THE CERN NEUTRINO BEAM

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1. THE 1967 NEUTRINO INSTALLATION

A new neutrino facility was constructed during 1965-66 at the south-east side of the CERN Proton Synchrotron (CPS). The experimental area and installations for the 1967 experiment are shown in Figs. 1 and 2. The design of this facility is such that the length available in the ejected beam direction can be utilized to the best advantage (e.g. the position of the target and secondary beam focusing elements with respect to the neutrino filter and bubble chamber).

The betatron oscillation required to make the circulating proton beam jump the septum magnet is excited by the kicker magnet located in straight section 97 of the CPS (i.e. $4\,^{13}/_{16}$ betatron wavelengths upstream). The septum magnet in section 74 is stationary, the beam being steered near it by backleg windings on the CPS magnet.

After ejection from the CPS, a system of pulsed bending and focusing magnets brought the proton beam from the PS ring tunnel to a target situated in the 80 m long, 3.5 m diameter neutrino tunnel. During 1967 the target, which was contained in the magnetic horn, essentially comprised a 60 cm long, 6 mm diameter boron carbide rod surrounded by an aluminium cylinder of thickness 0.5 mm.

Eight zinc-sulphide screens, viewed by television cameras, and five induction monitors were placed along the length of the external proton beam. The beam transport elements were set up approximately with the aid of the television system, and optimized

a) for minimum loss using the induction monitor information, and

b) for maximum efficiency by reference to the muon flux measured in the neutrino filter.

The structure and the position of the proton beam in front of the target were determined by measuring the radioactivity (^{24}Na, half-life 15 hours) induced in crossed aluminium wires, and were continuously monitored by a pierced ZnS screen and a standard CPS secondary emission monitor.

The total number of protons hitting the target during an experiment was obtained by integration of the signal from the induction monitor close to the target, and by measuring the ^{22}Na (half-life 2.6 years) induced in two aluminium foils placed in front of the target. During times when the heavy-liquid (propane, C_3H_8) bubble chamber (HLBC) was inoperative (e.g. film change) these foils were automatically flipped out of the proton beam.

The secondary particles produced in the target were focused by the magnetic horn$^{1)}$ and two pulsed toroidal lenses$^{2)}$ (reflectors R2, R3) such that positive and negative charged particles were focused and defocused, respectively. During part of the 1967 experiment, those high-energy particles produced in the forward direction, which would be unaffected by the focusing devices, were stopped by a plug of tungsten situated at the downstream end of the target. This was necessary in order to satisfy the requirements of a lepton number conservation spark chamber experiment.

That part of the neutrino tunnel (57 m) between the target and the neutrino shielding is generally called the "decay tunnel" since it is here that the charged pions and kaons decay, producing muons and neutrinos. Thus at the beginning of the 20 m long iron shielding there is a beam comprising neutrinos, muons, and hadrons. The latter are quickly stopped by the shielding, whilst the muon beam is gradually attenuated, leaving a clean beam of neutrinos to pass through the heavy-liquid bubble chamber. In order that the sensitivity of the bubble chamber could be periodically checked, a 15 m long pipe filled with mercury was installed along the axis of the neutrino shielding. By lowering the mercury level muons were allowed to pass periodically to the chamber, and their tracks were photographed with a hand camera thus providing rapid feedback of the chamber conditions. During the 1967 series of experiments, 1.08 million pulses were ejected from the synchrotron at a proton momentum of 20.6 GeV/c with a repetition rate of 2.3 seconds (for part of the run the repetition rate was 2.0 sec). Seventeen of the twenty circulating proton bunches were ejected, the remaining three bunches being ejected in the fast-slow mode to the 2 m hydrogen bubble chamber. The ejection efficiency and beam transport efficiency were continuously monitored electronically by reference to the signals from the beam current transformers, and visually by means of the ZnS screens. The total number of protons ejected onto the target during the experiment was

6.8×10^{17}. A typical example of the proton beam profile determined by measuring the ^{24}Na activity induced in aluminium wires placed 10 cm in front of the target is shown in Fig. 3 [3]. It is clear that at this point, ∿98% of the proton beam is contained inside an ellipse of major and minor axes 4.8 mm and 3.3 mm, respectively, and it is to be noted that from similar measurements made further upstream, the proton beam is converging to a focus ∿15 cm inside the target.

The magnetic horn and the two reflectors were normally pulsed at currents of 285 kA, 400 kA, and 320 kA, respectively.

2. NEUTRINO BEAM MONITORING

The purpose of a neutrino beam monitoring system is to guarantee the maximum number of photographed neutrino events per ejected proton, and to provide the information necessary for the analysis of the experiment (i.e. the absolute neutrino spectrum). Thus it is necessary to have control of

a) the proton intensity at ejection and at the target,
b) the proton beam size and position at the target,
c) the secondary beam.

Points (a) and (b) have already been discussed above.

The secondary beam can be monitored by measuring in the neutrino filter (Fig. 4) the flux of muons associated with the neutrinos in pion and in kaon decay. Such measurements monitor the combined efficiencies of the target and focusing currents as well as the beam symmetry. To this end, a series of horizontal channels were built in to the neutrino filter (Fig. 5), their axes being perpendicular to the secondary beam axis. Ionization chambers and scintillators were used to monitor the muon fluxes below and above ∿13 GeV/c incident momenta (13 GeV/c corresponds to a range of ∿10 m iron). The ionization chambers (Fig. 6) comprised small glass cylinders (diameter 2-3 cm) closed by Kovar plates (separation ∿2 cm) acting as electrodes, and filled with argon (97%) and propane (3%). The gas pressure ranged from 100 to 700 Torr depending on the region of the shielding in which a particular chamber was destined for use. The chambers were mounted in a plexiglas body, on which was situated a charge-sensitive preamplifier. The whole was placed in a vacuum-tight steel housing. A slot was cut into each housing in order that nuclear emulsions could be used to calibrate the ionization chambers. Graduated aluminium rods were fixed to the steel housings to provide a means of moving the ionization chambers to known positions in the channels of the neutrino shielding.

Plastic scintillators (NE 102 A) mounted on 53 AVP photomultipliers were used in the lower flux region (i.e. ∿1 particle/burst). The size of these scintillators varied from 1 cm^2 in the region where the ionization chambers were still operative, to 2400 cm^2 near the end of the shielding. As with the ionization chambers, a graduated aluminium rod was fixed to each scintillator unit.

It was found empirically that the secondary beam could be constantly monitored by means of three ionization chambers situated at a longitudinal depth of 4.7 m in the shielding. This corresponds to initial muon energies of 6 GeV. Two of these chambers, in channels 80 cm above and below the beam axis, monitored the symmetry of the muon beam, whilst the third chamber, placed as close as possible (15 cm) to the beam axis, monitored the efficiency of the secondary beam with respect to the number of protons hitting the target. The signals from each ionization chamber passed through a preamplifier and a main amplifier to a gated analogue to digital converter (ADC). The output of the ADC was split, one signal train going through an inverter to a gated 35 MHz scaler, whilst the other entered a buffer scaler. On the other hand, the signals from the scintillator array passed through pulse shapers to gated trigger units, the outputs of which were split in the same manner as those from the ADC's.

The signals stored in the buffer scalers were read and stored in the memory of a 1024 pulse-height analyser if the following conditions were fulfilled:

a) the HLBC flash tubes triggered,
b) the test beam was closed.

The HLBC flash-tube trigger pulse was generated if:

i) at least one of the ejected proton bunches had $\gtrsim$3% of full bunch intensity;

ii) the HLBC was cycling;

iii) the cameras had advanced (manual by-pass for one or two failing cameras was provided);

iv) the films were pressed against the reference plates;

v) no "film end" signal had arrived.

3. EXPERIMENTAL RESULTS

During the 1967 neutrino experiment the heavy-liquid bubble chamber was exposed for 1.08×10^6 pulses corresponding to 6.8×10^{17} protons hitting the target. The neutrino beam parameters were as shown in Table 1. A total of $\sim$1000 neutrino interactions were photographed.

The muon flux distribution in the neutrino shielding was monitored throughout the experiment, and daily flux scans were made. The ionization chambers were calibrated relatively by comparison of their signals when traversed by the same flux, and absolutely by track counting in nuclear emulsions mounted on the chambers for a known number of CPS bursts. The observed radial distribution of muons at 5 m depth (6 GeV) in the shielding is shown in Fig. 7 for various focusing conditions (normal operation refers to currents of 285 kA, 400 kA, and 320 kA in the horn and two reflectors, respectively). The effects of various focusing conditions are evident, the narrowest radial distribution being obtained when all three elements are operative (curve "c"). Comparison of distributions "b" and "c" indicate the effects of the two reflectors, neither of which were present in the 1963-65 neutrino experiments. The dip in distribution "a" at small radii is due to the target and tungsten stopper shadow, whereas the sharp cut-off at about 1.7 m radius is due to the tunnel wall shadow. The radial distributions as a function of shielding depth have been integrated and are shown in Fig. 8. Figure 9 shows the depth intensity curve for the muons on the beam axis. The derivation of the neutrino spectrum will be discussed in the following paper (H.W. Wachsmuth). A pulse-height spectrum from the ionization chamber placed on axis at a shielding depth of 4.7 m is shown in Fig. 10. This distribution, obtained during a short test which was not representative of the normal experimental conditions, demonstrates the sensitivity with which the focusing status of the secondary beam was monitored.

4. FUTURE IMPROVEMENTS TO THE CERN NEUTRINO BEAM

It is expected that the Gargamelle heavy-liquid chamber will be commissioned during 1969. Gargamelle comprises a cylinder of radius 96 cm and length 4.5 m, and may be filled with propane, freon, or a propane-freon mixture. The liquid will be viewed by eight cameras and has a fiducial volume of ~ 10 m^3. The magnet has already been installed at CERN (Fig. 11), and the chamber body is scheduled for delivery at Saclay in June 1969. The expected number of events are compared in Table 2 [4]) with those expected in the 7' Brookhaven National Laboratory hydrogen chamber.

During the 1968 shutdown, the repetition rate of the CPS was improved by a factor of 2. The booster (1972) is expected to enhance the circulating proton beam intensity tenfold. Whilst both of these improvements will increase the neutrino flux/sec in the detector by corresponding factors, they will also give an increase in the radiation level near the target. In view of this, a system for the remote handling of the magnetic horn in the case of an accident has been designed. The current pulse will be supplied to the horn via a 10 m long parallel plate conductor connected to the horn plate by four pistons (with another four for the return current) thus obviating the necessity of having cables in the high radiation area downstream of the target. These pistons, as well as the water connections and horn locking devices, will be controlled by compressed air cylinders. In order that the horn can be changed using the remotely controlled overhead crane which will be installed in the tunnel, the horn shielding is designed so that it can be moved downstream on a short railway track.

An over-all gain (relative to that obtained in the 1967 runs) in neutrino flux per sq.m. of $\sim 10\%$ can be had for energies greater than 1 GeV by changing the shape of the inner conductor of the horn. This horn shaped, energized by 300 kA, yields a gain of $\sim 5\%$ for neutrino energies greater than 3 GeV. (These gains refer to neutrinos from pion decay only, and a 95 cm long target.)

An increased number of detectors will be used for the next neutrino experiment in order to facilitate radial scans of the muon distribution in the filter. In addition the horn and reflector, currents should be continuously recorded ensuring an accurate knowledge of the pulse for pulse operation of the experiment. Finally, an improved system for data acquisition and display is being studied.

REFERENCES

1) D.H. Perkins and W. Venus, (unpublished).

2) A. Asner and C. Iselin, CERN 65-17 (1965) and CERN 66-24 (1966).

3) K.M. Vahlbruch (private communication).

4) D.H. Perkins, Gargamelle Users' Meeting, Milan, October 1968, CERN-TCC/68-40, NPA-GAR/69-1.

Table 1

Parameters of the 1967 CERN neutrino beam

Proton momentum	20.6 GeV/c
No. of bunches	17
Target	B_4C (7 mm Ø, 60 cm long)
CPS repetition rate	2.3 sec
Magnetic horn current	285 kA
R2 current	400 kA
R3 current	320 kA
Decay tunnel length	57 m
Neutrino shielding (6000 t steel)	19 m long
Density	7.3 gm/cm^{-3}
Neutrino detector	CERN 1.1 m^3 HLBC
Detector liquid	C_3H_8
Total pulses for HLBC	1.08×10^6
Total protons	6.8×10^{17}
Total ν events	$\sim$1000

Table 2

The number of events expected in Gargamelle

Reaction	CERN 1963/4	Gargamelle CF_3Br	Gargamelle C_3H_8	BNL	
				H_2	D_2
$\nu + N \rightarrow \mu^- + N + n\pi$ (n > 2)	350	9000^*	900^*	450	900
$\nu + N \rightarrow \mu^- + Y + K + n\pi$	30	750	75	37	75
$\nu + n \rightarrow \mu^- + p$	600	15000			750
$\bar{\nu} + p \rightarrow \mu^+ + n$	70	1750	175^*	85	
$\bar{\nu} + N \rightarrow \mu^+ + \Lambda, \Sigma$	~ 2	$\sim 50^*$	$\sim 5^*$	~ 3	
$\bar{\nu} + p \rightarrow \mu^- + p + \pi^+$	900	22500	2250	1100	
$\nu + n \rightarrow \mu^- + n + \pi^+$ $\rightarrow \mu^- + p + \pi^0$	300	7500			1500

No. of events shown are per 10^6 pulses.

Fiducial volumes assumed: Gargamelle 6 m^3

BNL (7') 4 m^3

Asterisks indicate predominant advantages of Gargamelle over hydrogen chambers.

Fig. 1

An aeriel view of the CERN neutrino area.

LAYOUT OF NEW NEUTRINO FACILITY AT CERN PS

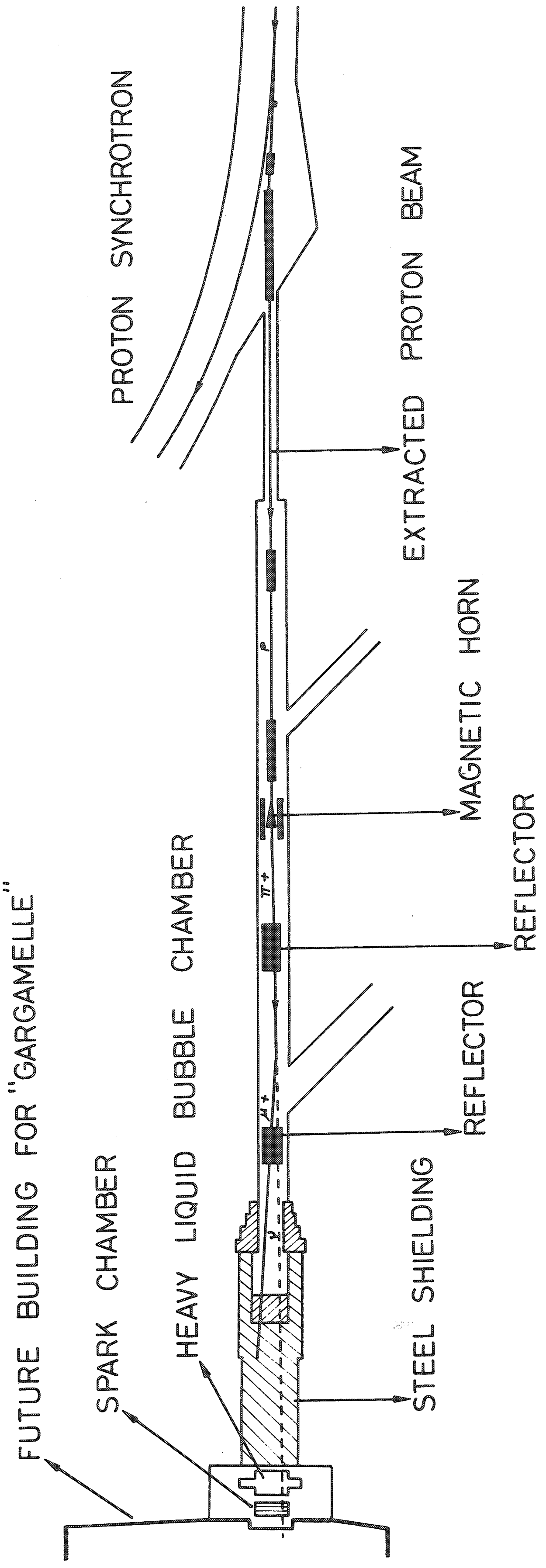
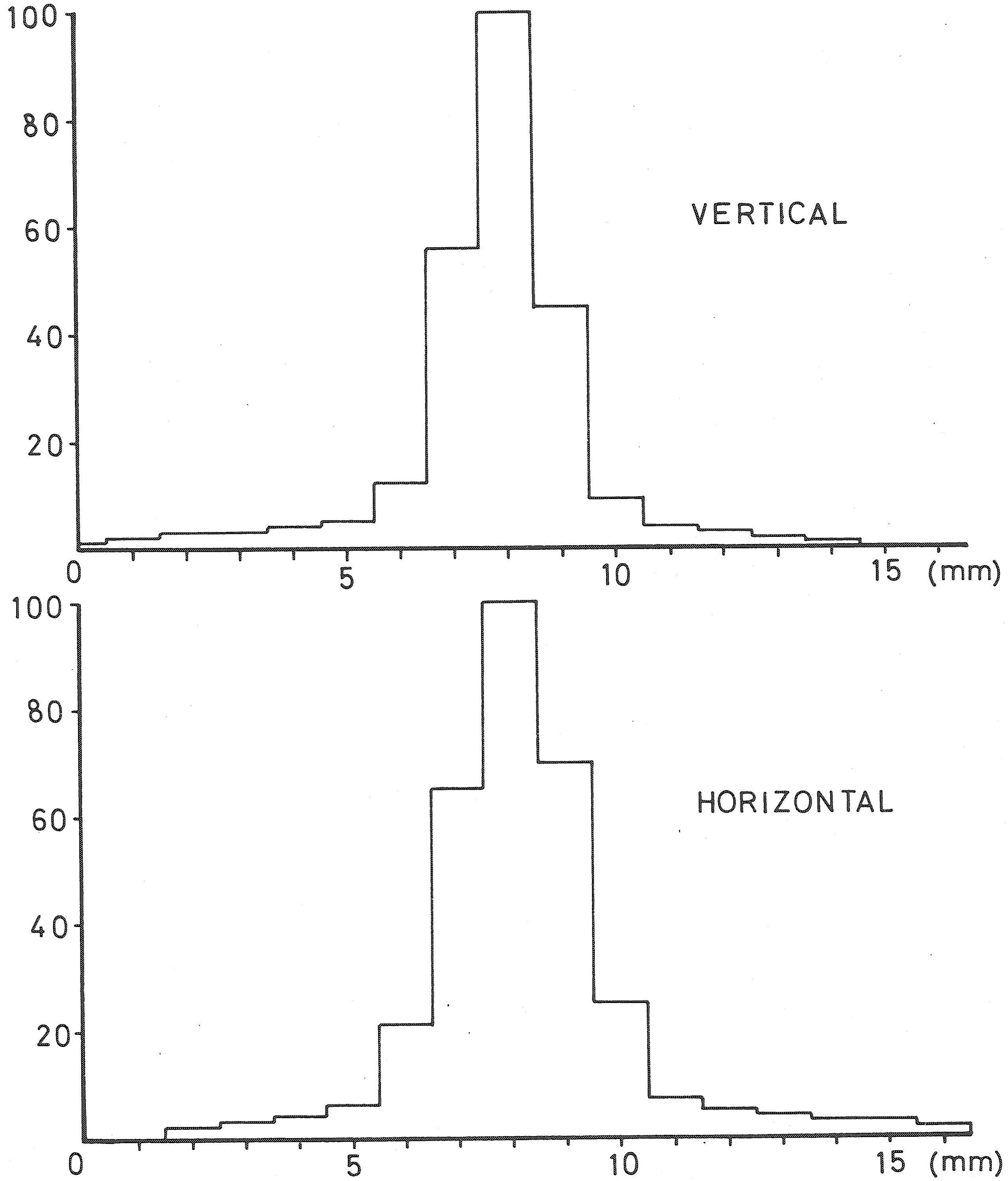


Fig. 2



VERTICAL

HORIZONTAL

Structure of the external proton beam at the target

Fig . 3

Fig. 4
The neutrino filter
under construction.

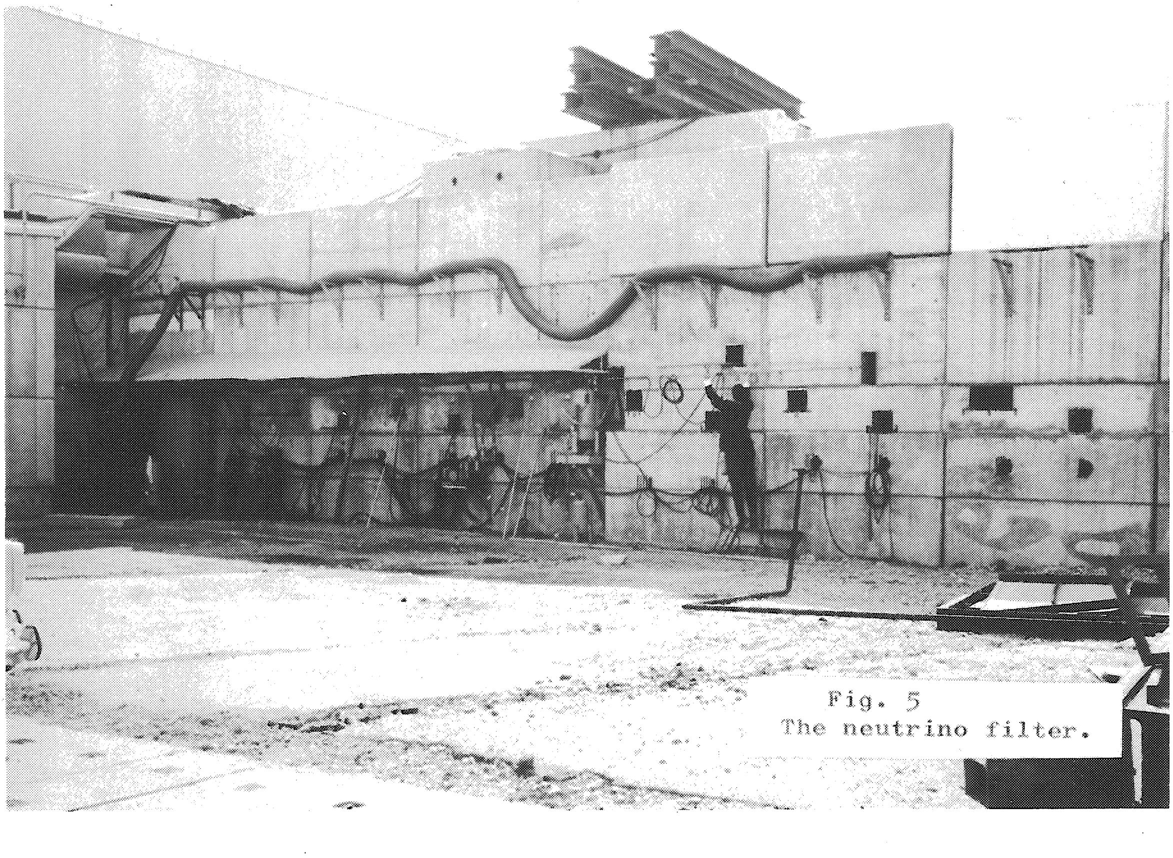


Fig. 5
The neutrino filter.

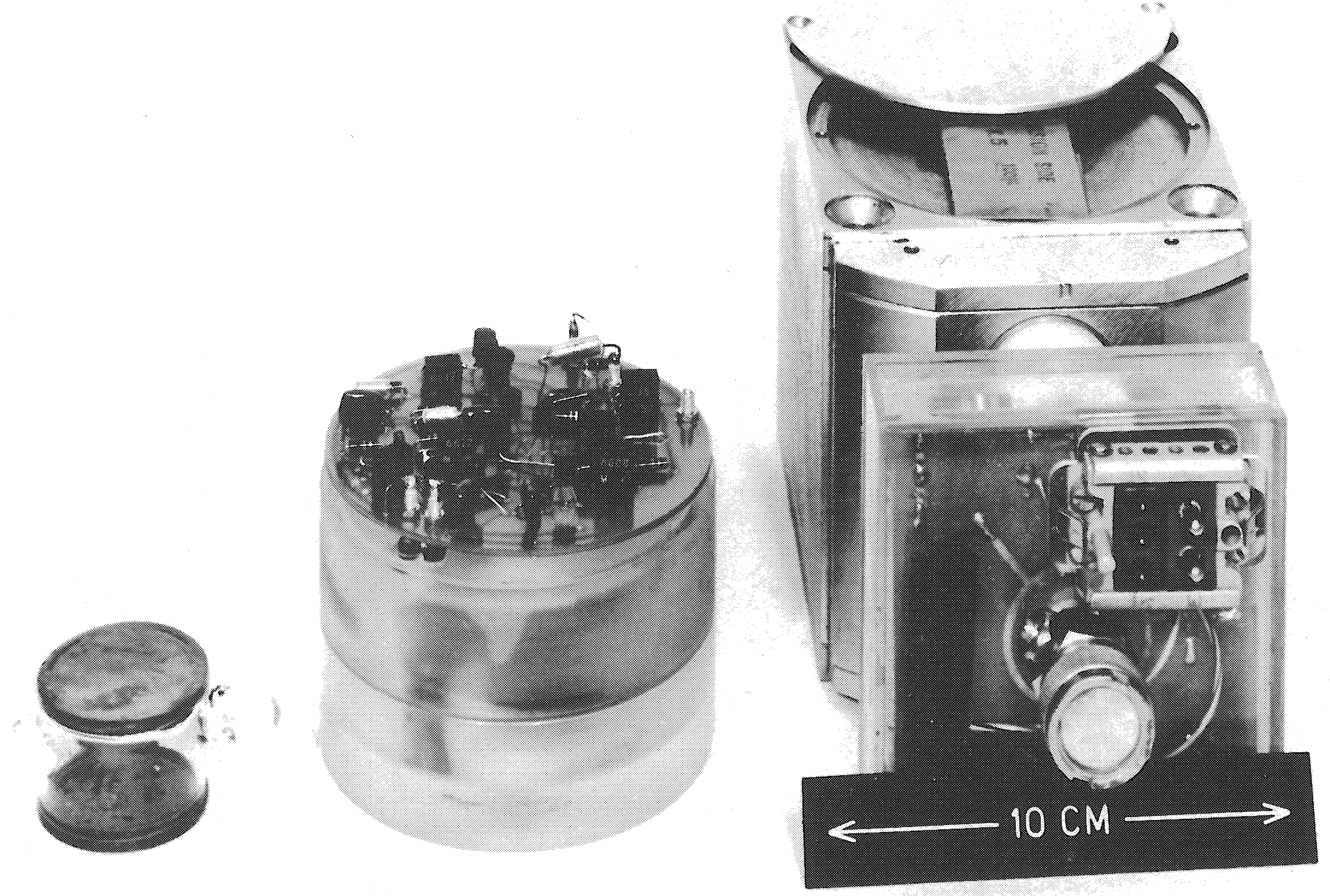
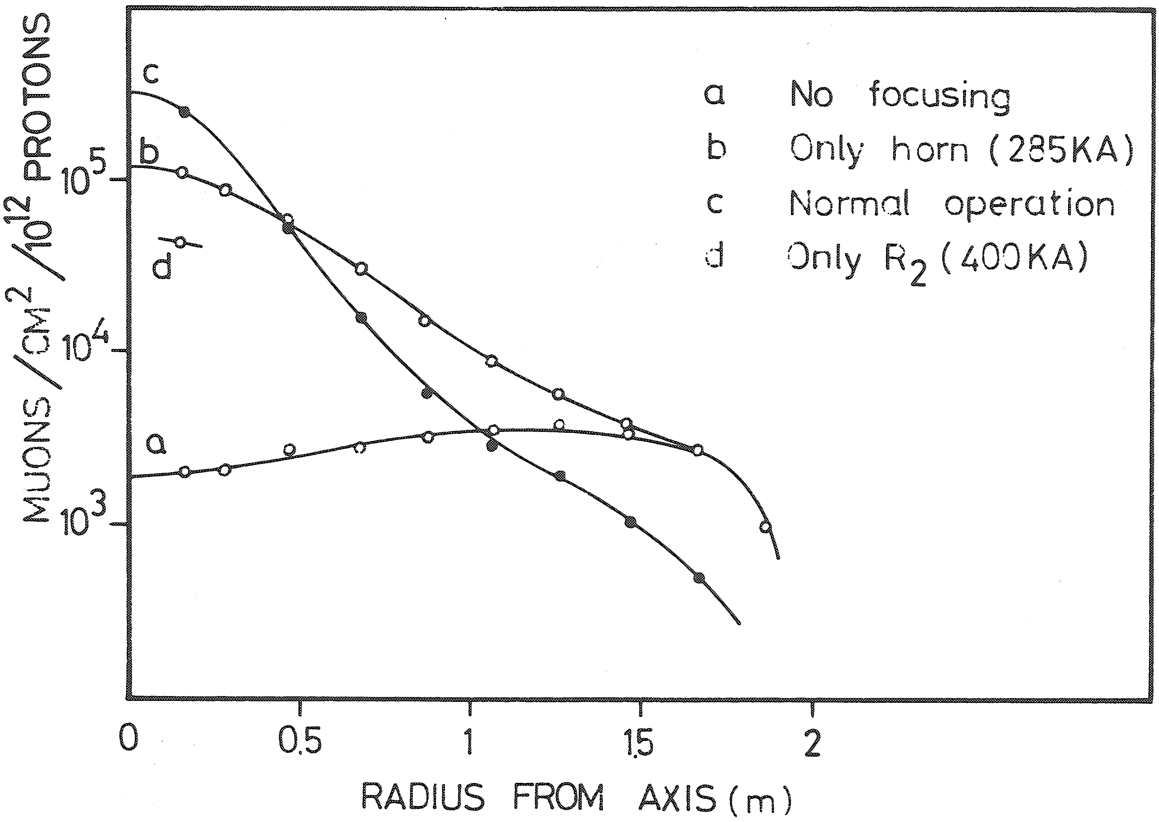
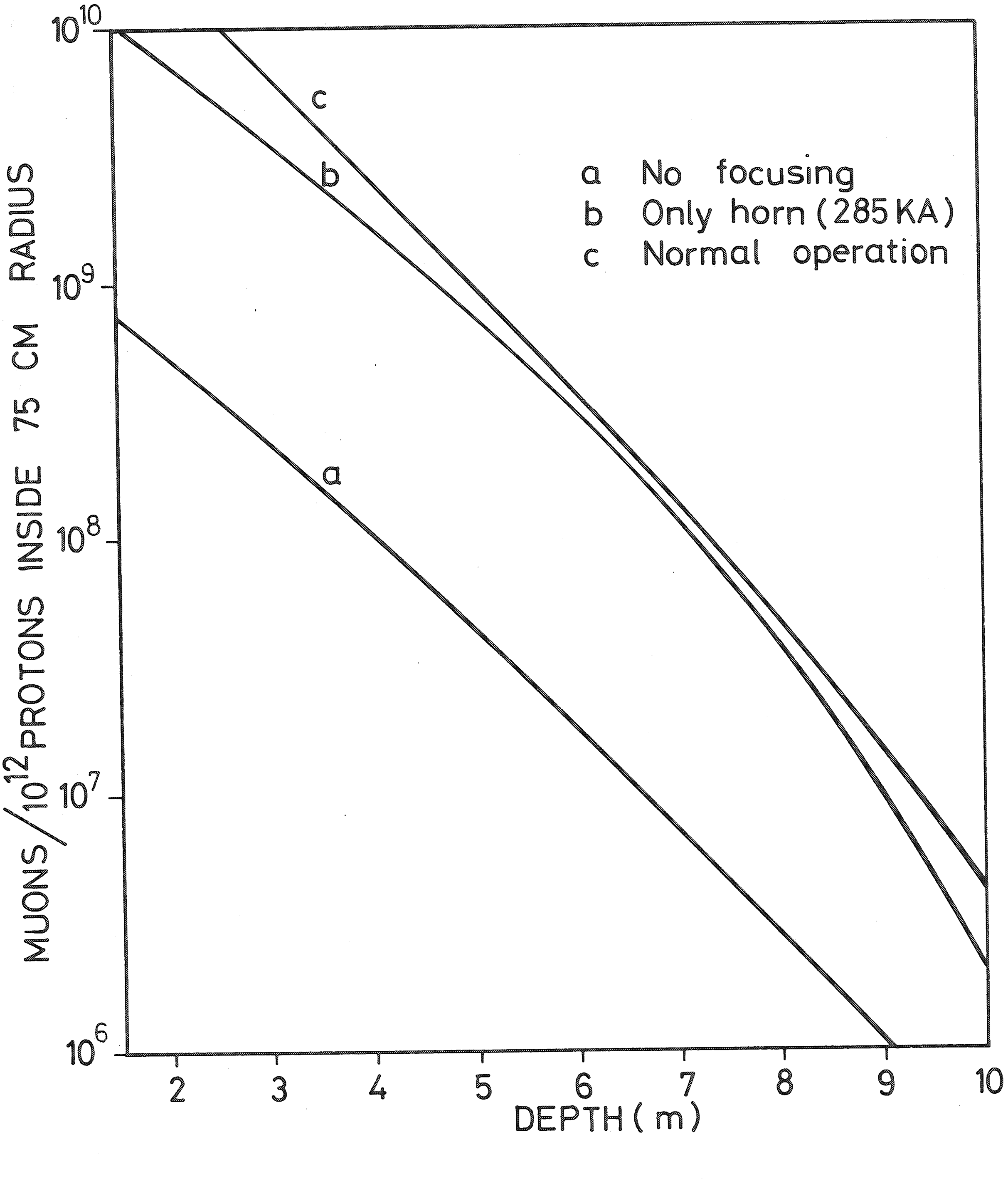


Fig. 6
An ionization chamber.



The radial distribution of muons at 4.7 m depth for various focusing conditions.

Fig. 7



The muon flux integrated over 75 cm radius as a function of shielding depth.

Fig.8

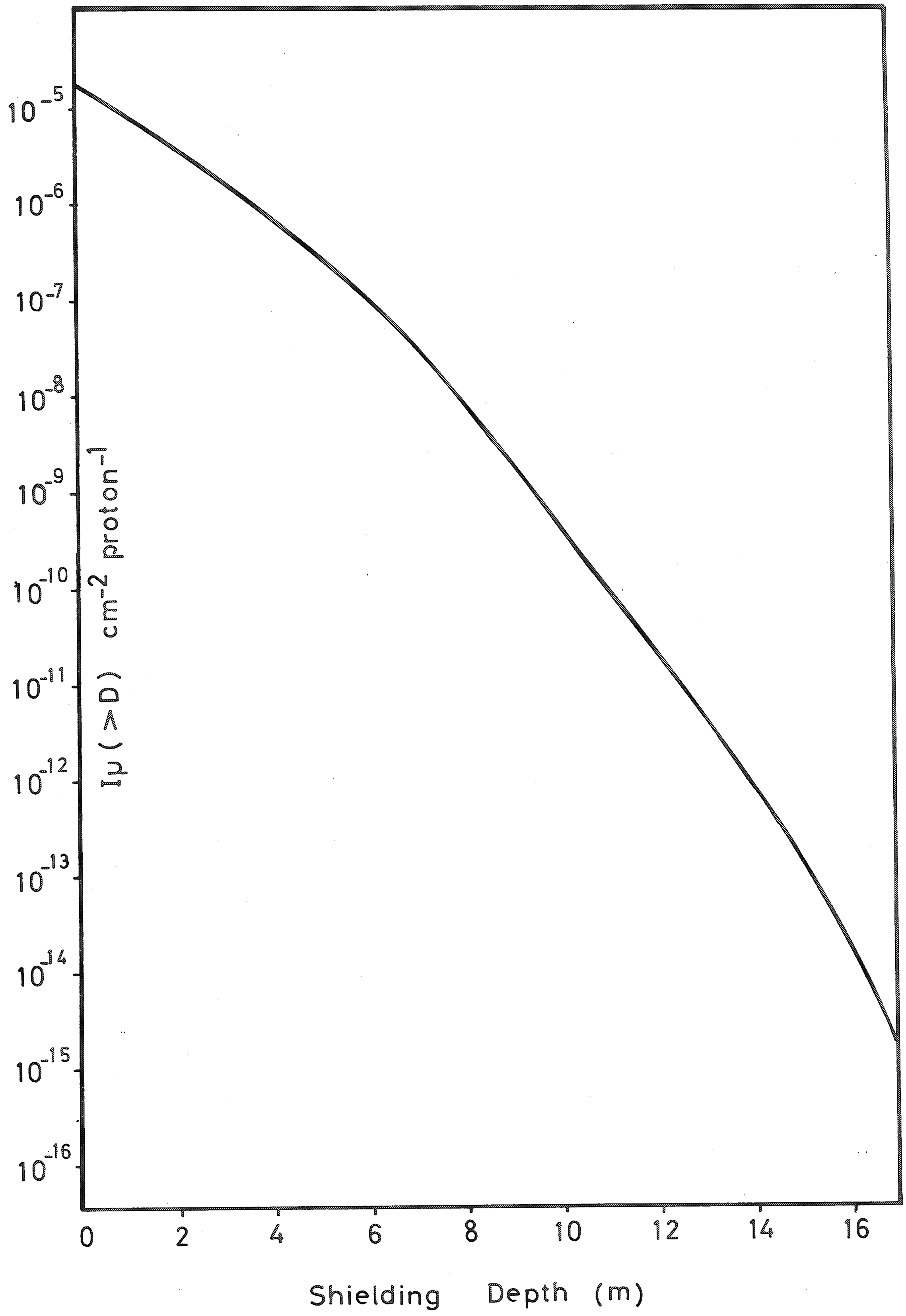
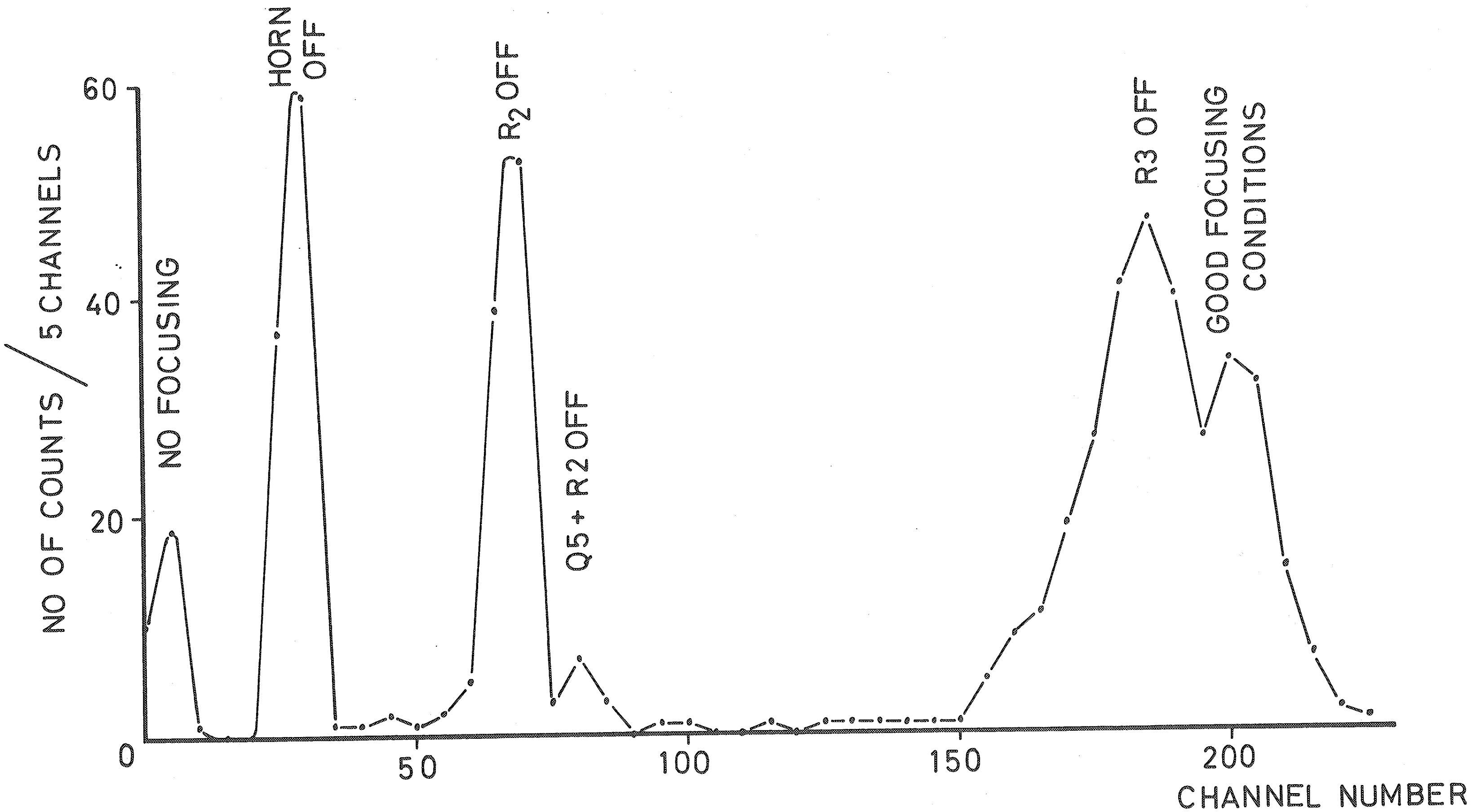

10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-14}
10^{-15}
10^{-16}
$I\mu\,(>D)$ cm^{-2} proton^{-1}
0
2
4
6
8
10
12
14
16
Shielding Depth (m)

Fig. 9



The pulse height spectrum of a muon flux monitor

Fig.10

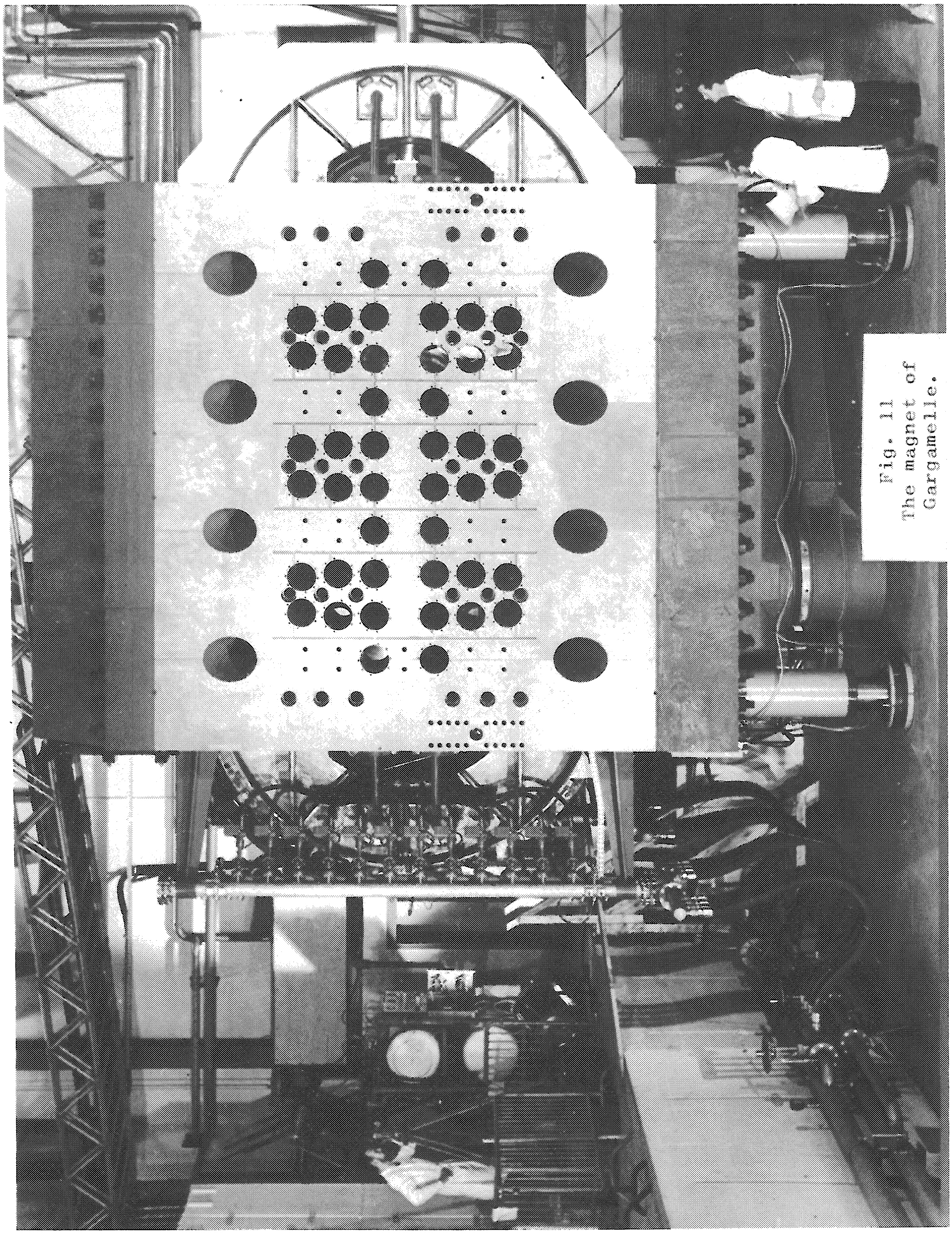


Fig. 11
The magnet of Gargamelle.