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Study of an optical trigger to be used for beauty search in fixed target mode at the LHC

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Abstract

We propose a research and development study of an 'Optical trigger' to be used for B-meson selection in a LHC fixed target experiment. The optical trigger relies on the Cherenkov light detection using a fast photodetector. The device is sensitive to charged particles with large impact parameter arizing from secondary vertices belonging to the B-meson decay chain but is blind to charged particles with small impact parameter arizing from the primary vertex in a small target. We expect a rejection factor of 50 to 100 for the unwanted minimum-bias events while keeping a good detection efficiency for b-quark pair events. It could permit operation of LHC fixed target experiments at the forecast high rate.

1 Introduction

The production of heavy quarks is expected to be abundant at the next generation of hadron colliders. The study of the rare decays of B-meson as a probe of possible new physics beyond the standard model and the observation of CP-violation effects, so far observed only in the neutral K system, will be one of the most challenging and important problem at the Large Hadron Collider [1]. In the case of a fixed target experiment, the cross-section for b-quark pair production at the LHC energy is many hundred times larger than for existing electron machines. In addition in a fixed target experiment an equivalent luminosity as high as $10^{33}\mathrm{cm}^{-2}\mathrm{sec}^{-1}$ can easily be obtained in a hadronic machine, whereas such a luminosity is considered as a technological challenge for the electron machine [2].

The cross section in a collider mode experiment is about 300 times higher. However a fixed target experiment has many advantages. Multiplicities are smaller, particles are more energetic and the primary vertex is precisely localized. As an example, using an internal gas jet target [3], the transverse dimensions of the interaction region are of the order of 200 μm and its length along the beam can be of the order of 1 mm in order to achieve a $10^{33}\mathrm{cm}^{-2}\mathrm{sec}^{-1}$ equivalent luminosity. The average B decay length is about 40 mm, an order magnitude larger than in the collider mode. In addition, in the collider mode no trigger system has been so far proposed which expoits the full luminosity and therefore take benefit of the higher cross-section. In a submitted collider mode experiment proposal, the luminosity was reduced to $10^{31}\mathrm{cm}^{-2}\mathrm{sec}^{-1}$, to allow a real time selection using a silicon microvertex detector [4].

In the fixed target mode experiment with $10^{33}\mathrm{cm}^{-2}\mathrm{sec}^{-1}$ equivalent luminosity, 10^3 b-quark pairs are produced per second, but the time between two bunches (15 ns) is too short for a first selection based on the silicon microvertex detector. However, if the rate is reduced by a factor of 100, the average time between two selected interactions is 1 μs which still allows to operate a second level trigger based on real time processing of the silicon microvertex detector looking for a secondary vertex.

A general pretrigger scheme, the so-called "Optical Trigger for Beauty" has been proposed by some of us [5] in early 1991 to select b-quark pairs in a high luminosity hadron machine. Most of the studies and the examples were given for a fixed target experiment at the Tevatron machine. Following this approach we wish to investigate the application of the optical trigger for a fixed target experiment at LHC. Results of a Monte-Carlo simulation program based on a first conceptual design of this device, indicates that this technique is feasible. Hereafter we propose a research and development program to study and test it.

2 The principle of the Optical Trigger

The principle of the Optical Trigger is illustrated in Figure 1. The radiator is a thin [illegible] crystal with a refractive index close to $\sqrt{2}$ shaped as a shell limited by two portions of concentric spheres. The transparent material is of low density and can be made of lithium or magnesium fluoride. The beam-target crossing point, has small dimensions compared to the mean impact parameter (600μ) of the charged particles from B-meson decays and is located at the center of curvature of the spheres.

A relativistic particle emerging from the target generates Cherenkov light. Most of it is refracted out of the crystal, the small reflected part (5%) is rapidly attenuated before reaching the photodetector, due to multiple reflections in the crystal shell. For particles produced off the center of the device with a non zero impact parameter, the above refraction condition will not be met any more. A sizable fraction of the Cherenkov light produced in the crystal is totally reflected, trapped inside the crystal shell and reaches the detector with negligible losses.

In three dimensional geometry, the incident angle θ_{in} of a Cherenkov photon on the external spherical surface is given by the relation :

$$cos(\theta in) = \frac{1}{R}\sqrt{R^2 - \rho^2 + (P\ sin\theta_c\ cos\phi_c + \frac{\lambda}{n})^2} \qquad \lambda = \sqrt{\rho^2 - P^2} \qquad (1)$$

where R is the external radius of the crystal, θ and ϕ are the polar and azimuthal angles of the Cherenkov photon emitted at distance ρ from the center of the device and P is the impact parameter of the emitting charged particle. Total reflection occurs if θ_{in} is lower than the total reflection angle given by the refractive index of the crystal. Figure 2 shows for two refractive indices and a crystal having 100 mm radius, the propability of a Cherenkov photon to be reflected as a function of the distance ρ and the impact parameter of the incident charged particle. It is worth to note that the propability never exceeds 50%. It is also clear that a minimum impact parameter (P_{min}) is required to satisfy the total reflection condition. This minimum increases rapidly with a small decrease of the refractive index from the optimum value of $\sqrt{2}$ and its variation deduced from relation (1) is given by :

$P_{min} = R(2 - n^2)/n^2$ (2)

From Figure 2 we can also deduce that for small impact parameters only photons emitted close to the exit surface of the crystal can be totally reflected and contribute to the detection signal. For a given impact parameter P the useful track length l, i.e. the track length which emits Cherenkov light before exiting from the crystal is given by:

$P = P_{min} + l$

and hence the impact parameter from which all depth of the device can give totally reflected photons is :

$P_0 = P_{min} + d$, where d is the crystal thickness.

Between P_{min} and P_0 the useful track length is independent of the depth of the detector. Since the mean impact parameter of the B-meson decays is about 600 μm, the maximum thickness of the crystal should not exceed few millimeters, so we will use a 2 mm thick crystal.

The important requirement on the radiator is that its refractive index must be close to but not exceed $\sqrt{2}$ for the largest band width of the radiated Cherenkov light. This is well satisfied by the LiF and MgF_2 crystal for wavelengths above 250 nm.

In order to be sensitive to very small impact parameters the radius of the sphere should be small but sufficient for the acceptance of B decays.

3 Monte Carlo simulations - LHC conceptual design

The production of B-meson pairs, for 8 TeV incident proton energy on a fixed target, has been simulated with PYTHIA [6].This program assumes gluon-gluon fusion and quark-quark interaction for B-meson pairs production. In the middle of the crystal a hole of 3 mm in diameter will let the beam particles and most of the hadrons from the primary vertex go through. A radius R=100 mm is a good compromise between the sensitivity of the device which decreases with R and the loss in acceptance due to the central hole. A spherical shell with transverse dimension R_t=30 mm provides full acceptance for B-meson decays [7].

In such a configuration, the particles generated on the small target are tracked through the crystal and polarized Cherenkov light is generated. Each individual photon is refracted or reflected on the crystal exit surface according to Fresnel equations, and the trapped photons are traced through their multireflection process in the crystal shell, until they reach the photodetector. Photons are detected by a Quartz window photomultiplier having a commonly used bialcali photocathode. The photon acceptance is defined from the photocathode quantum efficiency cut-off of λ=500nm and an optical filter cuting wave lengths below λ=250nm. Figure 3 shows the correlation between the impact parameter of an incident charged particle and the exit angle of trapped Cherenkov photons with respect to the normal on the exit side surface of the crystal. Since the impact parameter (Figure.4) of the B-meson of the charged particles from the B-meson decays is small, not exceeding few millimeters, the dispersion of the exit photon angle is limited to a few degrees. We must also point out that for large impact parameters the exit angles become large. Taking into account the limiting aperture of the photon collection system, the photodetector can be blind to the very large impact parameters. This is an appreciable property of the optical trigger system, since δ-rays produced in the crystaland simmulating large impact parameters and decaying long lived particles i.e K^0 and hyperons can be rejected with a carefull design of the light collection system.

Two light collection devices are considered. One is based on quartz fiber read-out. The bundel of fibers is adjusted to the exit surface of the crystal and the light is guided to the photodetector. Figure 5 gives a schematic view of the crystal equiped with 100μm fibers of hexagonal section, grouped in 60 bundles and connected with two photomultipliers. The bunch of fibers is supported by a conical arm, and the crystal is pressed by pins on the fiber entrance, the optical contact being insured by an UV optical grease. A calibration lamp can be substituted to one of the photomultipliers for transmission quality checks. Several sights will allow a preliminary optical positionning of the device.

Another approach is the focussing of the exit light using an appropriate light concentrator. The exit light from the crystal is focussed off beam axis at an angle of 10 degrees by an ellipsoidal mirror. The spot size at the focus depends on the impact parameter and a diaphragm can be used to cutoff large impact parameters.

The B-meson collection efficiency and the rejection of the minimum bias events have been studied with a Monte Carlo simulation. The two collection systems give in a first approximation comparable results. The mean value of photoelectrons detected, from B-meson events, is about 3. It is compared to the minimum bias events background and to cc PYTHIA generated events. With a discrimination level at 4 photoelectrons 32% of the B-meson pairs events are selected while about 2% of the minimum bias events and about 5% of cc events are still accepted.

4 Limitations - Future improvements

Delta rays produced in the crystal shell could be a severe limitation on the rejection ability of minimum bias events. However, they should have a minimum energy of about 1 MeV to produce Cherenkov light. The probability to produce delta rays with energy above 1 MeV (Cherenkov threshold) is estimated to be at the level of 3% per incident track for the 2 mm LiF crystal. The exit angle of most of the photons resulting from Delta rays is larger than 200 mrd, whereas the acceptance of both light collecting devices is limited to less than 200 mrd. Taking into account this effect the probability that Delta rays trigger the device is reduced to 0.1% per track.

Another important limitation will come from hadronic interactions in the crystal itself producing secondary particles with a high impact parameter. This propability is estimated to be of the order of 1 to 2% per minimum bias event in the 2 mm LiF crystal. Further reduction can be obtained by reducing the thickness of the crystal, but there are technical limitations because the material is fragile.

As it was mentionned in the previous section, the detected signal produced by B-meson pairs pairs in a fixed target LHC experiment, corresponds to about 3 photoelectrons. A way to improve the signal is to increase the quantum yield of the photodetector. Reflection type photomultipliers are expected to give higher quantum efficiency (≈45%) to be compared with 25% efficiency of the transmission ones. Silicon avalanche photodiodes have a quantum efficiency close to unity, but their gain is limited at the level of a few hundred. The possibility to improve their sensitivity, lowering the noise by operating at low temperature is under study.

A way to enhance Cherenkov light production is the use of a higher refractive index crystal i.e sapphire (n_1=1.81 at λ=350 nm). In order to satisfy the total reflection condition this material should be sandwiched between two thin layers of the low refractive idex material i.e quartz (n_2=1.5). With such 3 layer device the total reflection condition will be the same as for the LiF crystal provided :

$n_1^2 - n_2^2 = 1$ (3)

Relation (3) should be satisfied for the largest possible bandwidth, which is feasible with present technology by doping the cladding (quartz) with an appropriate material. Despite the reliability of the 3 layer configuration, an important profit can be obtained, by extending it to a multilayer device. As an examble Figure 7 compares the number of reflected photons as a function of the impact parameter for a 2 mm thick LiF crystal (1 slice) with a 4 slice configuration, of the same total thickness. It comes out that for small impact parameters the number of detected photons increases almost linearly with the number of slices, reflecting the fact that only a small part of the particle path in the crystal contributes to the signal. For a larger number of slices (N=10, each 200 μm thick), the major part of the produced Cherenkov photons, above a certain threshold (Pmin), is collected. An optical trigger based on this idea of using multilayer is under study. We plane to deposite alternate layers of sapphire and quartz on a low Z substrate (i.e carbon fiber).

5 Beam tests - Milestones

A first prototype made of LiF or MgF_2 single crystal is expected to be ready and tested at the beginning of next year. The behaviour of the whole optical trigger system will be tested in a particle beam, without the use of a target. Particle trajectories will be defined using finely segmented hodoscopes and a movable train supporting the optical trigger device and will permit to simulate with precision particle impact parameters. The dependence of the collected signal with the impact parameter of the incident particle will be measured and compared to Monte-Carlo results. Charge collection measurements for zero impact parameter incident particles , are important to evaluate the limitations of the system which are mainly due to the contribution of delta-rays and nuclear interactions in the crystal. At the same time alignment and calibration studies will be performed and valuable information and experience will be acquired.

This first experimental investigation has to be carried out on a fast time scale during the year 1992. A second prototype based on the multilayer coating technique should be simulated and designed. If there is no technical obstacles, the second prototype is expected to be operational at the end of 1992 and tested as soon as possible. A final test in a fixed target experiment, combining the Optical Trigger and a microvertex detector to select secondary vertices from charm production, is under study. The possibility to collaborate, for this test, with an existing fixed target experiment or other microvertex R@D projects, is open.

The milestones for the Optical Trigger development project can be summarized as follows :

- End 1991: design, construction and laboratory tests of the first prototype.
- During 1992: test of the prototype in a test beam. Conceptual studies and development of a multilayer crystal device.
- 1993 : beam tests of the second prototype based on the multilayer technique.

6 Budget requirements

The request excludes personnel and travel expenses, assuming that this is included in the internal home institution support, as well as computing time needed for simulation and analysis work. We must also point out that the estimation of the cost for the second prototype, ased on the multilayer technique, is very preliminary.

The budget request is summarized in table 1.

Table 1: Estimated budget for the development of the Optical Trigger

Year	Item	Cost [kSF]
1992	Crystal construction	20
	Fiber read-out development	20
	Optical concetrator	10
	Phototubes	6
	Electronics and DAQ	20
	Mechanics of test-beam installation	5
	Laboratory tests	10
1993	Multilayer prototype	50

References

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Figure captions

- Figure 1: Shematic of an optical trigger
- Figure 2: The figure shows, for two refractif indices, the propability of a Cherenkov photon to be reflected in the crystal exit surface, as a function of its depth of production iside the crystal and the impact parameter of the incident charged particle.
- Figure 3: Correlation between the exit angle of trapped Cherenkov photons in the crystal and the impact parameter of the incident particle.
- Figure 4: Impact parameter of B-meson decay particles, in a LHC - fixed target experiment.
- Figure 5: Schematic view of an Optical Trigger and its assosiated optical fiber read-out.

- Figure 6: Light collection device with an ellipsoidal collecting mirror. Totally reflected photons produced in the crystal are concentrated off beam axis at an angle of 10 degrees by a portion of a ellipsoidal mirror.
- Figure 7: The number of internally trapped photons versus the impact parameter of the incident particle for a 2 mm thick crystal (single slice) is compared to a 4 slice device, each slice having 400 μm thickness.

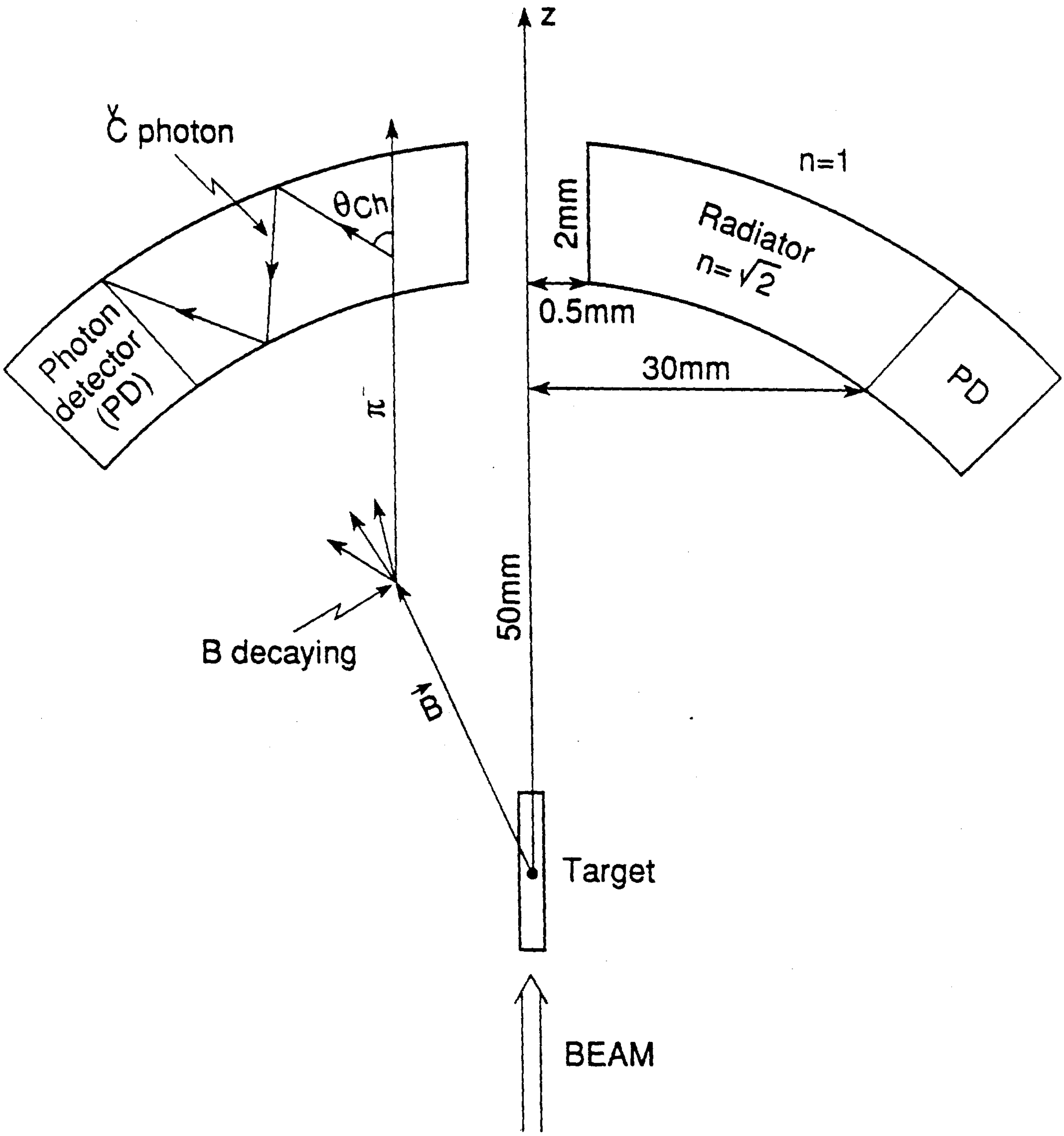
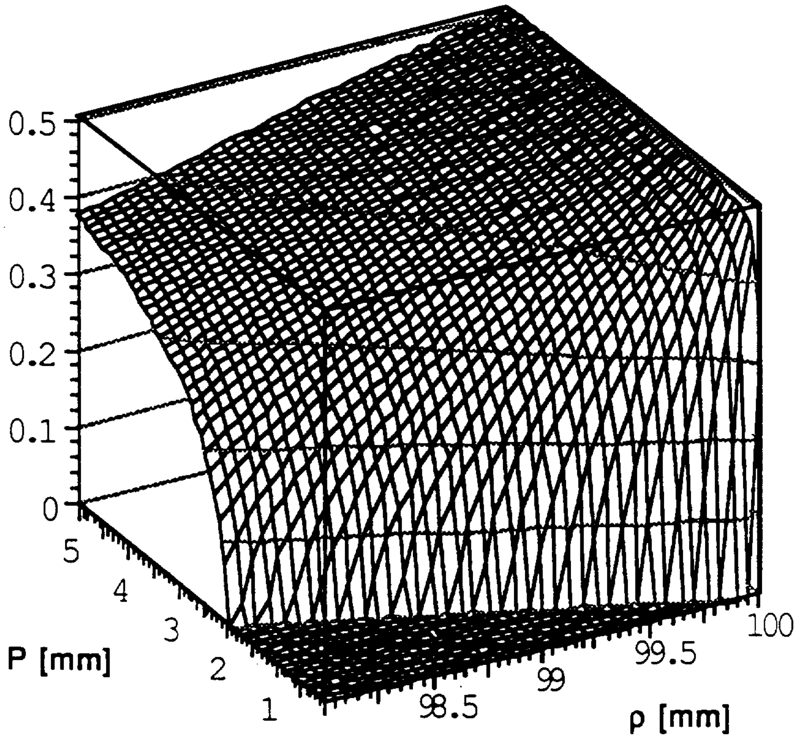
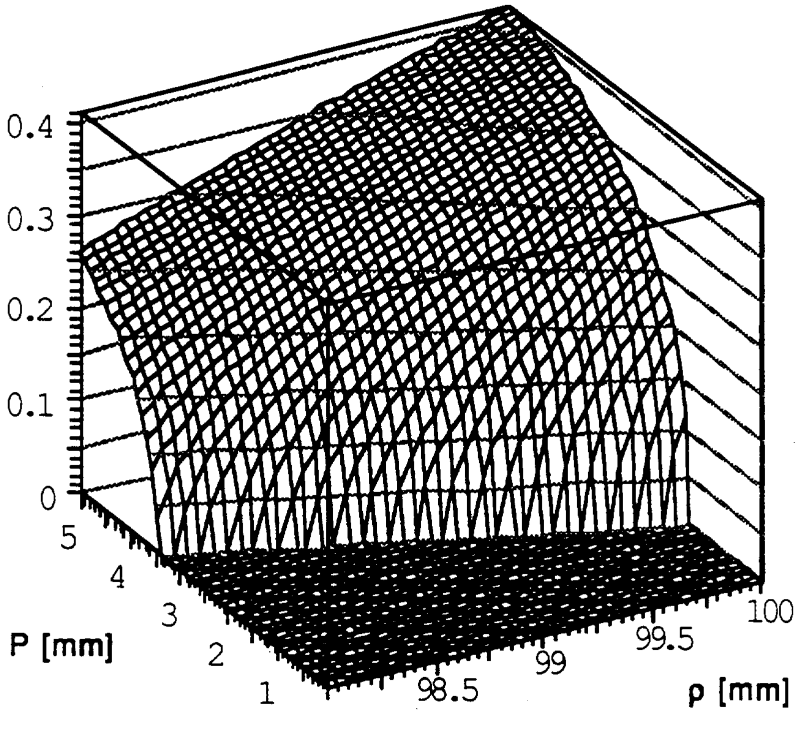

z
Č photon
θCh
n=1
2mm
Radiator
n=√2
0.5mm
30mm
Photon detector (PD)
PD
π⁻
50mm
B decaying
B
Target
BEAM

Fig. 1



Refractive index n = √2



Refractive index n = √2 - 0.01

Figure 2

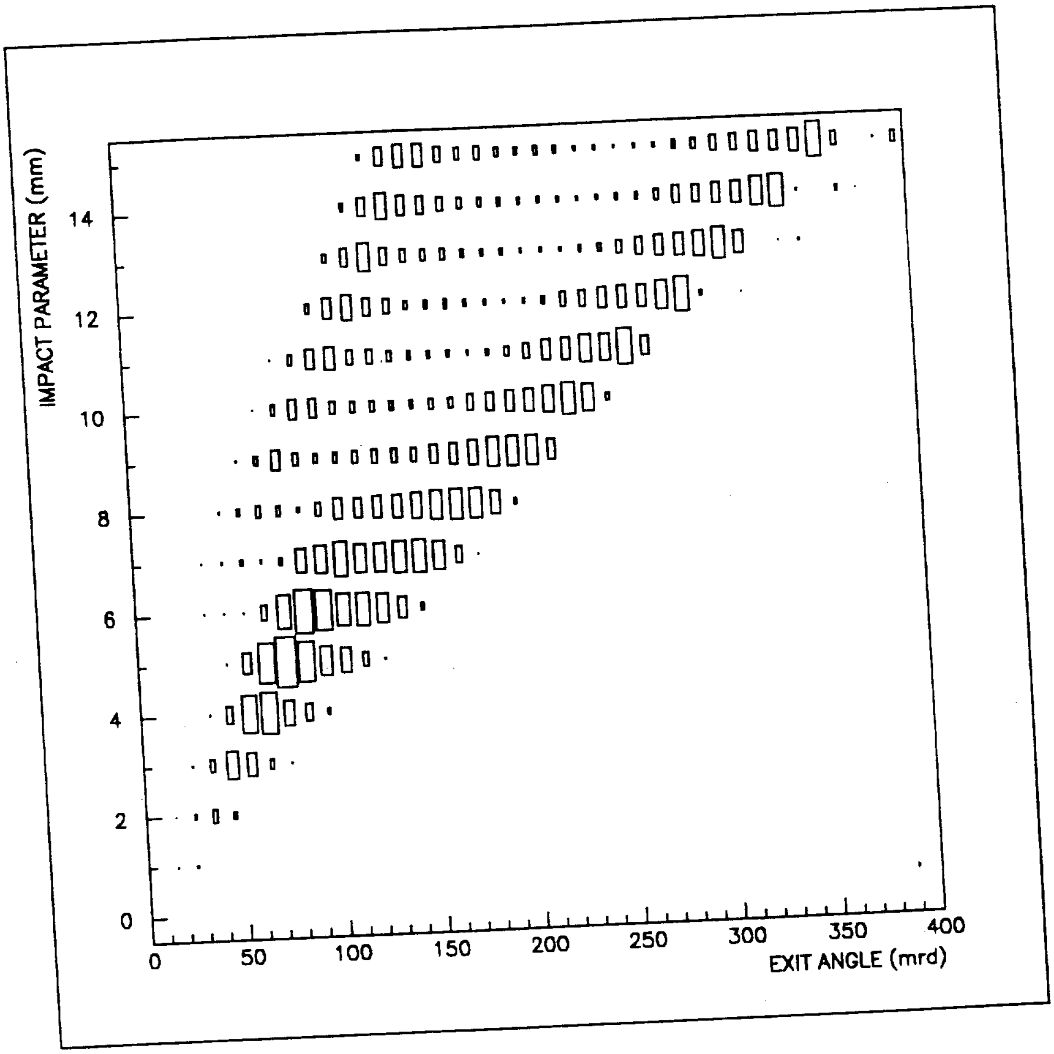

IMPACT PARAMETER (mm)
0
2
4
6
8
10
12
14
EXIT ANGLE (mrd)
0
50
100
150
200
250
300
350
400

Fig. 3

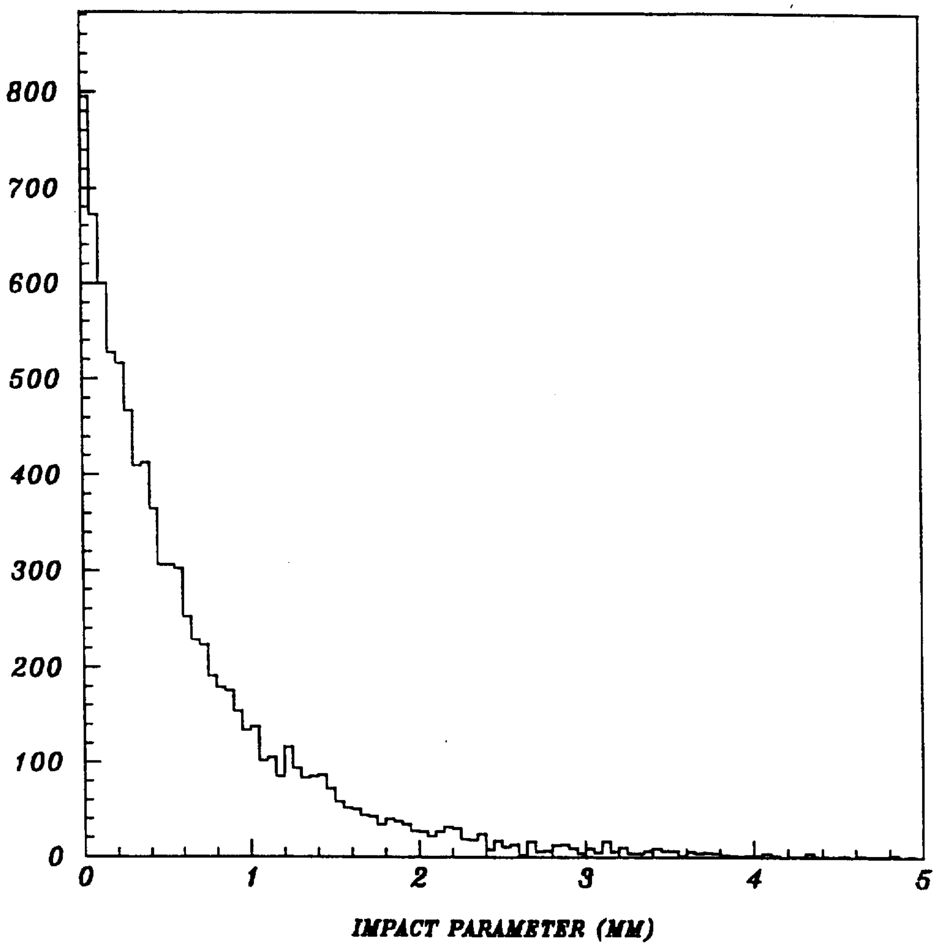
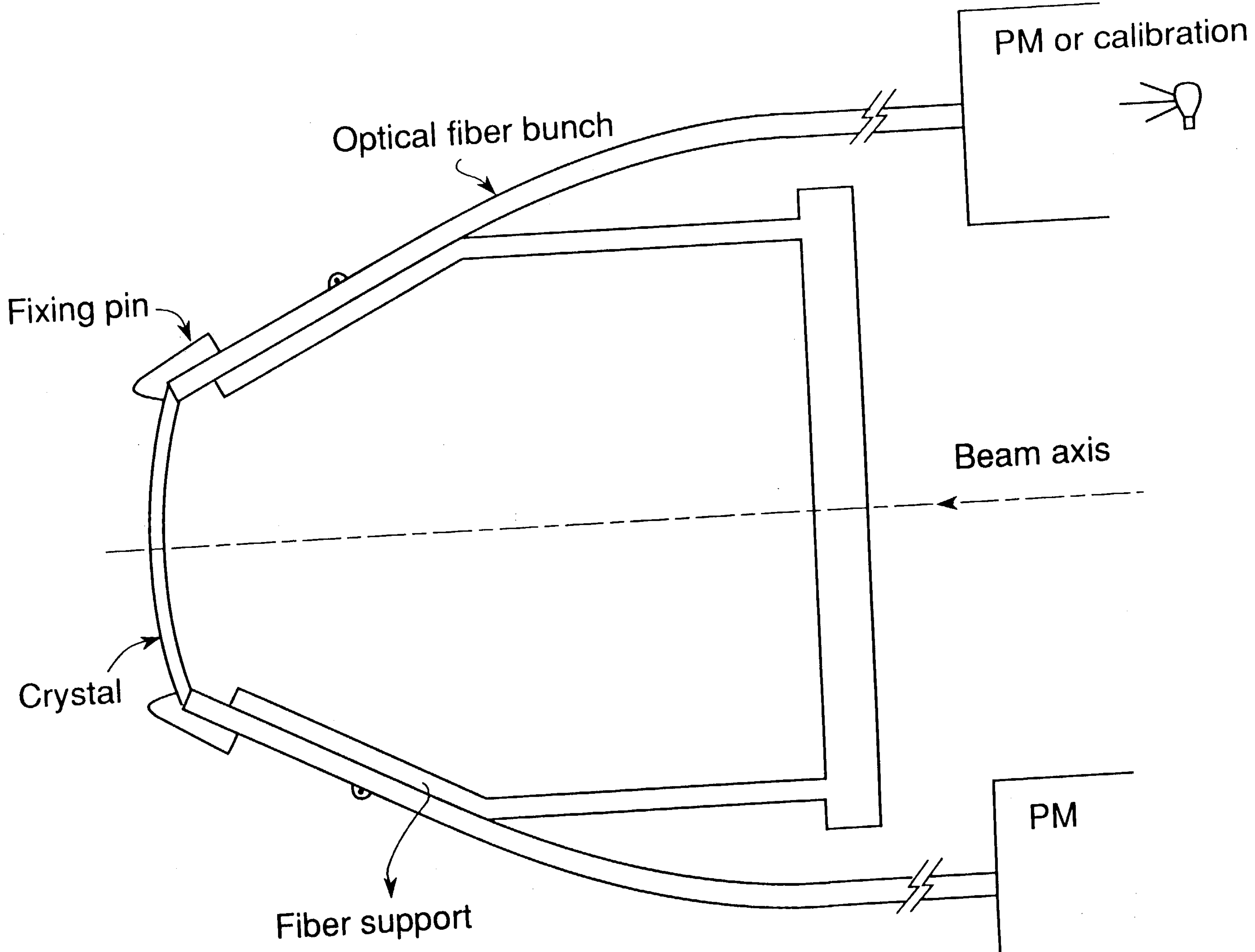


Fig. 4



Top view

Fig. 5

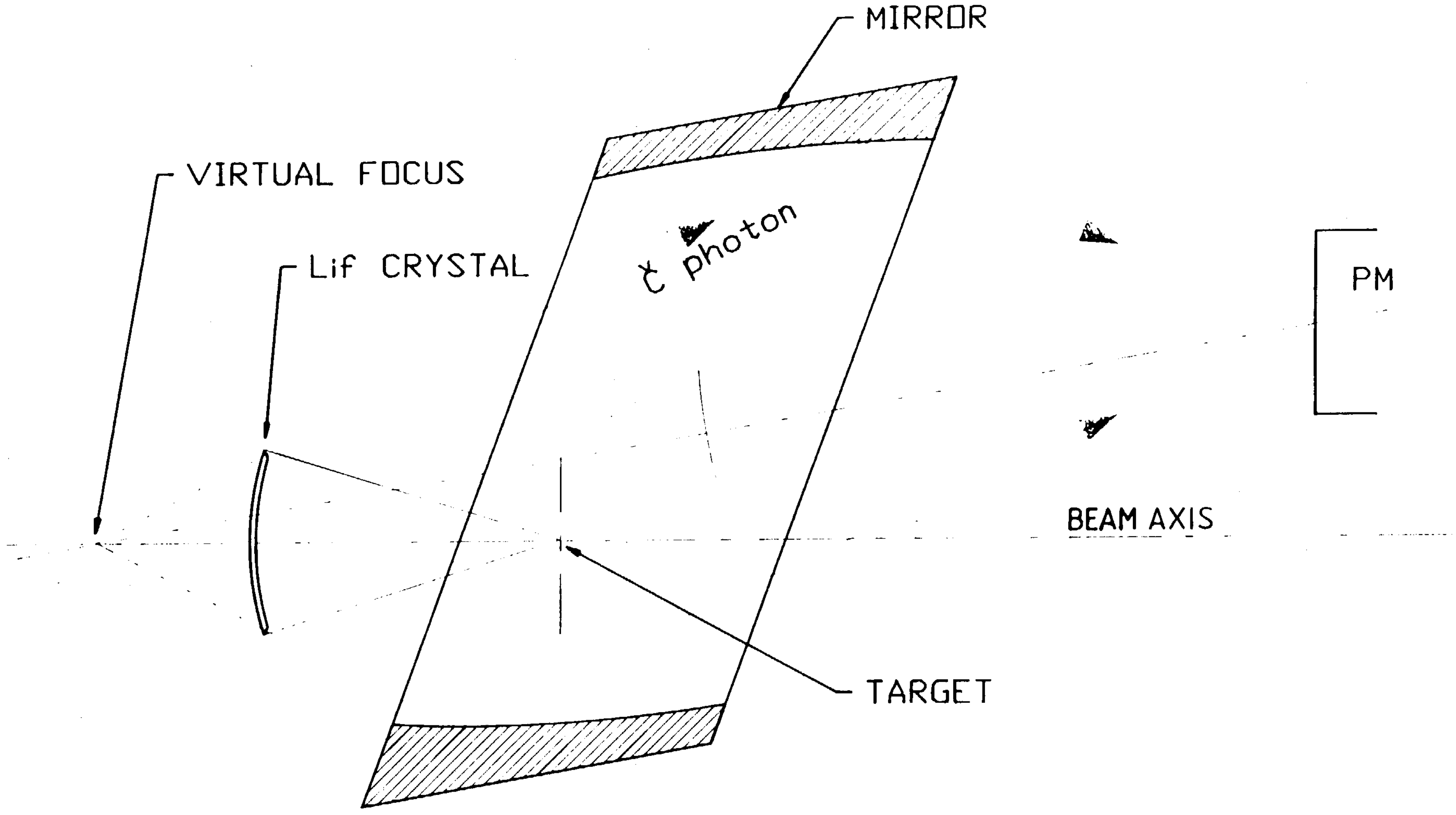

MIRROR
VIRTUAL FOCUS
Lif CRYSTAL
Č photon
PM
BEAM AXIS
TARGET

Fig. 6

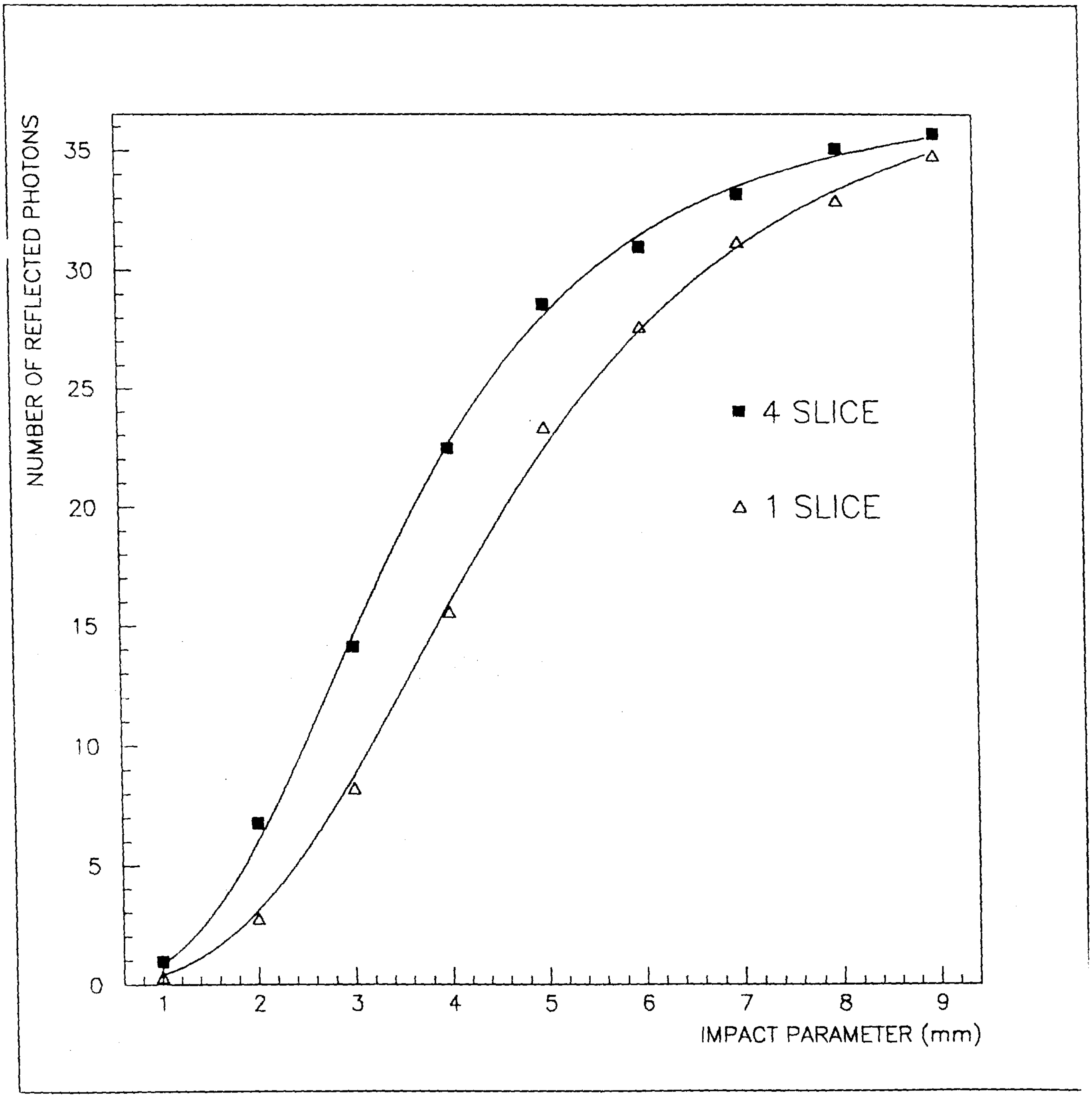

NUMBER OF REFLECTED PHOTONS
0
5
10
15
20
25
30
35
1
2
3
4
5
6
7
8
9
IMPACT PARAMETER (mm)
■ 4 SLICE
△ 1 SLICE

Fig. 7