exposed to the beam during the experiment was 0.915 MGy. No clear reduction in signal was observed during the experiment.

DISCUSSION

There are several relatively straightforward improvements for advancing the technique presented here. First and foremost, the coupling from the transport fibre to the SiPM should be well controlled, and the distance between them should be set according to the active area of the SiPM and the numerical aperture of the transport fibre. This is easily achievable with a specialised mounting. A future instrument utilising this technology would likely not need to change the pressure of the gas during operation. Techniques to seal the HCF after filling with a gas mixture have previously been demonstrated [16, 17]. Sealing the HCF after filling would make the assembly of the instrument simpler and free up one end of the HCF for mounting either a mirror or a calibration light source. While HCF have been demonstrated to be extremely radiation hard, and no degradation was observed after the fibre absorbed 0.915 MGy in this experiment, a dedicated study carried out in an irradiation facility like the IRRAD [18] facility at CERN showing the degradation of the signal, or lack thereof, when a larger dose is absorbed by the HCF filled with scintillating gas, is needed to conclusively demonstrate the radiation hardness of the technique. A publication presenting the full dataset obtained in the experiment reported here and a previous experiment is being prepared.

CONCLUSION

We have demonstrated a novel radiation-hard beam sensing technique utilizing a hollow-core fibre filled with scintillating gas. The signal obtained is sufficient for reconstructing beam profiles. These initial results are promising, but further tests are needed to demonstrate radiation hardness not only of individual components but of the complete system.

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