# SCINTILLATING OPTICAL FIBRES AND THE DETECTION OF VERY SHORT LIVED PARTICLES

C.M. Fisher(*)
CERN, Geneva, Switzerland

## ABSTRACT

The application of scintillating fiber optics to the problem of heavy flavour particle detection in both fixed target and collider experiments is reviewed. Brief specifications for both fibres and read-out systems are given.

---

(*) On leave from RAL, Rutherford Lab, Didcot, England

## 1. INTRODUCTION

"The evolution of scintillating optical fibres could represent the most exciting new technique for high energy physics since the invention of the bubble chamber".

The above statement made at the beginning of my talk could certainly be true - the next few years will tell! In one respect however, it is false: the technique is not new. In the late fifties and early sixties a great deal of work was put into the development of particle tracking systems using scintillating filaments, however, this program was dropped as a result of the appearance of alternative, and at that time superior techniques; notably the bubble and spark chambers. These techniques were well suited to the physics of the time i.e. the detailed study of the strange particles, resonance spectroscopy etc. The situation has now changed however, in two important respects: (a) the physics interest has shifted to the study of complex high energy interactions involving the production and decay of very short lived "heavy flavour" particles and (b) the fibre optic technology has developed to the point where, as we will see, exciting possibilities exist for the development of radically new detectors.

Modern high energy physics experiments pose two essential technical problems:

(a) The efficient detection of heavy flavour particles in complex interactions. These particles, known as Charm or Beauty flavoured hadrons, are characterised by short lifetimes ($\tau \sim 10^{-13}$ - $10^{-12}$ s) and complex decay modes. Short lifetimes imply a need for high spatial resolution in the tracking system which must be combined with high rates, short dead times and the possibility to trigger the data acquisition.

(b) Complete event reconstruction is required in collider exeriments to determine the overall event characteristics e.g. jet energies, missing $E_T$ etc. The scale of the calorimetry (and hence the cost) and the hermeticity of the design depend critically on the availability of a compact precise tracking system in the vertex region and a means of extracting the signal from the component calorimeter "towers" without loss of hermeticity.

The first problem (a) above, is referred to as micro-vertex detection and has application to the study of charm and beauty flavoured particle characteristics in both fixed target and collider experiments. The second problem refers to the detailed scaling and efficiency of design for the massive new collider detectors (i.e. for the $\bar{p}$-p collider, LEP, HERA, tevatron collider ...).

In this talk I will discuss the applications of scintillating optical fibres to questions of micro-vertex design and hence flavour tagging and reconstruction in both geometries. The more general implications of high resolution compact tracking systems to the design of collider experiments will be considered by Jasper Kirkby and the question of hermeticity and calorimeter design by Klaus Pretzl. These talks should clarify the reasons "why" for scintillating fibres; I hope the remainder of the meeting will help to answer "how".

It is probably unnecessary to demonstrate the need to develope second generation heavy flavour vertex detection techniques; it is a well known technical problem with several approaches already well developed e.g. silicon micro-strips and CCD detectors. High resolution scintillating optical fibre systems offer significant advantages over these approaches and, as my opening remark implies, could represent a revolution in the technology.

In the fixed target area we can list a series of important questions concerning heavy flavour properties which require a new technique offering the same high resolution topological information as the bubble chamber combined with high data rates and fast data analysis. My personal list of fixed target heavy flavour physics to be addressed in the next years is:

(a) systematic study of the F-meson, lifetimes, decay modes, production characteristics;

(b) $D^o$-lifetimes with high statistics and small systematic errors - are there some surprises (?)

(c) $\Lambda_c^+$ - and the search for higher mass charmed baryon states;

(d) $A^+$ - the charmed strange baryon ground states; confirmation and detailed study of the $A^{+,o}$ states;

(e) Beauty flavoured hadrons; lifetimes of $B^o$ and $B^\pm$, mixing, production properties, photoproduction and hadroproduction, decay modes ...;

(f) "A" dependence of heavy flavour production;

Micro vertex detection in collider experiments is perhaps even more exciting. The study of "jet" flavours from the tagging and reconstruction of B flavoured hadron decays via the $t \to b \to c$ decay chain is clearly fundamental and could lead to the observation of Higgs particles. We have for example the possibility to search for Higgs in $\bar{p}p$ via

$$\bar{p}p \rightarrow H^{o} + X$$
$$\rightarrow W^{\pm}X,\ t\bar{t},\ b\bar{b},\ c\bar{c}\ \ldots$$

with

$$\Gamma(H \rightarrow q\bar{q}) = \frac{3g^{2}}{32\pi}\frac{m_q^{2}}{m_W^{2}}\,m_H\left(1 - \frac{4m_q^{2}}{m_H^{2}}\right)^{3/2}$$

i.e. Higgs particles will decay predominantly into the heaviest flavour pair kinematically allowed i.e. If $m_t < m_H/2$ then $H \twoheadrightarrow t\bar{t}$ dominates.

To conclude this introduction, it is clear that there are many excellent reasons to develop sophisticated flavour tagging systems in both fixed target and collider geometries.

## 2. SCINTILLATING FIBRES TO STUDY CHARM AND BEAUTY IN FIXED TARGET EXPERIMENTS (ref. [1])

We learn a great deal from our experience using the high resolution hydrogen bubble chamber LEBC. Fig. 1 shows a typical interaction of a 400 GeV proton with a proton at rest (hence fixed target) in the bubble chamber. Many secondary charged (and neutral!) particles are produced which, because of the Lorentz boost in transforming from the centre-of-mass system to the laboratory, are strongly collimated in the form of a jet (90° in the c.m.s. corresponds to 70 mrad in the lab.). In fig. 2 a similar event is shown which contains two heavy flavour decays. The following points follow from these pictures:

(a) The bubble density per track is about 10/mm and each track contains ~ 500 points. Even when there are many close tracks there is no ambiguity concerning the definition of a track, provided it is resolved from its neighbour.

(b) The bubble images are well defined and have diameters of $\lesssim 20\ \mu m$ (in space). Thus the transverse resolution (i.e. normal to the "jet" axis) is $\lesssim 20\ \mu m$ whilst the longitudinal resolution (mean bubble separation) is $\gtrsim 100\ \mu m$.

(c) The secondary heavy flavour decay vertices are found by searching for tracks which do not point to the origin (see the anamorphic projection technique discussed by Hans Dreverman in these proceedings).

Consider now the resolution required to detect a decay. In complex events it is clearly important to have a detector giving high resolution in the plane transverse to the jet axis.

In fig. 3, where point A is the primary interaction vertex and point B the heavy flavour decay vertex, the detection of the decay depends critically on the distances x and y. We have

$$AB = L = \text{decay length} = \frac{p}{m}\,\tau c$$

$$BD = X = \text{transverse decay length} = \frac{p_T}{m}\,\tau c$$

$$AC = y = \text{impact parameter} = f\tau c \qquad f \leq 1$$

where p, m are the momentum and mass of the heavy flavour particle:

$\tau$, c are the lifetime and the velocity of light; $3.10^{10}$ cm/s;

$p_T$ is the transverse momentum of the heavy flavour particle;

f is a parameter depending on the transverse momentum in the decay and in general $f \leq 1$.

The quantities x and y are Lorentz invariant and therefore do not depend on the beam energy or the heavy flavour production mechanism. In the table below we give the lifetimes and decay distances for the known charm and beauty states.

TABLE 1

| | $\tau$ | L (30 GeV/c) | $c\tau$ |
|---|---|---|---|
| $D^{\pm}$ | $9.10^{-13}$ s | 4.3 mm | 270 µm |
| $D^{o}$ | $4.10^{-13}$ s | 1.93 mm | 120 µm |
| $F/\Lambda_c$ | $2.10^{-13}$ s | 0.9 mm | 60 µm |
| "B" | ~ $1.10^{-12}$ s | 1.8 mm | ~ 300 µm |

The objective of the scintillating optical fiber detector for fixed target experiments is to provide a high resolution image of the event viewed in the transverse plane. This transverse plane projection cannot be achieved using, for example conventional optical techniques or holography because of the well known depth of field problem either in data taking or in replay.

The target region for a fibre optic detector will consist of a coherent bundle of very fine (~ 10 µm) fibres in the form of a rod with axis parallel to the beam direction. As the particles cross the fibres they produce a pulse of scintillation light which is transmitted along the fibre to an imaging plane. The result is a transverse projection of the event (b) as required for the detection of heavy flavour decays. In fig. 4 we show a preliminary design for such a vertex detector. The rod is bent away from the beam and contains a magnification cone to avoid loss of resolution at the read-out and to take the read-out system out of the beam itself. We anticipate read-out via an image intensifier and a CCD system as described later.

To study the potential performance of such a system we have used data from the hydrogen bubble chamber experiment (NA16). Fig. 5 shows a pair of charmed particle decay vertices with the tracks projected onto the transverse plane with 10 μm resolution. Examples of other events observed in NA16 when viewed with the transverse plane projection are shown in fig. 6.

An important feature of the technique is the track quality. The events shown in figs 5 and 6 were projected assuming a hit efficiency of about 4/mm along the track in space (about half the LEBC bubble density). Measurements made using Cerium doped glass by Ruchti et al. [3] show that hit efficiencies of at least 2.5 mm can be achieved in the absence of serious attenuation. We now have good reason to believe that using alternative specialised glasses, or possibly plastic, significantly higher hit densities can be realised.

The reason that the track quality looks so good in figs 6 and 7 is clearly due to the transverse projection and the small angles of the tracks to the normal to this plane. In fig. 7 we illustrate this effect. The light output depends on the length of the track in the fibre i.e. light $\alpha$ $\phi/\sin\theta$ where $\phi$ is the fibre diameter and $\theta$ is the angle of the track to the fibre axis. If a track is produced in the forward direction in the centre-of-mass system then $\sin\theta \sim \tan\theta \leq 1/\gamma$ and light $\geq \phi\,\gamma$, where $\gamma$ is the Lorentz factor of the c.m.s. Thus the Lorentz factor boosts the light output and hence the track quality: 2.5/mm → 25/mm in the transverse plane.

We arrive at a specification for a Fixed Target Fibre Vertex Detector.

(a) Light output sufficient to give good track information in the transverse plane; $\geq 3$ detected photo electrons/mm for light trapped in fibres (after attenuation).

(b) $\tau_{sc} \leq 100$ ns (Ce doped glass $\tau_{Ce} \sim 60$ ns) to allow high data rates and triggering etc.

(c) Fiber diameters 10-20 μm.

(d) Coherence requirement: fibres parallel to ~ 10 μm to preserve resolution.

(e) No cross talk: resolution = diameter

(f) λ attenuation ≥ 20 c.m.s.

The arrangement under study for the read-out is illustred in fig. 8. Read-out will be via a two stage image intensifier followed by a CCD. The first stage intensifier must clearly have a high quantum efficiency photocathode, resolution ≥ 30 ℓp/mm and gain ~ 50-100. A proximity diode system (proxifier) is currently preferred. The output phosphor may be used to provide a memory (few μs) however, much depends on the characteristics i.e. persistance of available phosphors. If a suitable phosphor is available then the gain of the second stage may be triggered in ≤ 1 μs. The second stage will have micro channel plates to give high gain and an output phosphor matched to a CCD; the CCD is only exposed if the event trigger condition is satisfied.

Note that the CCD read-out gives the data in digital form i.e. a series of addresses corresponding to hits and possibly grey levels. We anticipate that track finding and vertex reconstruction techniques can be applied rapidly ("pseudo" on-line). No long data analysis chain should be required.

The requirements of the read-out system are therefore:

(a) A proximity focussed first stage with a high quantum efficiency photocathode at ~ 400 nm corresponding to Ce emission, (e.g. Bi alkali q.ε ~ 20%) and gain 50 ~ 100. The output phosphor having time constant ~ 1 μs to allow second stage triggering..

(b) A triggerable second stage with μ-channel plates giving "single photon" overall gain (~ $10^5$) i.e. sufficient to detect input single photons.

(c) Read-out via a CCD (or reticon). Either with standard clocking and fast clear rates (fast clear ~ 10 μs, read ~ 10 s) or, if a suitable intermediate trigger phosphor is not available, an antiblooming facility to give ~ 1 μs fast clearing. The overall resolution should be ~ (10 μm X magnification) i.e. ~ 30 μm to avoid loss of resolution for ~ 50 μm output fibres.

## 3. SCINTILLATING FIBRES FOR CHARM, BEAUTY, TOP ... EXPERIMENTS WITH COLLIDER GEOMETRY [2]

The general arrangement proposed for the collider geometry is shown in fig. 9. The fibres are arranged in shells concentric with the beam with fibre axes parallel to the beam pipe. Particles crossing a shell produce track segments projected onto the plane transverse to the beam direction (fig. 10).

A serious problem in the design of micro vertex systems for collider experiments is avoided by this arrangement. The problem arises because the interaction point is not well localised; the intersection region can be $\leq$ 50 cm long although its transverse dimension is ~ 1 mm. We therefore propose that, instead of attempting to cover a large cylindrical surface with silicon strips or CCD pixels, we use optical fibres to obtain high resolution track elements in the transverse plane.

In ref. [2] we have studied using Monte-Carlo techniques, the transverse resolution required to identify beauty flavoured hadrons in jets. The problem is both eased and complicated by the sequential decay of beauty to charm. In this case we are faced with two short lived particles in cascade. The result is that the transverse decay distance and the impact parameters in the charm decay are boosted by the effect of the beauty lifetime and decay dynamics. This is illustrated in fig. 11.

I will not reproduce details of the Monte-Carlo results here; for details see [2]. In fig. 12 we show the distribution of impact parameters for the decay products from B and subsequent $D^{\pm}$ or $D^{0}$ decays. All impact parameters are to the production vertex. The main conclusions from this study are:

(a) A relatively crude micro vertex detector providing a precision of ~ 100 µm an impact parameter is sufficient to tag beauty particle decays with efficiency ~ 60%.

(b) An improvement would be to detect the presence of more than one decay vertex i.e. B → D →. This requires a precision ~ 30-40 µm on the impact parameter.

(c) To achieve complete topological reconstruction of both beauty and subsequent charm decays with reasonable efficiency (~ 50%) requires a precision $\leq$ 20 µm on reconstructed impact parameter.

Translated into a crude specification for a fibre optic detector we have:

(a) Fibres arranged in ~ 4 concentric cylindrical shells as described.

(b) Fibre diameter < 100 µm with alignement such that track images are preserved with this precision to the read-out plane. This implies coherence to $\leq$ 100 µm over a length ~ 1 m.

(c) Shells should not exceed ~ 1% of a radiation length in thickness and should give ≳ 10 points i.e. "detected fibres" per track.

Condition (c) implies a detected "hit" efficiency for glass of ≳ 7 mm, although a factors of two lower might be acceptable. This must be folded with the attenuation so that the attenuation length must be ≳ 1 m for the signal in the scintillating glass.

We are currently studying Cerium doped glasses with high light yield as possible core glass. The choice of $Ce^{+++}$ as dope is determined essentially by the scintillating time constant $\tau_{sc} \sim 56$ ns i.e. short compared with collider crossing times.

Scintillating plastic fibres can also be drawn and may have higher light output and longer attentuation lengths than glass. The Saclay group are currently studying the possibilities to produce coherent arrangements of plastic scintillating fibres and will report to this conference.

Read-out and trigger possibilities follow closely the ideas given earlier for the fixed target detector. In this case however, very short time constant phosphors might be required for the first stage to avoid pile-up from successive beam crossings. The limiting case is the 100 ns for HERA; fortunately the X3 phosphor can cope but the problem is thrown to the trigger logic.

Many challenges exist to the fibre optic technology, however, from previous investigations there seems to be good hope of success. The rewards can be very considerable with the possibility of exciting fundamental physics for the future.

## REFERENCES

[1] M. Atkinson et al., Nucl. Instr. and Methods 225 (1984) 1.

[2] M. Atkinson et al., RAL 84-052, to be published in Nucl. Instr. and Methods.

[3] R. Ruchti et al., Proceedings of the Leipzig International Conference on High Energy Physics 1984;
and Proc. IEEE/NSS82 Washington.

Fig. 1

A 400 GeV/c p-p INTERACTION FROM LEBC. (NA27).

90° IN C.M.S = 70 MRAD IN LAB.

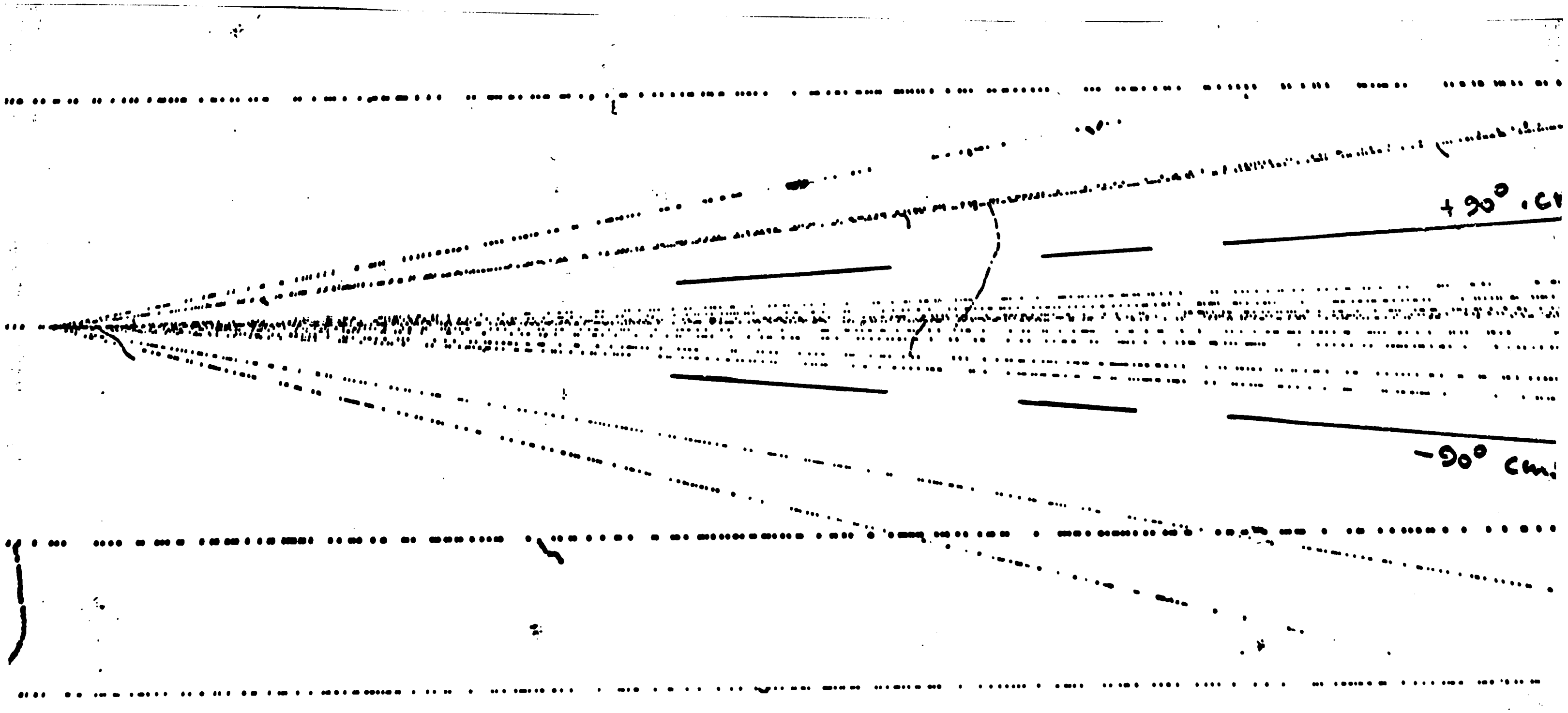
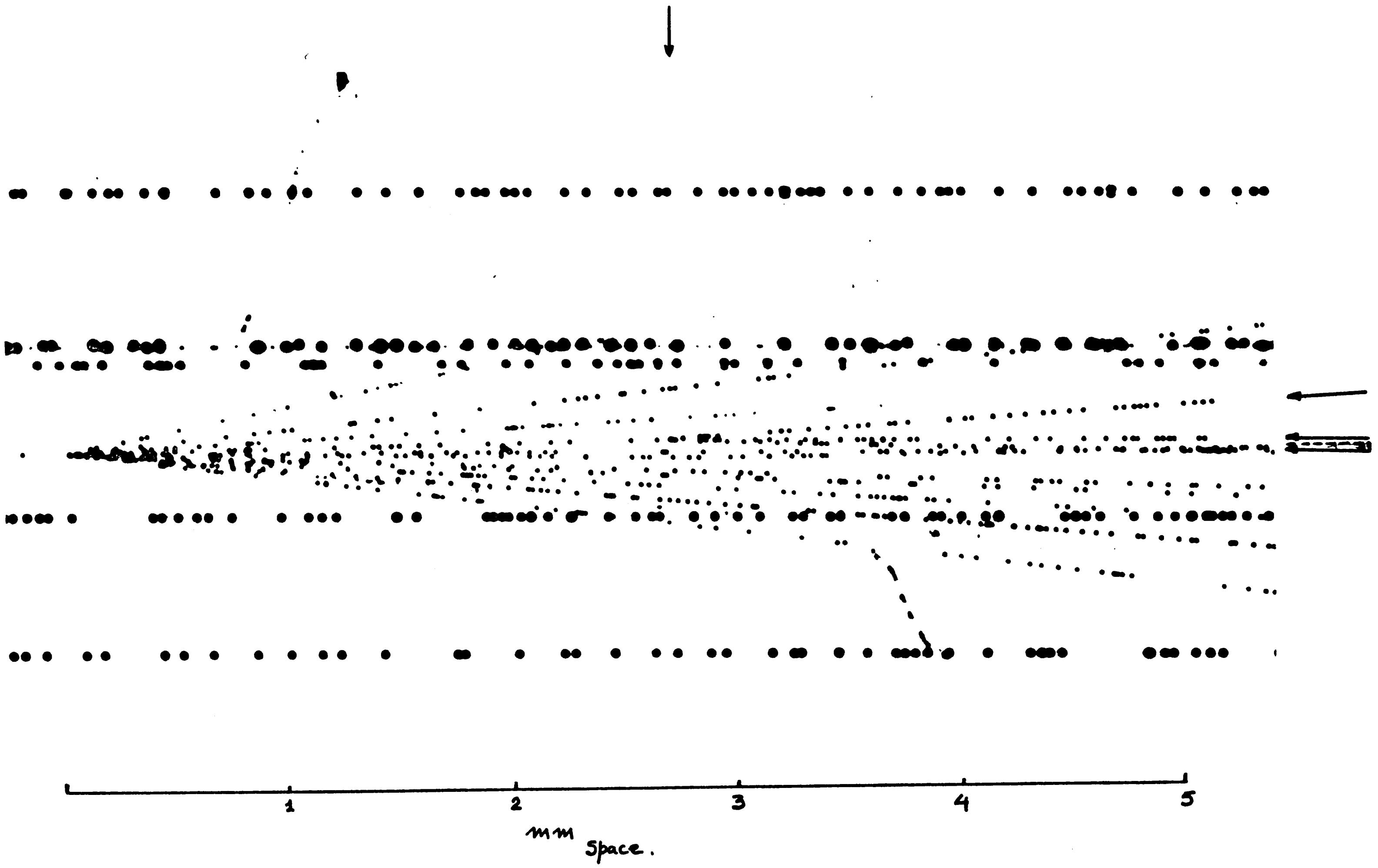


Fig. 2 . A fixed target jet at 400 GeV/$_c$ containing a pair of CHARM decays.



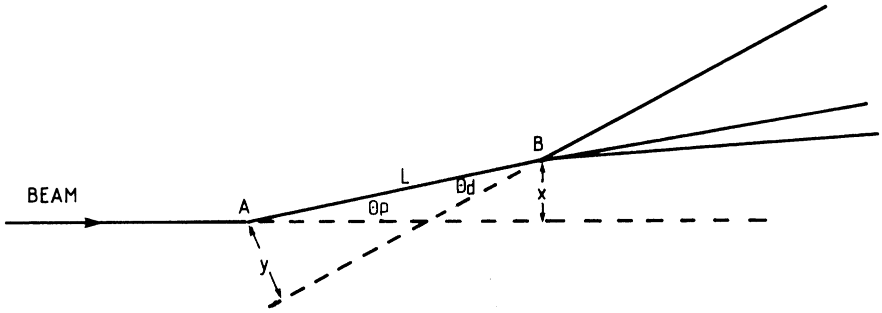

BEAM
A
B
L
θp
θd
x
y

Fig. 3

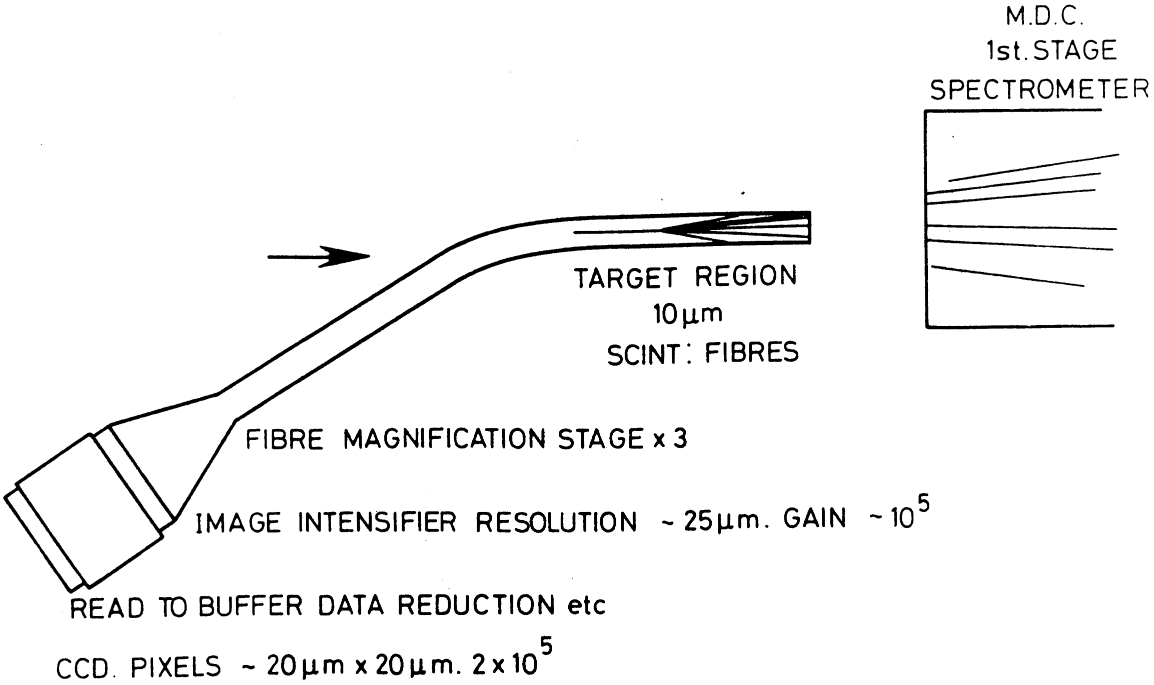

M.D.C.
1st. STAGE
SPECTROMETER
TARGET REGION
10 µm
SCINT: FIBRES
FIBRE MAGNIFICATION STAGE x 3
IMAGE INTENSIFIER RESOLUTION ~ 25µm. GAIN ~ 10^5
READ TO BUFFER DATA REDUCTION etc
CCD. PIXELS ~ 20µm x 20µm. 2 x 10^5

Fig. 4

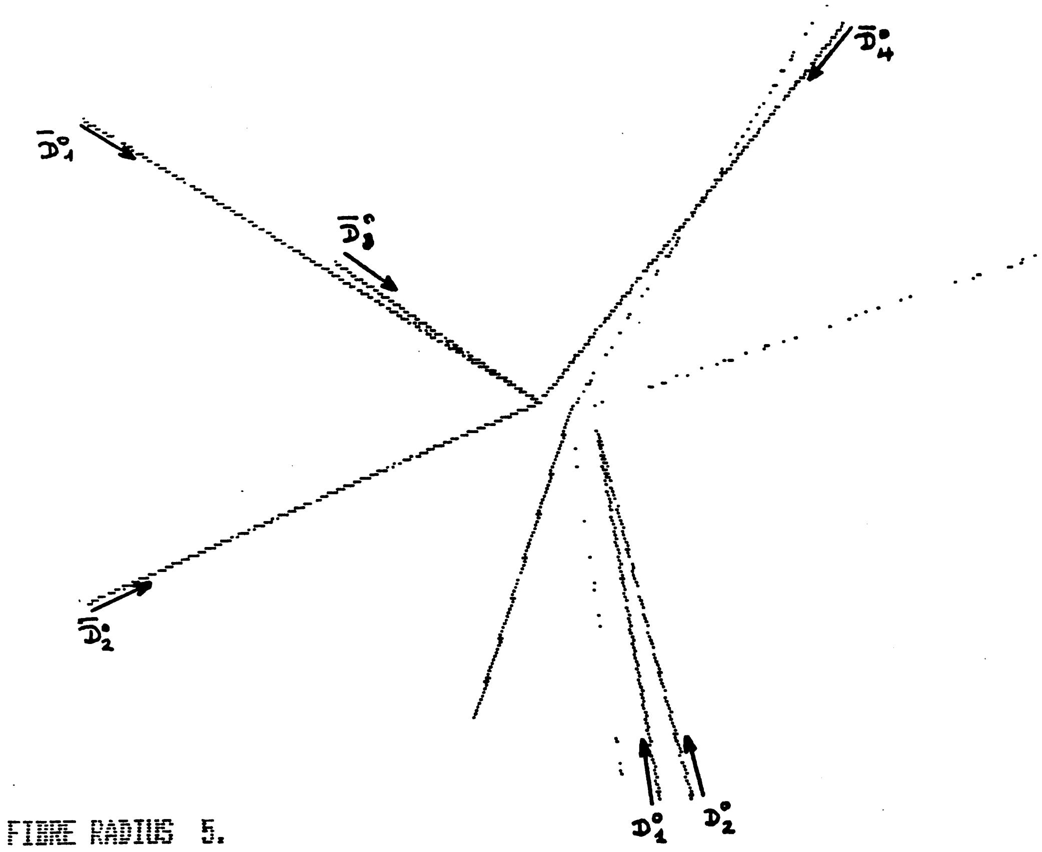


Fig. 5

NA16 Event viewed in transverse plane: 10 μm resolution

$\overline{D^0} \rightarrow K^+\pi^+\pi^-\pi^-$

$\overline{D^0} \rightarrow K^-e^+\nu$

Fig. 6a

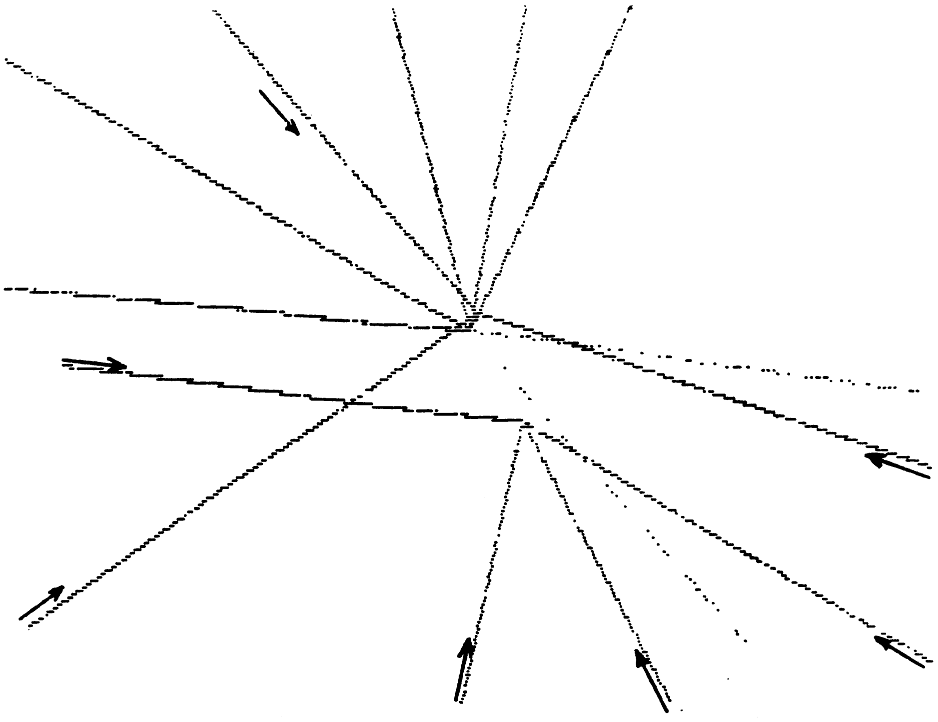
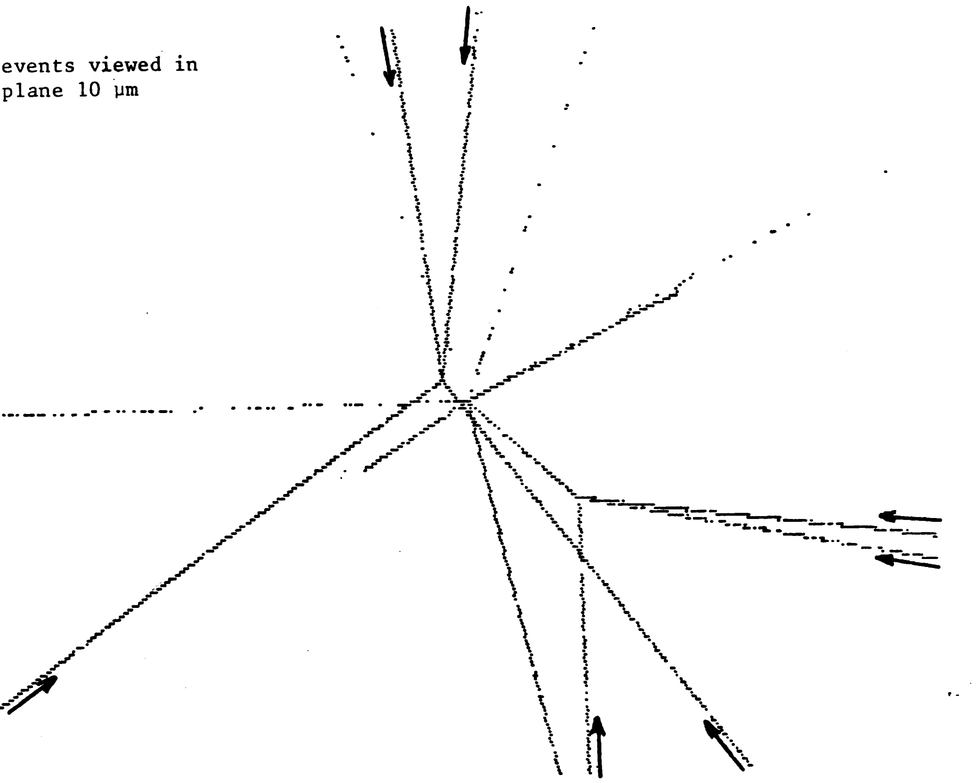


Fig. 6b

Other NA16 events viewed in transverse plane 10 µm resolution.



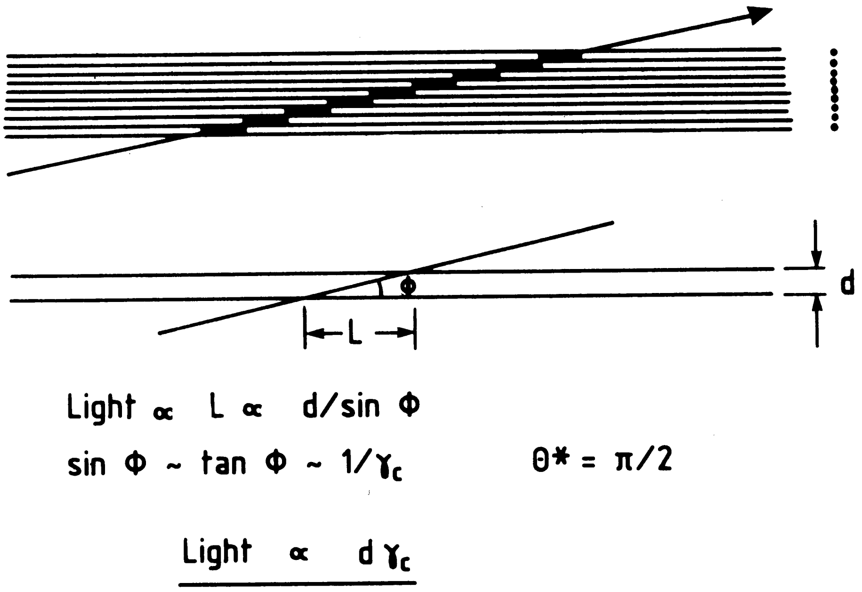

d
Φ
L
$\text{Light} \propto L \propto d/\sin\Phi$
$\sin\Phi \sim \tan\Phi \sim 1/\gamma_c$
$\theta^* = \pi/2$
$\text{Light} \propto d\,\gamma_c$

Fig. 7

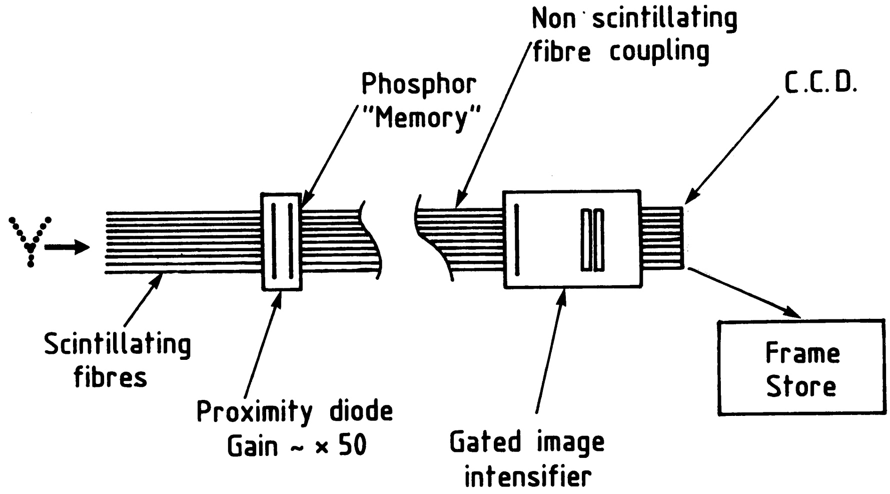

Non scintillating
fibre coupling
Phosphor
"Memory"
C.C.D.
γ
Scintillating
fibres
Proximity diode
Gain ~ × 50
Gated image
intensifier
Frame
Store

Fig. 8

SCHEMATIC ARRANGEMENT FOR S.O.F.T
MICROVERTEX DETECTOR

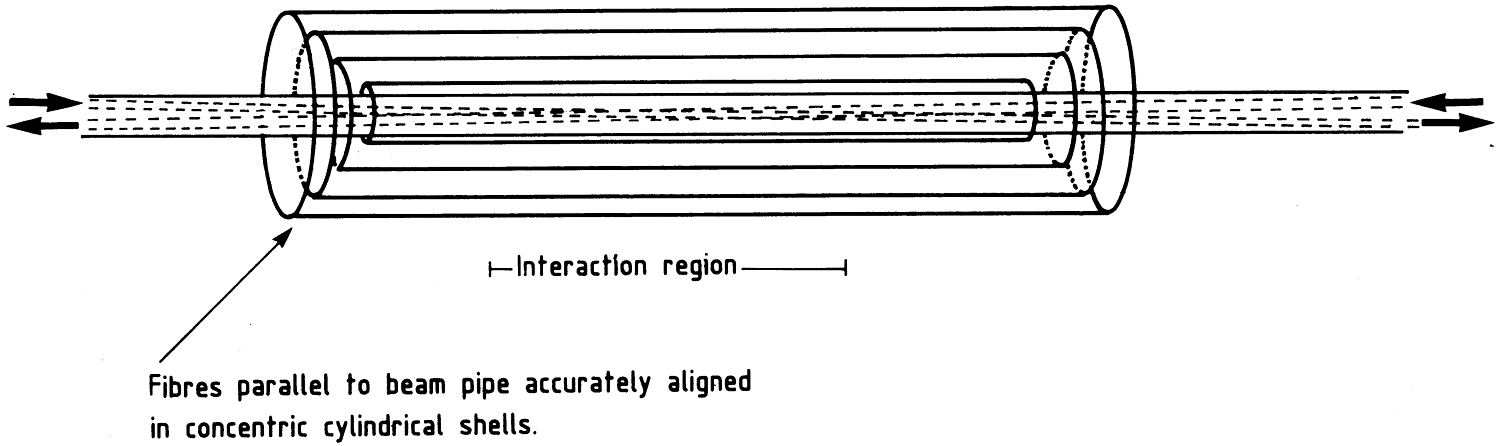


Fig. 9

## SCHEMATIC FIBRE OPTIC ARRANGEMENT. CENTRAL REGION

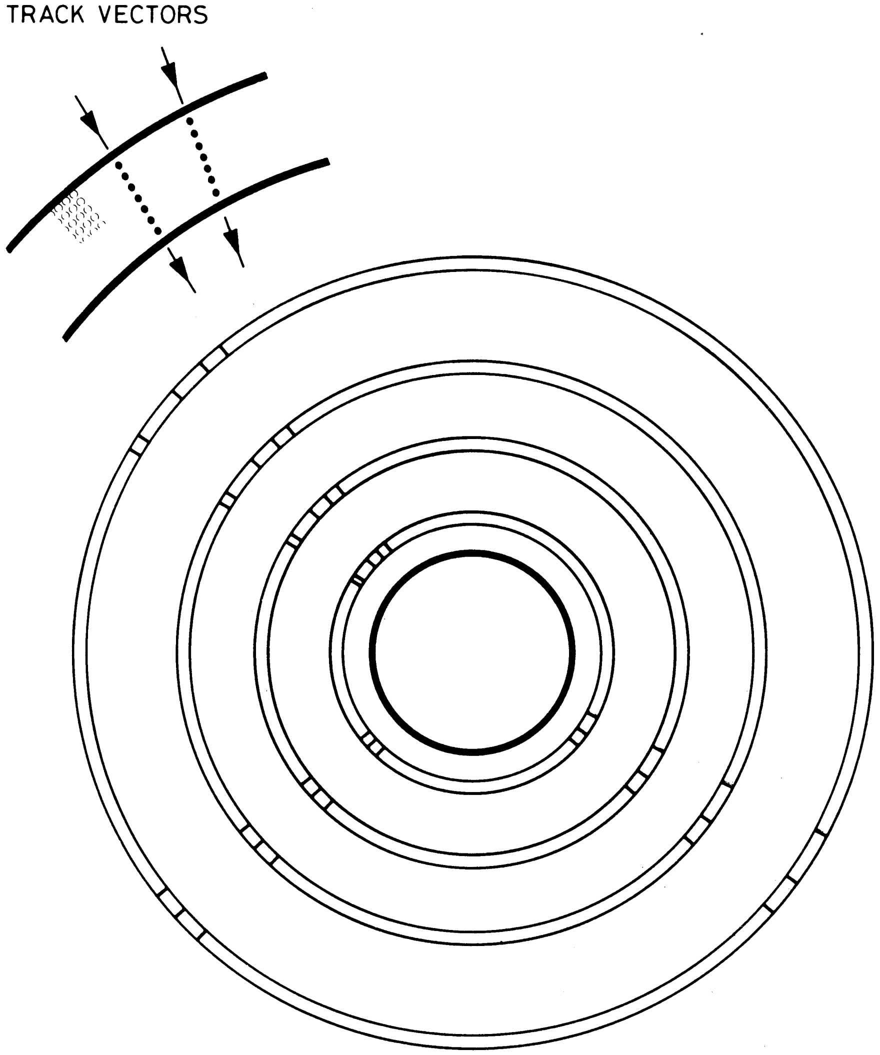


Fig. 10

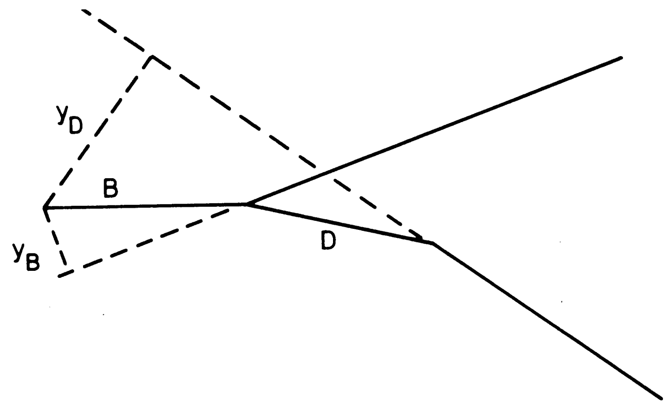

$y_D$
B
$y_B$
D

Fig. 11

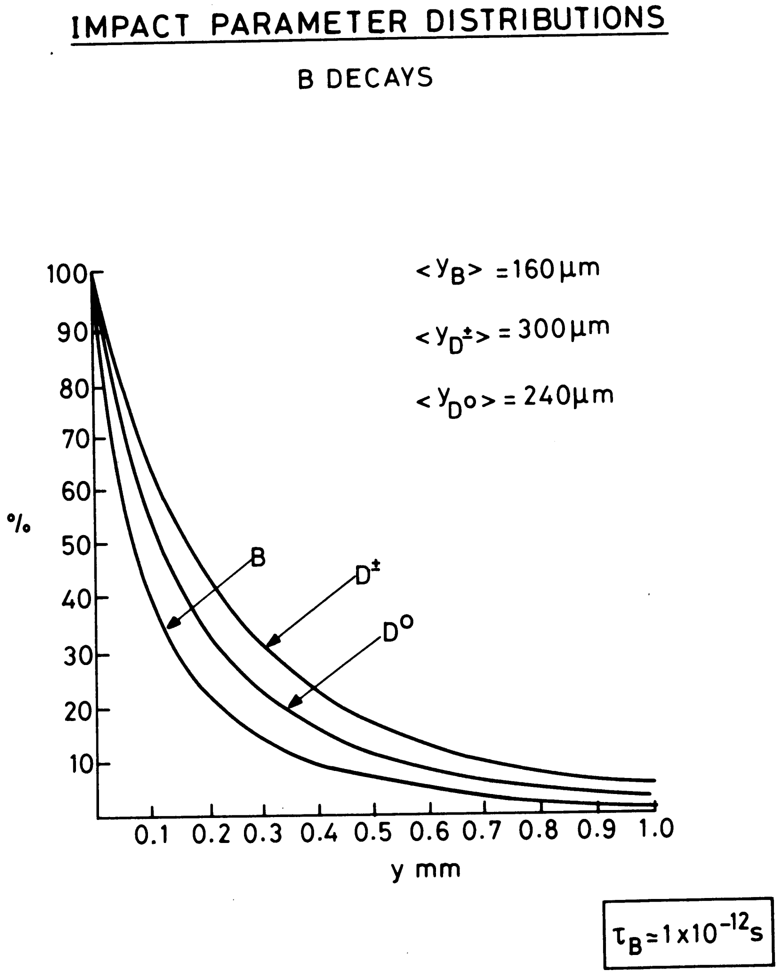

IMPACT PARAMETER DISTRIBUTIONS
B DECAYS
$<y_B> = 160\mu m$
$<y_{D^\pm}> = 300\mu m$
$<y_{D^0}> = 240\mu m$
100
90
80
70
60
%
50
40
30
20
10
B
$D^\pm$
$D^0$
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
y mm
$\tau_B \simeq 1 \times 10^{-12} s$

Fig. 12