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INITIAL TESTS OF A HIGH RESOLUTION SCINTILLATING FIBRE

(SCIFI) TRACKER

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ABSTRACT

We present our initial measurements of high resolution particle tracking in scintillating fibre (SCIFI) detectors. The scintillator under study is a glass, designated GS1, which is doped with the cerium Ce^{3+} emitter. We conclude from our measurements that present SCIFI detectors can be successfully used as small-volume 'active' targets, but that further developments are necessary before this technique can be applied to high precision tracking in collider detectors.

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1. INTRODUCTION

The concept of 'scintillation chambers' -- in which the tracks of charged particles are observed by detection of the light emitted in a scintillating medium -- originated in the late 1950's. At that time, coinciding with production of the first image intensifiers having adequate gain, an intensive effort was made to develop fast tracking devices based on solid scintillators, such as NaI, and coherent (parallel) bundles of plastic scintillating fibres¹⁾. At the same time work took place at Harwell (UK) on the development of scintillating fibres made from cerium (Ce^{3+}) glasses²⁾. The principle behind the fibre approach is that a certain fraction of the scintillation light is 'trapped' inside the fibres by total internal reflection and consequently the optical image of the tracks is preserved by the coherent geometry and transported to an output face (Fig. 1). This development came to a halt in the early 1960's when bubble chambers and spark chambers emerged as the clear leaders for particle tracking.

Recently, this technique has received a revival of interest because of its potential for:

- a) Fast, precise, live targets with digital readout, for application in fixed-target heavy-flavour lifetime experiments³⁾.
- b) Precise, compact tracking in the high rate and high particle density environment of collider detectors⁴⁾.

Furthermore, since the original work took place there have been substantial advances in associated technologies, such as scintillators, the manufacture of coherent fibre optics, image intensifiers, charge-coupled devices and other electronics. As a result, a renewed effort is being made to develop SCIFI trackers. The contemporary work on glass fibres has been pioneered by Ruchti et al.⁵⁾. Parallel development is taking place elsewhere on tracking in scintillating glass fibres^{6,7)}, plastic fibres⁸⁾ and liquid-filled capillaries⁹⁾.

The major design goals for precise SCIFI trackers are to measure particle tracks with an accuracy $\sigma \sim 10 \text{ } \mu\text{m}$ per 'hit' (detected photon) and with a two-hit resolution $\sim 50 \text{ } \mu\text{m}$. Furthermore, there must be a

high density of hits per unit path length (~ 5 per mm) for minimum ionizing particles. These criteria follow from the requirements for visual observation of short lived particles and for low mass of tracking chambers. (This hit density in glass fibres corresponds to ~ 1 hit per 2×10^{-3} radiation lengths.) Finally, the attenuation length of the emitted light propagating along the fibres should be longer than the device itself, i.e. a few centimetres for an active target, or ~ 1 m for a collider tracker.

The requirement on spatial accuracy sets a natural upper limit of ~ 25 μm for the fibre diameter. Currently this excludes the use of fibres made from plastic scintillators, which employ waveshifters having absorption lengths of ~ 0.3 – 0.5 mm. Narrow fibres made from such material would trap insufficient light since there would be two losses of typically 90%, corresponding to trapping the initial scintillation light followed by trapping the waveshifted light. It is certainly important to investigate whether other plastic scintillator/waveshifter combinations can overcome this problem since the remaining characteristics of plastic scintillators are well-suited to SCIFI tracking: good attenuation length (~ 2 m), good light yield (~ 5 hits mm^{-1} for 1 m fibre), low mass (1 radiation length ~ 40 cms) and relatively easy (i.e. low temperature) fibre production.

With the above considerations, our initial studies have involved fibres of scintillating glass. Among the various scintillating glasses which have been developed, the most attractive contain the cerium (Ce^{3+}) emitter since these have the most rapid decay time. After making several comparisons, especially with regard to high light output, we chose to investigate the cerium-doped glass designated GS1¹⁰⁾.

In the remainder of this paper we will describe first the physical properties of bulk GS1 followed by those of the fibre optic targets made from GS1. The subsequent sections will describe the measurements made in a test beam and we conclude with an evaluation of the current status of the fibre-tracking technique. The test beam work reported here involves the recording of the track images on photographic film; we describe elsewhere¹¹⁾ our results using direct electronic recording with a charge-coupled device (CCD).

2. PHYSICAL PROPERTIES OF GS1 SCINTILLATING GLASS

2.1 Overview

Table 1 presents a summary of our measurements of the properties of GS1 scintillating glass, manufactured by Levy Hill Laboratories¹⁰⁾. We mention that this and similar cerium glasses with high light-yield are difficult to manufacture and are presently limited to melts of $\sim 100 \text{ cm}^3$. This makes their proposed application⁶⁾ to electromagnetic and hadronic calorimetry difficult.

We measured a mean emission time constant, $\tau = 55 \text{ ns}$, by time analysis of single photon emission. A typical phototube pulse shape from GS1 scintillation light is shown in Fig. 2. Since this emission time is similar to the fastest available image intensifier phosphors (which, in fact, are also based on cerium emitters) it does not significantly limit the ultimate rate capability of a SCIFI tracker.

The refractive index is found¹²⁾ to display (Fig. 3) some dispersion through the region of the emission spectrum (360-500 nm).

2.2 Light yield

We observe, in GS1, 40 photoelectrons mm^{-1} for minimum ionizing particles, with an optical path length of 5 mm GS1, using a RCA 8850 quantacon phototube (bialkali photocathode). The calculated geometrical light collection efficiency is 28%. This translates to a photon yield of $(1.5 \pm 0.5) \text{ keV}^{-1}$, or an energy conversion efficiency into scintillation light of $(0.5 \pm 0.2)\%$. This yield is quite high (for example, good plastic scintillators produce $\sim 10 \text{ photon keV}^{-1}$, BGO $\sim 5 \text{ photon keV}^{-1}$ and NaI $\sim 40 \text{ photon keV}^{-1}$) and results from the near-crystalline state of the glass matrix. This property allows efficient propagation of the charged particle ionization energy through the atomic lattice to an embedded cerium ion where light emission can take place. It also leads to substantial difficulties in the fibre processing since the glass devitrifies readily, i.e. transforms to an opaque white crystalline ceramic.

We have also compared the responses of GS1 and a plastic scintillator, NE102A, to highly ionizing particles. Using an ^{241}Am source (5.5 MeV α) we find, for GS1, a light yield of 40% relative to the yield of a minimum

ionizing particle which deposits 5.5 MeV. Plastic scintillators show a far more serious saturation; our equivalent measurement with NE102A is 7%. Not only does GS1 have a good light yield for highly ionizing particles but it also has a high cross-section for slow neutron detection (via ^7Li capture). This and similar glasses are therefore used extensively in neutron experimentation¹³⁾.

The light yield as a function of cerium content in the GS1 is shown in Fig. 4. This shows a linear rise for small concentrations followed by saturation. At these high concentrations 'saturation quenching' is occurring. In this process neighbouring cerium ions are close enough to interact and lead to non-emissive de-excitation. Based on these measurements, and further data discussed below, we believe the optimal Ce_2O_3 fraction in GS1 is 2% by weight, rather than the nominal 4% by weight used in our targets.

2.3 Excitation and emission spectra

The excitation and emission spectra are shown in Fig. 5. The absorption process in Ce^{3+} is due to electronic excitation from the narrow 4f ground state to the lowest 5d excited levels, which are exposed to lattice interactions and therefore broad. A rapid lattice relaxation (Stokes shift) then takes place before de-excitation. The emitted light is thereby shifted to a slightly longer frequency and in this way the GS1 is largely transparent to its own scintillation light. However, the fast scintillation time is closely connected with the small Stokes shift and so the excitation and emission spectra are narrowly separated, as seen in Fig. 5. We observe some overlap of the two spectra. This leads to the undesirable property of self absorption, occurring most strongly at the shorter wavelengths.

2.4 Transmission and attenuation length

The transmission of GS1 vs. wavelength (shown in the curves labelled '4%' in Fig. 6) indeed displays a rapid attenuation below 400 nm, as well as absorption throughout the region of the emission spectrum.

The convolution of the emission spectrum with the transmission curve yields the attenuation curve for GS1 (Fig. 7). Consistent results are obtained for excitation using either minimum ionizing particles or a UV

source. We see a sharp attenuation ($\lambda \sim 2.5$ cms) in the first 2 cms followed by a flattening to $\lambda \sim 20$ cms at the furthest distances. The poorer transmission found in sample A (Fig. 6) is reflected by a steeper attenuation in Fig. 7.

This attenuation length is too short to allow the fibre tracking technique to be applied to collider detectors. We therefore have investigated the cause of the poor attenuation length by having modified GS1 samples prepared¹⁰⁾ with Ce_2O_3 fractions of 2%, 1%, 0.5% and 0% as well as the nominal 4%. The samples were manufactured during the same period under similar conditions. The results of the transmission measurements on these samples are shown in Fig. 6 and allow us to infer the following:

- a) The 0% cerium sample shows excellent transmission down to 340 nm (an attenuation length in the region of the GS1 emission spectrum of several metres). Poor transmission is therefore related to the cerium and not to trace impurities or other effects in the host glass.
- b) The absorption correlates only qualitatively with the amount of cerium added. This suggests that the Ce_2O_3 gives rise to an impurity, the amount varying with the particular conditions for that melt, which has a strong effect on the GS1 transmission. The most likely candidate is the ceric (Ce^{4+}) ion, which is produced during the melting process by oxidation of the cerous (Ce^{3+}) ion.

We have investigated this hypothesis by comparing the transmission of GS1 samples containing the nominal Ce_2O_3 (Ce^{3+}) with a sample containing CeO_2 (Ce^{4+}). The data (Figs. 8 and 9) show almost identical transmission through 25.6 mm of nominal GS1 (4% Ce_2O_3) and 0.45 mm of fully oxidized GS1 (4% CeO_2). Therefore the poor transmission in GS1 could be fully explained if $\sim 2\%$ of the Ce^{3+} oxidized into Ce^{4+} during glass production. This is quite feasible¹⁴⁾. We are therefore investigating¹⁰⁾ ways to improve the cerium reduction during the manufacture of GS1 and expect this substantially to improve the attenuation length.

2.5 Radiation hardness

We have studied the radiation hardness of GS1 and make here only a few comments since this work is reported in a separate paper¹⁵⁾.

A single GS1 cullet was cut and polished to produce several samples of dimensions $25.6 \times 10.8 \times 9.6 \text{ mm}^3$. These were exposed to secondary radiation produced near to external targets at CERN. This mixture of hadronic and electromagnetic radiation represents a close approximation to the type expected in normal operation of a SCIFI tracker. The transmissions were measured (Fig. 10) within a few days of the end of the exposure. The exposure took place over a period of 35 days near to the antiproton accumulator target (with the exception of the sample exposed to 10^8 rads; this took place in a 10 day period in a North Area target region).

Up to exposures of 3.5×10^5 rads we see (Fig. 10) relatively mild deteriorations in transmission (i.e. reductions in attenuation length by less than a factor of 2). At higher levels the glass becomes increasingly opaque to its scintillation light, although it remains fairly clear to visible light even at the highest exposure of 10^8 rads. The good resistance of GS1 to radiation is due to the strong electron affinity of cerium, which inhibits the formation of colour centres by ionizing radiation. In fact cerium glasses are widely used in high radiation environments such as reactors.

In the case of SCIFI detectors it is necessary for both the core and cladding glasses to be resistant to radiation (since the electromagnetic wave has a finite amplitude extending over a few wavelengths inside the cladding glass). Although we have not tested the N51A cladding glass used in our SCIFI detectors we have studied Pyrex glass (which is a candidate for the cladding glass). This deteriorated far more rapidly than GS1. For example, visually, after an exposure of 10^8 rads, Pyrex appeared a deep burgundy red, whereas GS1 was a weak yellow. We therefore anticipate that radiation-resistant SCIFI detectors will require a low refractive index cladding glass containing a small cerium admixture.

We investigated the possibility of improving the transmission of irradiated GS1 by temperature annealing. The results (Fig. 11) show a mild recovery at 200°C and a substantial improvement at 400°C . This indicates there are good prospects for recovering radiation-damaged SCIFI detectors providing they are constructed in such a way to allow disassembly and baking at high temperature.

3. SCINTILLATING FIBRE TARGETS

3.1 Manufacture

The raw GS1 was converted into fibre optic targets by Collimated Holes, Inc.¹⁶⁾. The process involves manufacture of a preform consisting of a GS1 core, of about $10 \times 10 \text{ mm}^2$ square cross-section surrounded by a cladding glass. The latter is a borosilicate glass, designated N51A, of density 2.36 g cm^{-3} and refractive index 1.49 (at 589 nm). Finally an optional extra mural absorber (EMA) of black glass is applied to the outer surface of the cladding glass. The preform is heated and drawn down by about a factor 20 in transverse dimension. The fibres are cut into short lengths, stacked into a square matrix of 20×20 fibres and then subjected to a second draw. This produces multifibre bundles of transverse dimension 0.6 mm which are cut and stacked into the appropriate target geometry. The bundles are bonded together either by fusion of the glass cladding under temperature and pressure, or with epoxy resin. Finally the targets are optically polished at the two faces perpendicular to the fibre axes.

Three targets were manufactured, with the following properties:

Target 1. No EMA, fusion bonded multifibres.

Target 2. With EMA, epoxy bonded multifibres.

Target 3. No EMA, epoxy bonded multifibres.

The nominal target dimensions are $25 \times 20 \times 10 \text{ mm}^3$, where the first dimension gives the fibre length. [In the case of target 1 there are, in fact, two smaller targets of dimensions $25 \times 10 \times 10 \text{ mm}^3$ which were used side-by-side to form a single target of width 20 mm.]

3.2 Geometry

Figure 12 shows microphotographs of the polished faces of the SCIFI targets. As demonstrated in these photographs, the fusion bonded target shows rather poor coherency, whereas the epoxy-bonded targets are substantially better. [It should be mentioned that target 1 was among the first to be manufactured when there existed little experience in drawing GS1.] We measure the fibres in targets 2 and 3 to be parallel typically to better

than one fibre diameter over their length. The largest deviations occur at the boundaries between multifibre bundles where 'steps' of up to 30 μm can occur, although the steps are typically $\sim 15 \mu\text{m}$. The individual fibres are seen (Fig. 13) to retain the original square cross-section of the preforms. Figure 13 also shows the presence of some 'dead' fibres (which appear darker than the others). The mean fibre dimensions of each target are summarized in Table 2.

3.3 Optical characteristics

The trapping efficiency in each direction for a fibre is approximately $0.5 \times [1 - n(\text{cladding})/n(\text{core})]$. (This expression is approximate because it does not properly account for non-meridional rays.) Since we have not measured the refractive index of the cladding material in the region of the emission spectrum of GS1, we have determined this quantity from a measurement of the numerical aperture (NA), where $\text{NA} = \sin \theta$, and $\theta = 1/2$ cone angle of the light emitted from the fibre. In this measurement we excited a narrow area of target 2 with UV light (300-400 nm) and recorded the circular image emerging from the target with UV-sensitive film. We find $\text{NA} = 0.482 \pm 0.008$. This value can now be combined with our measurement of the refractive index of GS1 (Fig. 3), averaged over the emission spectrum, $n(\text{GS1}) = 1.586 \pm 0.005$. We thereby determine the refractive index of N51A, averaged over the same spectrum, to be $n(\text{N51A}) = 1.511 \pm 0.006$. By means of a Monte Carlo calculation, which includes our square fibre geometry, we finally determine the trapping fraction in each direction to be 3.03%. The geometrical and optical parameters of an individual fibre from target 2 are summarized in Fig. 14.

4. TEST BEAM APPARATUS

4.1 General description

The data discussed here were recorded in a 5 GeV π^- test beam at the CERN PS.

The apparatus (Fig. 15) consists of a SCIFI target viewed at one end by a RCA 8850 quantacon phototube and at the other by a gateable multistage image intensifier. The entire assembly is mounted inside an aluminium tube which provides both a light-tight enclosure and also aligns the individual optical elements. The image intensifiers have planar fibre optic entrance and exit windows and are coupled using optical oil.

The SCIFI target was exposed to a beam which crossed the fibres orthogonally to their axes. A trigger was provided by an external set of small plastic scintillators in coincidence with a signal from the quantacon which was coupled to the SCIFI target. This trigger was used to gate open the final MCP image intensifier. (The first three stages were continually open-gated.) Light emerging from the final (dry) output window was recorded by high-sensitivity film, pressed into contact with the window.

4.2 Image intensification system

In order to maintain flexibility we chose to assemble our image intensification system from discrete single-stage units. Furthermore, because of their compactness, freedom from geometrical image distortions and low sensitivity to magnetic fields, we chose proximity-focussed devices. These are of two types: a) proximity-focussed diodes, where amplification is achieved by an accelerating voltage maintained across a narrow (~ 2 mm) gap separating the photocathode and phosphor; and b) proximity focussed, single micro-channel plate (MCP) devices where amplification is achieved using a combination of gain in the MCP followed by an accelerating voltage of ~ 6 kV onto the phosphor. The advantage of type a) is that it has a high effective quantum efficiency (since there is no loss due to the geometrical obstruction of the MCP and, in addition, a bialkali photocathode option is available) and the advantage of type b) is that it has a high gain and can be easily gated by switching the 200 V potential difference between the photocathode and MCP entrance.

The assembly used in these tests consisted of the following four stages, each with unit magnification (see Fig. 15):

- Stage 1. Proximity-focussed diode [Proxifier¹⁷⁾]. Bialkali photocathode $\rightarrow$ P11 phosphor¹⁸⁾. Photon gain, $G_Y = 4$. We define $G_Y = N_Y(\text{out})/N_Y(\text{in})$ at $\lambda(\text{in}) = 565$ nm. G_Y includes a fibre optic/fibre optic coupling loss of ~ 0.6 at the input.
- Stage 2. Proxifier. Bialkali photocathode $\rightarrow$ P20 phosphor. $G_Y = 10$.
- Stage 3. Proxifier. S20 photocathode $\rightarrow$ P20 phosphor. $G_Y = 20$.
- Stage 4. MCP image intensifier¹⁹⁾. S25 photocathode $\rightarrow$ P20 phosphor. $G_Y = 2700$.

The photon gains listed here represent the measured gains at the particular running conditions used in our tests. We have not measured the combination of the four elements but, from the measured gains of the individual elements and after correcting for the appropriate input spectrum, we calculate a photon gain of approximately 2×10^6 (including gating losses). The resolution of each of the stages 1, 2 and 3 is quoted by the manufacturer as 37 line pairs mm^{-1} and of stage 4 as 32 line pairs mm^{-1} . The resolution of the combined 4-stage device is therefore 18 line pairs mm^{-1} .

Each Proxifier phosphor is run at a potential of +21 kV relative to the photocathode at ground. The high voltage is generated by an internal potted power supply which is fed by an external supply at +32 V. Under normal operation, the external face of the (thick) output fibre optic spacer of each Proxifier is maintained at ground potential by an internal ground connection. This serves to drain small leakage charges from accumulating at the exit face. Stage 4 is run with the phosphor at ground potential (to protect the readout device) and the photocathode at approximately -7 kV. In order to avoid problems of discharge across the thin entrance window of stage 4 we found it necessary to hold the output face of the stage 3 Proxifier also at -7 kV.

The system is gateable but slow, due both to the presence of slow (P20) phosphors and of the film transport system. We recorded a single frame per beam spill. The first three stages are ungated and produced an event image on the third phosphor with a time constant of typically ~ 1 msec. (In fact, the P20 emission time is not a single exponential and also depends on intensity; we found very bright images persisted for several tens of msec.) This provides event storage while the trigger decision is made. Two triggers were used corresponding to different pulse height thresholds on the quantacon; the lower accepts single beam tracks whereas the upper favours an interaction to have occurred, involving several tracks. The trigger is used to generate a gating pulse for stage 4 of 200 V amplitude and width 1 msec. After exposure, the film is automatically advanced to the next frame in preparation for another trigger.

4.3 Film

We used a Kodak high speed 35 mm panchromatic film, designated Kodak 2475. The film was developed for approximately 20 minutes in D19 developer.

5. RESULTS

5.1 Track pictures

We compare, in Figs. 16 and 17, photographs of beam tracks and interactions, respectively, in the non-EMA target 1 with those in the EMA target 2. A dramatic decrease is seen in the amount of track-associated background light in target 2 due to absorption of untrapped light by the EMA. In the absence of EMA, the untrapped light, i.e. most (94%) of the total scintillation yield, can leave the initial fibre and pass through the surrounding fibres where it may scatter, absorb or lead to re-excitation of cerium ions. The ratio of observed light/trapped light is expected to be approximately $18\%/3\% = 6$, where 18% is the calculated photon acceptance of target 1. This is consistent with observations. The residual background light seen in the target 2 events is due to image intensifier photocathode noise occurring inside the 1 ms gating time. This contribution becomes entirely negligible if faster phosphors and correspondingly shorter gates are employed.

Our conclusion is that EMA is an essential ingredient of SCIFI trackers. A possible drawback is that the EMA may partially diffuse into the cladding and thereby cause a deterioration in the fibre attenuation length. There may be some evidence for this, as discussed below. An alternative approach is that the EMA could be applied only around the multifibres and not around individual fibres. This is essentially the situation in target 3 where a yellow epoxy layer surrounds each multifibre. In fact, we did observe far cleaner events in target 3 compared with target 1. However this 'pseudo-EMA' did not perform as well as the black glass EMA used in target (2).

5.2 Performance

5.2.1 Spot size

Figure 18 shows a densitometer scan of the exposed emulsion along the path of a beam track. Three 'spots' are seen above the gross fog level of the film. Each corresponds to a detected single photon emerging from a scintillating fibre. [The probability per fibre of a detected photon is very small ($< 10\%$), therefore the majority of the spots along tracks are due to single detected photons.]

The mean full width half maximum of the spots is found to be $60\text{ }\mu\text{m}$ ($\sigma = 26\text{ }\mu\text{m}$) with a spread of $\pm 10\text{ }\mu\text{m}$. This indicates a two-track resolution of $60\text{ }\mu\text{m}$. Figure 18 illustrates two hits, separated by $150\text{ }\mu\text{m}$, which are clearly distinguished. In fact, in the case of a sparse hit system such as this, the limit on the separation of two tracks depends on the measurement error of the centroid of each spot, not on the spot size. In practice therefore the two-track resolution should be less than $60\text{ }\mu\text{m}$.

We can estimate the photon gain of the image intensifier from our densitometer measurements. The typical spots display a peak film density of 1.0 above the gross fog, where density $= \log_{10} (I_{\text{in}}/I_{\text{out}})$. The manufacturer states this requires an exposure of $5 \times 10^{-2}\text{ ergs cm}^{-2}$ for 2475 film. In the case of the (green) P20 light this is equivalent to $1.4 \times 10^{10}\text{ photons cm}^{-2}$. So we estimate the number of photons in a typical spot to be $N_{\text{Y}} = \text{peak value} \times (2\pi \sigma^2) = 1.4 \times 10^{10} \times 2\pi (26 \times 10^{-4})^2 = 6 \times 10^5$. This is somewhat lower than our estimate of the gain of the image intensifier system.

5.2.2 Residuals

In order to estimate the measurement accuracy, we digitized, on a scanning table, the centroids of the spots displayed in the event shown in Fig. 17b. These digitizings were then fitted to straight lines and the spot residuals error found to be $\sigma = 20\text{ }\mu\text{m}$. The vertex position in this event was reconstructed from the fitted lines and the impact parameter error to the reconstructed vertex found to be $10\text{ }\mu\text{m}$. Based on our optical studies of the target we believe the dominant source of error in the measurement accuracy is fibre incoherency, largely at the boundary between the multifibre bundles.

Although these observations are rather qualitative, they serve to demonstrate a good future potential precision and resolution in SCIFI trackers. A more quantitative analysis, using data taken with CCD read-out, is presented elsewhere¹¹⁾.

5.2.3 Hit density

The observed film hit density for beam tracks using target 2 is approximately 2 per mm. It is difficult to present a more accurate value

because the film pictures were taken with broad trigger counters which illuminated the full length of the SCIFI target, and the target was later found to have a short attenuation length.

Using the quantacon phototube, we find, for beam tracks in target 2, an observed photoelectron yield per mm, $N = 3.6 e^{-l/22}$, where l (mm) is the impact distance from the phototube face. This is approximately a factor of 2 higher than the hit density observed on film, as expected due to the absence of the fibre optic coupling loss which is present at the input to the first stage image intensifier. This measurement of N confirms the presence of a good quality bialkali photocathode on the first Proxifier, i.e. with a quantum efficiency similar to that of the quantacon.

We can compare the quantacon measurements of the light yield from SCIFI target 2 with the yield from bulk GS1. At $l = 5$ mm we observe $3.6 e^{-5/22} = 2.8$ photoelectrons mm^{-1} for beam tracks in target 2. In solid GS1 we measure 40 photoelectrons mm^{-1} at $l = 5$ mm, with a calculated photon geometrical collection efficiency of 28%. We therefore expect a yield in the SCIFI target of $40 \times [3.0 (\epsilon_{\text{fibre}})/28] \times 0.66$ (packing fraction) $\times 0.9$ (fraction of live fibres) = 2.6 photoelectrons mm^{-1} . This is consistent with the yield observed in the SCIFI target and indicates that the GS1 scintillation efficiency has not substantially deteriorated during the target manufacturing process.

Finally we comment that, although a hit density of 2 mm^{-1} is rather poor for imaging tracks which cross the fibres orthogonally (Fig. 1b) it will however give clear transverse images (Fig. 1c). In the latter cases, the light output is increased by a factor $1/\sin \theta$ where θ is the angle of the track with respect to the fibre axis, e.g. in the case of a high-energy interaction, $\theta \sim (0.3 \text{ GeV}/c)/(3 \text{ GeV}/c) \sim 0.1$, and $1/\sin \theta = 10$.

5.2.4 Attenuation length

We measure an attenuation length of (22 ± 5) mm using beam tracks in target 2, i.e. for a fibre length up to 25 mm. In order to study the behaviour of longer fibres we retained several 60 cm sections of single multifibres which were manufactured at the same time as our targets. Each multifibre has a transverse dimension of about 0.6 mm and contains 400

individual fibres (see Fig. 12). The attenuation lengths of these fibres were measured using a UV excitation source coupled via a narrow diameter fibre optic guide to various points along their lengths. The fibres were coupled to a bialkali phototube whose DC anode current was recorded.

The measurements (Fig. 19) show a rapid attenuation at short distances which is consistent with the target data using beam tracks. This is followed by a gradual increase of the attenuation length until it reaches $\lambda \sim 25$ cm beyond $l \sim 40$ cm.

In comparison with the bulk GS1 (Fig. 7) we see a much shorter attenuation length for the fibres, e.g. the fibres suffer a loss of 10 (no EMA) to 15 (with EMA) between 1 and 16 cm, compared with a loss of 3 in the case of bulk GS1. The extra attenuation in the fibres can be caused by:

1. Absorption, due to $\text{Ce}^{3+} \rightarrow \text{Ce}^{4+}$ oxidation during fibre manufacturer, or to diffusion of the EMA into the cladding glass.
2. Scattering, due to poor surface conditions (and therefore poor reflection) at the core-cladding interface, or to the presence of microscopic devitrification centres ('stones') in the GS1 core.

We believe the dominant cause of light loss is absorption. This follows since we observe an attenuation length of $\lambda \sim 25$ cm at long distances. Since the scattering losses will not vary substantially along the length of a fibre this value indicates their maximum contribution to the attenuation length at any point.

The steep attenuation lengths at shorter distances is therefore probably largely due to $\text{Ce}^{3+} \rightarrow \text{Ce}^{4+}$ oxidation in the GS1 during the fibre pulling process when the hot glass is in contact with air. We remark here that a trial experiment was performed²⁰⁾ where GS1 was poured from the crucible of manufacture into a pyrex tube. This resulted directly in a preform in which the GS1 was protected from contact with air. The preform was pulled down to fibres of diameter ~ 1 mm. These fibres were found to have attenuation lengths identical to the bulk GS1. With these encouraging observations we plan to investigate whether this technique can be used to improve the attenuation lengths in SCIFI targets.

We also observe in Fig. 19 some additional deterioration in the attenuation length due to the presence of EMA. This may be caused by diffusion of the EMA into the cladding or by the effective reduction by a factor 2 of cladding thickness due to the opaque EMA boundary separating adjacent cladding layers.

Finally we comment that the response of a small active target can be made more uniform simply by polishing and aluminizing the opposite face. This improves the apparent attenuation length as well as increases the overall light yield by up to a factor of two. No aluminizing was employed in the measurements described here.

6. CONCLUSIONS

These studies demonstrate that small volume active targets of GS1 scintillating glass fibres can be successfully made. They allow the visual observation of tracks with a positional measurement accuracy per hit $\sigma \sim 20 \mu\text{m}$ and with a two-track resolution of $60 \mu\text{m}$. Among the advantageous bulk properties of GS1 perhaps the most important is a good resistance to radiation damage.

On the negative side, we find a relatively poor light yield (2 hits mm^{-1}) and a poor attenuation length $[(22 \pm 5) \text{mm}]$ in the SCIFI targets. Furthermore, GS1 glass is an extremely difficult glass to manufacture and to reprocess into fibres; it devitrifies readily at temperatures where the fibre-drawing must take place.

There are several areas where improvements and further work are required:

1. Attenuation length. The conversion of Ce^{3+} to Ce^{4+} must be minimized in both the original manufacture of the GS1 and in the fibre drawing.
2. Light yield. The largest potential gain could be made by an increase in the fibre trapping efficiency, which is presently only 3.0%. This could be achieved by an increase in the refractive index of the GS1 or by the use of a cladding with a lower refractive index. A modest improvement is also possible by increasing the target packing fraction,

i.e. by employing a thinner cladding. Based on previous studies it seems unlikely that an alternative and more efficient fast inorganic scintillator can be found to replace Ce^{3+} in the glass matrix.

3. Target coherency. The current limitation to the measurement accuracy is the geometrical quality of the target itself. Conventional fibre optics can be made with fibres parallel to a few μm over their length. It is therefore likely that the present targets can be substantially improved as more operational experience is gained with this difficult glass.
4. Plastic scintillators. In view of their attractive properties, it is important for more effort to be devoted to organic plastic scintillators/waveshifters which may be drawn into very narrow (25 μm) efficient fibres.

In conclusion we believe the performance of present scintillating glass fibre trackers is well-matched to the requirements of small volume active targets for the direct observation of short-lived heavy-flavour particles. The special advantages offered by SCIFI active targets are the density of tracking points and the ability to provide the optimal view of an interaction i.e. transverse to the beam direction. The potential future application towards high precision tracking in collider detectors will require substantial improvements in the performance of SCIFI trackers, especially with regard to the poor attenuation length.

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Table 1

Properties of GS1 scintillating glass

Composition, by weight ^{1.} :	SiO ₂	55%
	MgO	24%
	Al ₂ O ₃	11%
	Li ₂ O	6%
	Ce ₂ O ₃	4%
Density ^{2.} , ρ	2.64 $\pm$ 0.1	g cm ⁻³
Mean refractive index ^{2.} (GS1 spectrum), n	1.586 $\pm$ 0.005	
Transition temperature ^{1.}	620	°C
Linear thermal expansion coefficient ^{1.} , α	75 $\times$ 10 ⁻⁷	°C ⁻¹
Radiation length ^{3.} , X ₀	9.77	cm
Hadronic interaction length ^{3.} , λ	37.4	cm
dE/dx ^{3.} (minimum ionizing particles)	4.6	MeV cm ⁻¹
Photon yield (minimum ionizing particles)	1.5 $\pm$ 0.5	Photons keV ⁻¹
Mean decay time, τ	55	ns
Wavelength of peak emission	395	nm
Approximate cost ^{1.}	8	\$ US cm ⁻³

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 2. Ref. 12.
 3. Calculated value.

Table 2

Mean fibre dimensions (μm) of the SCIFI targets

Target	Centre-to-centre spacing	Core size	Cladding (+ EMA) thickness
1	30 ± 5	25 ± 5	2.5
2	30.8	25.6	2.6
3	29.9	24.9	2.5

Figure captions

- Fig. 1 : Principle of the scintillating fibre (SCIFI) target. The solid scintillator (a) is replaced by scintillating fibre bundles which transport either a longitudinal (b) or transverse (c) optical image of the interaction to an output face.
- Fig. 2 : Phototube pulse shape from GS1 scintillating light excited by a 5.5 MeV α source. The horizontal scale is 50 ns per division.
- Fig. 3 : Refractive index of GS1 vs. wavelength.
- Fig. 4 : Light yield of GS1 vs. Ce_2O_3 fraction by weight. The dots represent (two separate measurements of) excitation by minimum ionizing particles and the crosses by 5.5 MeV α particles. The curves are normalized to unit pulse height at a Ce_2O_3 fraction of 4%.
- Fig. 5 : Excitation and emission spectra of GS1. The excitation curve shows the relative emission intensity (with the detector fixed at 395 nm) when GS1 is excited by a UV source at the indicated wavelength and with a fixed intensity.
- Fig. 6 : Transmission vs. wavelength for samples of GS1 involving different fractions of Ce_2O_3 . Two different samples (A and B) of nominal GS1 (4% Ce_2O_3) are displayed. The curves are normalized to 100% transmission at 560 nm. The measured transmissions at 560 nm range between 80-88%, corresponding largely to reflective losses at the entrance and exit faces and at scattering centres, such as small bubbles, inside the glass.
- Fig. 7 : Light yield of polished GS1 blocks of dimensions 168 x 11 x 10 mm³ (sample A) and 176 x 25 x 13 mm³ (sample B). The horizontal scale indicates the distance of the excitation point from a bialkali (quantacon) phototube. The black dots represent excitation by minimum ionizing particles and the open circles by UV light in the range 300-400 nm. The curve is a Monte Carlo calculation of sample B based on measurements of the scintillation emission spectrum (Fig. 5) and transmission curve (Fig. 6). The vertical

scale shows the observed photoelectron yield for sample A (for which the calculated photon collection efficiency is 28%).

- Fig. 8 : Transmission vs. wavelength for nominal GS1 samples [4% Ce_2O_3 (Ce^{3+})] and a fully-oxidized GS1 sample [4% CeO_2 (Ce^{4+})]. The curves are normalized to 100% transmission at 560 nm.
- Fig. 9 : Transmission vs. wavelength for a fully-oxidized GS1 sample of thickness 24.8 mm. The curve is corrected for reflective losses at the entrance and exit faces by a vertical scale factor of $1/0.88$.
- Fig. 10 : Transmission vs. wavelength for GS1 samples after exposure to secondary radiation from external targets at CERN. The curves are not corrected for reflective losses.
- Fig. 11 : Temperature annealing of a GS1 sample after exposure to 1.1×10^8 rads. The indicated annealing times are cumulative (e.g. the total annealing time at 200°C is 16.5 hours). The curves are not corrected for reflective losses.
- Fig. 12 : Microphotographs of the SCIFI targets: a) target 1 (no EMA, fusion bonded multifibres), b) target 2 (EMA, epoxy bonded), and c) target 3 (no EMA, epoxy bonded). Photographs b) and c) show clearly the multifibre bundles, of transverse dimension 0.6 mm, which are composed of matrices of 20×20 individual fibres. The bright lines are the images of a pair of illuminated parallel straight slits of width 30 μm and separation 1 mm. The slits are placed in contact with the entrance face of each SCIFI target and viewed through 25 mm fibre length at the exit face.
- Fig. 13 : High magnification views of individual fibres from target 2. The transverse dimension of a core (bright square) is 26 μm and the centre-to-centre spacing between fibres is typically 31 μm .
- Fig. 14 : Geometrical and optical parameters of an individual scintillating fibre from target 2.

- Fig. 15 : Test beam apparatus.
- Fig. 16 : Minimum ionizing tracks recorded on film using: a) target 1 (no EMA) and b) target 2 (with EMA).
- Fig. 17 : Interactions recorded on film using: a) target 1 (no EMA) and b) target 2 (with EMA).
- Fig. 18 : Densitometer measurement through the centre of three spots along a track recorded on film. The slit width of the densitometer (along the track direction) is 10 μm .
- Fig. 19 : Measurement of the attenuation of scintillation light in single multifibre bundles manufactured during production of SCIFI targets 1 ('No EMA') and 2 ('With EMA'). The fibres are excited by a UV source.

a) SOLID SCINTILLATOR

b) SCINTILLATING FIBRE BUNDLE (FIBRES PERPENDICULAR TO TRACK)

c) SCINTILLATING FIBRE BUNDLE (FIBRES PARALLEL TO TRACK)

Fig. 1

Fig. 2

Fig. 3

Fig. 4

Fig. 5

Fig. 6

Fig. 7

Fig. 8

Fig. 9

Fig. 10

Fig. 11

a)

b)

c)

0 800 μm

Fig. 12

a)

0 200 μm

b)

0 40 μm

Fig. 13

Fig. 14

Fig. 15

a)

0 5 mm

b)

Fig. 16

a)

0 5 mm

b)

Fig. 17

Fig. 18

Fig. 19