CHARGED PARTICLE BEAM PROFILE DETECTOR BASED ON Yb-DOPED OPTICAL FIBERS*

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Abstract

A radiation robust, high dynamic range beam profile detector based on scintillating fibers will be presented. The beam profile detector has been developed for particle therapy type ion beams of multiple hundreds MeV/n in the intensity range from 10^5 to 10^9 ions/s as a simple and less expensive replacement for MWPC based detectors. Scintillating fibers are typically based on doped polymers, which are sensitive to radiation damage. Here we report on the advantage of using silica optical fibers doped with rare-earth elements for the purpose of detecting ionizing radiation. Specifically, we find that ytterbium doped fibers generate a strong emission signal in the near-infrared from the Yb^{3+} state when penetrated by ionizing radiation, and that the fiber emission has a high radiation resistance. We demonstrate the use of such fibers in a beam profile detector for charged particle beams in medical applications (radionuclide production and hadron therapy); more generally they are a promising alternative for prolonged use in ionizing radiation, such as accelerator diagnostics equipment or space applications.

INTRODUCTION

Knowing the particle beam position and profile is a prerequisite for running an accelerator or performing an irradiation. Particle beam detectors exist in numerous designs, based on different physical principles, and planned with various beam parameters in mind [1].

We have designed and build a detector concept for measurement of the beam profile of the extracted high energy beam in a particle therapy facility. The typical detector for this purpose is the well-established multi wire proportional chamber (MWPC). The MWPC serves the purpose, but is a relatively expensive and delicate equipment to apply, since it involves sensitive electronics, high-voltage, gas, and an elaborate mechanical construction. The MWPC is not vacuum compatible, which is also a disadvantage.

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Here we present a more simple and less costly alternative detector solution based on scintillating optical fibers [2].

The generic beam specifications at the detector location are listed in Tabel 1. Notice, that the active elements of the detector have to cover an even larger dynamic range in order to measure a profile.

Table 1: Beam Specifications

	^{1}H	^{12}C	
Energy (min)	48	88	MeV/u
Energy (max)	220	430	MeV/u
Intensity (min)	$4 \cdot 10^6$	$1 \cdot 10^5$	s^{-1}
Intensity (max)	$4 \cdot 10^{10}$	$1 \cdot 10^9$	s^{-1}

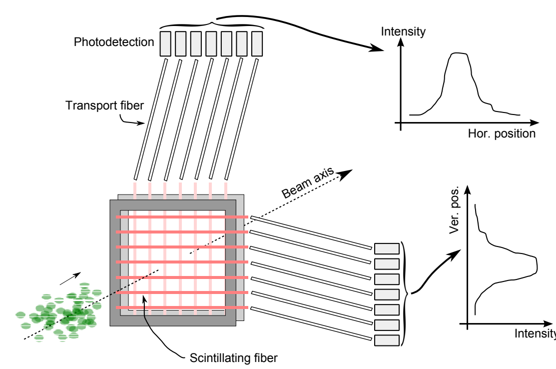

Figure 1: Schematic illustration of a detector for beam profile measurements based on scintillating optical fibers.

Scintillating Optical Fibers

Scintillating fibers have been in use for particle detection for many years [3], and applied in various detector designs and particle beams [4]. When ionizing radiation intersects the scintillating core, light is generated and transported along the fiber due to total internal reflection.

For radiation detection, the obvious benefits of scintillating fibers are 1) small cross-section, and 2) transport of the signal out of the radiation area. The small cross section allows for measurements with good spatial resolution and design of transparent detectors, while the ability to transport the signal without loss, to a less noisy area, relieves the design constraints on the detection electronics.

The layout of the fiber based detector is illustrated in Figure 1. Such a detector scheme is not new; the critical difference in the present work is the choice of using ytterbium (Yb) doped optical fibers as the active element.

Scintillating fibers are most commonly based on organic materials, i.e. plastic fibers. However, plastic scintillators are well-known to be sensitive to radiation induced damage, making them opaque and even fragile over time. Our measurements (not presented here) and other reports [5] demonstrate that this is indeed the case for plastic fibers exposed to the radiation load expected in a particle therapy facility. This motivates the interest in finding an alternative and more radiation hard fiber.

Silica (quartz) is a radiation hard material, and silica based optical fibers are the obvious place to look. Silica fibers are available with numerous dopant compositions and geometrical layouts. Rare-earth dopants in silica are known to have a favorable electronic structure for radiative transitions. Especially Yb-doped silica is known to have a simple electronic structure with a well-defined near-infrared transition associated with the Yb^{3+} ion state, a low tendency to form non-radiating de-excitation channels upon clustering, and low probability of interaction with defect states in the glass-based material. Qualified by these observations, it was decided to narrow the investigations to Yb-doped fibers.

Yb-doped Fibers

Rare-earth doped silica fibers are typically used for laser and amplification purposes, and produced as double clad fibers. The double clad fiber consists of a doped core surrounded by an inner and outer cladding. A laser fiber has a core of relatively small diameter (< 10 μm), for single-mode operation, while the inner cladding has a relatively high diameter in order to catch the pumping light. To function as a radiation detector, we need a fiber with as large a core diameter as possible and a large dopant concentration; this narrows the field of relevant commercial available fibers to a handful.

TESTS AND RESULTS

Radiation Response

The response of selected Yb-doped fibers to radiation has primarily been tested in proton beams in air at the 32-MeV Scanditronix (MC32) medical cyclotron for radionuclide production at Rigshospitalet in Copenhagen. A typical test setup consisted of an Yb-fiber segment (ca. 5-10 cm), spliced to a transparent transport fiber leading to a photodetector (or spectrometer) outside the accelerator bunker. The light yield as a function of irradiation parameters (time, intensity, . . .) could then be studied.

What we observe in general (not shown in here) for Yb-doped fibers is that 1) the fibers emit a strong scintillation signal in the near-infrared, around 1000 nm, upon irradiation as expected, 2) the fibers are indeed radiation hard, and show little change in yield at the absorbed dose level expected at normal use in a particle therapy facility.

The fiber tests demonstrated that Yb-doped silica fibers could be an interesting and useful solution for particle detection, and allowed us to identify a suitable fiber, to be used as the active element in a detector setup (see below).

A Detector Setup

In one realization of the detector concept, Figure 2, we had 32 by 32 Yb-fibers [nLight (Liekki), Yb600-80/400DC] mounted in a plastic frame, with a 2 mm spacing, and connected via 5 m transport fiber [Thorlabs FT200EMT] to an in-house developed detection electronics based on Si-photodiodes. For ease of handling, the Yb-fibers were etched to a smaller diameter (200 μm), before they were spliced to the matching transport fibers. The whole setup was mounted on horizontal/vertical linear drives for additional scanning of the beam.

An example of beam profiles measured with this detector setup in the 32 MeV proton beam is shown in Figure 2.

Only 16 (vertical) by 16 (horizontal) fibers were read out in that specific setup. The sensitivity of each detector channel was calibrated by scanning the detector through a constant beam and normalizing all the fibers to the same position in the beam.

Measurements with a smaller setup have also been done at the experimental station of the particle therapy facility HIT in Heidelberg with beams of protons and ^{12}C. The studies are less extensive, but useful profiles could be extracted as shown in Fig. 3.

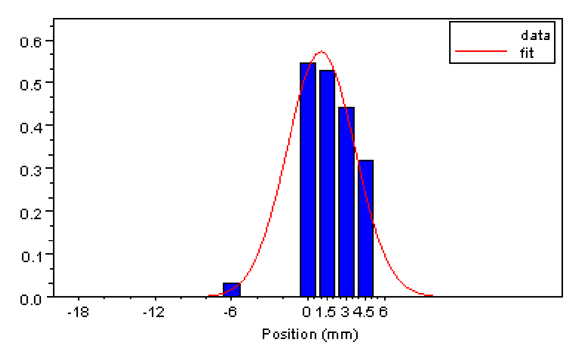

Figure 3: 108 MeV/u carbon beam at $3 \cdot 10^7$ s^{-1}.

The fiber tests and detector setups indicate that robust profile measurements of high energy beams in particle therapy are feasible with a detector based on Yb-doped fibers.

DISCUSSION

It should be emphasized, however, that more work characterizing the Yb-doped fibers still needs to be done, in

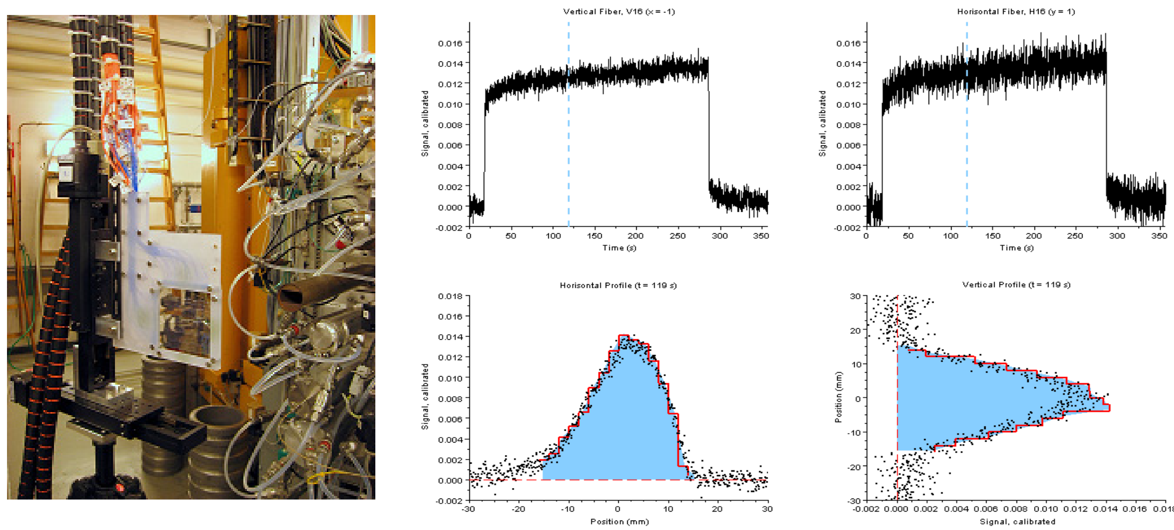

Figure 2: *Left:* A detector setup with Yb-doped fibers at the beam exit (tube with rectangular opening) from a 32 MeV medical radionuclide-production cyclotron. The fibers are mounted in the white plastic frame and connected via transport fibers (the two orange/black bundles) to the detection electronics (not shown). *Right:* Measurements in air of a 32 MeV proton beam. Top row shows the signal from two selected fibers, one vertical and one horizontal, as a function of time. Bottom row shows the extracted beam profiles, horizontal and vertical, at a selected time; the calibrated signals from the 2 x 16 fibers are shown as the red curve, while the black dots are data from scanning a single fiber through the beam.

order to firmly establish the technological limitations, and the best way to handle the fibers in a practical detector.

During the tests, two observations were made: First, when a pristine Yb-doped fiber is irradiated, we find that the scintillation yield increases and reaches a stable level with time. Second, applying a temperature transient on the fibers seems to cause a transient in the scintillation yield.

The pre-irradiation phenomenon appears to be handleable, because we have seen that the fiber remembers the improved yield value even after prolonged storage (year). The temperature effect is a complicated response as a function of time scale and temperature gradient; presently the practical solution is to operate at a stable temperature.

We consider both phenomena to be related to relative changes in the population of Yb^{3+} and Yb^{2+} ion states. More studies may reveal how to tune these phenomena in order to increase yield or improve other detector properties.

While particle therapy facilities and radionuclide production may seem a small niche for a detector concept, it is worth noticing that, recently, there has been demonstrated a detector concept based on scintillating plastic fibers for conventional radiotherapy linacs with the purpose of online detection of the positions of the multi-leaf collimator system during treatment [6]. Radiotherapy linacs are by far the most prevalent type of accelerator, and could be an interesting field to look for applications of Yb-doped fibers.

It should also be emphasized, that the interest in radiation hard detectors goes beyond the medical context considered here. Accelerator facilities for research, where high radiation levels and noisy environments are found, or space applications, where longevity of equipment is crucial, could also be attractive fields of applications for Yb-doped silica fibers.

CONCLUSION

We find that ytterbium doped silica optical fibers are radiation hard sensors of ionizing particle radiation. A detector concept based on such fibers has been proposed as a more simple and less costly alternative to a multi wire proportional chambers in a particle therapy facility.

ACKNOWLEDGMENT

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