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PERFORMANCE OF A TIME-PROJECTION CHAMBER[+]

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ABSTRACT

We report the design and operation of a position sensitive three-dimensional drift chamber with the capability of ionization sampling. This detector allows simultaneous measurement of the momentum and the mass of charged particles. The device is a prototype for a large detector system to be built at the PEP storage ring facility.

I. INTRODUCTION AND GENERAL PRINCIPLES

In this paper we report the design and operation of a novel low-mass device which allows the simultaneous measurement of the momentum and charge-to-mass ratio of charged particles. This was developed as a prototype of the Time Projection Chamber detector[1] being constructed by a collaboration from Lawrence Berkeley Laboratory, University of California at Los Angeles, University of California at Riverside, Johns Hopkins University and Yale University for use at the PEP electron-positron colliding beam facility.

The device described here, which we shall call the Dipole Time Projection Chamber (DTPC), is an ionization sampling drift chamber which is capable of providing three dimensional spatial coordinates along trajectories of charged particles. Proportional wires and a segmented cathode plane provide the two coordinates orthogonal to the drift direction. Time information determines the coordinate along the drift direction. Figure 1 depicts schematically the geometry of the DTPC. A pressure vessel located in a dipole magnet is filled with a gas with high electron mobility, low electron attachment, and good proportional counting characteristics. An electric drift field, which is parallel to the magnetic field produced by the dipole magnet ($\bar{E} \times \bar{B} = 0$), is generated in the gas volume. As a result, ionization electrons left in the gas by the passage of charged particles are caused to drift along the field direction to the bottom of the pressure vessel. Here they are detected by an array of proportional wires,some of which have

locally segmented cathodes (see Figures 1 and 2). The tracking function of the DTPC is accomplished by detecting these electrons as they reach the proportional wire array in such a way as to be able to determine their point of origin in the gas volume. The dipole magnetic field serves two functions: first, to bend charged particles in a plane parallel to the proportional wire array in order to permit measurement of their momenta, and second, to reduce the diffusion of ionization electrons as they drift under the influence of the electric field.[2]

The density of ionization electrons reflects the energy loss (dE/dx) in the gas of each charged particle. The well-known relationship between energy loss and particle velocity can be used with the measured momentum for particle identification. With a particular choice of operating parameters, the DTPC has the capability of identifying individual electrons, pions, kaons and protons over a momentum range from a few hundred MeV/c to $\geq$15 GeV/c. Particle identification can be accomplished even within multiparticle events entering the chamber fiducial volume. This use of energy loss for particle identification is discussed in quantitative detail below.

II. PARTICLE IDENTIFICATION BY dE/dx

The ionization electrons left along the path of a charged particle, which in the DTPC are caused to drift to the proportional wire array for position information, can also be used to measure the energy loss of the particle. Figure 3 shows, for several species of particles, the most probable energy loss (E_{mp}) as a function of momentum in 4 mm of Argon gas at 10 atmospheres.

In the region where $\beta << 1$, the most probable energy loss varies as $1/\beta^2$, while in the relativistic region the most probable energy loss varies as the logarithm of $\beta\gamma$. At sufficiently high velocities, the transverse electric field generated by the particle is of sufficient strength to polarize the medium leading to the saturation of the logarithmic rise of E_{mp}. For solids and liquids the saturation sets in at such a low velocity that there is very little relativistic increase of ionization. The theory, still approximate, is discussed extensively in the literature.[3]

The use of energy loss for particle identification, especially in the relativistic region, requires the determination of E_{mp} with a resolution of $\leq$3% (RMS). Unfortunately, the energy loss of a particle in a thin layer of material varies enormously because of the so-called "Landau fluctuations" which result from the infrequent but energetic delta rays produced in passing through the material. These fluctuations make impossible a high resolution measurement of E_{mp} with a single sample. <u>The key to achieving high resolution is many independent samples of the energy loss for the same particle</u>. In fact, to achieve the desired resolution of $\leq$3% RMS, several hundred samples of the energy loss (dE/dx) are required over many meters of path length in gas at STP. This is discussed in some detail in Ref. 3.

In order to acquire several hundred useful measurements of dE/dx, the DTPC is pressurized to 10 atmospheres so that an adequate total path length is presented to the particles. The proportional wire array is segmented to sample the ionization electrons left along a particle track nearly two hundred times over a track length of approximately 80 cm.

III. THE DTPC PROPORTIONAL WIRE ARRAY

The Dipole Time Projection Chamber must determine the trajectory of the ionizing track to sufficient accuracy and must provide ≈200 samples of dE/dx along the track. Both of these functions must be performed in time intervals of ≲100 ns to provide tracking resolution of <1 mm along the drift direction and segmentation of the DTPC volume into sufficiently small subvolumes to minimize the overlap probability in multitrack events.

The proportional wire array configuration is shown in Fig. 2. The array consists of 200 parallel proportional wires in a plane perpendicular to the drift electric field and magnetic field. To avoid edge effects, four sense wires at each end are not instrumented, leaving 192 wires to provide independent samples of the energy loss. The wire spacing is 4mm. Ionization electrons from a typical track drift completely onto this wire array independent of the dip angle. These proportional wires are of two sorts. Each operates as a sampler of the ionization electrons on each track that drifts onto them so as to give the requisite dE/dx information for particle identification. For eight of the 192 proportional wires, spaced

equally from one another, the cathode plane below is locally segmented into square segments 7.5 mm on a side and separated by 0.5 mm (see Figs. 4-7). The use of these eight wires for dE/dx measurements is unaffected by the cathode segmentation. The amplitude of the pulses induced on these segments varies approximately as a Gaussian function of the distance between the point on the proportional wire where an avalanche has developed and the geometric center of the pad. The center of this distribution contains information from all electrons collected by that proportional wire and can be found to an accuracy of $\lesssim$100 μm (RMS).[4] The coordinate along each of these eight wires for a track in the DTPC is then determined by centerfinding, using signals induced on segments by the proportional avalanches on the wires. This method for measuring position along a wire is discussed in Ref. 5 and illustrated in Fig. 4. Using this method in conjunction with pulse timing electronics on each wire and cathode segment, the array provides intrinsically three-dimensional tracking information. The three coordinate directions are determined by the pattern of wires hit, the position along the eight wires derived from induced pulses on the cathode segments, and the drift time of the ionization electrons to the wires. This intrinsically three-dimensional spatial segmentation, achieved with electronics, proportional wires, and cathode segmentation rather than with physical detectors in the DTPC fiducial volume, is the key to very high efficiency for track reconstruction.

In addition to the high quality spatial information, the proportional wire array provides dE/dx information from the 192 proportional wires described above. Here again the information is recorded as a function of time in $\lesssim$100 ns time intervals so that each sample of dE/dx information from a given wire can be correlated in time with a particular track.

A detailed picture of the configuration of sense, grid, field wires and segmented cathode pads is shown in Fig. 5. The grid is arranged to funnel the field lines from the main drift field so that a 4mm projection of ionization electrons is focused onto a single sense wire. The field wires (76 μm diameter) are placed between neighboring sense wires (20 μm diameter) in order to reduce the wire-to-wire cross talk caused by positive ions moving away from a given sense wire. The sense wire to field wire spacing is 2mm. The grid-to-sense wire and sense-wire to cathode spacing are 4 mm. Cathode segmentation is present only for the wires which read.

IV. ELECTRONICS

The DTPC proportional wire electronics must function in a novel manner in order to read out analogue information from each dE/dx wire and cathode segment at $\lesssim$100 ns time intervals. The components critical to this readout are, for each element: a low noise ($\lesssim$1000 electrons RMS) FET input preamp,[6] located inside the DTPC pressure vessel close to each readout element; a remote shaper-amplifier; and an analogue shift register to store the pulse-height information as a function of time.

A particular shift register, called a Charge Coupled Device delay line (CCD), is now available commercially from Fairchild (CCD 321A).[7] Each such device contains two independent linear arrays of 455 charge storage cells. Charge (i.e., pulse height) information is shifted along this array in response to an external clock which cycles as fast as 20 MHZ (or as slow as 10 KHz for readout). Experience has shown that 13 MHz gives best performance. With such a device on the readout of each detector element (sense wire or cathode pad), one can store all analogue information for up to 35 μs (455 × 77 ns). A CCD delay line can store the entire analogue history of a single readout element for more than the maximum time it takes the data from an event to drift the distance to the DTPC wire array. Thus, at a time of up to 35 μs after the event occurs, the complete array of delay lines is ready to present the full information set for that event. The array of CCD delay lines can then be read out through a special function processor which can address each word by detector element and time slice. The delay lines are read out as their clocks continue to run. A readout sufficiently slow to permit subsequent digitizing is achieved by reducing the clock rate to 110 KHz.

A full system of CCD delay lines has not been fully integrated into the operating electronics system of the DTPC. Instead, we have used the Large Scale Digitizer system[8] developed at LBL in order to provide each detector element (wire or cathode segment) with a single digitization per event with a common gate time for all channels. As a result, only a single interval of drift time can be detected per event. The electronics thus limits detection to those events with a track (or tracks) located in a plane parallel to the proportional wire array.

We have, for a short test run, implemented 16 channels of charge coupled devices. These have been integrated into the readout electronics in parallel with the Large Scale Digitizers for direct comparison with the digitizing system. Ultimately it would be desirable to instrument all proportional wires and cathode segments in the DTPC with CCD readout in order to provide full capability for three-dimensional data with complete drift time sampling.

V. DESIGN DETAILS AND OPERATING CONDITIONS

A schematic plan view of the DTPC is shown in Fig. 2. The pressure vessel is 100 cm long and is held in the gap of a 74 cm wide by 91 cm long by 20 cm high dipole magnet. The pressure vessel is designed for 10 atmospheres. There are shims to increase the gap of the magnet to 21.5 cm so that the magnet can reach 13 kG with sufficient field uniformity to avoid serious $E \times B$ distortion of ionization tracks during electron drift. During the beam tests reported here, the DTPC operating conditions were $E/P = 0.2$ V/cm/Torr with a filling gas of 80% Argon and 20% CH_4. Gas flow into the system proceeds through a commerical purifier[9] designed to reduce oxygen concentrations below 0.1 ppm. The DTPC has 4.7 mm dome-shaped aluminum beam window in order to minimize beam particle interactions.

The fiducial volume of the system is defined by the area of the proportional wire array, 19.2 cm by 76.8 cm, and the 10 cm maximum drift distance. The wire array was typically operated with +3750 volts on the sense wires, +400 volts on the field wires and with the grid wires grounded. Figure 6 is a photograph of the proportional wire array. Figure 7 is a photograph showing a closer view of the wires themselves and a single row of 7.5 mm × 7.5 mm cathode segments.

In order to minimize noise the preamplifiers were placed as close to the wires and segments as possible. Preamplifiers for the wires were located at one end of the sense wires as shown in Fig. 2. Preamps for the cathode segments were located immediately under the cathode plane, below each segment. Design details of these preamps are discussed elsewhere.[6] Figure 8 is a photograph of the backside of the cathode plane showing the arrangement of the preamps for the cathode segments.

Signals from all preamps were routed on twisted pair cables through hermetically sealed connectors located on the front plate of the pressure vessel then on coaxial cable to shaping amplifiers. The shaping amplifiers, located approximately 5 meters from the DTPC, produce a bipolar output with a rise time of approximately one microsecond. This shaped pulse is then sensed at its peak by the digitizers with a 50 ns gate. The timing of this gate with respect to the arrival time of the ionization electrons at the wire array is determined by the summed pulse from the group of 16 proportional wires in the middle of the wire array. This timing pulse is required to be in coincidence with the beam particle trigger described in Section VII.

VI. CALIBRATION AND MONITORING OF DTPC PERFORMANCE

In order to measure dE/dx by multiple sampling of the ionization of a single particle, the relative sensitivity of each sampling channel must be determined, and changes in sensitivity with time must be monitored. In the DTPC this calibration procedure and monitoring may be broken down into three operations. The relative gains of the

electronics serving each sense wire is measured by applying a standard electronic pulse to all of the field wires. This pulse is capacitively coupled to all of the sense wires and the regular spacing of all wires assures that the signals at the amplifier inputs are identical. The relative gains of the electronics serving each cathode segment are obtained in the same way. For cathode segment electronics, accurate relative calibration over a few adjacent channels is sufficient.

With the relative electronic gain known, one then needs to measure the relative sensitivity of each wire in the device to a known energy deposition in the gas. This calibration is accomplished by measuring the response of each channel to the ionization produced by a nuclear x-ray. A convenient source for the pressurized DTPC is Fe^{55} which has an x-ray of 5.9 keV energy. In the pressurized DTPC operating at 10 Atm with a sampling length of 4mm, a minimum ionizing particle has a most probable energy loss per sample of about 6 keV, so that the iron x-ray will deposit an energy well matched to the dynamic range of the analogue electronic system.

Fe^{55} sources for this purpose are located both at the top of the drift region and immediately under the cathode plane. The long source at the top of the drift region is located over the centers of the wires and illuminates all wires simultaneously. The source beneath the cathode plane can be moved in a direction perpendicular to the proportional wire lengths to illuminate wires individually through 6mm long holes of 1mm diameter.

Since these relative calibrations are quite stable, both the electronics and wire calibrations need be done only periodically.

Typically such calibration runs are taken before and after each data run of several days. The density of the gas, or rather, the effect of its variations on the gas multiplication around any wire, however, must be monitored continuously in order to identify temporal fluctuations in the sensitivity of the DTPC. This is accomplished by illuminating a selected wire within the DTPC with an Fe^{55} x-ray source and taking pulse height spectra continuously.

Finally, the gas composition of the DTPC is monitored regularly in order to ensure that it is free of gaseous impurities having high electron capture cross sections. The most likely impurity is oxygen, and there are commercial oxygen analyzers having sufficient sensitivities to determine if oxygen contamination has reached troublesome levels.

VII. BEAM LAYOUT AND PARTICLE TRIGGER

Tests of the DTPC were performed at the Bevatron in a momentum selected beam of high energy particles. The trajectory and identity of individual beam particles were determined independently of the DTPC. Time of flight measurements allowed the separation of protons from other beam particles at all energies of interest. A lead glass counter array downstream of the DTPC served to identify electrons in the standard manner. A pressurized Cerenkov counter provided additional identification in a manner determined by beam momentum and the counter pressure. For example, electrons were tagged at momenta below 1 GeV/c and pions and electrons were tagged above 1.4 GeV/c. This enhanced the ability of the overall beam detector system to identify

protons at the higher momenta. The beam detector system served to identify particles with accuracy sufficient for our understanding of DTPC operation for particle identification.

Scintillation counters were used to define a beam particle trigger. A timing trigger was formed by a coincidence between a beam particle trigger and a timing pulse generated by the analogue summed signal of the sixteen proportional wires located in the center of the DTPC wire array. The precise timing of this trigger pulse, which was used to gate the digitizer on each DTPC readout channel, was determined by the analogue summed signal.

Three sets of X-Y proportional wire chambers with 2mm wire spacing were located in the beam, one set at either end of the pressurized Cerenkov counter and one set immediately downstream of the DTPC. These defined individual beam particle trajectories independently of the DTPC.

In addition, pulse heights from the various scintillation counters were recorded on an event by event basis in order to permit multiple particle events and beam spray to be eliminated from the event sample used to study the DTPC response.

Typically, the beam was operated with fluxes of several thousand particles per Bevatron pulse. Details of the beam layout and ratios of particle types as a function of Bevatron energy and of beam momentum are described elsewhere.[10]

VIII. SUMMARY OF DTPC RESPONSE TO BEAM PARTICLES

Detailed results of beam tests with the Dipole Time Projection Chamber will be discussed in a subsequent paper. Here we summarize briefly some of the most pertinent results which were obtained operating the DTPC at 10 atmospheres pressure with an 80% Argon + 20% Methane filling mixture. The drift field was 1500 V/cm, the magnetic field 7.5 kG. Gains of the DTPC proportional sense wires were approximately 10^3. Under these conditions the following results were obtained

a. System electronic noise was ~800 electrons (RMS) per channel.

b. The contribution to the signal on the cathode segments from the sense wire immediately above the segments was ~20% of the signal appearing on the sense wire itself.[4]

c. Spatial resolutions from the cathode segments obtained with 1.8 GeV/c tracks were 100 ± 3 μm (RMS).

d. The most probable energy loss (E_{mp}) of individual pions was estimated with a simple algorithm which calculates the arithmetic mean of the pulse heights on the 70% of the proportional wires with the smallest pulse heights. This procedure has the effect of eliminating the ionization samples containing high energy delta rays. With a sample of several hundred pions in the fiducial volume of the DTPC at a momentum of 1.8 GeV/c a resolution of

2.7% (RMS) was obtained in the estimator of the most probable energy loss. Beam tracks were used to calibrate the relative responses of the proportional wires.

e. The relativistic rise (defined at 800 MeV/c as the ratio of most probable energy loss of electrons to that of pions) in the 80% Argon + 20% CH_4 mixture has been measured to be 1.50 ± 0.02 at 1 atmosphere pressure and 1.35 ± 0.02 at 10 atmospheres pressure.

f. A study of the response of individual wires to beam particles shows random variations at the 5% level along the wire. Possible systematic variations from wire to wire are observed at the few percent level. It is these variations, both systematic and random, which at the present time appear to limit the resolution in the most probable energy loss.

g. Data taken with CCD readout of proportional wires or cathode segments indicates that the resolutions obtained with the digitizer system as reported above are not appreciably degraded by CCD readout.

h. Using the CCD readout on 16 of the proportional wires, a resolution in the drift direction of <200 μm (RMS) was obtained with beam tracks.

IX. SUMMARY

We have described the design and operation of a novel charged particle detector which allows the simultaneous measurement of the momentum and mass (modulo charge number). Such a device could be used as a low-mass dipole multiparticle spectrometer with full particle identification capability for individual tracks within multiparticle events. The device could also be used to study heavy ion collisions where the combination of momentum analysis and dE/dx capability can distinguish between states of differing charge/mass ratios.

We wish to thank the Lead-Glass Wall Collaboration for use of their lead glass blocks, and the staff of the Bevatron for their continued cooperation. We also wish to thank Ray Fuzesy, G. Schnurmacher and Garth Smith for expert technical assistance and our many collaborators in the Time Projection Chamber for useful suggestions. We wish to acknowledge R. Hagstrom, J. Mallet, P. Nemethy, and P. Oddone for valuable aid in analyzing data from the DTPC.

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FIGURE CAPTIONS

Fig. 1. Schematic of Dipole Time Projection Chamber showing drift field electrodes, drift volume and proportional wire detectors used in position and ionization measurements. Details of grid, sense and field wire geometry are shown. The dipole magnet which produces the magnetic field, B, is not shown.

Fig. 2. Plan view of DTPC showing wire array, cathode segment rows and amplifier boards for sense wire signals.

Fig. 3. Most probable energy loss for e, μ, π, K, P in 0.4 cm of Argon at 10 atmospheres.

Fig. 4. Details of principles of operation of DTPC indicating the geometry of the proportional signal wires and of the cathode segments (pads). Also shown is a typical particle trajectory, electron drift paths and avalanche positions.

Fig. 5. Details of proportional wire array geometry and cathode segment readout.

Fig. 6. Photograph of DTPC showing the fiducial volume and rows of cathode segments. Preamplifiers for the proportional wires appear on either side of the device.

Fig. 7. Detailed photograph of DTPC proportional wire array and several rows of cathode segments. Beam direction is indicated by the index finger, ionization electrons drift in the direction indicated by the thumb.

Fig. 8. Photograph of back side of cathode plane showing preamplifiers for cathode segment signals.

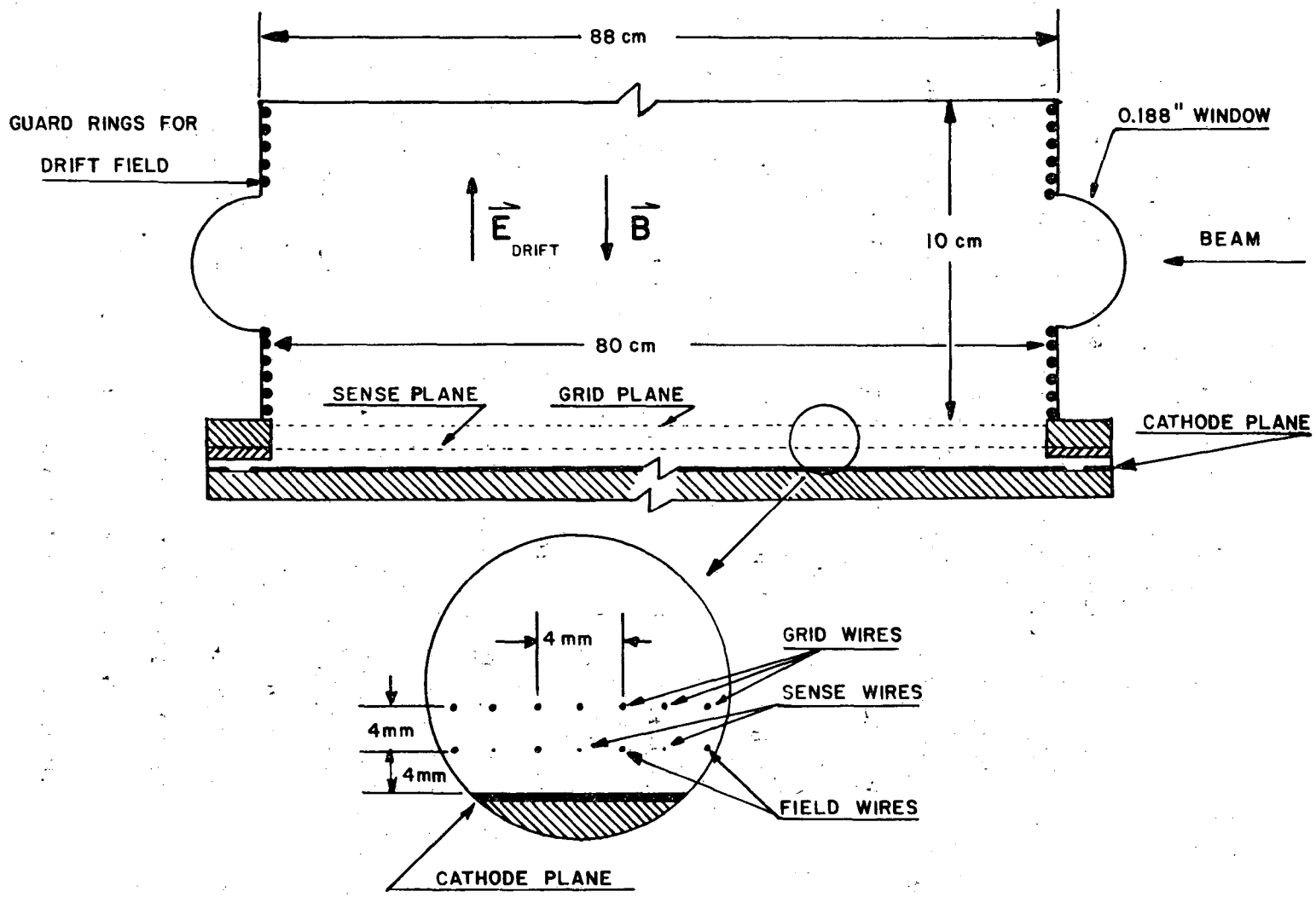

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Fig. 1

TEST PRESSURE VESSEL

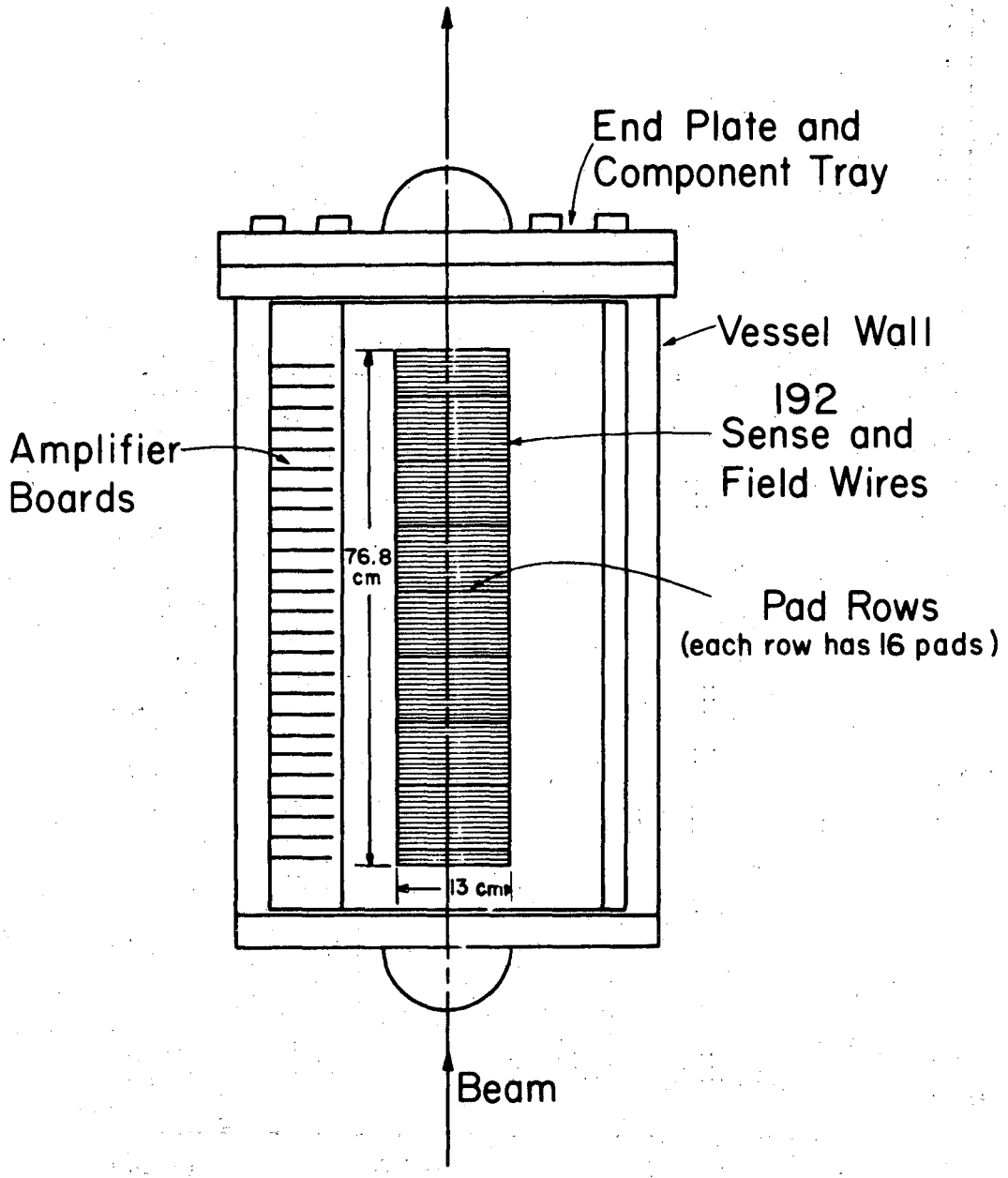

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Fig. 2

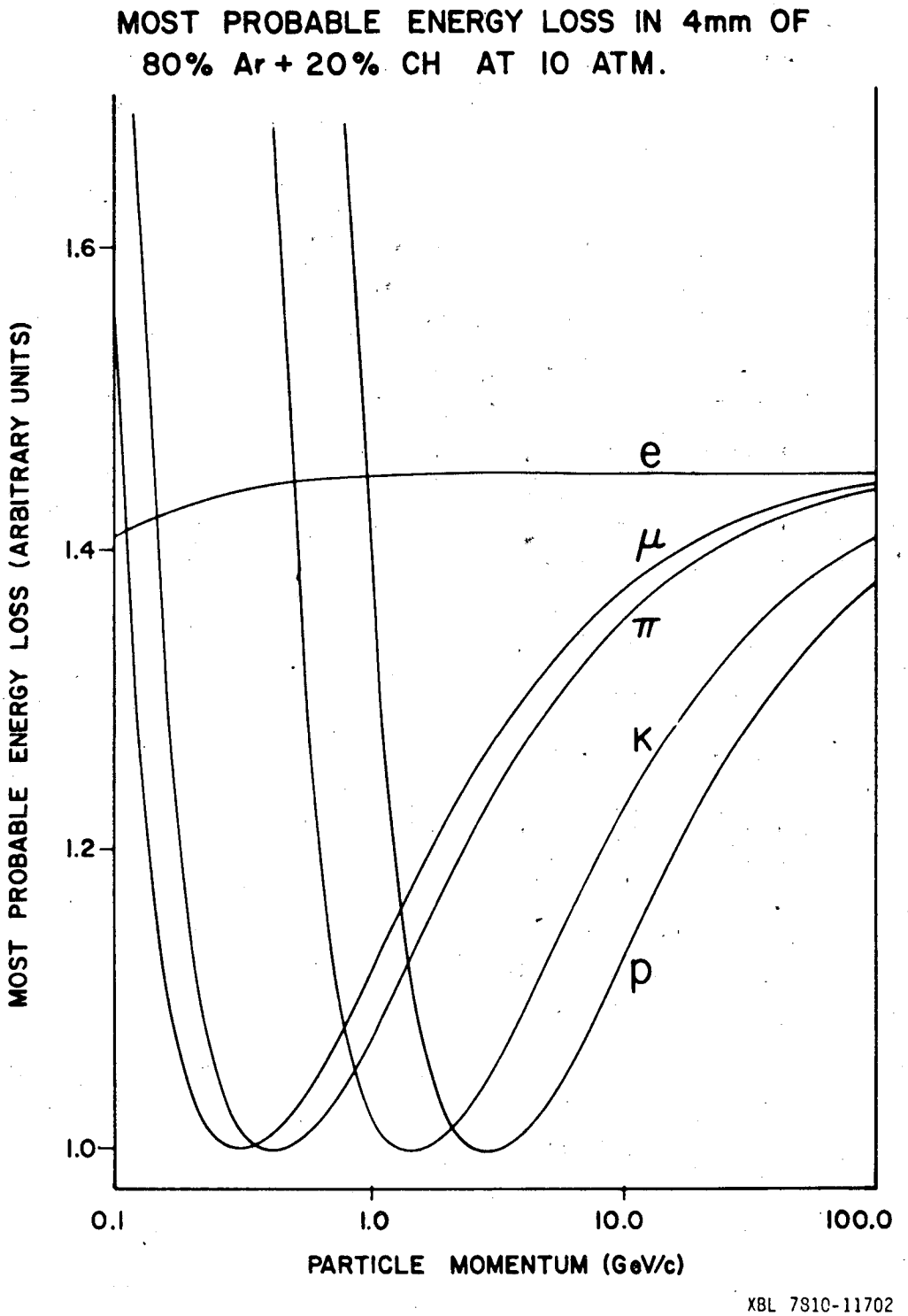

MOST PROBABLE ENERGY LOSS IN 4mm OF
80% Ar + 20% CH AT 10 ATM.
MOST PROBABLE ENERGY LOSS (ARBITRARY UNITS)
1.6
1.4
1.2
1.0
e
μ
π
K
p
0.1
1.0
10.0
100.0
PARTICLE MOMENTUM (GeV/c)
XBL 7810-11702

Fig. 3

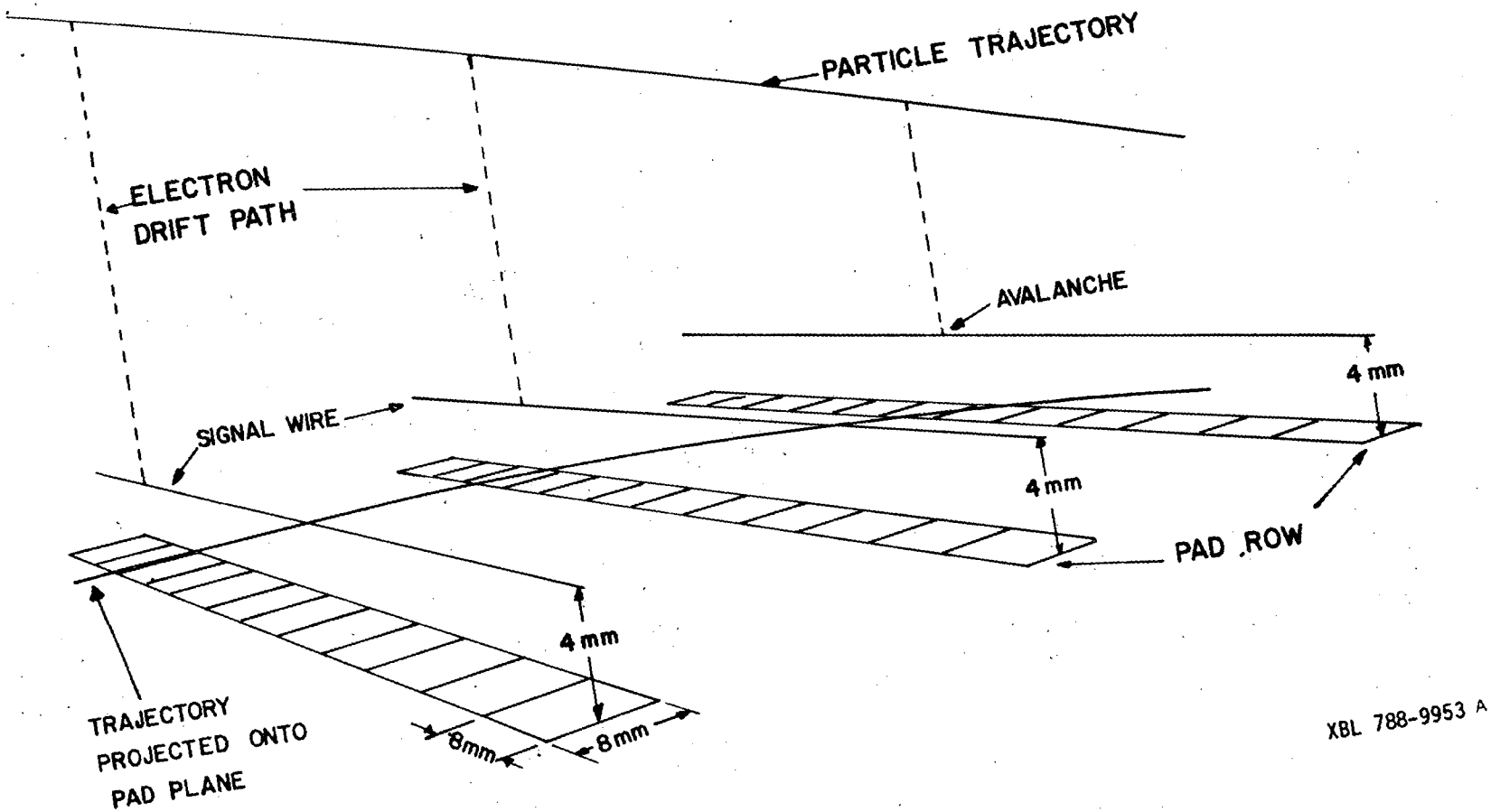
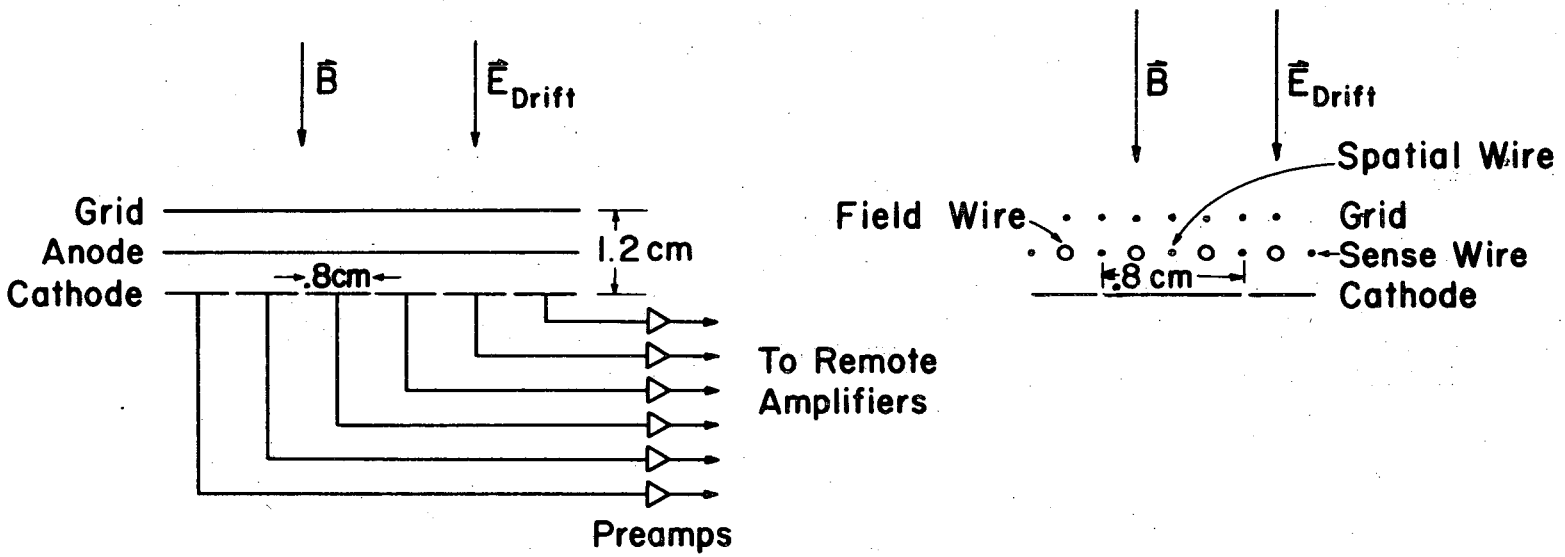

PARTICLE TRAJECTORY
ELECTRON
DRIFT PATH
AVALANCHE
4 mm
SIGNAL WIRE
4 mm
PAD ROW
4 mm
TRAJECTORY
PROJECTED ONTO
PAD PLANE
8mm
8mm
XBL 788-9953 A

Fig. 4

DETAIL OF WIRE GEOMETRY



Segmented Cathode Readout

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Fig. 5

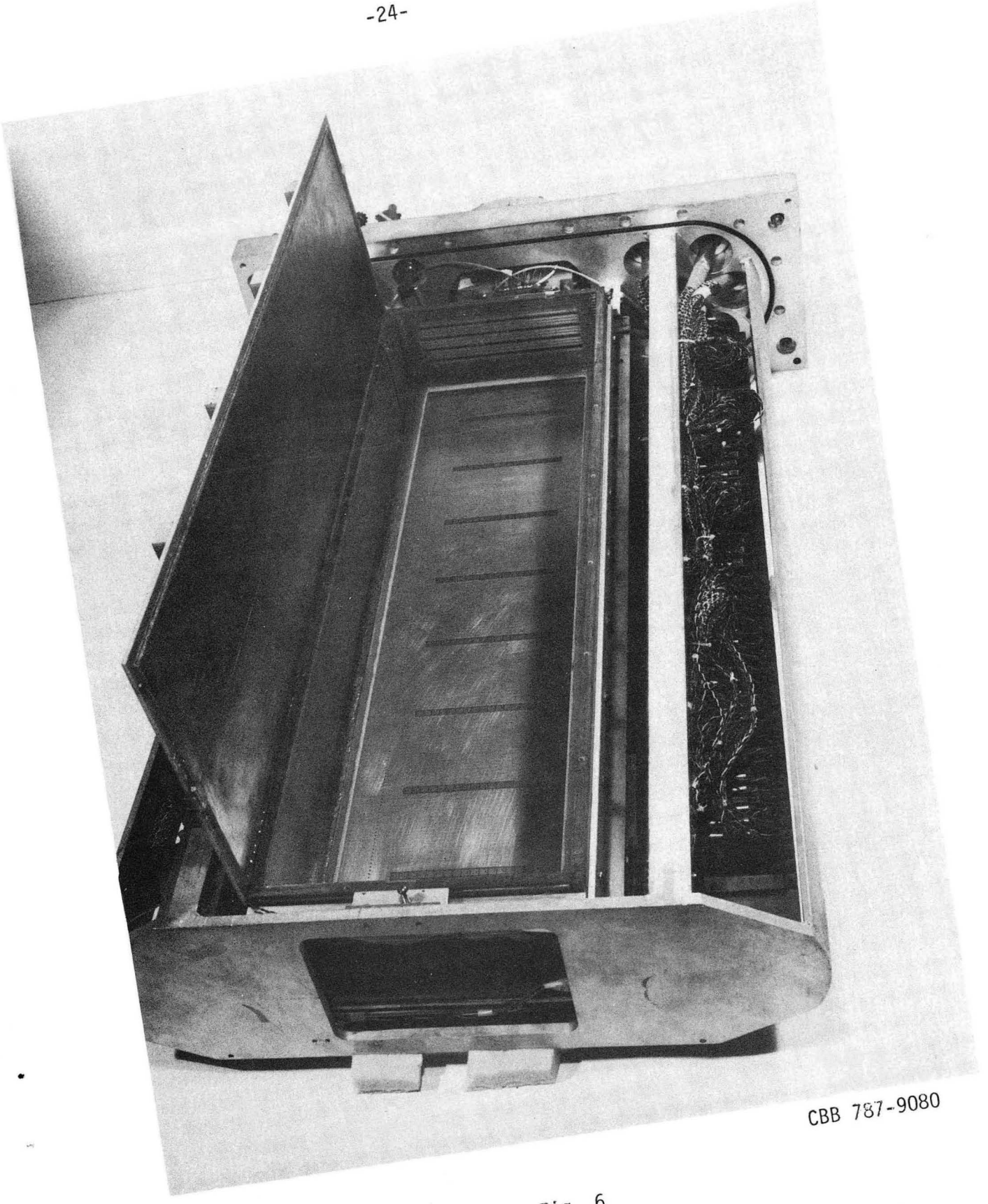

Fig. 6

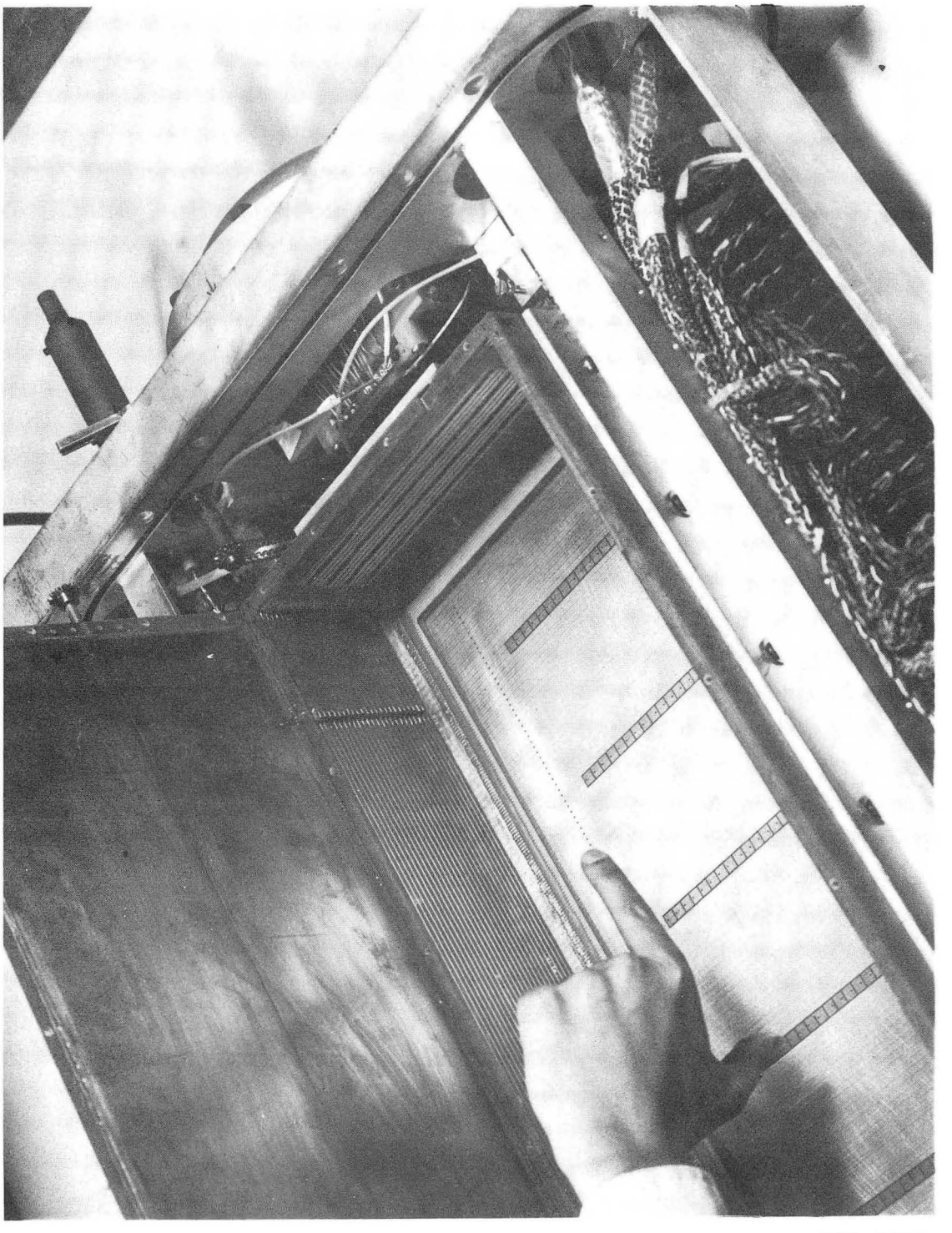

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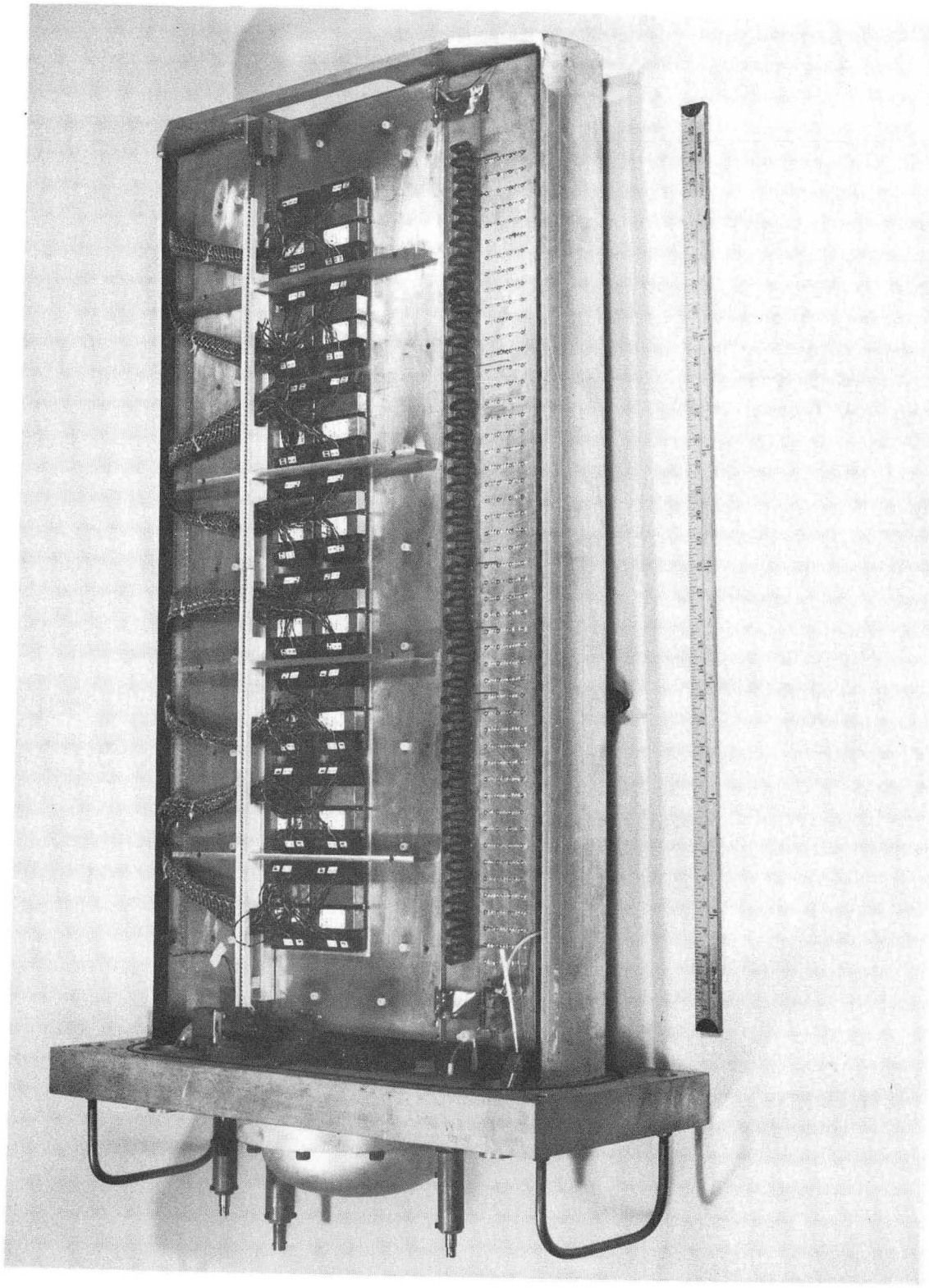
Fig. 7



CBB 772-1299

Fig. 8

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