Fermi National Accelerator Laboratory

FERMILAB-Pub-95/004

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January 1995

Submitted to *Nuclear Instruments and Methods A*

Operated by Universities Research Association Inc. under Contract No. DE-AC02-76CHO3000 with the United States Department of Energy

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Abstract

An electromagnetic (EM) calorimeter constructed from high-pressure gas-ionization tubes with sinusoid-like longitudinal profile (wiggler tubes) has been assembled, and tested in an electron beam at the CERN SPS. This design greatly improves the EM energy resolution compared to a calorimeter constructed from straight tubes and eliminates the resolution dependence on the beam angle. An EM energy resolution of $\delta E/E = (32.0 \pm 1.6)\% /\sqrt{E} \oplus (2.9 \pm 0.3)\%$ has been achieved. Further improvements of the EM energy resolution are discussed. The calorimeter is very radiation hard, has a fast response, and it is stable and mechanically robust; it is intended for the forward region of the LHC collider detectors.

1. Introduction

In a previous paper [1] we reported on a hadronic calorimeter constructed of high-pressure (100 atm) gas-ionization tubes arranged with their axes nearly parallel to the direction of incident particles. This calorimeter is very radiation hard (≥ 1 Grad [2]), stable , linear with energy, mechanically robust, and cost effective. The intrinsic hadronic energy resolution of this calorimeter, which is almost independent of the tilt angle between the tube and the incident particle directions, was found to be [1]:

$$\delta E/E = (70 \pm 12)\% /\sqrt{E} \oplus (7.4 \pm 1.2)\% . \quad (1)$$

The constant term in this formula is the result of the inequality of the calorimeter response to electrons and hadrons ($e/\pi = 1.3$ at $E = 50$ GeV). A software procedure for e/π compensation has been developed [1] which effectively reduces the constant term to less than 3%. The calorimeter time resolution was limited by the electron collection time. This was about 38 ns for the 1.6 mm gas gap filled with a 95% Ar + 5% CH_4 gas mixture at 100 atm. The electronic noise of a module with a volume of 10x10x300 cm^3 was 1 GeV.

The calorimeter's electromagnetic (EM) energy resolution, however, depended strongly on the tilt angle. The EM constant term varied from 7% for a tilt angle of 9.1^o to 21% for 0.9^o. The main reason for such a poor EM energy resolution was channeling effects of the transversely-narrow EM shower along the rather large (12.7 mm outer diameter) straight tubes. With the aim of improving the EM resolution we have constructed a new calorimeter of smaller diameter tubes. The tubes have been bent so that they have a sinusoid-like longitudinal profile (wiggler tubes) to suppress the channeling effect and thus improve the EM energy resolution and decrease the dependence on the tilt angle. (The idea is similar to that exploited in liquid argon accordion calorimeters [3]). Furthermore, the tubes were arranged in a hexagonal (closer packed) matrix rather than the rectangular one used in the earlier calorimeter. The ratio of passive material to readout gas volume was also decreased and the gas manifold at the front of the module was redesigned to reduce its thickness.

In this paper we describe the new EM calorimeter and present the results of the first test of this calorimeter at the CERN-SPS T1-X1 test beam.

2. Calorimeter construction

The design of a single tube ionization chamber is shown in fig. 1. It consists of a 9.5 mm outer diameter, 66 cm long stainless steel tube with a 7.9 mm diameter hole. A 4.0 mm diameter copper rod at the center of the tube is held at a positive potential to collect the electrons produced by ionization. Insulating ring spacers center the rod every 3.8 cm and ensure a 1.95 mm gas gap. The spacers have narrow slots to allow gas passage. A high-voltage, high-pressure feedthrough is welded to one end of the tube and a gas fitting to the other end. The electrical capacitance of one of these tubes, filled with atmospheric air, is 53 pF. The tube impedance is 42 Ω.

The tubes were bent before welding the feedthroughs and the gas fittings according to the following procedure. The rods with the spacers were inserted into straight tubes and the space between the rods and the tubes was filled with distilled water. The water was frozen by inserting the tube-rod assembly into liquid nitrogen. The tubes were then pressed one by one between sinusoid-like shaped dies. This procedure was quite fast and reliable: 140 tubes were shaped in five hours without a single failure. After warming and removing the water, the tubes were dried and tested for high voltage breakdown in air. There were no breakdowns at voltages as high as 4.5 kV. This indicates that there was no significant narrowing of the gas gap during the bending. A visual inspection of a few shaped tubes, cut longitudinally, showed no visible displacement of the rod relative to the tube center.

The calorimeter module consists of 127 tubes arranged in a hexagonal matrix as shown in fig. 2. The spaces between the tubes are not filled with any material. The gas fittings are welded to the inner surface of the stainless steel manifold's back plate. Nineteen tubes have longer gas fittings, and they are welded to both the back and the top plates to strengthen the manifold. The back and the top plates are welded together peripherally. The double-welded gas fittings allowed us to reduce the plate thickness to 12.7 mm each, compared to 25.4 mm in our earlier calorimeter [1].

A spare tube with the welded feedthrough and gas fitting was tested hydraulically at pressures up to 667 atm without failure. Also a specially made manifold was tested hydraulically. At the pressure of 593 atm one of the thread junctions leaked, but the unit itself did not fail. The assembled calorimeter successfully passed a 150 atm gas pressure test at CERN, in accordance with standard safety regulations.

The calorimeter was filled with a gas mixture of 95% Ar + 5% CH_4 at a pressure of 97.3 atm. The average density of the calorimeter is 3.3 g/cm^3, and the average radiation length is 4.0 cm. The volume ratio of the steel to the readout gas is 0.92. The average amount of steel in the manifold in front of the active part of the calorimeter is about 1.4 X_0.

3. Test-beam setup, electronics, and calibration

The calorimeter was tested at the CERN - SPS T1-X1 beam line in the West Hall in September 1994. We used electron beams in the energy range 10 to 70 GeV. A scintillator telescope of two 2.54 x 2.54 cm^2 coincidence counters and a veto counter with a 2 cm (horizontal) by 1 cm (vertical) hole defined a beam at the center of the calorimeter front surface in the horizontal plane and 0.5 cm above the center in the vertical plane. The calorimeter was installed on a table with its axis parallel to the beam to within ± 0.5°. The bend plane of the tubes was horizontal.

For readout purposes the calorimeter was divided into 6 triangular sectors of 21 tubes each as shown by dashed lines in fig. 2. The central tube was read out separately. The amplifiers are described elsewhere [1]. Each of the low-impedance (12 Ω) inputs of these amplifiers was connected to three tubes. Signals from the 21 tubes of each sector were summed by the amplifier circuit. The resulting 7 amplifier outputs were connected to analog-to-digital converters (ADC) through 40 m long RG-58 cables. The ADC gate width was 80 ns .

During data taking the electronic system was periodically calibrated with a 40 ns long rectangular signal of known amplitude distributed between all the amplifier inputs. The gains of individual channels were stable to within 0.2%. Pedestal instability contributed about 0.06 GeV to the total energy uncertainty.

The total electronic noise of the 7 channels was equivalent to 1.0 GeV (r.m.s.). The main source of this noise was external electromagnetic noise from the experimental environment. The internal electronic noise of the amplifiers was equivalent to 0.3 GeV.

4. Calorimeter response

An oscilloscope trace of the sum of the 7 output signals for 50 GeV electrons at a calorimeter voltage of 1.5 kV is shown in fig. 3. The full signal width at this voltage is about 70 ns.

The dependence of the signal amplitude on the calorimeter voltage for 70 GeV electrons is shown in fig. 4. (Hereafter the signal amplitudes are expressed in units of electric charge on the amplifier inputs.) These measurements were made with a fixed gate width of 80 ns. The full signal charge was not collected at low voltages (< 0.7 kV) where the electron collection time exceeded this gate width. Nevertheless, there is a clear plateau in the voltage characteristic above 0.9 kV, which testifies to good gas quality. The operating voltage was chosen to be 1.5 kV, where the electron collection time is lowest, about 45 ns [4].

The calorimeter response to electrons as a function of the beam energy is shown in fig. 5. The average signal amplitudes were corrected for energy losses in the manifold in front of the active volume (1.4% at 10 GeV and 0.3% at 70 GeV). The corrections were calculated by Monte Carlo simulations. The data in fig. 5 demonstrate good linearity within statistical errors (< 0.5% for $E \geq 20$ GeV).

The pressure dependence of the calorimeter response to 50 GeV electrons (fig. 6) shows about a 12% decrease in the collected charge at 100 atm (relative to the value at zero pressure obtained by linear extrapolation). We believe that electron-ion recombination, which is proportional to gas density, is responsible for this decrease.

5. Energy resolution

A pulse-height distribution for the 70 GeV electrons is shown in fig. 7 a. The distribution is asymmetric with a long low-amplitude tail. This tail was caused by the small empty spaces between the horizontal layers of tubes. (The tubes were bent in the horizontal plane, and the gaps between the tubes were not filled with any material.) Some of the incident electrons could travel a considerable distance through these cracks before interaction, causing substantial shower leakage out of the rear of the calorimeter.

To partially correct for this leakage we installed a 1.35 cm (2.4 Xo) lead plate in front of the calorimeter, which causes most of the beam electrons to interact before the calorimeter. The result is shown in fig. 7 b. The low-amplitude tail is almost completely suppressed and the peak shape is Gaussian . The energy dependence of the peak r.m.s. width (after subtraction of the electronic noise in quadrature) is shown in fig. 8. A fit of the calorimeter energy resolution to the quadratic sum of a stochastic and a constant term yields:

$$\delta E/E = (32.0 \pm 1.6)\% /\sqrt{E} \oplus (2.9 \pm 0.3)\% \tag{2}$$

Two further measurements were made at the beam energy of 50 GeV. First, the calorimeter was shifted horizontally by 1 cm relative to the initial position and second, the calorimeter was tilted by 2.9° to the beam direction in the vertical plane. No noticeable changes in the peak position or width were observed in either case. This proves that with the wiggler design we have mainly solved the EM shower channeling effects observed with the previous calorimeter made of straight tubes [1].

The pressure dependence of the calorimeter intrinsic energy resolution (electronic noise subtracted) for 50 GeV electrons is shown in fig. 9. There is only a slight improvement in resolution with increasing pressure.

A more detailed analysis of the experimental data and Monte Carlo simulations indicates that the constant term in formula (2) is caused by the residual effect of the cracks between the tube layers and by a small dependence of the calorimeter response (~ 4%) on the vertical position of the shower. (Since the tubes are bent in the horizontal plane the calorimeter is almost homogeneous for showers in this plane, but it is not homogeneous in the vertical plane.) Fluctuation of the shower energy absorbed in the lead plate and the manifold contribute about $18\%/\sqrt{E}$ to the stochastic term.

For these reasons we anticipate considerable improvement of the present calorimeter energy resolution after the following two modifications. First, we plan to fill the space between the calorimeter tubes with an epoxy compound containing a large percentage of iron. This should eliminate both the crack problem and the necessity of the lead preshower in front of the calorimeter. Second, we will rearrange the signal readout scheme to read signal amplitudes from each horizontal tube layer independently. Information from individual tube layers could be used for correction of the dependence of the calorimeter response on shower position transverse to the tube bend plane. With these two changes we expect to reduce the stochastic term in the energy resolution to (20 - 25)%/√E and the constant term to the 1% level.

6. Summary

The new design based on wiggler tubes considerably improves the EM energy resolution found with a calorimeter constructed from straight tubes and makes it independent of the angle between the beam and the calorimeter axis. An EM energy resolution of $\delta E/E = (32.0 \pm 1.6)\% / \sqrt{E} \oplus (2.9 \pm 0.3)\%$ has been achieved. We hope to improve this resolution with the modifications described above. Further improvement of the EM energy resolution could be obtained by decreasing the tube sizes. We are also designing a faster amplifier with signal shaping to shorten the output signal.

Tube-based high-pressure gas calorimeters are very radiation hard, fast, stable, mechanically robust, and cost effective. With the present EM, and previously achieved [1] hadronic energy resolutions they satisfy well the requirements for the forward region of the LHC collider detectors.

Acknowledgements

This work was supported by the U.S. Department of Energy and the Texas National Research Laboratory Commission. We thank the Fermilab Physics Department for providing support during the construction of the calorimeter. We also thank the CERN SPS coordinator Giles Barr and the CERN beam support personnel, especially Per Grafstrom and Robin Dillon, for their help during the test. We are thankful to Ivan Stauersboll of the Fermilab Technical Support Division for the excellent welding job.

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2. L. Demortier et al., Radiation Damage Studies on High-Pressure Gas-Ionization Calorimetry, FERMILAB-Pub-95/011.
3. B. Aubert et al., Nucl. Instr. and Meth. A309 (1991) 438.
4. N.D. Giokaris et al., Nucl. Instr. and Meth. A333 (1993) 364

Figure Captions

Figure 1: Schematic of a wiggler-tube ionization chamber.

Figure 2: Cross-section of the EM tube calorimeter and schematic diagram of the front end gas-collection unit. Dashed triangles on the end view mark the individually read-out sectors of the calorimeter. The central tube was read out separately.

Figure 3: Oscilloscope trace of the signal for 50 GeV electrons.

Figure 4: Collected charge as a function of voltage for 50 GeV electrons. The pressure was 97.3 atm and the gate width was 80 ns.

Figure 5: The ratio of collected charge to beam energy, as a function of beam energy. The pressure was 97.3 atm and the high voltage was 1.5 kV.

Figure 6: Collected charge, normalized to gas pressure, as a function of pressure. The operating voltage was proportional to the pressure at each point, with the voltage-to-pressure ratio equal to 15 V/atm.

Figure 7: Pulse-height spectrum for a 70 GeV electron beam without (a) and with (b) a 1.35 mm lead plate in front of the calorimeter. The solid curves are Gaussian fits to these distributions.

Figure 8: Calorimeter energy resolution for electrons, as a function of beam energy. The data were corrected for electronic noise.

Figure 9. Calorimeter energy resolution as a function of pressure. The beam energy is 50 GeV. The data were corrected for electronic noise.

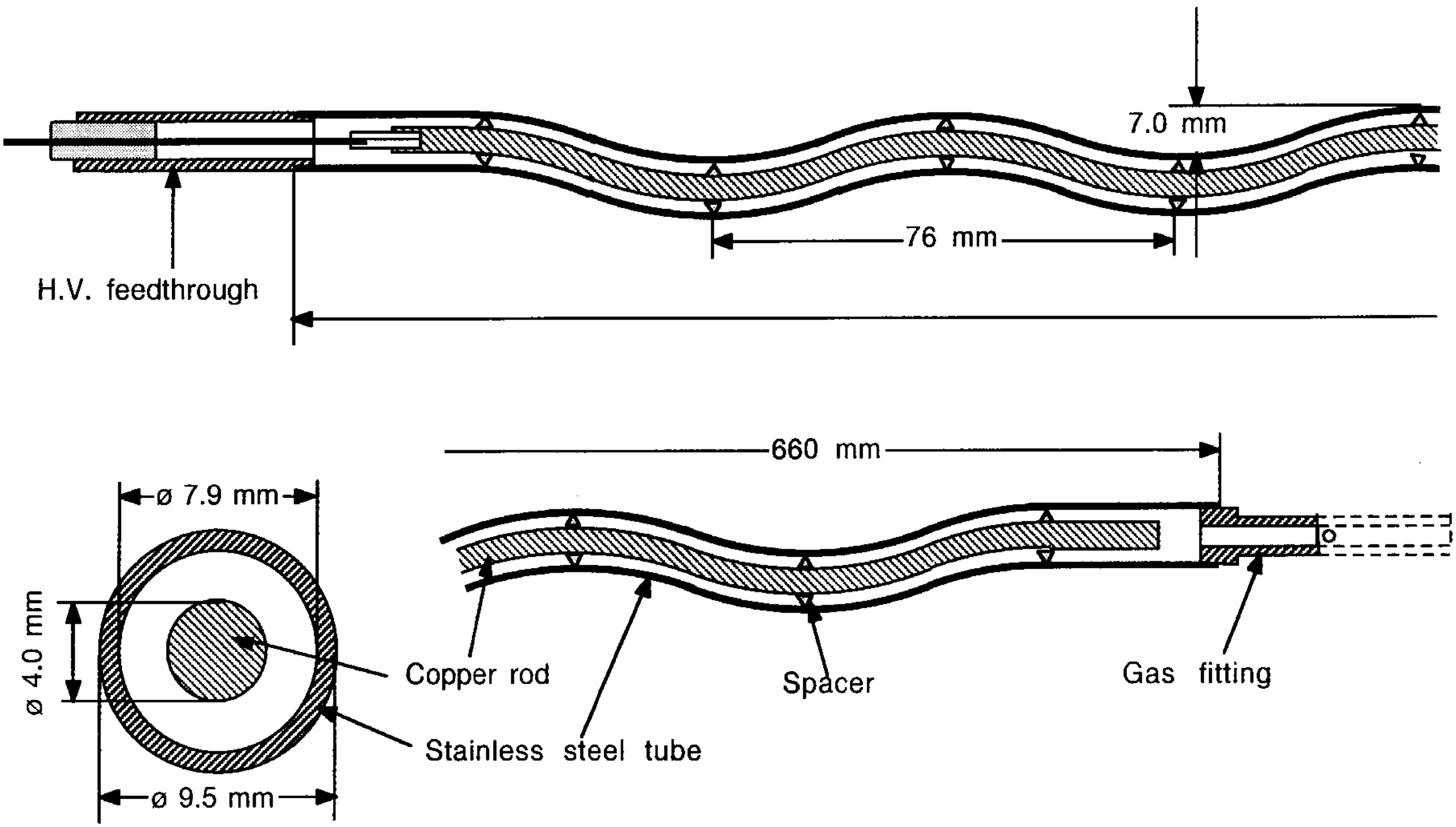

7.0 mm
76 mm
H.V. feedthrough
660 mm
ø 7.9 mm
ø 4.0 mm
ø 9.5 mm
Copper rod
Stainless steel tube
Spacer
Gas fitting

Figure 1

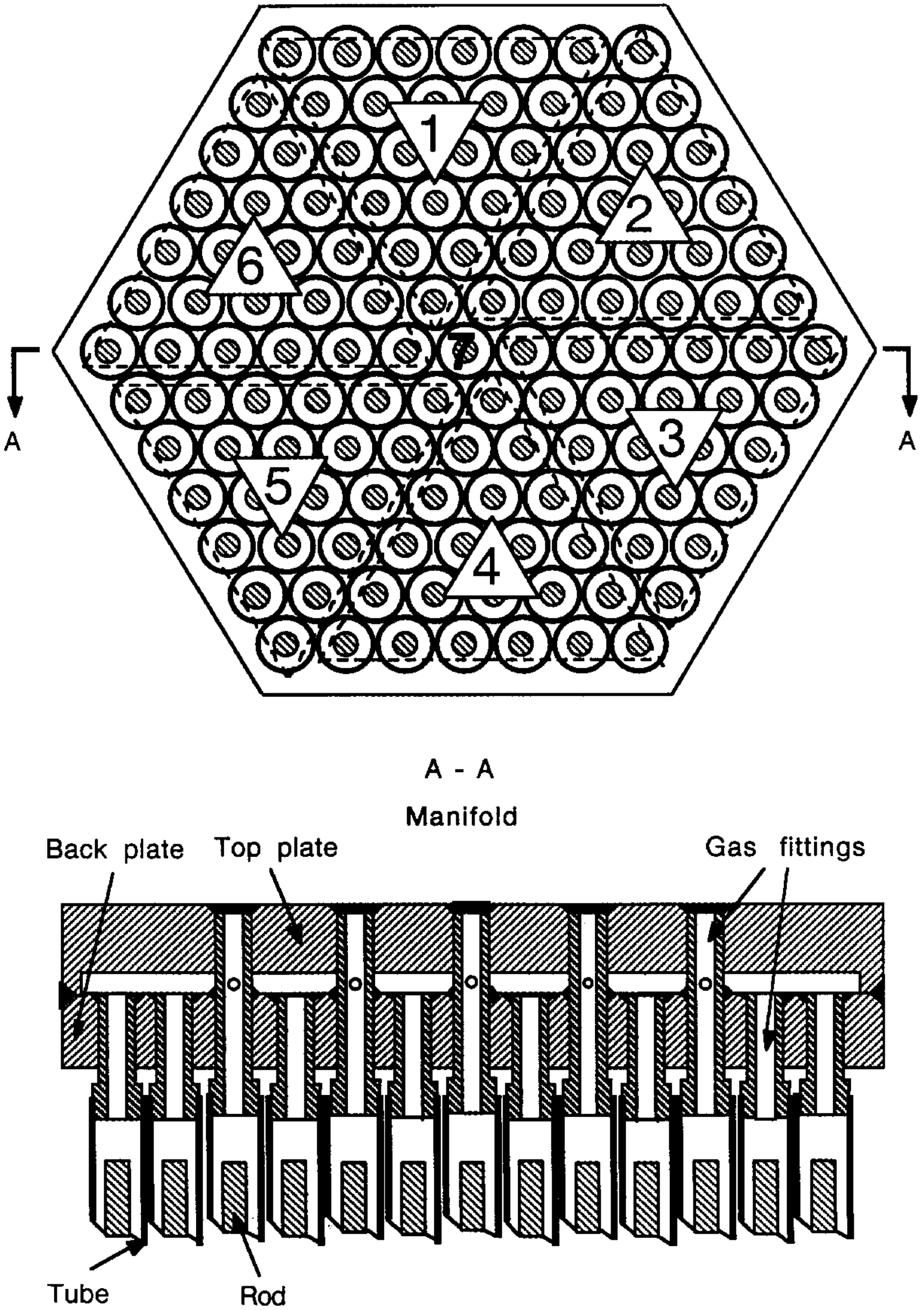

1
2
6
7
A
A
3
5
4
A - A
Manifold
Back plate
Top plate
Gas fittings
Tube
Rod

Figure 2

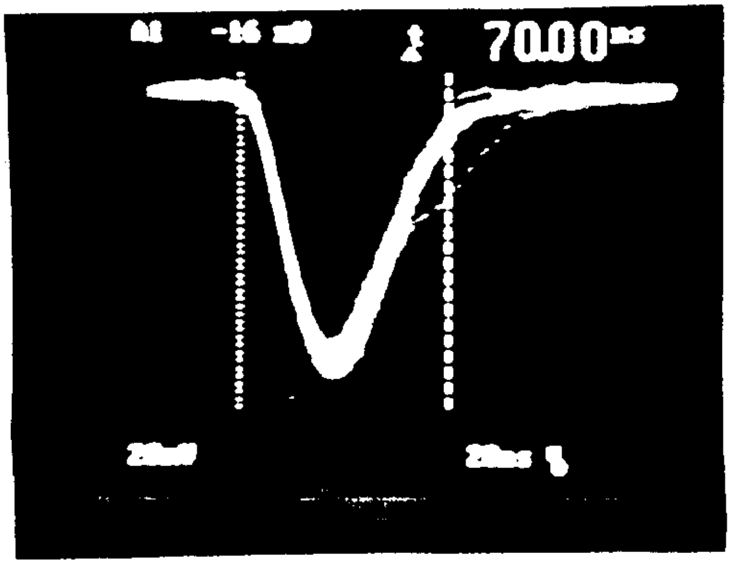


Figure 3

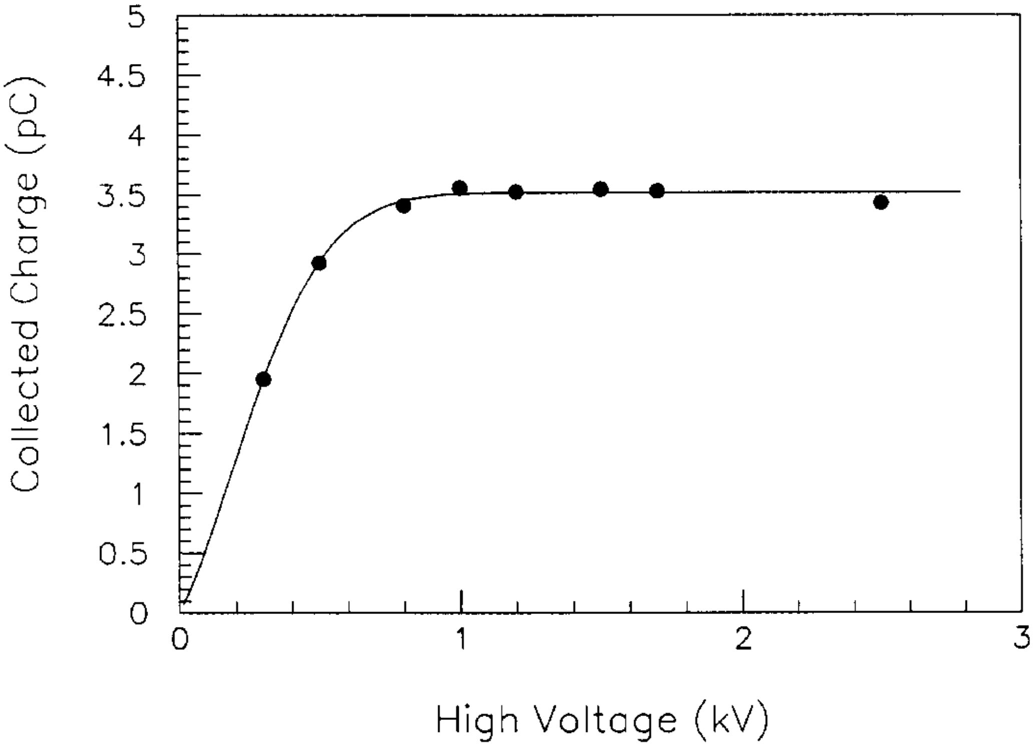

Collected Charge (pC)
5
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
0
1
2
3
High Voltage (kV)

Figure 4

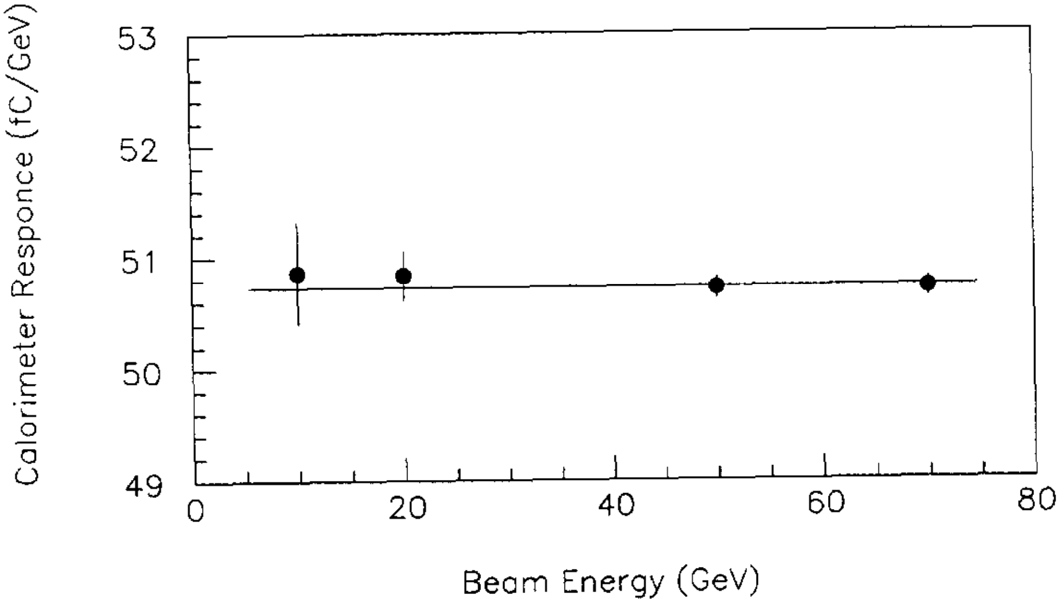
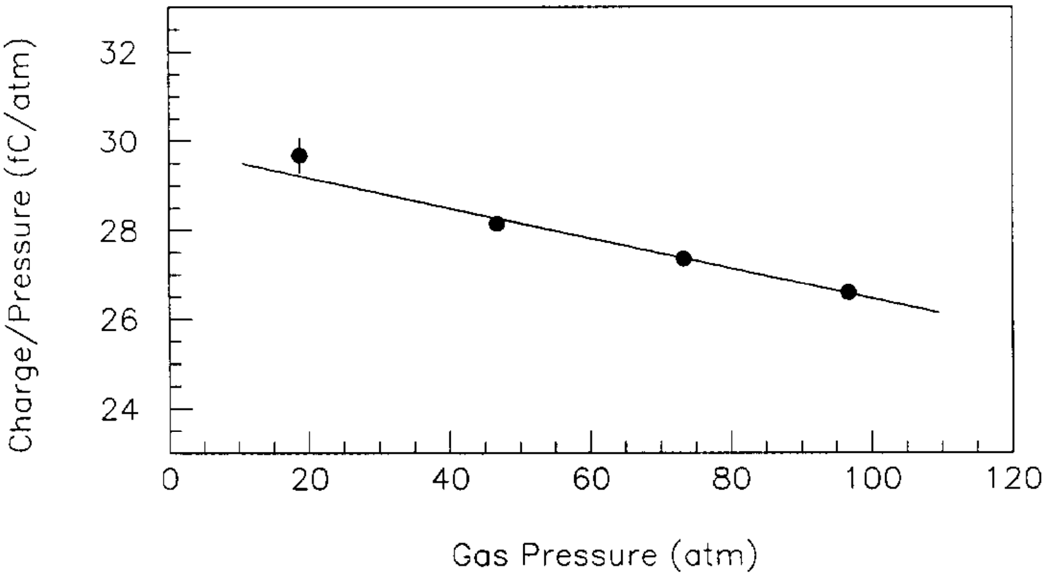

Calorimeter Responce (fC/GeV)
53
52
51
50
49
0
20
40
60
80
Beam Energy (GeV)

Figure 5



Charge/Pressure (fC/atm)
32
30
28
26
24
0
20
40
60
80
100
120
Gas Pressure (atm)

Figure 6

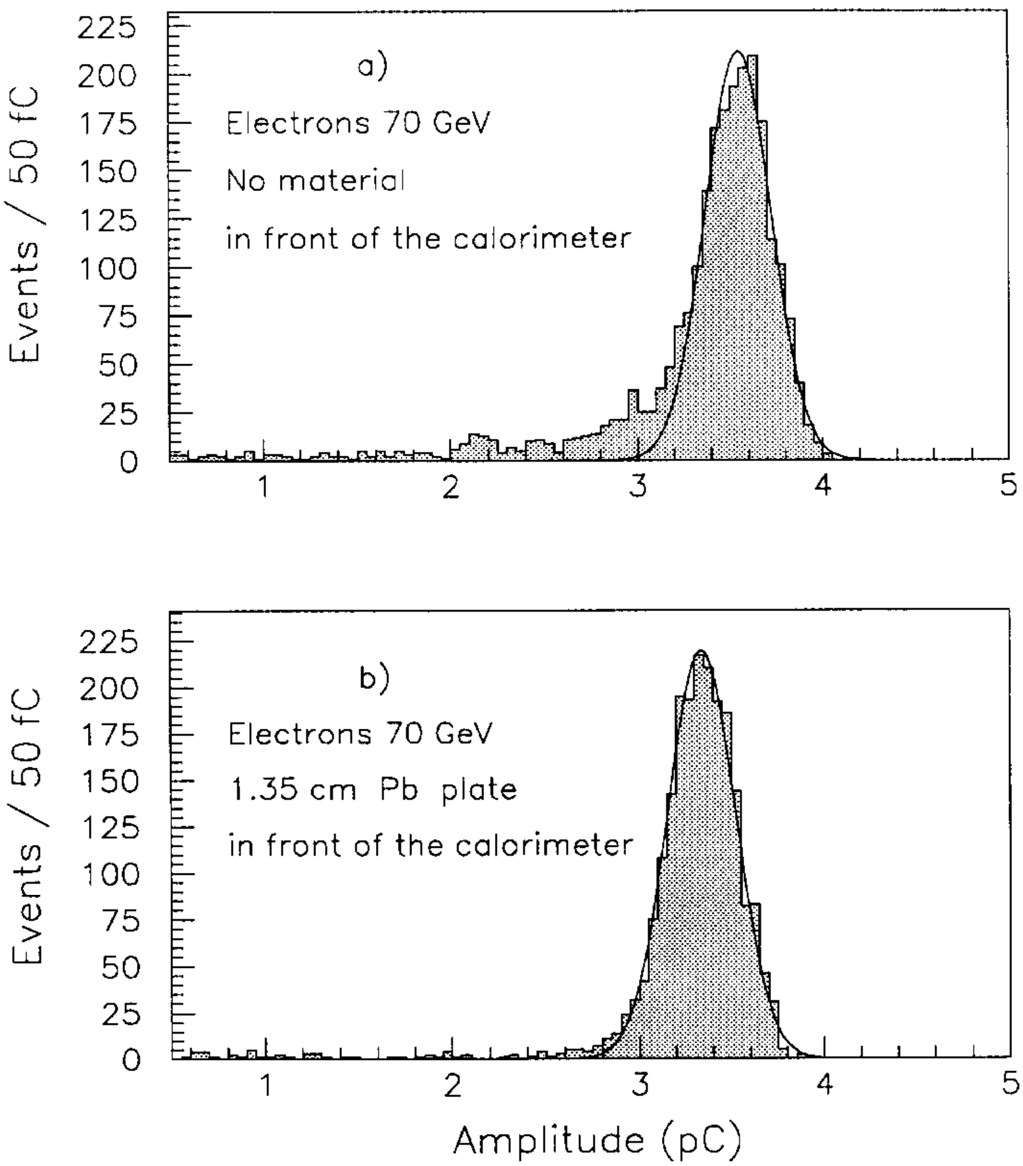
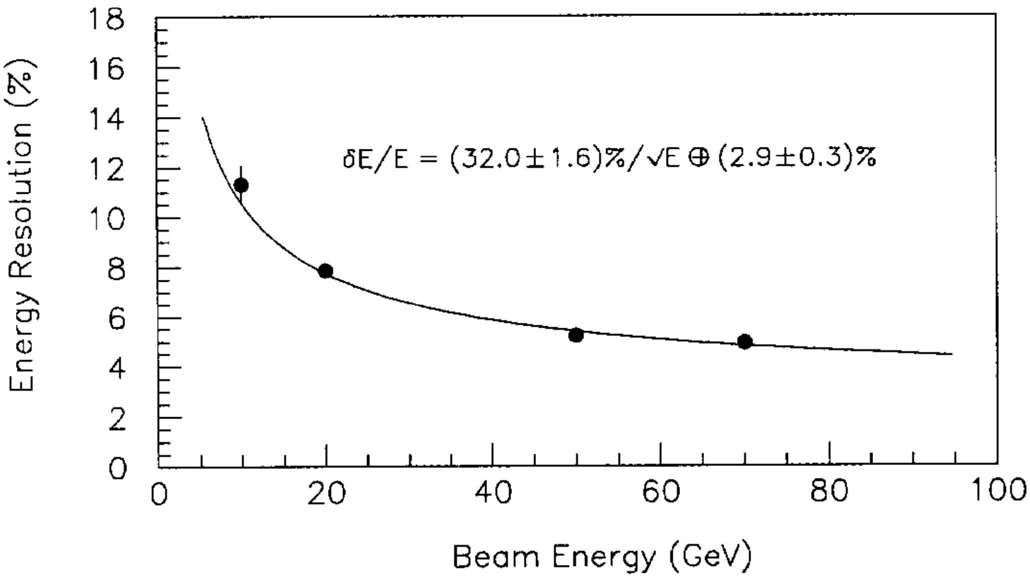
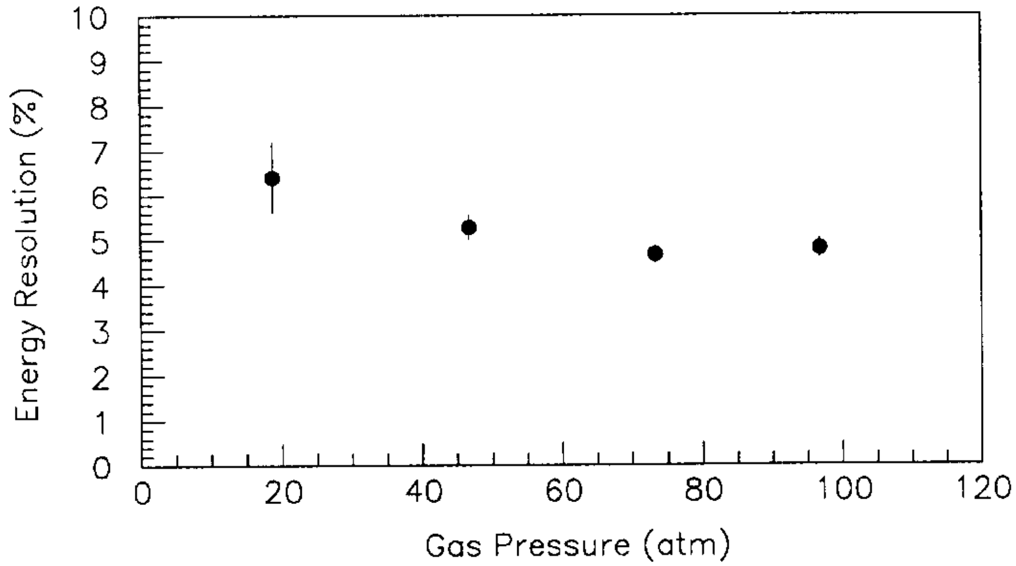

a)
Electrons 70 GeV
No material
in front of the calorimeter
Events / 50 fC
0
25
50
75
100
125
150
175
200
225
1
2
3
4
5
b)
Electrons 70 GeV
1.35 cm Pb plate
in front of the calorimeter
Events / 50 fC
0
25
50
75
100
125
150
175
200
225
1
2
3
4
5
Amplitude (pC)

Figure 7



Energy Resolution (%)
0
2
4
6
8
10
12
14
16
18
Beam Energy (GeV)
0
20
40
60
80
100
δE/E = (32.0±1.6)%/√E ⊕ (2.9±0.3)%

Figure 8



Energy Resolution (%)
0
1
2
3
4
5
6
7
8
9
10
0
20
40
60
80
100
120
Gas Pressure (atm)

Figure 9