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HIGH-RESOLUTION TRACKING WITH SCINTILLATING FIBRES

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ABSTRACT

A progress report is presented on the development of a high-resolution tracking detector based on scintillating optical glass-fibres. It is planned to use this technique in the WA84 experiment^{*)} at the CERN Super Proton Synchrotron for the study of heavy-flavour production and decay.

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^{*)} This experiment was initiated by Colin Fisher, whose untimely death is a sad loss to the members of this Collaboration.

1. OUTLINE OF THE EXPERIMENT

The principal aims of the WA84 experiment [1] include the measurement of the lifetimes of the charged and neutral B mesons (mesons containing the b-quark), and the search for B- $\bar{B}$ mixing and for non-charmed decays of B mesons.

The experiment uses a 340 GeV/c π^- beam in the CERN Omega spectrometer [2]. At these energies the $B\bar{B}$ production cross-section is of the order of a few nanobarns [3]. The mean B decay length in the plane perpendicular to the beam is about 400 μm . A typical event will have five vertices close to one another, and a high track multiplicity. Figure 1 shows a view in the plane transverse to the beam direction obtained from a Monte Carlo simulation of the set-up described hereafter.

The small cross-section and complicated topology imply that a viable experiment must include the following features:

- a high beam intensity (at least 10^6 particles per second);
- a vertex detector, radiation-resistant and triggerable, with a high spatial precision;
- a magnetic spectrometer to allow momentum measurement of tracks downstream from the vertex detector. The detector should have a wide angular acceptance and allow particle identification.

Our vertex detector involves a new technique, based on scintillating optical glass-fibres [4], viewed by a gateable optoelectronic chain. The image, obtained after the final intensifier, is read out using a charged-coupled device (CCD).

A silicon microstrip detector will be installed downstream from the scintillating glass target. It will complement the target by providing high-precision track coordinates that allow a measurement of a vertex position in a direction parallel to the beam. It will help in matching the tracks seen in the active target with those measured in the spectrometer, and it will also allow detection of the secondary decays that occur downstream from the active target (40 mm long).

2. THE SCINTILLATING GLASS-FIBRE DETECTOR

Our target consists of a bundle of parallel glass-fibres of $25 \times 25 \mu\text{m}^2$ cross-section, doped with a cerium-oxide (Ce_2O_3) scintillator, whose fluorescence decay-time has been reported [4, 5] to be about 60 ns.

The target is made in the shape of a rectangular parallelepiped, with dimensions $4 \times 4 \times 40 \text{ mm}^3$. The individual fibres, 40 mm long, are aligned with the beam direction. This configuration provides a transverse view of the event at the end of the bundle (fig. 2). The transverse dimension ($4 \times 4 \text{ mm}^2$) has been chosen so as to contain most of the B-decay vertices, assuming that the beam diameter is 2 mm. The target length (40 mm) provides a 20 mm average interaction region, followed by a 20 mm decay region. In total, it corresponds to about 0.1 interaction lengths.

The choice of fibre orientation parallel to the beam has the advantage that a high-momentum secondary track, emitted typically at a small angle to the beam, travels for an appreciable length within each fibre, with a consequent substantial increase in the amount of emitted light per fibre, compared with a geometry in which the incidence is normal. In our experiment this light yield should — because of this geometrical effect — increase by a factor of 20 on the average, allowing good tracking information to be obtained.

The core of each fibre is made of GS1 scintillating glass^{*)}, whose main characteristics are given in table 1 [6]. A problem with this glass is its low photon yield, which is quite lower than that provided by plastic scintillators such as NE102A.

In experiments where the beam flux is relatively large, an important feature of the target is its radiation hardness. Figure 3 shows the measured emission spectrum of GS1 scintillating glass. In the

^{*)} Levy-Hill Laboratories, Ltd., Cheshunt, Herts., EN8 9TJ, UK.

same figure we present the transmission spectrum of a 10 mm thick sample, before and after exposure to an integrated dose of 4 kGy (corresponding to a run of approximately 25 days in our experiment), showing that the target is quite workable.

The refractive index of the GS1 glass is 1.59. Each fibre has a core of $20 \times 20 \mu\text{m}^2$ cross-section, which is surrounded by glass cladding, of refractive index 1.51. The amount of light that is trapped by total internal reflection within the fibre is expected to be about 3% in each direction (fig. 4). Cross-talk between fibres is reduced by having each fibre coated by a thin layer of black glass. This layer, known as Extra-Mural Absorber (EMA), absorbs most of the light that is not trapped and guided by the fibre.

The manufacturing of the target^{*)} proceeds in several stages. First, a long fibre is drawn. This fibre, of square cross-section, is cut into 400 equal lengths. These are then carefully assembled into a coherent bundle of 20×20 fibres (called a multifibre bundle, or simply a multi). The multi is then drawn to the final cross-section and cut into 64 equal lengths, which are again assembled into a bundle (a multi-multi) and epoxy glued. This is the final target. An extremely careful manufacturing process is necessary in order to obtain a target having the required coherency.

The intrinsic attenuation length of the GS1 bulk glass used in the core of each fibre has been measured [4] to be about 20 cm. However, this result is not observed for the glass in the form of fibres. Because of the large number of reflections in each fibre, and due to the fact that the reflection coefficient is slightly less than one (mainly because of surface imperfections), the effective attenuation is not adequately described by an exponential. The length after which the transmitted light is reduced to $1/e$ was found to be about 2 cm.

3. OPTOELECTRONIC SYSTEM AND READOUT

The image of an interaction occurring in the target clearly needs intensification before reaching the readout system, which consists of a CCD of the type used in TV cameras. A complex optoelectronic chain has been developed for this purpose, and the function of the various components is described below.

Most image intensifiers cannot work in the presence of even low magnetic fields. In our experiment, the target system is located in the first part of a magnetic spectrometer. The (vertical) field intensity around the target is about 1.8 T. We have therefore decided to split the optoelectronic chain into two stages. The first stage, having a relatively modest intensification (~ 20), is located very close to the target. An image guide, 2.5 m long, is then used to transport the image to a region where the residual magnetic field is around 0.01 T. There, a magnetic shielding permits a further intensification stage ($\sim 10^4$) to be installed before readout.

Stage 1 of this optical readout chain is sketched in fig. 5. As can be seen in this figure, the target is optically coupled, via a fibre-optic bend followed by a fibre-optic taper, to a proximity-focused image-intensifier tube (Proxifier^{**)}). This tube is electrostatically focused and can work in a uniform magnetic field $\vec{B}$, provided the electric field in the tube is parallel to the $\vec{B}$ field. The bend serves to bring the image out of the beam line in such a way that it can arrive on the entrance face of the first image intensifier, which has to be perpendicular to the $\vec{B}$ field. The bend has to be radiation-hard, since it is traversed by the beam. This forces us to use a glass which is not 100% transparent in the blue part of the spectrum (the maximum of the GS1 emission spectrum). In order to keep the light attenuation to a minimum, we therefore use the shortest possible bend. The bend is followed by a taper, which magnifies the image and matches the resolution of the target to that of the Proxifier.

*) Collimated Holes, Inc., Campbell, Calif. 95008, USA.

**) Proxitronic GmbH, 6140 Bensheim, Fed. Rep. Germany.

After intensification, the image is transported through the 2.5 m long image-guide (undergoing an attenuation of about 5) to the second stage of the optoelectronic chain.

Stage 2, shown in fig. 6, is composed of four separate parts: three image intensifiers followed by a CCD. Most of the intensification ($\sim 10^3$) takes place in the second part, which is a microchannel-plate image intensifier, manufactured by ITT^{*)}. This has a first section that consists of a gateable proximity-focused image intensifier. The gate is very convenient in our experiment, and it is used to trigger on events of interest. Unfortunately, however, microchannel-plate image intensifiers have a relatively poor spatial resolution. The tube we have chosen has an area which is large enough to compensate for the poor resolution. Therefore the image is magnified to match the entrance face of the ITT tube by using a Varo electrostatic image intensifier^{**)} having a magnification of 1.8 and a gain of 5. After the ITT, the image has to be demagnified to match the (fibre-optic) entrance face of the CCD. The demagnification is performed by using a DEP electrostatic image intensifier^{×)}, with a demagnification of 4.4 and a gain of 6.

The fourth and last part of Stage 2 is a Thomson CCD^{××)}, used for storage and readout of the image. The surface of the CCD is divided into an image zone and a memory zone, both containing about 160,000 pixels. It is provided with an antiblooming facility that can be used to perform a fast clearing of the image stored in the image zone. This operation is completed in $\sim 1 \mu\text{s}$. The transfer of an image from the image zone to the memory zone is performed in about $150 \mu\text{s}$. The readout of the memory zone has been tested at 4 MHz, but is planned to work at $\geq 10 \text{ MHz}$ with a readout time of less than 16 ms. The overall magnification of the optoelectronic chain is such that every scintillating fibre of the target is viewed, on the average, by 4.5 pixels of the CCD.

4. THE TRIGGER SYSTEM

The trigger system is implemented at two levels. The first-level trigger is essentially an interaction trigger, provided by small scintillation counters placed immediately around and downstream from the fibre target. The counters are viewed by small, fast photomultipliers. This interaction trigger opens the gate of the first stage of the ITT image intensifier about 80 ns after the interaction occurs. During this time the scintillating-fibre target and the phosphor of the proximity-focused image intensifiers act as a memory which stores the image of the event. The memory time is the convolution of the decay time of the scintillator (55 ns), of the phosphor screen in the Proxifier (55 ns), and of the phosphor screen of the Varo magnifying image intensifier (35 ns). Figure 7a shows the expected light intensity as a function of time, and fig. 7b shows its integral distribution. From these distributions it can be seen that, if the first-level trigger is implemented in 80 ns, only 25% of the light arriving at the output of the Varo image intensifier is lost.

The gate of the ITT image intensifier is opened for about $1 \mu\text{s}$. With a beam flux of 10^6 particles per second, the rate after the first-level trigger is lower than 10^5 Hz .

A second-level trigger is provided by a set of large scintillator hodoscopes installed in the spectrometer. Correlations between the hits in these hodoscopes effectively place a lower bound on the transverse momentum of fast charged particles produced in the interaction. The requirement we plan to impose is that of having at least four particles with a transverse momentum larger than 600 MeV/c. This condition reduces the trigger rate to about 30 Hz. The fraction of events containing B particles that is kept by this requirement has been estimated, using a Monte Carlo simulation, to be

*) ITT F4113: PO Box 3700, Fort Wayne, Indiana 46801, USA.

***) Varo, Inc., Electron Device Division, Garland, Texas, USA. Ref. 25/46.

×) Delft Electronische Producten, Postbus 60, 9300 AB Roden, The Netherlands.

××) Thomson-CSF TH 7864 CCD, BP 305, 92102 Boulogne-Billancourt, Cedex, France.

approximately 10%. The second-level trigger decision takes about 400 ns. If a trigger is present, then the CCD is read out in about 40 ms. If a trigger is not present, the CCD is cleared, and after about 1 μ s it is ready to receive a new image.

The large amount of information contained in the CCD (address and pulse height from 160,000 pixels) is digitized and, after zero suppression, is stored on tape. The Data Compactor Module, which performs the zero suppression and data buffering, reduces the data to less than 10 kbytes for an average event.

5. TESTS PERFORMED IN A PARTICLE BEAM

In order to test the system, we installed the target and complete optoelectronic chain in a 10 GeV/c hadron beam at the CERN Proton Synchrotron (PS). Figure 8 shows the beam/target arrangement used, and figs. 9a–c show images of beam tracks as seen by the CCD. Images of typical interactions obtained with the arrangement of fig. 2 are shown in fig. 10.

The main conclusions of our tests are the following:

- The hit density on tracks is, on the average, 0.7 hits per millimetre in space. This should lead to about four hits on the track of a charged B meson.
- The two-hit resolution is about 35 μ m.
- Some noise is present on the images, which is probably not due to the electronics since it is correlated with the presence of tracks or events on the frames (frames with no tracks have no noise). The origin of this noise is at present being investigated.

We are now working on the improvement of our system, in particular on the following points:

- a) An increase in light yield may be obtained by changing to fibres of $30 \times 30 \mu\text{m}^2$ cross-section. This will not affect the spatial resolution significantly. The light yield should increase because of the smaller number of reflections.
- b) The transparency of the input window of the first Proxifier may be improved.
- c) The photocathode quantum efficiency of the first Proxifier may be bettered. Alternatively, a second Proxifier in series can be used at the first intensification stage.
- d) The track-associated noise may be reduced by an increase in the amount of EMA around each fibre.
- e) The readout time of the CCD can be reduced by increasing the clock rate—up to 10 MHz should be feasible.

Some of these improvements will be tested in the Omega spectrometer during this year. Other laboratory bench-tests are forthcoming. Should they be successful, an experiment can be performed that will allow a large sample of $B-\bar{B}$ events to be collected.

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Table 1
Properties of GS1 scintillating glass

Composition by weight (in %)	SiO ₂ : 55 MgO: 24 Al ₂ O ₃ : 11 Li ₂ O: 6 Ce ₂ O ₃ : 4
Density	2.64 g/cm ³
Mean refractive index (emission spectrum)	1.586 ± 0.1
Transition temperature	620 °C
Linear thermal expansion coefficient	75 × 10 ⁻⁷ °C ⁻¹
Radiation length	9.77 cm
Interaction length	37.4 cm
dE/dx (minimum ionizing particle)	4.6 MeV/cm
Light decay-time ^{*)}	55 ns
Photon yield (fast component, minimum ionizing particle)	1.5 ± 0.5 photons per keV
Wavelength of peak emission	395 nm
Attenuation length ^{**)}	20 cm

^{*)} Measurements are in progress indicating also the presence of a slower decay component.

^{**) This is the value for bulk glass. For fibres of 25 × 25 μm² cross-section, we measured an attenuation length of about 2 cm.}

Figure captions

- Fig. 1 : A view of $B-\bar{B}$ production and decay in the plane transverse to the beam, obtained by a Monte Carlo simulation.
- Fig. 2 : Fibre target showing the fibres aligned with the beam direction and giving a transverse optical image.
- Fig. 3 : Emission spectrum and the effect of radiation dose on the transmission of GS1 scintillating glass.
- Fig. 4 : Operation of an individual scintillating fibre.
- Fig. 5 : First stage of the optoelectronic readout chain.
- Fig. 6 : Second stage of the optoelectronic readout chain.
- Fig. 7 : a) Light intensity as a function of time at the photocathode of the ITT.
b) Integral distribution of the light intensity.
- Fig. 8 : Orientation of beam and target used in tests.
- Fig. 9 : Image of beam tracks as seen by the CCD. The angle between beam and target fibres is about 25 mrad in (a) and (b), and about 13 mrad in (c).
- Fig. 10 : Images of typical interactions of a 10 GeV/c hadron in the target.

Fig. 1

Fig. 2

Fig. 3

Fig. 4

Fig. 5

IMAGE INTENSIFIER #3

microchannel type

$\varnothing 40\text{mm}$
gain : 800

C.C.D

$6.6 \times 8.8\text{mm}^2$
 $288 \times 550 = 158400$ pixels

VIDEO signal
(10MHz)

IMAGE INTENSIFIER #2

electrostatic type

magnification=1.8

In : $16 \times 16\text{mm}^2 (\varnothing 23\text{mm})$

out : $29.4 \times 29.4\text{mm}^2 (\varnothing 42\text{mm})$

gain : 5

IMAGE INTENSIFIER #4

electrostatic type

$\varnothing 80 \rightarrow \varnothing 18\text{mm}$

demagnification=4.4

Image:

In : $29.4 \times 29.4\text{mm}^2 (\varnothing 42\text{mm})$

out : $6.6 \times 6.6\text{mm}^2 (\varnothing 9.3\text{mm})$

gain : 6

Fig. 6

Fig. 7

Fig. 8

Fig. 9

Fig. 10