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BEAM STUDIES OF EM-CALORIMETER PROTOTYPE BUILT OF $PbWO_4$ CRYSTALS

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Abstract

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Further studies of the EM–calorimeter counters built of heavy fast-scintillating lead tungstate crystals $PbWO_4$ are described. The characteristics of more than 30 industrially produced large-size cells (up to 25 X_0 long) are measured. Beam test results on the calorimeter prototype are presented, the energy resolution and coordinate accuracy are measured with 4, 9, 17 and 26 GeV electrons at the IHEP 70 GeV proton accelerator.

Аннотация

Буянов О.В. и др. Исследование прототипа электромагнитного калориметра, изготовленного из кристаллов $PbWO_4$, на пучках частиц: Препринт ИФВЭ 93-144. – Протвино, 1993. - 11 с., 16 рис., 2 табл., библиогр.: 7.

Приведены результаты дальнейших исследований счетчиков электромагнитного калориметра, изготовленных из тяжелых, быстро-сцинтиллирующих кристаллов вольфрамата свинца $PbWO_4$. Измерены характеристики более чем 30 изготовленных в промышленности ячеек большого размера (длиной до 25 X_0). Представлены результаты испытаний прототипа калориметра в пучках частиц 70-ГэВ ускорителя ИФВЭ. Энергетическое разрешение и координатная точность измерены при энергиях электронов 4, 9, 17 и 26 ГэВ.

INTRODUCTION

A search for a new generation of dense, fast and radiation-hard scintillators has become very intense during last years. There are two main directions of these investigations: the fluorides (CeF_3, BaF_2, PbF_2...) and the oxides (BGO, GSO, $NaBi(WO_4)_2$, $PbWO_4$ ...).

In previous publications [1]-[3] we have shown that lead tungstate $PbWO_4$ (PWO) is a very promising material for precise EM-calorimetery in high-energy physics. Multicell calorimeters built of this very dense (heavier than iron) crystal, fast, radiation-hard, compact and suitable for industrial production, would provide an attractive solution to the high-precision photon (electron) detection problem in the experiments at future colliders (LHC, $RHIC$, e^+e^- factories) as well as at the fixed-target accelerators. In particular, such calorimeter plays a key role in the $ALICE$ project [4], the heavy ion experiment at LHC (search for the QGP thermal photons, etc.).

We started systematic studies of the PWO calorimeter prototypes a year and a half ago. Below a short summary of our $R\&D$ results obtained by the summer of 1993 is given (see also [5]).

1. *PWO* CRYSTAL PROPERTIES

1.1. PROPERTIES OF *PWO* SINGLE CRYSTALS

The PWO single crystals are grown by the Chohralski method in platinum crucibles at $\approx 1000°C$ in the air-like atmosphere. The crystals are 30 to 34 mm in diameter and 200 to 240 mm long, they are easy to machine with a standard equipment.

PWO is a very dense material ($\rho = 8.3\ g/cm^3$) with one of the smallest, among the known crystals, radiation length ($X_0 = 8.7\ mm$). Its Moliere radius is also small (2 cm). This provides small lateral dimensions of EM-showers and high spatial photon (electron) resolution. The main characteristics of PWO and some other single crystals are listed in table 1.

Table 1. Basic characteristics of some heavy crystals

Crystal	Density (g/cm^3)	Radiation length (cm)	Moliere radius (cm)	Light yield (% of BGO)	Decay time(ns)	Peak emission (nm)	Refraction index
BaF_2	4.89	2.05	4.4	40	0.9/630	210/320	1.49
CeF_3	6.16	1.68	2.6	45	5/20	300/340	1.62
BGO	7.13	1.12	2.3	100	300	480	2.15
$PbWO_4$	8.28	0.87	2.2	5	2/10/30	440–530	2.16
$NaBi(WO_4)_2$	7.57	0.98	2.7	č	-	-	2.05
$Gd_3Ga_5O_{12}$	7.02	1.45	2.4	č	-	-	2.00
PbF_2	7.56	0.95	2.2	č	-	-	1.82

1.2. SPECTROSCOPY OF *PWO* CRYSTALS

Under the UV-excitation, the luminescence spectra of PWO show at least three bands with maxima around $420, 490$ and 650 nm. The crystals show the absorption dichroism in the 300 to 490 nm region, the growing conditions have been optimized to let the optical axis be parallel to the direction of minimal absorption in the visible light region. Under gamma-excitation (^{57}Co, 122 KeV), the observed spectra are the superposition of the above bands (fig. 1). The relative intensities of the blue and green bands and their contribution to the total spectrum depend strongly on the crystal purity and its growing condition. As a result, the position of luminescence spectrum maximum varies from 440 nm to 530 nm.

The light yield of PWO crystal was measured relative to a BGO one. Both $1 \times 1 \times 1$ cm^3 crystals were excited by ^{57}Co. Comparision of the areas under the luminescence curves (fig. 2) shows that the PWO light yield is at least 5% of that of BGO.

The amplitude spectra obtained with the PWO and BGO crystals irradiated by the ^{137}Cs (660 KeV) and ^{241}Am (60 KeV) photons, respectively, are shown in fig. 3. The samples were polished and wrapped up an aluminized mylar. The scintillation yield of PWO is about 5% of that of BGO, when measured with the bialkali PMT.

The kinetics of the PWO crystal luminescence has been measured under the UV-excitation. The luminescence in the green band (480 nm) is very fast, it can be described with two exponentials, of 4 ns and 20 ns slopes.

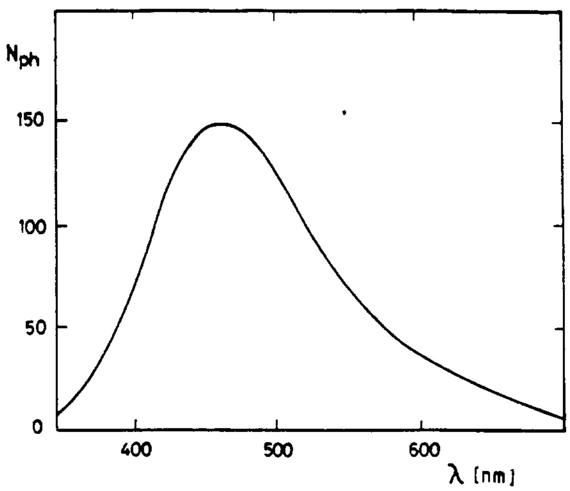

Figure 1. The 122 KeV (^{57}Co) γ-excited luminescence spectrum of the PWO crystal. T = 300°K.

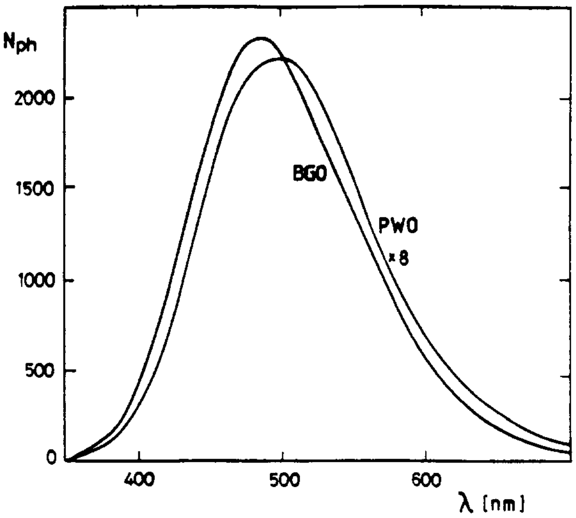

Figure 2. The luminescence spectra of PWO and BGO crystals under the gamma excitation of ^{57}Co, the PMT sensitivity being corrected by a standard spectroscopic tungsten lamp.

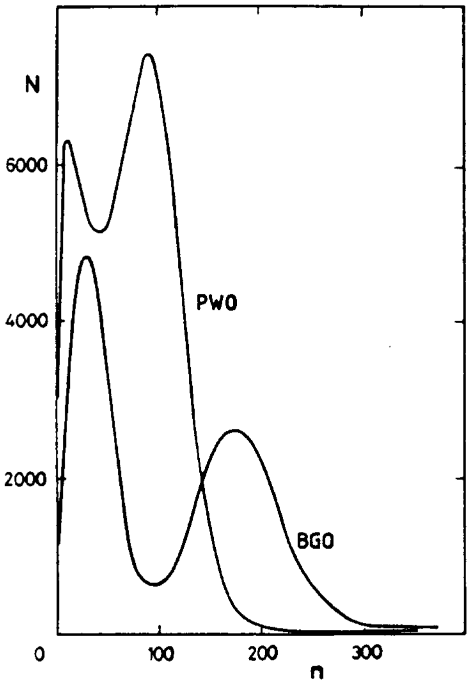

Figure 3. The amplitude spectra of PWO and BGO crystals measured with a bialkali PMT, the crystals being γ-irradiated with ^{137}Cs (660 KeV) and ^{241}Am (60 KeV), respectively. Here and further n is the ADC channel.

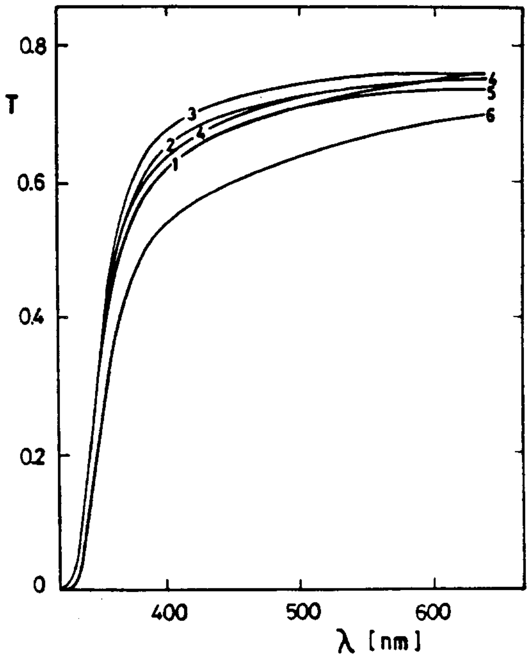

Figure 4. The dependence of PWO transmittance on the absorbed γ-dose (^{60}Co). 1: before irradiation, 2: $5 \cdot 10^3$ rad, 3: $5 \cdot 10^4$ rad, 4: $5 \cdot 10^5$ rad, 5: $5 \cdot 10^6$ rad and 6: $7 \cdot 10^7 rad$.

The *PWO* crystals grown under optimal conditions show strong radiation hardness, their transparency depends only little on the absorbed γ-dose up to 10 *Mrad.* Below 5 *Mrad* the *PWO* transparency even improves under irradiation (fig. 4).

2. BEAM TESTS

2.1. MEASUREMENT CONDITIONS

The characteristics of the EM-calorimeter prototype have been measured with 4, 9, 17 and 26 *GeV* electron beams produced at the IHEP 70 *GeV* proton accelerator. Four *PWO* crystals (serial numbers 1, 2, 5 and 6) have been selected for these beam studies. Their properties were not the same due to different growth conditions.

The transverse cell dimensions ($22 \times 22\ mm^2$) have been chosen taking into account the optimal size of the *GAMS*-type calorimeter, which is about one Moliere radius [6]. The cells #1 and #2 were 150 *mm* long, the cells #5 and #6 were 160 and 180 *mm* long. These values correspond to 17, 18 and 20 radiation lengths, respectively. All crystals were polished and wrapped up an aluminized mylar.

Table 2. Crystal matrix

GGG $17X_0$	*PWO*1 $17X_0$	*NBW* $18X_0$	*GGG* $17X_0$
*PWO*2 $17X_0$	*PWO*6 $20X_0$	*PWO*5 $18X_0$	*NBW* $19X_0$
GGG $17X_0$	*NBW* $18X_0$	*NBW* $17X_0$	*GGG* $17X_0$
GGG $17X_0$	*GGG* $17X_0$	*GGG* $17X_0$	*GGG* $17X_0$

Two types of small PMT were used as photodetectors: home-made FEU-147 PMT with the multialkaline photocathode and Philips XP1911. For the studies of single cells, PMTs with larger photocathode were also used: FEU-84-3 and Philips XP2020Q. The PMT signals were digitized with 12 bit charge-sensitive ADCs. The PMT gain was monitored with a light-emitting diode.

Four cells made of $NaBi(WO_4)_2$ (*NBW*) crystals and eight cells made of $Gd_3Ga_5O_{12}$ (*GGG*) were used to complete a 4×4 matrix (table 2). These heavy crystals are pure Cherenkov radiators.

The coordinate accuracy of the calorimeter prototype as well as the EM-shower profile were determined by moving the matrix across the electron beam, electron coordinates being measured with a silicon 200 μm pitch microstrip detector.

2.2. MEASUREMENT RESULTS

2.2.1. Time characteristics, light attenuation

Each cell was tested in the 26 GeV electron beam with XP2020Q, before assembling the matrix. This PMT is not optimal for the PWO scintillation light, its quantum efficiency at 480 nm is less than 10%, while for the Cherenkov light in GGG or NBW this value amounts 30%.

The amplitude spectra measured with the NBW and PWO #6 cells are presented in fig. 5. These two crystals have similar refractive index and radiation length. Fig. 5 shows that the signal ratio in these cells is ≈ 4. The ratio increases to 10 when FEU-84-3 is used.

The signal observed in the PWO cell #6 with XP2020Q has 15 $nsec$ width (FWHM), it is 25 $nsec$ wide at 10% level. The signal tail becomes negligible after 60 $nsec$. Fast decay constant contributes the same value to the signals in other PWO cells but the tails of these signals are much longer, up to 150 $nsec$. This difference is illustrated by fig. 6, where the collected charge is plotted versus the ADC time gate. For comparison, similar data for the GGG Cherenkov radiator are also shown.

The intrinsic light attenuation was measured in the muon beam in each PWO cell. The matrix was turned perpendicular to the beam, muon coordinates being defined with a 2 mm scintillation hodoscope. Fig. 7 shows the results obtained with the PWO cell #6. The light attenuation length, λ_{att}, is larger than 1 m in the cell. This is enough to achieve the constant term in the energy resolution σ_E/E, arising from the longitudinal EM-shower fluctuations, smaller than 1%.

2.2.2. Energy resolution

Below we present the results of the first beam measurements of the energy resolution of the PWO calorimeter prototype. The measurement conditions in these tests were not optimal:

- the momentum spread of the electron beam was large, comparable with the expected calorimeter resolution;
- small size PMT (FEU-147) was not enough time stable;

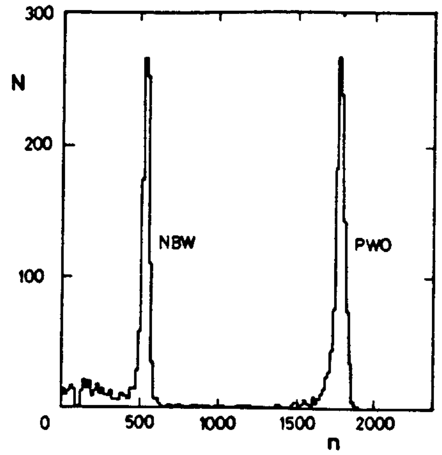

Figure 5. The amplitude spectra of *NBW* and *PWO* single cells measured in the 26 *GeV* electron beam with a bialkali PMT.

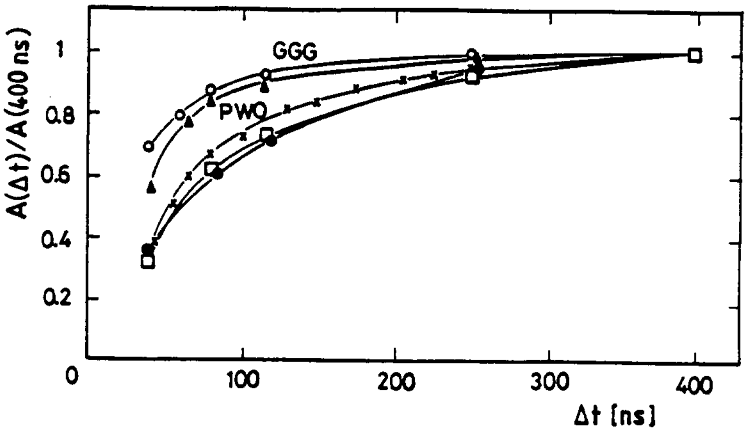

Figure 6. The *PWO* signal dependence upon the ADC gate width (after the 95 *m* cable, [illegible] cells: #1 (×), #2 (□), #5 (•) and #6 (▲). Similar data for *GGG* is also shown (○).

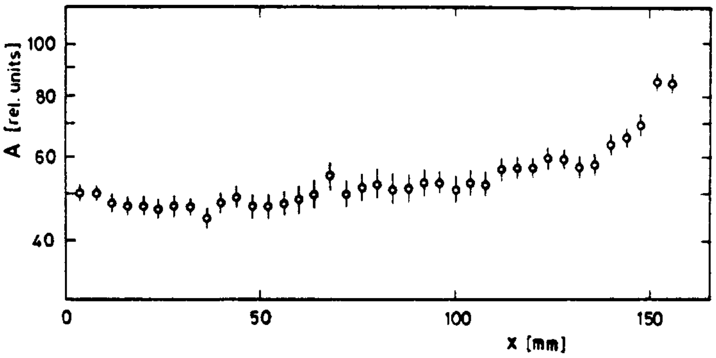

Figure 7. The signal of PMT (which is to the right-hand side) versus a muon coordinate.

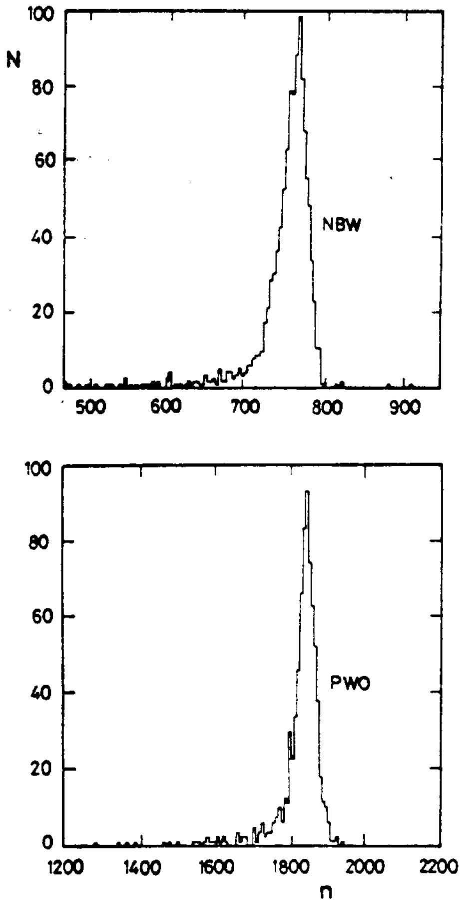

Figure 8. Similar to fig. 5.

– all crystals in the matrix had different characteristics;

The amplitude spectra in single cells of *NBW* and *PWO* #6, measured in the 26 *GeV* electron beam (3×3 mm^2 beam spot) with XP2020Q, are shown in fig. 8. The energy resolution of *PWO* cell, $\sigma_E/E \approx 1\%$, is two times better than that of *NBW*. Similar measurements were carried out at 9 *GeV* with larger beam spot (10×10 mm^2), the resolution is $\approx 2\%$. Using the beam with smaller spot one may expect 1.5% resolution with this single *PWO* cell, according to the Monte Carlo calculations.

The amplitude spectra of the matrix measured with 4 *GeV* electrons and muons are presented in fig. 9. The energy resolution obtained for the matrix is worse than that in a single cell with XP2020Q. The main reasons for this are the time instability of our small PMTs and light losses (this PMT collects six times less light than XP2020Q due to its smaller photocathode).

The σ_E/E dependence on the electron energy is given in fig. 10. It shows that the constant term in the energy resolution does not exceed 0.5%. This value is in a good agreement with the Monte Carlo calculations based on real parameters of our *PWO* cells.

Taking into account the results obtained with the single cell and XP2020Q one may expect the energy resolution of the *PWO* calorimeter to be:

$$\sigma_E/E \leq 2.5\%/\sqrt{E} + 0.5\%.$$

The matrix uniformity is illustrated by fig. 11, the signal remains constant within ± 1%. There is no change in the energy resolution too.

2.2.3. Coordinate resolution

The method of precise coordinate measurements with the multicell lead-glass *GAMS*-type EM-calorimeter was described in [6,7]. The coordinate accuracy of the lead-glass calorimeter with the cell dimensions of 40×40 mm^2 is $\sigma_x \approx$ 1.5 *mm* for initial photons or elecrons of $\approx$ 20 *GeV* energy. In case of the *PWO* crystal calorimeter, the transverse size of the EM-shower is two times smaller than that in lead glass. As a result, σ_x value in the *PWO* calorimeter with an optimal cell size should be two times smaller, i.e. better than a millimeter.

A sample of $100K$ 26 *GeV* electron induced events has been collected to measure σ_x and the shower width in the *PWO* cells at four positions of the matrix relative to the beam, from the middle of *PWO* #2 to the middle of *PWO* #5 (table 2). Fig. 12 shows the coordinates, measured as a center-of-gravity of the cell signals, versus the real electron positions determined with the

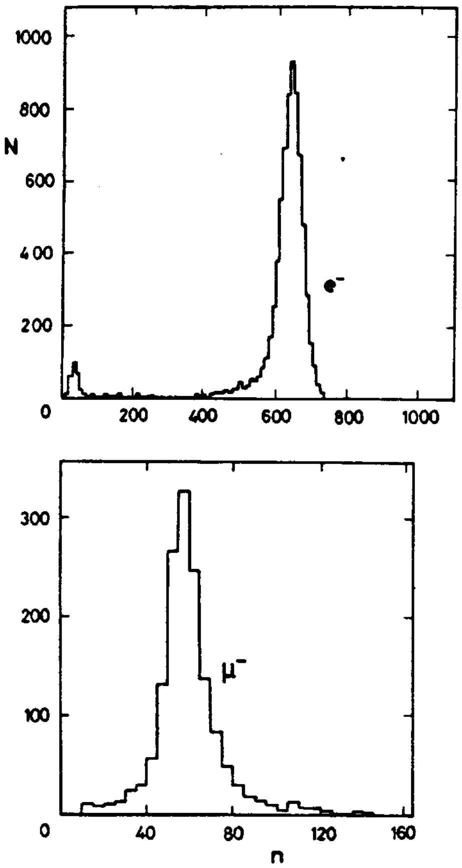

Figure 9. The amplitude spectra of the matrix signal measured in the 4 GeV electron and muon beams.

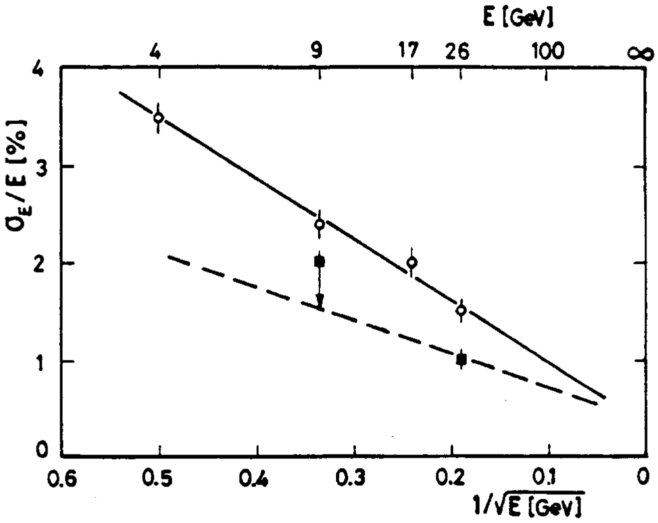

Figure 10. σ_E/E versus the electron beam energy: matrix (o), single *PWO* cell (■). Straight lines are for the $a/\sqrt{E}+b$ dependences.

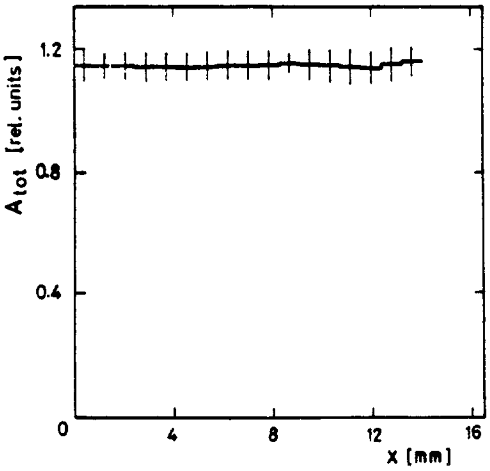

Figure 11. The matrix signal dependence on the electron impact coordinate. Vertical bars show the σ_E/E values.

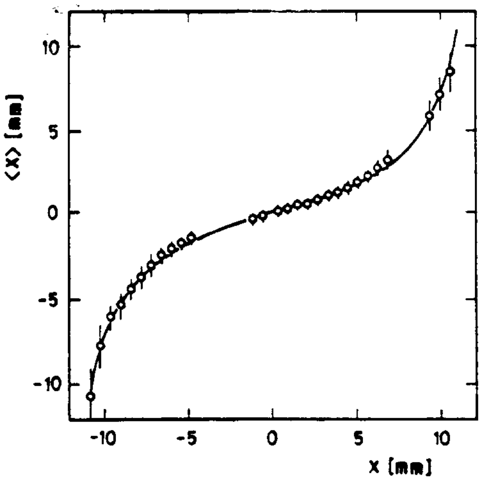

Figure 12. The coordinate of the shower center-of-gravity, $< x >$, versus the real electron coordinate x.

microstrip detector. After the correction [6], this dependence becomes linear (fig. 13).

The position resolution of the matrix for various impact points of incoming electrons is shown in fig. 14. σ_x is smaller than 400 μm near the edge of the cell, it rises to 900 μm in the cell center (fig. 14).

The EM-shower profile was measured with 26 GeV electrons (fig. 15). It changes only slightly with energy. Up to 85% of the EM-shower energy is absorbed in our $22 \times 22\ mm^2$ cell. This appears to be not optimal for such type of detectors. As it was recommended [3], the size of a cell for the *PWO* calorimeter should be smaller, 19 to 20 *mm*.

The EM-shower profiles in the *GGG*, *NBW*, *PWO* and *TF*1 lead-glass ($\approx$ *SF*2) calorimeters are presented in fig. 16. Showers in heavy crystals are two times narrower than those in the *TF*1 lead glass. Using *GAMS* experience of the shower reconstruction, two photon (electron) showers can be reliably separated in a *PWO* calorimeter when they are only 1 *cm* apart. This is a crucial number for the *ALICE* experiment due to the high occupancy of its detectors [4].

CONCLUSION

Our technological studies and the very first beam tests of the *PWO* calorimeter prototype built of the first industrially produced large crystals have shown that:

– the light yield in the crystals with the 500 *nm* emission peak is about 5 % of BGO;

– *PWO* is a fast scintillator, 80% of the light is emitted within 20 *nsec*;

– *PWO* intrinsic light transmittance is high, $\lambda_{att} > 1\ m$;

– *PWO* is radiation-hard, with no significant changes up to 5 *Mrad*;

– the technology of growing the calorimeter-size *PWO* crystals (up to 25 X_0 long, 6 *cm* in diameter) is developed.

As for the *PWO*-built *PHOS* calorimeter of *ALICE* [4]:

– the energy resolution σ_E/E is expected to be better than $3\%/\sqrt{E}$, with the constant term smaller than 0.5%;

– the uniformity of response is better than 2%.

– the distance of *PHOS* to the beam-beam collision point can be reduced due to its high spatial shower resolution.

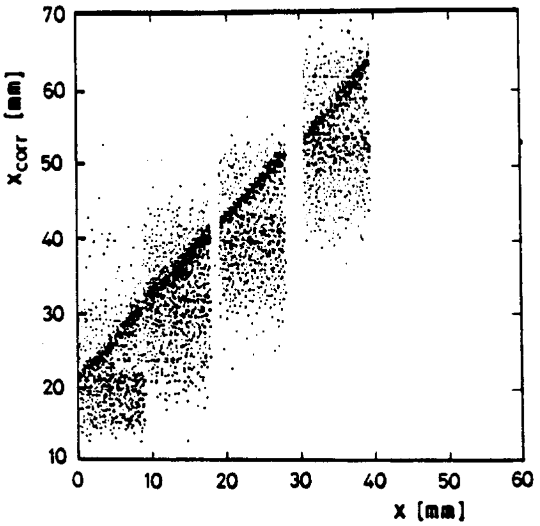

Figure 13. Electron shower coordinate after the correction.

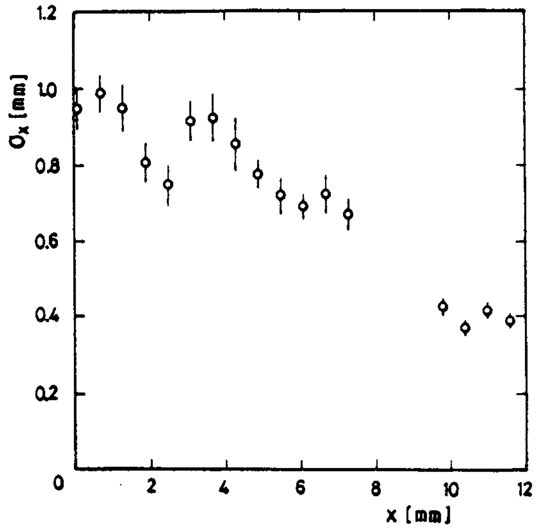

Figure 14. The electron coordinate precision across the *PWO* cell.

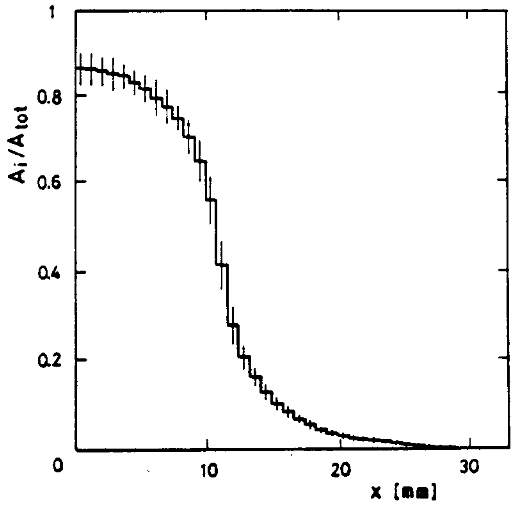

Figure 15. The 26 GeV electron induced shower profile in the *PWO* cell. A_i/A_{tot} is the ratio of the *PWO* cell signal to that of the total matrix, x is the distance between the electron impact point and the cell center.

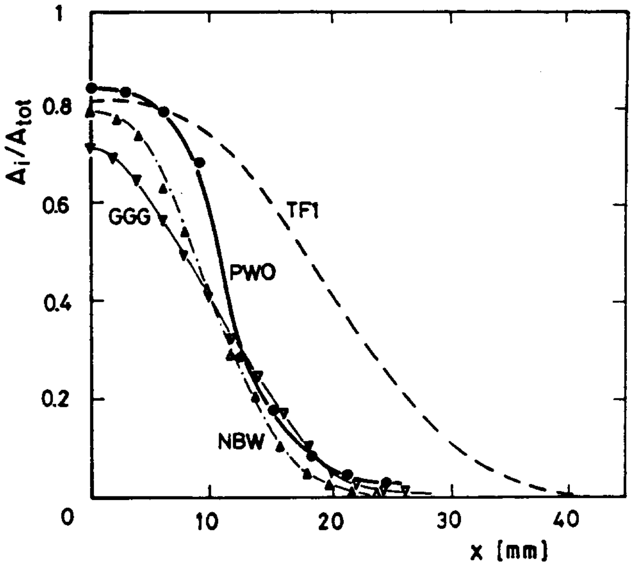

Figure 16. The shower profiles in heavy crystals (22 × 22 mm^2 cell) and TF1 lead glass (38 × 38 mm^2 cell).

Our nearest plans are:

– beam tests of the 25 cell *PWO* calorimeter prototype this autumn using the NA-12/2 *GAMS* setup at CERN [1];

– further investigations of the *PWO* crystal properties to improve the industrial crystal growing technology.

We believe the *PWO* built $\gamma(e)$-detectors will provide a break-through for the high precision EM-calorimetry at the collider energies [3].

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[1] Beam tests were completed in October 1993.

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