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NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH Section A

Influence of magnetic fields on the response of a uranium scintillator electromagnetic calorimeter

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The response of a uranium scintillator sampling calorimeter to incident electrons and to the uranium radioactivity was measured in transverse magnetic fields up to 1.4 T. The signal from electrons rises by as much as 9% due to the expected increase in light output of plastic scintillators in magnetic fields. For fields below 0.3 T the response to the uranium radioactivity tracks the electron signal to within about 0.5%. At higher fields it drops sharply, reaching −1.5% at 1.4 T. The consequences for the calibration of the ZEUS uranium scintillator calorimeter are discussed. We found no evidence for a change in the electromagnetic sampling fraction for fields below 0.3 T.

1. Introduction

The ZEUS collaboration at the electron–proton storage ring HERA has built a high resolution sampling calorimeter consisting of interleaved layers of depleted uranium and scintillator. With 100 GeV incident particles this calorimeter gives an energy resolution of approximately 2% for electrons and 4% for hadrons [1,2]. Attaining and maintaining this fine resolution requires an energy calibration of 1% [1]. The radioactivity of the depleted uranium provides the chief signal for fixing the energy calibration and monitoring its variation. A tower-to-tower and module-to-module energy calibration of 1% has been achieved, and its stability monitored to 0.2% [3]. These results were obtained in test beams with no applied magnetic field. In ZEUS however, the calorimeter will operate in the fringe field of a superconducting solenoid. Where the calorimeter is situated, this field will range typically from 0 to 0.3 T, but it will reach maxima of 0.8 T locally [4] (fig. 1).

Previous studies have shown that magnetic fields increase the light output of plastic scintillator [5–9]. No effect on wavelength shifters has been observed [6]. This article reports an experimental investigation of the influence of transverse magnetic fields on the electron signal and the signal from the uranium radioactivity of a test calorimeter with the same segmentation as the electromagnetic section (EMC) of the ZEUS

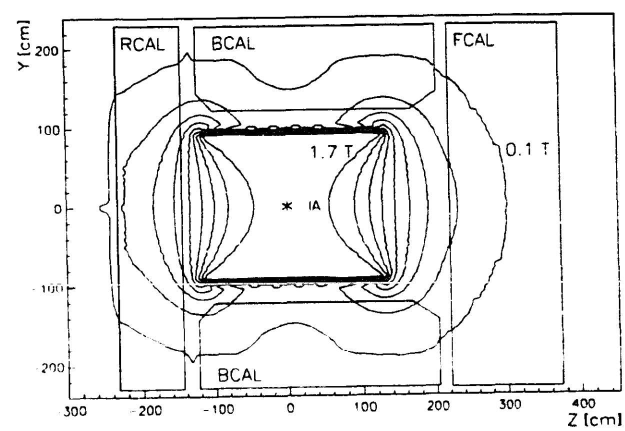

Fig. 1. Contour lines of equal magnetic field in steps of 0.2 T in the ZEUS calorimeter (vertical cut through the ZEUS calorimeter; dimensions are in cm. IA: interaction point; FCAL: forward calorimeter; BCAL: barrel calorimeter; RCAL: rear calorimeter).

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calorimeter [1,10] (3.3 mm depleted uranium clad in 0.2 mm stainless steel and 2.6 mm scintillator SCSN-38 wrapped in one layer of Tyvek paper). Still under study are the effects of longitudinal fields, cladding thicknesses (0.2 mm vs 0.4 mm), and the magnetic properties of the cladding [11,12].

2. Experimental setup

Fig. 2 shows a sketch of the uranium scintillator calorimeter used for the tests. Its dimensions and segmentation correspond to one electromagnetic tower (type HAC0) of the ZEUS forward calorimeter (see table 1). The photomultipliers (PM) were Hamamatsu R-580 supplied with HV by active Cockcroft–Walton bases as in the ZEUS calorimeter [1].

Fig. 3 shows the layout of the experimental setup in the test beam area 21 at DESY. The calorimeter was placed inside a dipole magnet which produces fields between 0.1 and 1.4 T. Special care was taken to shield the two PMs from the magnetic field. A steel box surrounded the PMs. In addition, we followed the ZEUS calorimeter design, and inserted the tubes in cylinders of iron and mu-metal. The stability of the PM gain in the magnetic field was checked carefully using a green light-emitting diode (LED). Since the light output of the diode varied by about one percent due to the magnetic field, it too was shielded. The electron energy could be set anywhere in the momentum range from 1 to 6 GeV/c, with 0.5% momentum spread. The incoming particles were monitored by scintillator counters: a paddle (10×10 cm^2), finger counters B1 and B2 (2×1 cm^2), and a veto counter (10×10 cm^2 with a hole of $r = 1$ cm). The beam size at the calorimeter was ~ 1 cm.

Fig. 4 shows the readout electronics and the data acquisition system which runs under the control of a Motorola 68000 processor. The data were transferred to a VAX (VMS) for off-line analysis. The following data types were routinely recorded:

- UPED: Pedestals for the measurement of the uranium signal (UNO). For these runs the PM high voltage was reduced to 400 V so that the offset of the integrator and ADC were measured. The typical stability was ~ 1 ADC channel, which corresponds to an anode current of 1.6 nA.
- UNO: Measurement of the uranium signal after an amplifier which integrates the incoming signal over 1 s (a schematic drawing of the integrator was shown in fig. 4). 400 Events were taken per run. The typical spread was ± 1 ADC channel for an 800 channel signal (1.3 μA anode current). The typical reproducibility of UNO was 1 ADC channel over a 1 h time period. It was dominated by the gain stability of the PM.
- PED: Pedestals for the pulse measurements, which included the uranium radioactivity over the 180 ns gate length. Usually 1600 events per run were taken. The mean spread was about 1 ADC channel. The time stability was well below 1 ADC channel over a 24 h period.
- LED: Measurement of the LED pulses again with 180 ns gate. 2500 Events were taken for each run.

Table 1
Test calorimeter segmentation and dimensions

Dimensions	
Total length	2095 mm
Total width	223 mm
Total height	280 mm
Active length	154 mm
Segmentation	
25 active layers each of:	
Scintillator (SCSN-38)	$203.0 \times 199.4 \times 2.5$ mm^3
Stainless steel cladding	$200 \times 200 \times 0.2$ mm^3
Uranium plates	$199 \times 199 \times 3.1$ mm^3

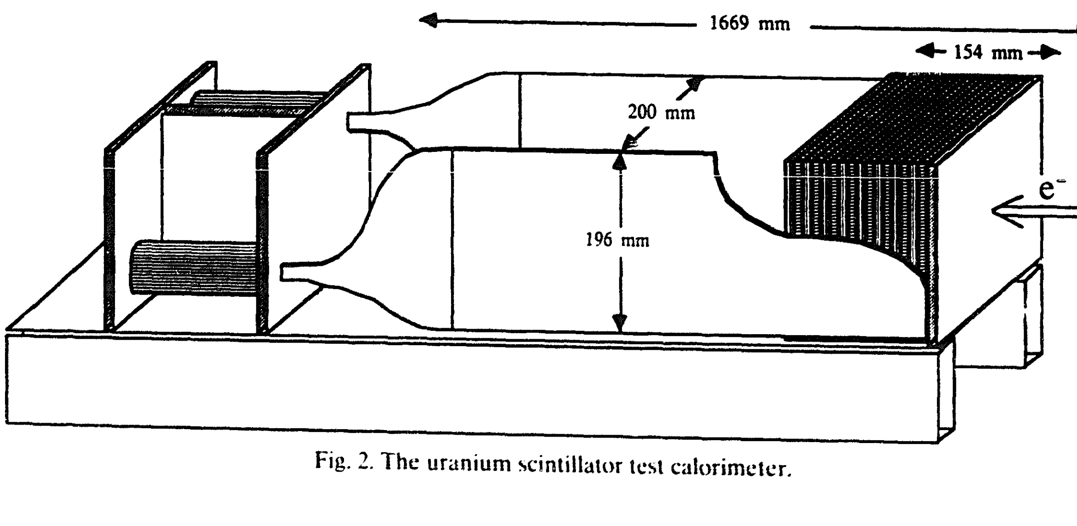

Fig. 2. The uranium scintillator test calorimeter.

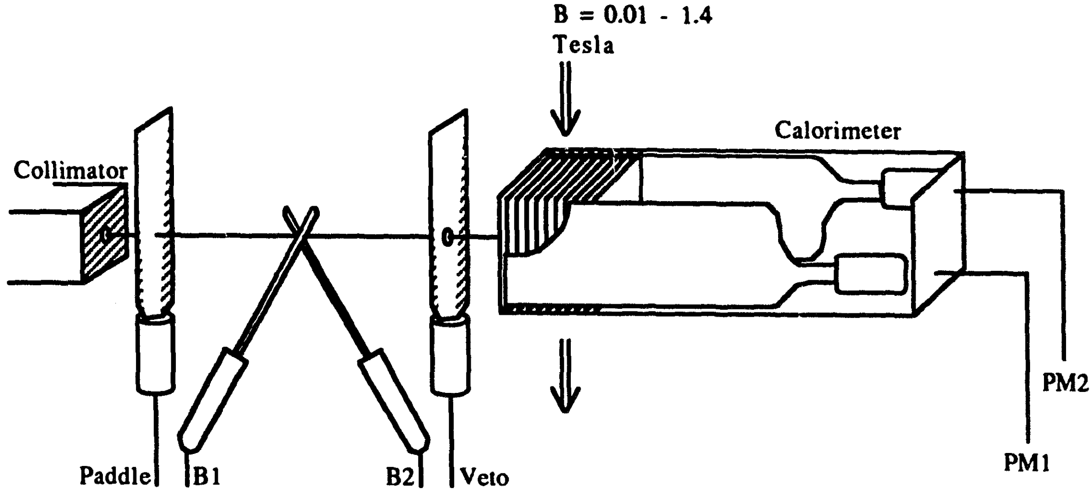

Fig. 3. Experimental setup in the DESY test beam.

The 5% width of the distribution was due to photoelectron statistics. The reproducibility of the mean was around 2 ADC channels for a 500 channel signal.

– BEAM: Measurement of the response to electrons. Two energies were chosen (2 GeV and 6 GeV) and 10^4 events per run were taken. All measurements were taken with a 180 ns ADC gate.

UPED runs were taken once a day. UNO, PED, LED and BEAM runs without magnetic field were taken every three hours to control the time stability of the system.

3. Measurements and results

Since the measurements aimed at achieving an accuracy of 0.25% for magnetic field effects, the follow-

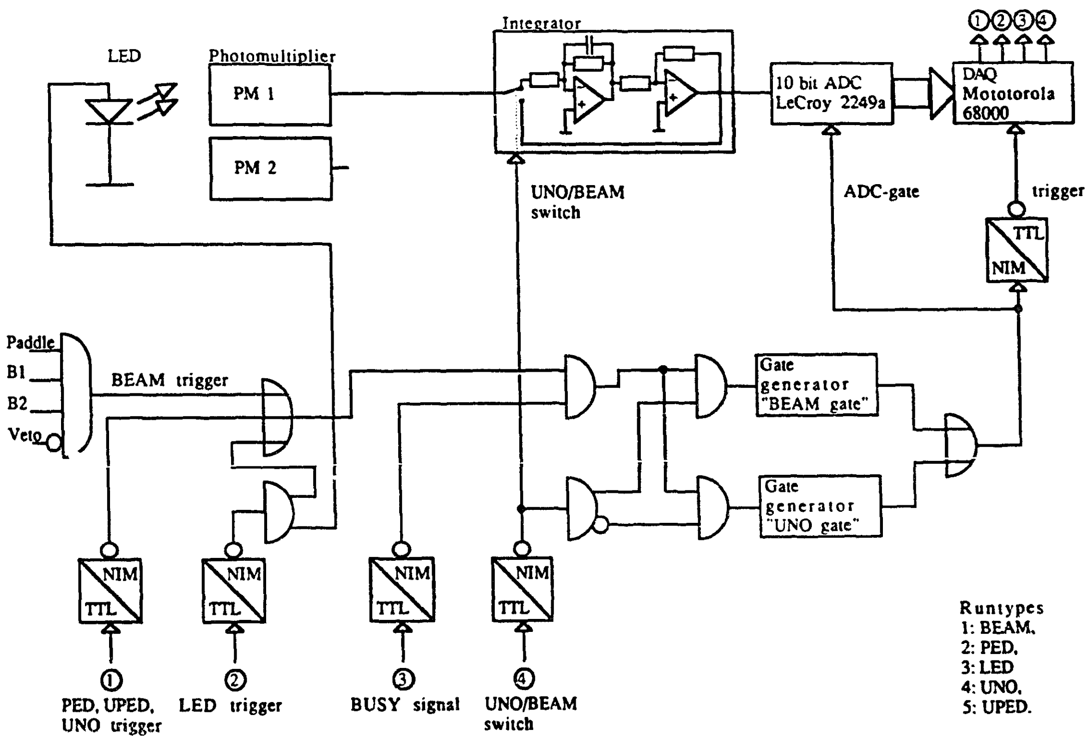

Fig. 4. Schematic of readout electronics and data acquisition system.

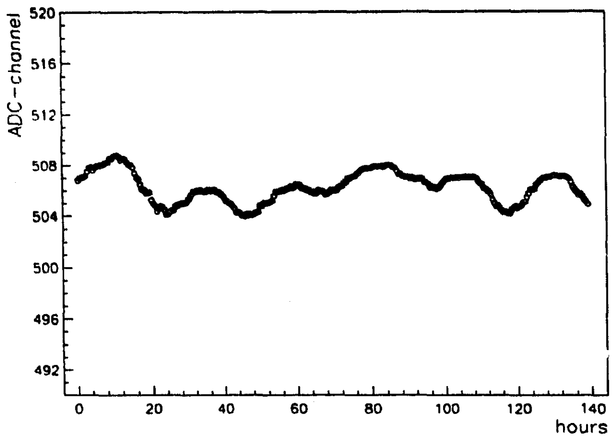

Fig. 5. The variation of the UNO signal over a period of five days. The average value of the signal from photomultiplier number one is shown as a function of time. Each point represents the average of 50 UNO events. A 24 h cycle is observed due to the diurnal temperature variation. The combined system of PM and base has a temperature coefficient of 0.06%/ °C.

ing sources of random and systematic errors were investigated:

- time stability,
- influence of the magnetic field on the PM gain,
- influence of the deflection of the incident electron beam by the magnetic field.

The PM gain was adjusted to have the maximum expected signal (6 GeV electrons) at ADC channel number 600.

3.1. Time stability

For the discussion of the stability of the pedestals (UPED and PED) we refer to the previous section. The stability of the setup has been investigated by measuring the uranium signal via UNO runs over a period of five days. The results are shown in fig. 5.

The short term reproducibility is 0.1%. The long term behavior shows a 24 h period related to the temperature changes in the hall. It is compatible with the temperature dependence of the complete calorimeter system (light yield of scintillator, quantum efficiency of photocathode and gain of the photomultiplier).

For the actual measurements, UNO runs were taken every three hours without field. A linear interpolation of the response for the times in between corrected for drifts within about 0.1%.

3.2. Influence of the magnetic field on the PM gain

The light from a single LED has been fanned out to the two PMs of the calorimeter. The typical short time stability of the LED signal without change of the magnetic field is 0.1%. Fig. 6 shows the LED signal versus magnetic field for PM1. The gain is independent of the magnetic field within the statistical error of 0.2% which is also true for PM2. Typical gain changes are below 0.2%. The spread of the measurements illustrates the typical random error of the measurements.

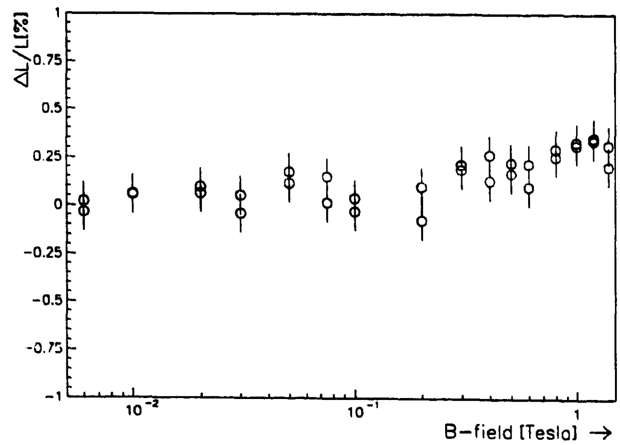

Fig. 6. Signal of LED light injection on the PM cathodes (signals are corrected for temperature-dependent gain changes).

3.3. Influence of the deflection of the incident beam

The beamline geometry was chosen such that the incident electrons hit the center of the calorimeter face when no magnetic field was applied. With the magnet turned on, the beam was deflected horizontally. For 6 GeV electrons, we estimate a deflection of approximately 0.6 cm when the magnetic field is 1 T (1.9 cm for 2 GeV electrons). To study the effect of this deflection on the data, 2 and 6 GeV electrons were scanned over the width of the calorimeter. The results are shown in fig. 7.

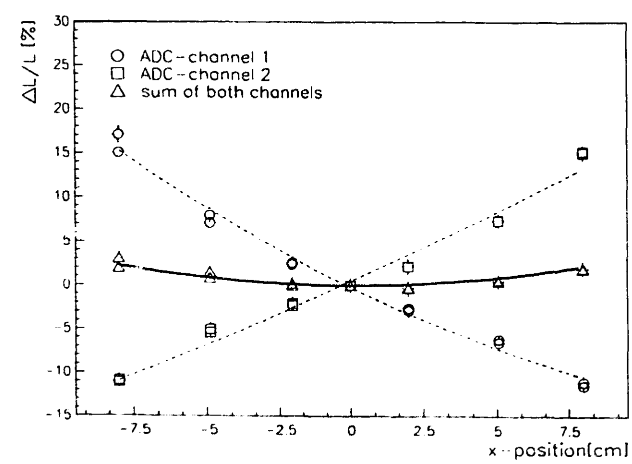

Fig. 7. Signal of 2 and 6 GeV electrons vs position of entrance (relative units) with the magnetic field off.

The data show that the scintillator had an effective attenuation length $\lambda \approx 80$ cm. In addition, it should be noted that the sum of the left and right PM signals rises as the beam moves away from the center, and is increased by one percent at ± 5 cm. In the offline analysis, corrections for this rise were done by calculating the mean deflection of the electrons. Then, using the effective attenuation length, the left and right signals were corrected separately. A final comparison of the separately corrected channels insured a maximum error of 0.1% for the 6 GeV electron beam measurements (0.2% for 2 GeV) due to deflection in the magnetic field [10].

3.4. *Magnetic field dependence of the electron signal*

The signal change $\Delta L/L = (L(B) - L(0))/L(0)$ for 2 and 6 GeV electrons vs magnetic field is shown on fig. 8. Statistical errors are of the size of the symbols. The maximum systematic errors were estimated to be 0.25% for 6 GeV and 0.32% for 2 GeV electrons. Shown for comparison is the previously measured $\Delta L/L$ of the SCSN-38 scintillator. We see that our measurements are compatible with the known changes in the light output of SCSN-38 scintillator in magnetic fields [6,7]. Both measurements agree: a rapid rise to about 1% between 0 and 0.02 T, a plateau up to 0.1 T and a rise to 8% at 1 T. From the comparison we conclude that, within the measured accuracy, the rise in electron signal is due to the increased light yield of the scintillator and there is no evidence, for fields below 0.3 T, of a change in the electromagnetic sampling fraction.

3.5. *Magnetic field dependence of the signal from the uranium radioactivity*

Fig. 9 shows the signal change $\Delta L/L$ for the signal from the uranium radioactivity vs magnetic field. The

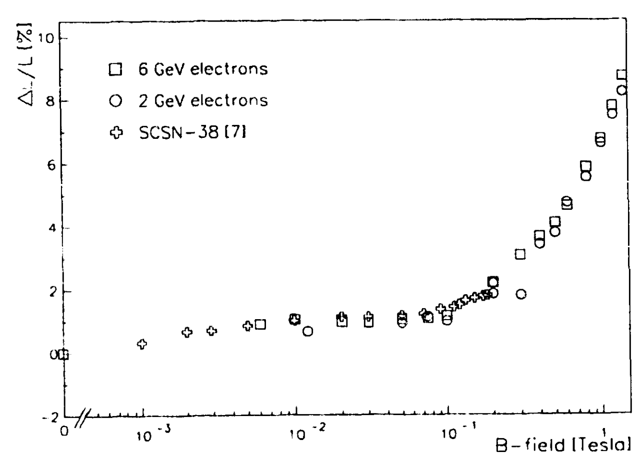

Fig. 8. BEAM signal vs magnetic field.

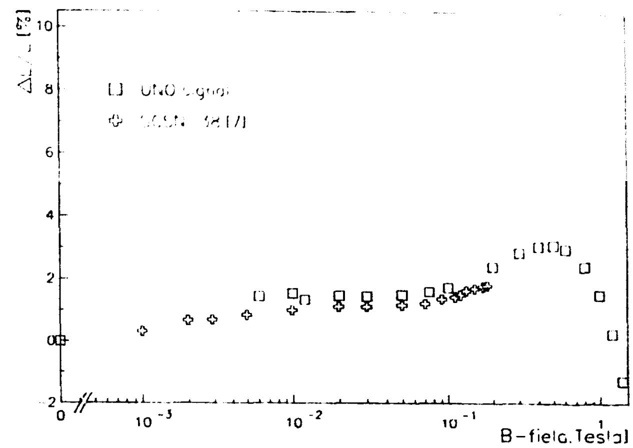

Fig. 9. UNO signal vs magnetic field.

$\Delta L/L$ for SCSN-38 alone is again shown. Up to a field of 0.1 T the shapes are similar, although $\Delta L/L$ for UNO is about 0.5% above $\Delta L/L$ for SCSN-38. For a field of 0.4 T $\Delta L/L$ for UNO reaches a maximum and drops to a value of -1.5% at the maximum field of 1.4 T. We explain this decrease by the trapping of low energy electrons in the uranium due to curling in the magnetic field (the typical radius of curvature is ~ 5 mm for an electron of 1 MeV kinetic energy at 1 T). The 0.5% difference between $\Delta L/L$ for UNO and electrons or SCSN-38 appears significant and could be due to an increase of light with a long decay time.

4. Conclusions

The response of a uranium scintillator calorimeter to incident electrons and to the uranium radioactivity have been investigated in transverse magnetic fields up to 1.4 T. The main results are summarized in table 2 and fig. 10:

- The light yield of the scintillator increases with magnetic field,
- The response to electrons follows the dependence of the light yield,
- Up to 0.3 T the response to the uranium signal follows the light yield of the scintillator to within 0.5%. Above 0.3 T the scintillator light yield increases whereas the uranium response drops rapidly.

The ratio of the electron and uranium signal, which is used for the calibration of the ZEUS calorimeter, shows the following magnetic field dependence. It deviates from 1 by -0.5% between 0.05 T and 0.2 T, which is the typical field for most of the ZEUS calorimeter. Between 0.2 and 1.4 T the deviation increases to 10% and requires a significant correction for parts of the ZEUS calorimeter. We expect that using the results from this and further measurements, the correction can be performed to 0.5%. For fields below 0.3 T, where the change in light output of the scintilla-

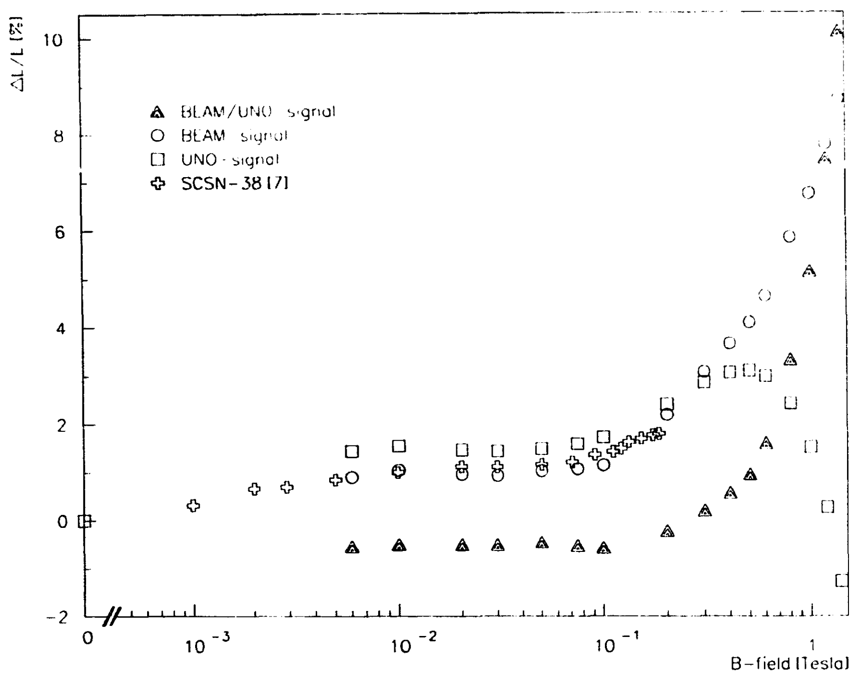

Fig. 10. BEAM/UNO signal vs magnetic field.

Table 2
Relative change of the calorimeter signals vs magnetic field. Given are statistical errors as well as the estimated systematical errors

B [T] $\delta_{sys} = 2.5\%$	UNO [%] $\delta_{sys} = 0.32\%$	6 GeV e^- [%] $\delta_{sys} = 0.25\%$	2 GeV e^- [%] $\delta_{sys} = 0.32\%$
0.0006	1.45 ± 0.01	0.90 ± 0.08	-
0.001	1.55 ± 0.01	1.05 ± 0.08	-
0.012	1.34 ± 0.01	-	0.66 ± 0.11
0.02	1.47 ± 0.01	0.97 ± 0.08	-
0.03	1.45 ± 0.01	0.94 ± 0.08	-
0.05	1.49 ± 0.01	1.04 ± 0.08	0.92 ± 0.11
0.075	1.60 ± 0.01	1.08 ± 0.08	1.13 ± 0.11
0.1	1.73 ± 0.01	1.15 ± 0.08	0.99 ± 0.11
0.2	2.41 ± 0.01	2.20 ± 0.08	1.85 ± 0.11
0.3	2.86 ± 0.01	3.08 ± 0.08	2.18 ± 0.16
0.4	3.07 ± 0.01	3.66 ± 0.08	1.81 ± 0.11
0.5	3.10 ± 0.01	4.10 ± 0.09	3.42 ± 0.11
0.6	2.99 ± 0.01	4.64 ± 0.08	4.75 ± 0.12
0.8	2.43 ± 0.01	5.85 ± 0.09	5.56 ± 0.12
1.0	1.52 ± 0.01	6.75 ± 0.09	6.65 ± 0.12
1.2	0.28 ± 0.01	7.78 ± 0.09	7.56 ± 0.12
1.4	-1.27 ± 0.01	8.71 ± 0.09	8.32 ± 0.22

tor SCSN-38 has been studied by others [6,7], we find that the electron signal closely follows the scintillator behavior. Thus there is no evidence for a change in the electromagnetic sampling fraction in this region within the measured accuracy.

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