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Beam test results of a $PbWO_4$ crystal calorimeter prototype

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Abstract

Beam tests of an EM-calorimeter prototype made of $PbWO_4$ crystals, produced after significant improvement in growth technology, have been performed at the CERN SPS. The measured energy resolution is $\sigma_E/E = 2.8\%/\sqrt{E} \oplus 0.47\%$.

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1. Introduction

Lead tungstate $PbWO_4$ (PWO) crystals have been considered a promising material for electromagnetic calorimetry for more than two years [1, 2]. Significant progress has been made during this time both in investigations of basic crystal properties [3–7] and of specific applications to high-energy electromagnetic calorimetry [8, 9].

Among the important results so far obtained have been a good energy resolution measured in beam tests at CERN and KEK with 3 × 3 PWO matrices of $20 \times 20 \times 180$ mm^3 crystals [8, 9], and a significant variation in crystal characteristics along the ingot axis [7]. This variation, together with a rather strong temperature dependence of the light yield (about $-2\%/°C^{-1}$) would spoil PWO calorimeter energy resolution. Therefore, one could expect much better performance with uniform and temperature-stabilized crystals.

Optimization of the crystal growth procedure, as well as precise stoichiometry control, result in a new set of crystals of greater uniformity.

The improvement in PWO crystal radiation hardness through controlled Nb doping also leads to better transparency below 400 nm and very good uniformity along the crystal growth axis [7].

Presented below are the results of the beam tests of the electromagnetic calorimeter prototype made with the new PWO crystals. These tests were performed during the summer of 1995 at CERN [10].

2. Experimental set-up

The measurements were made in the X1 beam of SPS at CERN with electron momenta of between 10 and 70 GeV/*c*. Beam momentum spread during the test was $\sigma p/p = (0.3 \pm 0.1)\%$. The measurement set-up is sketched in Fig. 1.

The test calorimeter was built as a matrix of 5 × 8 cells. Each cell was made of $20 \times 20 \times (180 \div 200)$ mm^3 PWO crystal wrapped in 100 µm TYVEK paper. Two specially shaped plastic pieces where attached to the front and back of each crystal for holding, respectively, an optical fibre of the monitoring system light distributor and a photomultiplier. The pieces were kept together by four stretched 50 µm mylar strips.

In addition, at the sides of the crystal 50 μm black polyester adhesive tape was used to hold in place the TYVEK wrapping and ensure optical isolation from cell to cell. The total gap between crystals in the matrix was less than 300 μm.

Philips XP1911 photomultipliers (PMT), optically connected to the crystals by the Dow Corning Q2-3067 couplant (refractive index 1.48), were used for light detection. With its 15 mm diameter photocathode, the PMT covered ≈ 40% of the crystal back surface.

The 5 × 8 matrix, surrounded by massive copper plates, with water circulating pipes for temperature stabilization, was kept in a special light and thermal isolation box. The top row of crystals was equipped with temperature sensors. All measurements were performed at (14.5 ± 0.2)°C.

The impact points of the beam particles were measured with 1 mm pitch scintillator hodoscopes.

The PMT signals were digitized by a 12-bit charge ADC with 100 ns gate. A double step monitoring system, based on red LEDs triggered by a temperature stabilized generator and light pulser made of YAP-crystal with ^{238}Pu radioactive source [11], was used to control the PMT gain and the ADC stability to a precision of 0.2%.

3. Beam test results

3.1 Energy resolution

The characteristics of the PWO calorimeter prototype were measured with 10, 20, 50 and 70 GeV electrons. The calibration of calorimeter cells was performed in two steps. First, all cells were irradiated by a narrow 50 GeV electron beam with a spot size of 2 × 2 mm^2. The peak position obtained from a Gaussian fit of the amplitude distribution for each cell was used as a first approximation for the second step, a minimization procedure to determine the optimal calibration coefficients.

The calibrated signal sum of the 5 × 5 PWO matrix irradiated by a 6 × 6 mm^2 70 GeV electron beam is shown in Fig. 2. The energy resolution at the different electron energies is obtained using a Gaussian fit of calibrated sum spectrum (Table 1 and Fig. 3). The energy resolution after correction of beam spread can be parametrized as:

$$\sigma_E/E = (2.8 \pm 0.2)\% / \sqrt{E[\mathrm{GeV}]} \oplus (0.47 \pm 0.06)\% \quad . \qquad (1)$$

3.2 Light yield

The light yield of the PWO crystals was measured by several groups, mainly under laboratory conditions, using low energy photons from radioactive sources. To compare this value with the light output obtained with EM showers, the PMT in one cell was replaced by a Hamamatsu PIN diode S3590-03 (PD). With its 10×10 mm^2 sensitive region, the PD covers a quarter of the rear surface of the cell. The signal of the muons used as minimum ionizing particles (MIP) passing through the PWO crystal but missing the PD, is shown in Fig. 4a. The PD signal when MIP passes both the crystal and the diode is shown in Fig. 4b. Figure 4c presents the amplitude spectrum of 5 GeV electron.

From a comparison with the number of e-hole pairs created by an MIP in the 300 μm PD (25000 [12]), the number of electrons produced in a diode by the photons from EM shower in the PWO cell is shown to be about 16 photoelectrons/MeV. Considering a geometrical matching factor of 1/4 and that the PD quantum efficiency $\approx$ 50% (the mean value for the PWO emission spectrum), the PWO crystal light output is estimated to $\approx$ 120 photons/MeV, in agreement with previous evaluations [8].

Also taking into account the ratio of the geometrical factor and quantum efficiency between PMT and PD, integrated on the PWO light emission spectrum [7], six photoelectons/MeV are then expected for the PMT readout. This is in good agreement with a lower limit estimation of five photoelectrons/MeV obtained with a GEANT-based simulation [13].

Nevertheless the photostatistic part of $\sigma E/_E$ in Fig. 3 is larger than expected from the value above due to additional fluctuation factors, including the multiplicator variance and first-stage collection fluctuation of the photomultiplier, which should be taken into account [14].

3.3 Temperature dependence of the light yield

The light yield temperature dependence was measured after the energy scan with the temperature stabilization system switched off. The temperature of the crystals increased from

14.34°C to 17.44°C over four hours. This slow rise in temperature ensured the absence of significant temperature gradients along the crystals — also controlled by the temperature sensors attached to the front and back of one cell. The matrix was continuously irradiated with 50 GeV electrons. The temperature dependence of the cell signal is presented in Fig. 5. It is well fitted by a straight line with a slope of $(-1.92 \pm 0.02)\%/°C$ at 14.5°C.

3.4 Comparison with Nb doped crystal

Only one radiation-hard Nb doped crystal was available during the test. The amplitude spectrum for 20 GeV/*c* electrons in Fig. 6 shows that a similar performance can be obtained with Nb doped crystal.

4. Conclusion

Beam tests of an EM-calorimeter prototype made of PWO crystals grown with improved technology have been performed. The better crystal uniformity and good temperature stabilization result in a significant improvement in the calorimeter performance.

The energy resolution of better than 1% above 10 GeV obtained so far is close to the design parameters of CMS [15] and ALICE [16] electromagnetic calorimeters. This result, together with good radiation hardness [6, 7] and rather fast decay time constant make PWO-based calorimeters very attractive for the future collider experiments[1].

Acknowledgement

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References

[1] V.G. Baryshevsky et al., Nucl. Instrum. Methods Phys. Res., **A322** (1992) 231.

[2] M. Kobayashi et al., Proc. CRYSTAL 2000 Intern. Workshop, Chamonix, Ed. Frontières.(1993) 375,

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[1] Now PWO crystals are considered as a baseline option for the electromagnetic calorimeters of CMS [17] and ALICE experiments at LHC.

[3] V.A. Katchanov et al., IEEE Conf. Record, Nucl. Science Symp. and Medical Imaging Conf., San Francisco (1993) 146.

[4] M.V. Korzhik et al., Preprint LAPP-EXP 94–01, LAPP, Annecy (1994).

[5] M.V. Korzhik et al., presented at MRS'94 Meeting, San Francisco (1994).

[6] A. Fyodorov et al., presented at IEEE Conf., Nucl. Science Symp. and Medical Imaging Conf., Norfolk (1994). Preprint LAPP-EXP 94–24.

[7] A. Fyodorov et al., Preprint LAPP 94–25, Dec. 1994; submitted to Radiation Measurement.

[8] O.V. Buyanov et al., Nucl. Instrum. Methods Phys. Rev., **A349** (1994) 62.

[9] S. Inaba et al., Preprint KEK 94–105, Tsukuba (1994); submitted to Nucl. Instrum. and Methods.

[10] G.A. Alexeev et al., Proc. 5th Intern. Conf. on Calorimetry in High Energy Physics, BNL, Upton (1994), to be published.

[11] V.A. Kachanov et al., Nucl. Instrum. Methods Phys. Rev., **A314** (1992) 215.

[12] Particle Data Group, Phys. Rev., **D50** (1994) 1173.

[13] Yu.D. Prokoshkin, A.V. Shtannikov, Preprint IHEP 93–156, Protvino (1993); submitted to Nucl. Instrum. Methods.

[14] Photomultiplier tubes. Principles & applications. Philips Photonics (1994).

[15] Letter of Intent by the CMS Collaboration, CERN/LHCC 92–2, Geneva (1992).

[16] Letter of Intent by the ALICE Collaboration, CERN/LHCC 93–16, Geneva (1993).

[17] CMS Technical Proposal, CERN/LHCC 94–38, Geneva (1994).

Figure captions

Fig. 1 Experimental set up: a) general layout, b) detailed photodetector housing.

Fig. 2 Calibrated signal sum of 5×5 PWO matrix measured in the 70 GeV electron beam. The beam (spot size 6×6 mm^2) enters the central 20 cm long cell ($23X_0$). The curve shows a Gaussian fit.

Fig. 3 σ_E/E corrected for beam momentum spread versus electron beam energy. The curve is the fit with formula (1).

Fig. 4 Amplitude distributions measured in one cell with the PIN diode readout:

a) signal produced by MIP (muon) in the crystal,

b) signal from MIP passing both the crystal and the diode,

c) signal from the 5 GeV electron.

Fig. 5 Temperature dependence of the 50 GeV electron peak position in a PWO cell.

Fig. 6 Amplitude spectrum of 20 GeV electron for a) one Nb doped crystal and b) one non-doped crystal.

Table 1 : PWO matrix energy resolution

Electron beam energy E (GeV)	σE/E, measured (%)	σE/E, beam spread quadratically subtracted (%)
10	1.04 ± 0.03	0.99 ± 0.04
20	0.84 ± 0.02	0.78 ± 0.05
50	0.71 ± 0.02	0.64 ± 0.06
70	0.61 ± 0.01	0.53 ± 0.06

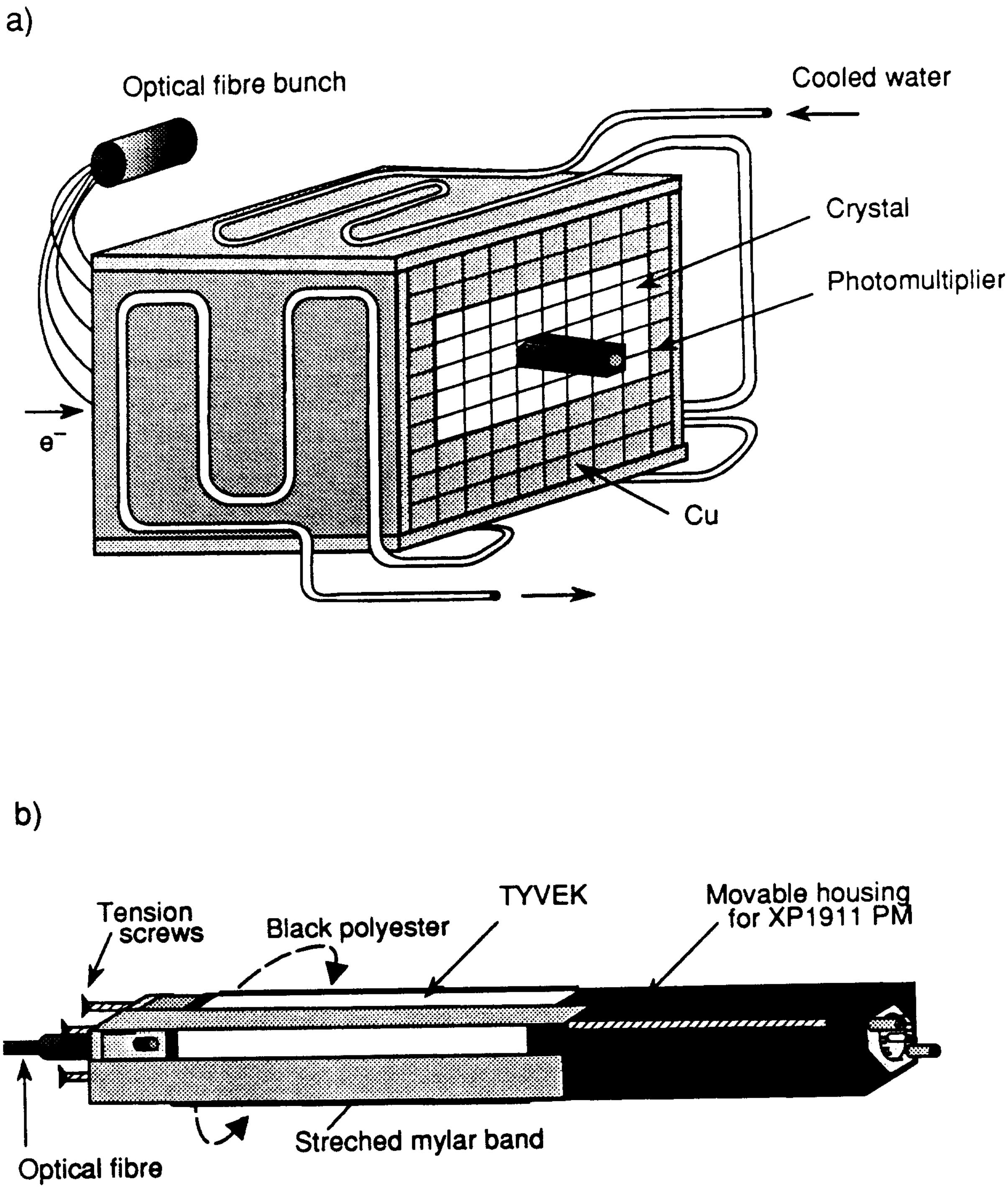
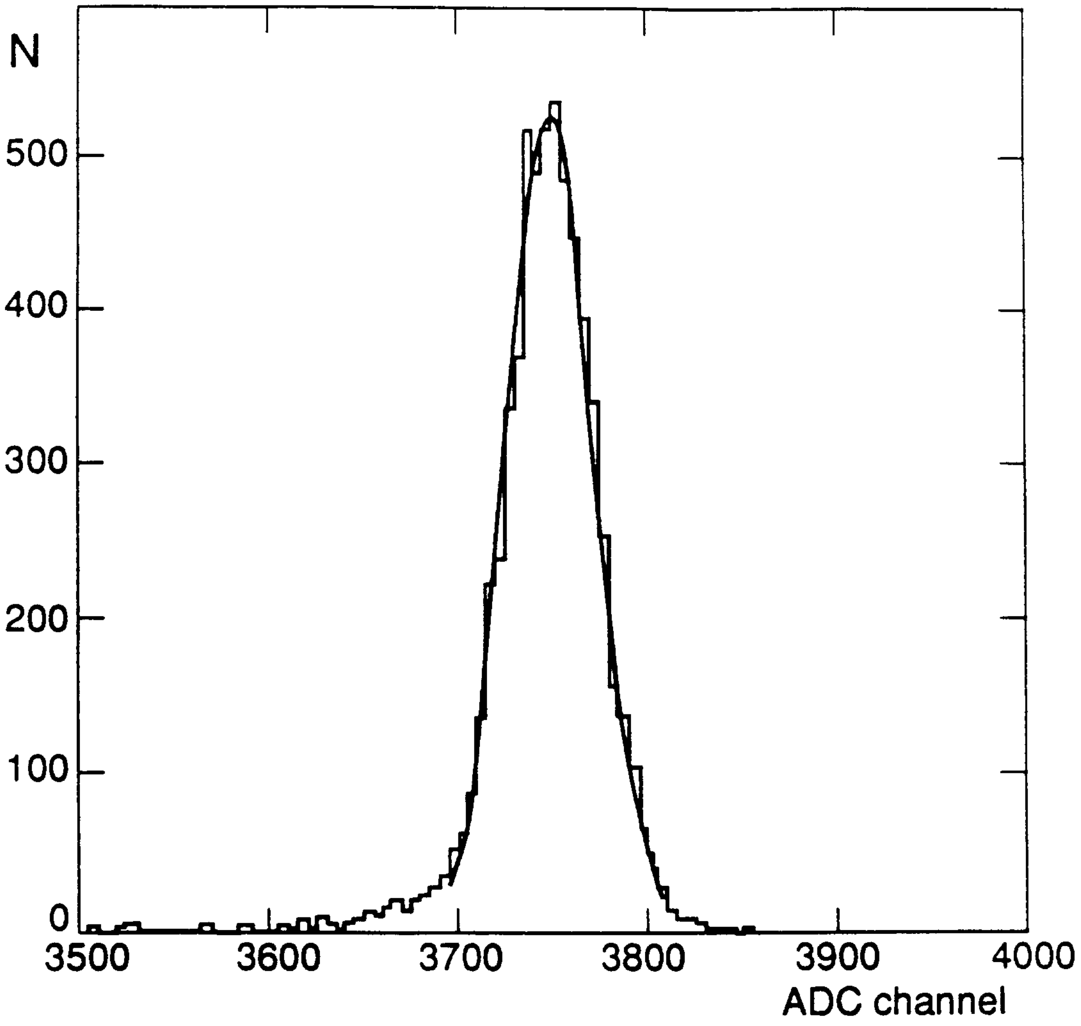

a)
Optical fibre bunch
Cooled water
Crystal
Photomultiplier
e⁻
Cu
b)
Tension screws
Black polyester
TYVEK
Movable housing for XP1911 PM
Optical fibre
Streched mylar band

Fig. 1


N
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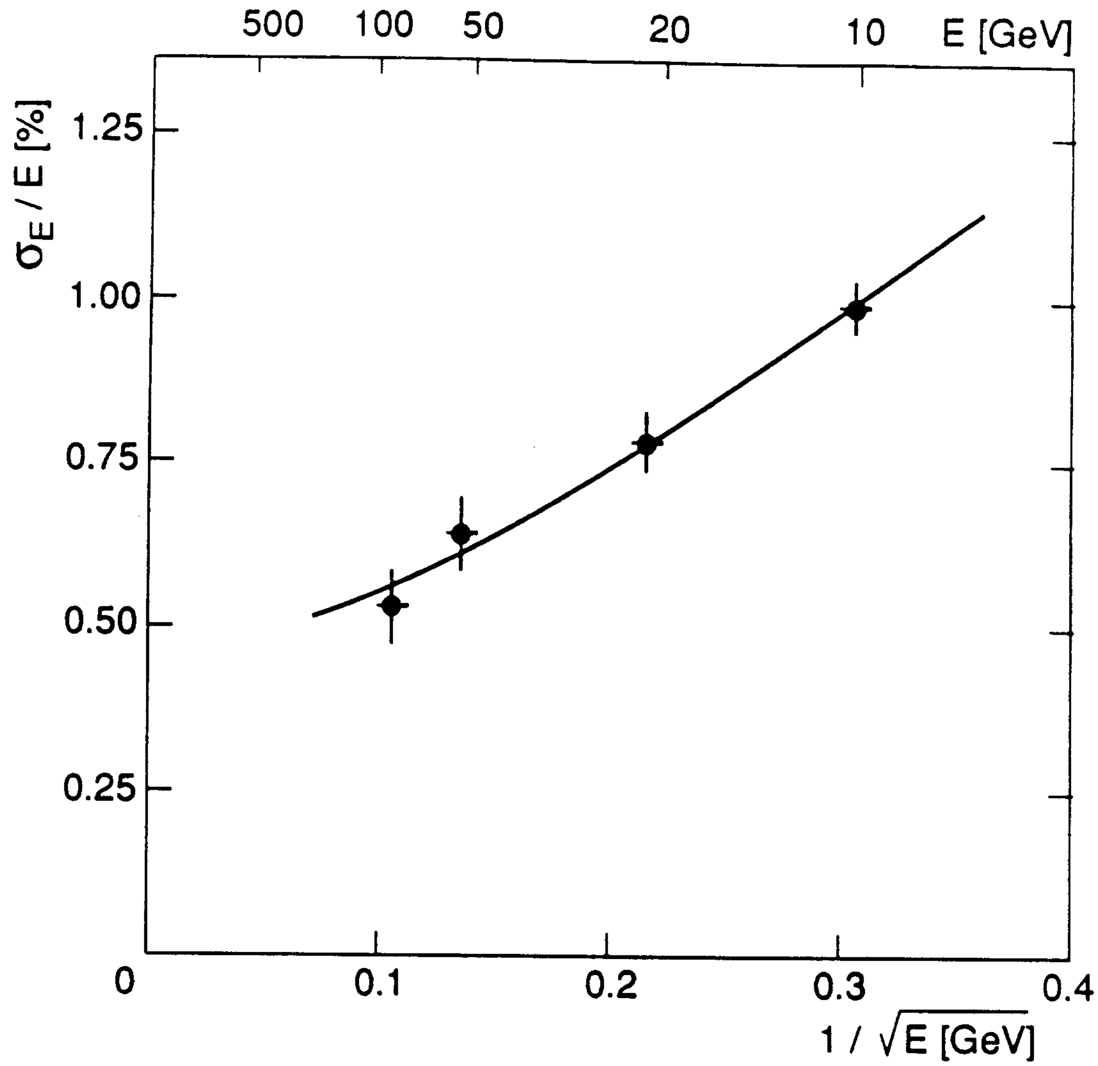
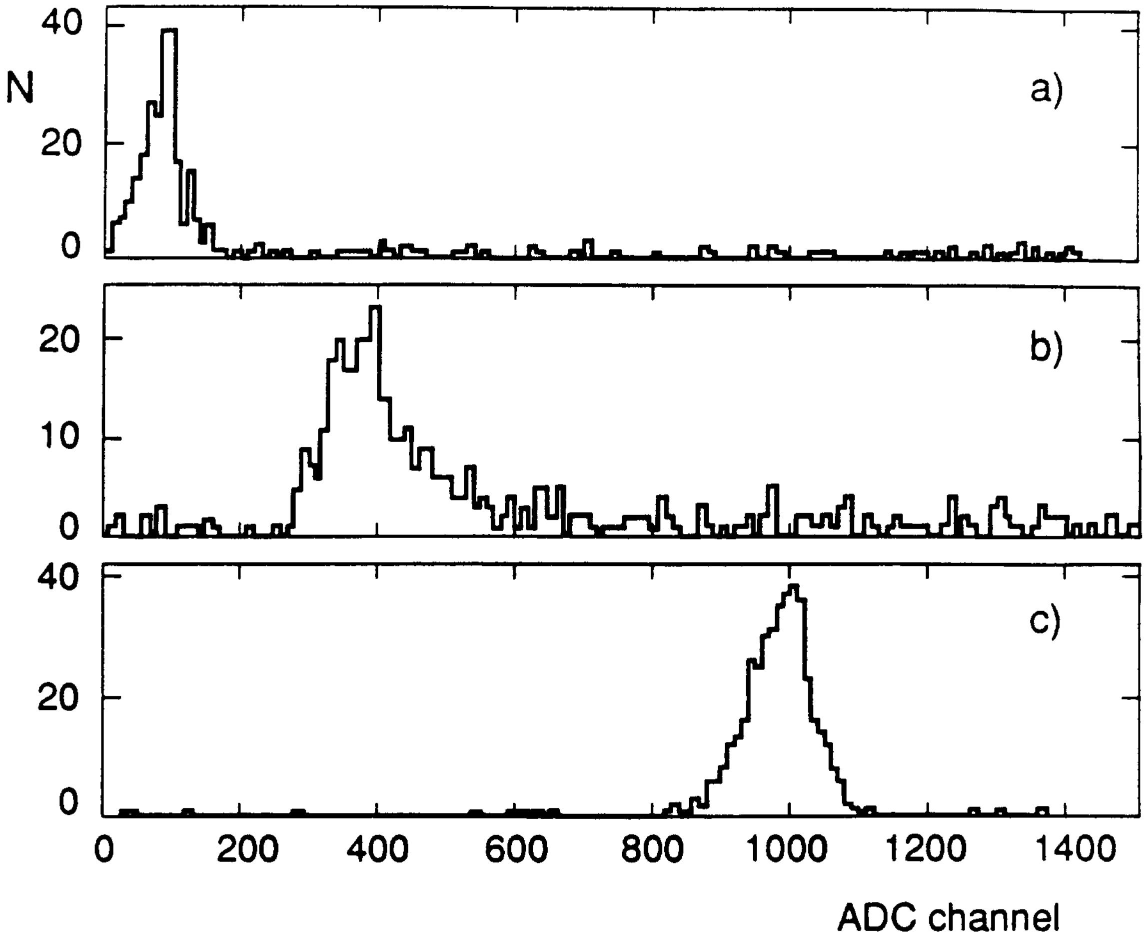
400
300
200
100
0
3500
3600
3700
3800
3900
4000
ADC channel

Fig. 2



500
100
50
20
10
E [GeV]
σ_E / E [%]
1.25
1.00
0.75
0.50
0.25
0
0.1
0.2
0.3
0.4
$1 / \sqrt{E}$ [GeV]

Fig. 3


N
a)
b)
c)
40
20
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20
10
0
40
20
0
0
200
400
600
800
1000
1200
1400
ADC channel

Fig. 4

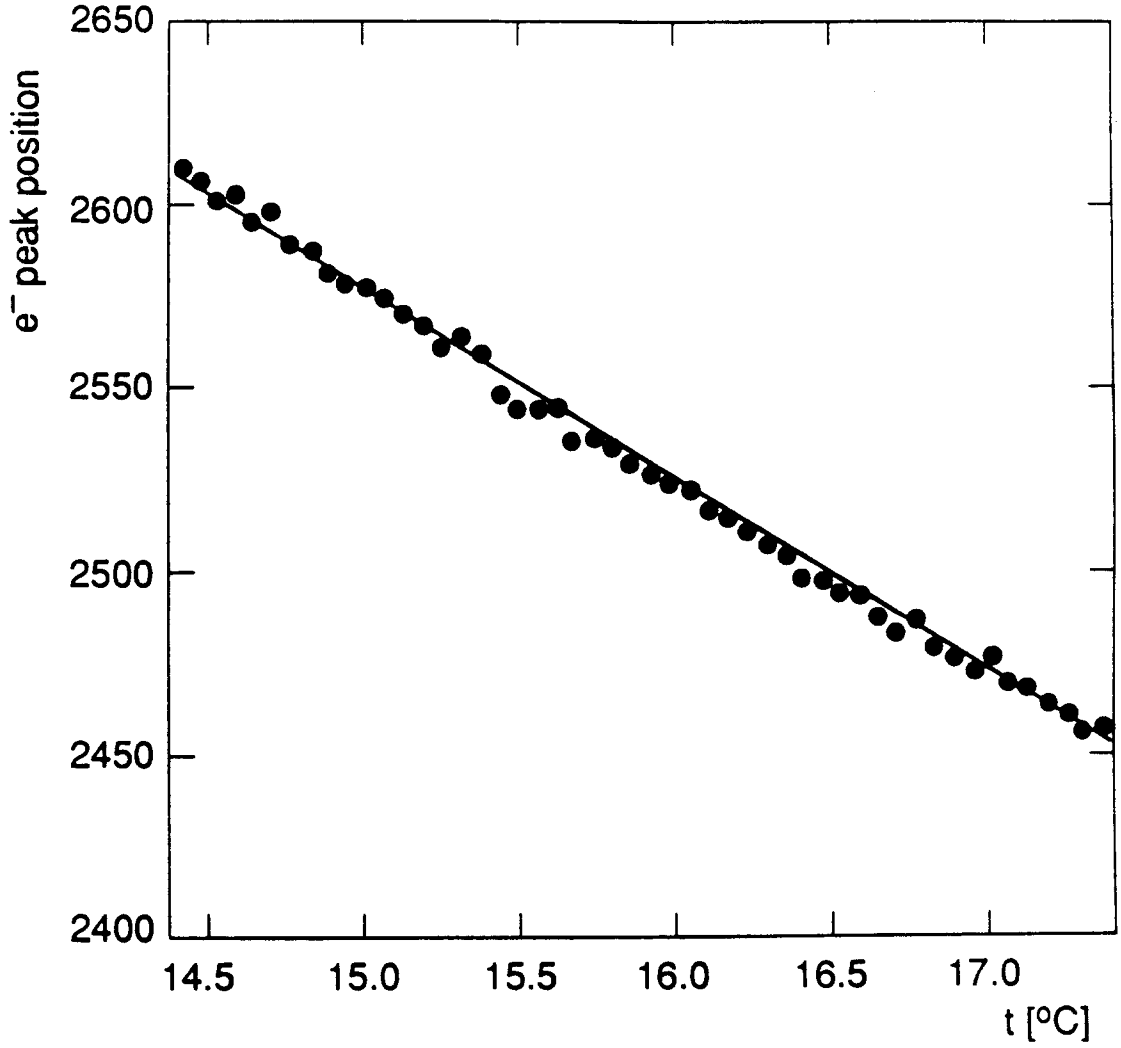
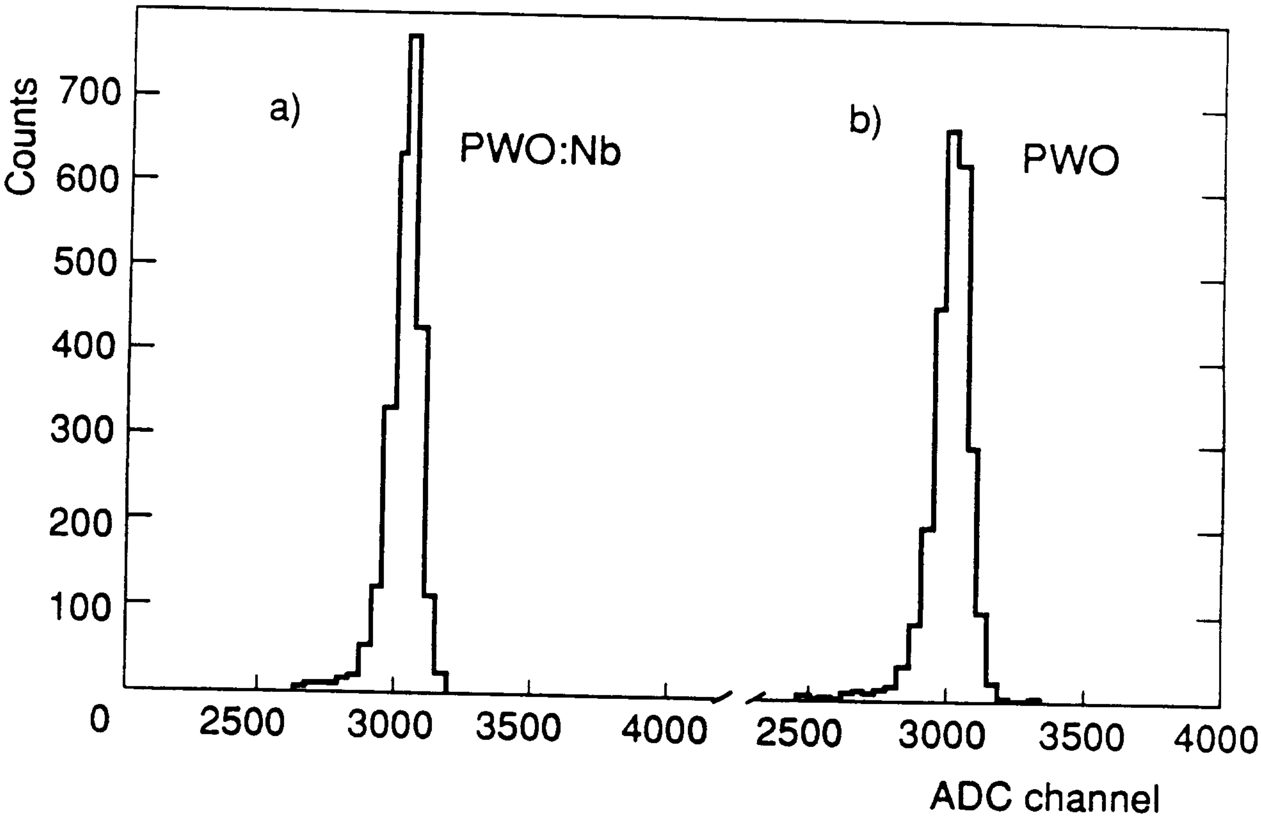

2650
2600
2550
2500
2450
2400
e⁻ peak position
14.5
15.0
15.5
16.0
16.5
17.0
t [°C]

Fig. 5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600
500
400
300
200
100
0
a)
PWO:Nb
b)
PWO
2500
3000
3500
4000
2500
3000
3500
4000
ADC channel

Fig. 6