Search for magnetic monopoles with the Soudan 2 detector

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(Received 10 July 1992)

A search for grand unified theory magnetic monopoles making highly ionizing tracks in argon gas has been conducted using the Soudan 2 nucleon decay detector. This underground detector is a large fine-grained tracking calorimeter comprised of long drift tubes read out by proportional wires. No monopole candidates were observed in data taken over almost three years, yielding an upper flux limit of 8.7×10^{-15} cm^{-2}s^{-1}sr^{-1} for monopole velocities of $\beta > 2 \times 10^{-3}$.

PACS number(s): 14.80.Hv, 96.40.De

I. INTRODUCTION

The possibility of the existence of magnetic charge was given a solid basis in 1931 when Dirac [1] showed that the existence of magnetic monopoles could be related to the quantization of electric charge. In 1974, understanding of the physics of monopoles was further advanced when 't Hooft [2] and Polyakov [3] showed that monopoles were a necessary consequence of the grand unified theory (GUT) symmetry breaking which produces the electromagnetic group U(1). This work also pointed to the likely mass of such monopoles as being of the order of $M_x/\alpha_{\mathrm{GUT}}$, or 10^{16} GeV. Such "GUT" monopoles would be highly penetrating, allowing their observation in underground ionization detectors. Experimental searches have relied on either the high-ionization, magnetic induction, or low-velocity properties of monopoles [4–14]. This paper presents the results of a search for fast GUT magnetic monopoles passing through the Soudan 2 detector. The signature for such a monopole would be a straight and uniformly highly ionizing track. The result reported here places a new more stringent limit on this flux for searches using gas ionization detectors.

II. MONOPOLE IONIZATION

To be detected in Soudan 2 a monopole must leave a path of ionization in an argon-CO_2 gas. The rate of

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ionization of a monopole decreases rapidly with decreasing velocity. For $\beta > 10^{-2}$, the calculation of expected ionization is well understood. The electric field caused by the Lorentz transformation of the monopole magnetic field increases with velocity and contributes to increasing ionization. Ahlen[15] has calculated that the ionization rises from about $10\times$ to $> 1000\times$ minimum ionization as β approaches 1. At velocities below $\beta = 10^{-2}$ the ionization calculations become more uncertain. It has been estimated [16] that at $\beta = 10^{-3}$ the ionization is only $\sim 6\times$ minimum ionization. For $\beta < 10^{-3}$, the ionization falls rapidly since the possible energy transfer approaches the electron atomic-binding energy. Calculations for monopoles in hydrogen and helium [17], and in helium, neon, and argon [18], show that electrons can still be liberated by the shifts in atomic energy levels in the slowly varying magnetic field of the low-velocity passing monopole. In argon this gives a threshold [18] of $\beta = 2.4 \times 10^{-4}$. The results of these calculations are combined schematically in Fig. 1.

A monopole of GUT mass can impart little energy to an individual electron, except at very relativistic velocities. From the kinematics of a collision between a very massive monopole and an electron, the maximum kinetic energy imparted to the electron is

$$T_{\max} = 2m_e c^2 \beta^2 \gamma^2,$$

where m_e is the electron mass, β and γ are calculated from the monopole velocity, and it has been assumed that the monopole is much more massive than the electron. In the Soudan 2 detector, knock-on electrons can produce ionization out of the path of the track. On average one extra hit is produced per 12 MeV of electron kinetic energy. Four such hits associated with an otherwise clean track can easily be identified. Muons traversing the detector frequently produce such electrons. At lower monopole ionizations, where a muon and a monopole might be confused, the presence of a knock-on electron can be used to unambiguously reject the monopole hypothesis.

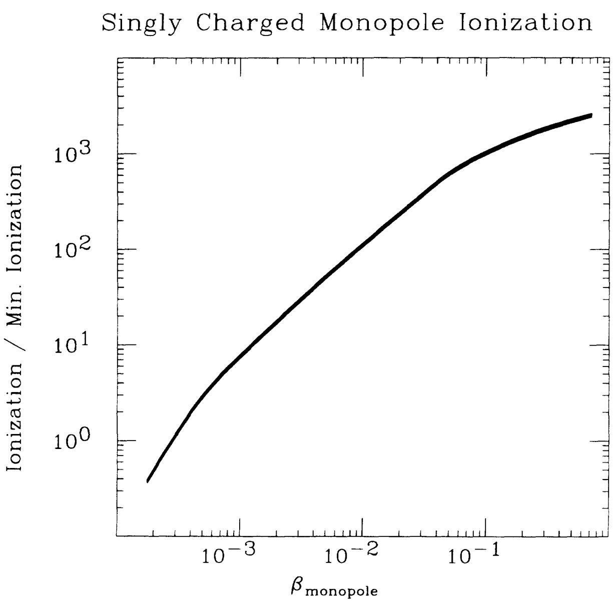

FIG. 1. Approximate monopole ionization as a function of β. For this experiment the threshold for high ionization was placed at $10\times$ minimum ionization which corresponds to $\beta > 2 \times 10^{-3}$.

III. THE DETECTOR

The Soudan 2 detector is a large, underground, fine-grained, tracking calorimeter which is being built to search for nucleon decay [19–21]. It is located 713 m below Soudan, Minnesota, at 2100 meters of water equivalent (mwe).

Each $1.1 \times 2.7 \times 1.1$ m^3 module is constructed of 241 stacked corrugated steel sheets and weighs 4.3 tons. Each module has 7560 slightly conducting, 1 m long, 16 mm diameter Hytrel plastic tubes in the hexagonal holes formed by the steel sheets. Copper electrodes, in contact with the tubes, are graded from -9 kV at the center to ground potential at the two ends. This results in a uniform electric field directed parallel to the axis of the tube. The tubes are insulated from the steel by sheets of Mylar and polystyrene. A section of a module is shown in Fig. 2. The whole stack is enclosed in a gas-tight container which is filled with Ar-CO_2 (85%-15%) gas. An ionizing particle traversing a tube yields ionization electrons which drift along the tube axis under the influence of the electric field with a velocity of 0.6 cm/μs. Electrons emerging from the drift tubes are collected and amplified by a proportional-counter plane of crossed vertical anode wires and horizontal cathode strips. These serve to determine which tube was crossed by the particle. The anodes and cathodes are connected to current sensitive preamplifiers and the resulting signals, after some pulse shaping, are fed to 6-bit analog-to-digital converters (ADC's) operated in a bilinear mode and digitized every 200 ns. Only digitized signals above a predetermined threshold are recorded for off-line analysis. A charged particle crossing a drift tube

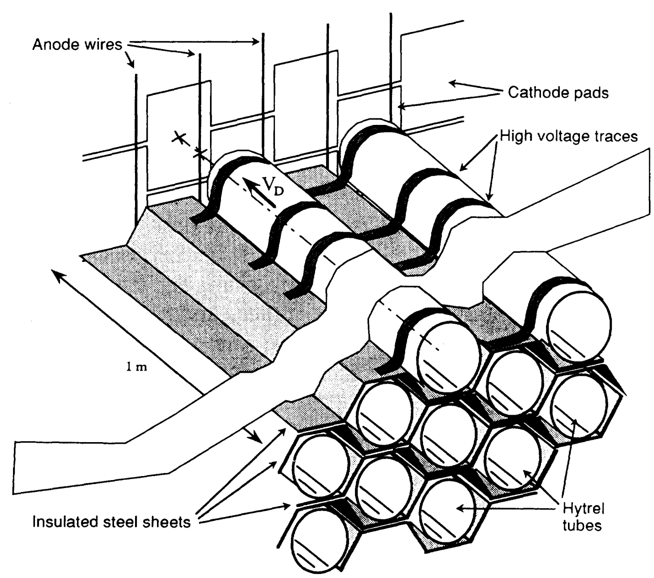

FIG. 2. Section of the detector showing drift tubes in the corrugated steel stack.

will be recorded as a group of contiguous digitizations above threshold. The summed pulse height is proportional to the total pulse charge seen by the ADC. Since the drift velocity is constant the time of the first digitization of such a group of hits is proportional to the drift time and therefore the third coordinate of the hit. Thus, for each point on a track, all three spatial coordinates and the ionization are recorded. The detector has a spatial resolution of $\sim$1 cm in all coordinates and records several hundred points for a typical cosmic-ray muon track, allowing it to produce bubble-chamber-like displays of events. This capability makes it easy to identify electromagnetic showers, multiple tracks, and other complex interaction topologies from computer displays of the events.

Because of the modularity of the detector it was possible to record data during the construction period. During the exposure reported here, the detector size increased from $4.5 \times 5.4 \times 9.0$ m^3 to $9.0 \times 5.4 \times 11.3$ m^3.

Although the response of the detector to the charge deposited in the gas is linear over the range of ionization normally encountered, it is not expected to be linear for very heavily ionizing tracks due to several effects, particularly the saturation of the gas-amplification mechanism. Estimates of this effect, which is due to the presence of a cloud of positive ions close to the anode wire which reduces the gas-amplification factor, suggest that the total amplified charge produced by a 1000$\times$ minimum ionizing track will be in the range 20–80 times that produced by a minimum ionizing track. The exact figure will depend upon several factors, including the orientation of the track with respect to the direction of the anode wires. The maximum reading of the sampling ADC's is set to about four times minimum ionizing and will also degrade the linearity of the overall response. Saturation of the ADC's means that, for large pulses, information on dE/dx is contained in the time above threshold of the digitized pulse. For pulses equivalent to more than 10$\times$ minimum ionization, the total measured summed pulse height increases approximately logarithmically with dE/dx.

Only tracks with ionizations of $> 4\times$ that of the average cosmic-ray muon were considered in this experiment. The average energy of a muon at the underground Soudan 2 detector is 300 GeV and at this energy muon ionization will have achieved the full relativistic rise of approximately 1.6. The response of the detector, its readout, and the track reconstruction software to variations in ionization were calibrated by studying tracks which crossed the tubes at various angles, and thus deposited various amounts of ionization in the gas in each tube. The ionization response of the detector was also studied using stopping muon and proton tracks. Combining the effects of the relativistic rise and the detector response, an observed ionization of $> 4\times$ the average cosmic-ray muon ionization corresponded to $> (8 \pm 2)\times$ minimum ionization. The estimated error is from systematic uncertainty in extrapolating the ionization response up to 4$\times$ the average muon ionization. Referring to Fig. 1, a monopole velocity can be found corresponding to this ionization range. A value of $\beta > 2 \times 10^{-3}$ was taken as the range over which this experiment was sensitive. This value is conservatively high to account for the uncertainty of the curve in Fig. 1 at these velocities.

IV. DATA ACQUISITION AND ANALYSIS

All wire plane readout channels and therefore all active elements of the detector participated in the trigger decision. The trigger required that there be at least six hits separated in time in any 72-μs window. These hits were required to come from within groups of 16 contiguous readout channels, with no channel being counted more than once. The trigger configuration and threshold were set to be sensitive to small nucleon decay and atmospheric neutrino events. Therefore a fast, highly ionizing, magnetic monopole would trigger with high efficiency. Cosmic-ray muon tracks accounted for about 40% of the recorded events and almost all of the rest were random coincidences of noise due to radioactive decays or from the electronics.

The method used to find monopoles relied on finding tracks in the detector which had significantly higher ionization than the average muon. All the recorded events were examined by an off-line track-finding algorithm. For all the tracks which were found the track length and the average summed pulse height per unit track length were calculated. To be flagged as a possible monopole candidate, a track was required to be at least 1.5 m long and to have an average summed pulse height per unit track length of at least four times that of the cosmic-ray muons. The track length cut assured that the track was long enough so that the average ionization along it was not unduly influenced by Landau fluctuations on individual hits or by local instrumental effects such as the increased ionization near the readout wire planes. The average cosmic-ray muon summed pulse height per unit length was determined by averaging this quantity for all tracks within approximately one hour (>500 tracks) of the track being considered. This averaging provided a correction for the effect of slowly changing conditions such as atmospheric pressure. A final cut was made to ensure that the track had a good fit to a straight line. Figure 3 shows a scatter plot of the track length versus the average summed pulse height per track length for a typical run.

10 254 events were flagged as possible monopole candidates. For each of these, event displays of the raw data were scanned by a physicist using an interactive graphics program. The main criteria for rejection of events during the scan by a physicist were based on the fact that a monopole of GUT mass would be uniformly heavily ionizing and could not make a visible knock-on electron or a larger electromagnetic shower.

In order of frequency of cut application, the events were required (i) not to have a shower on or with the track, (ii) not to have an inelastic interaction yielding secondary tracks, (iii) not to have a knock-on electron coming off the track, and (iv) to be uniformly highly ionizing. The last cut removed tracks which had gone through regions of the detector which produced larger than average pulses.

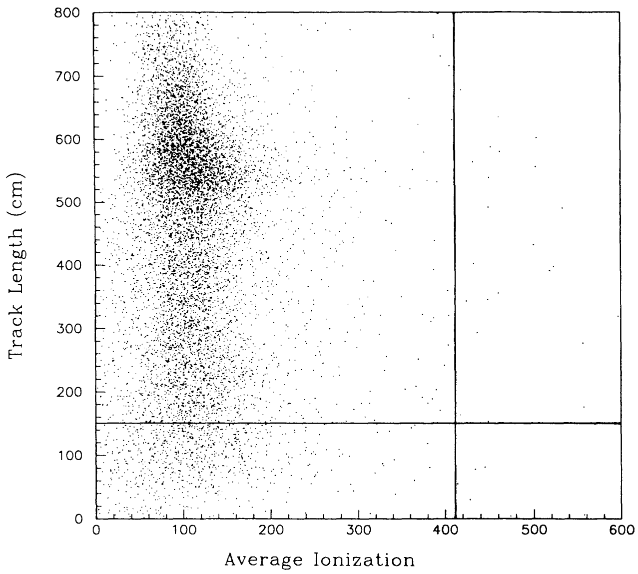

FIG. 3. A scatter plot of the track length vs the average summed pulse height for 20 typical runs (the total sample consisted of 11 211 runs). The cuts of 150 cm track length and 4× average muon ionization are shown.

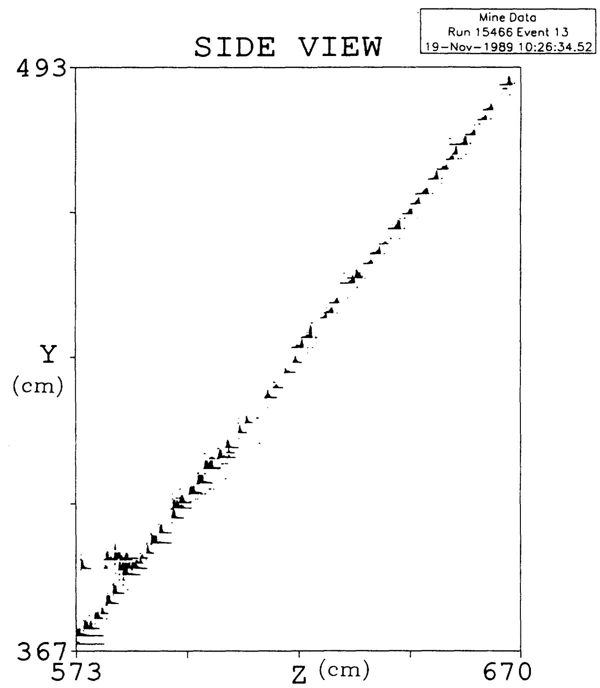

FIG. 5. An event with a small knock-on electron associated with the track. This muon track also failed the high ionization cut.

Figure 4 shows a typical showering track. Figure 5 is an example of a muon track which clearly shows a small knock-on electron (this event also failed the high ionization cut).

No events passed all cuts.

In order to measure the overall efficiency of the data analysis process for detecting monopoles, a set of fake monopole tracks was created. Real cosmic-ray muon events with single, straight, noninteracting tracks were selected. A subset of these was then chosen which traversed the detector isotropically as sufficiently energetic monopoles would be expected to do. The raw data from these muon tracks were then altered to increase the ionization by various factors. In addition, cross talk was added to neighboring channels and the pulse shapes were altered to match what was observed with large pulses in

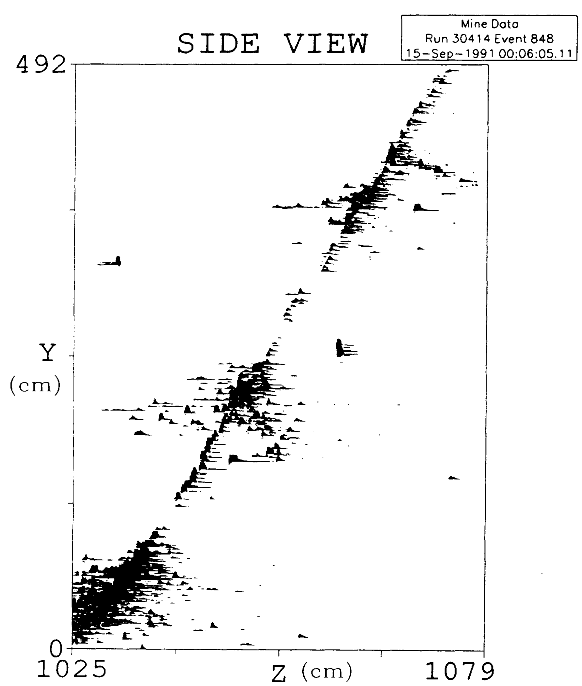

FIG. 4. An event rejected due to showers along the track.

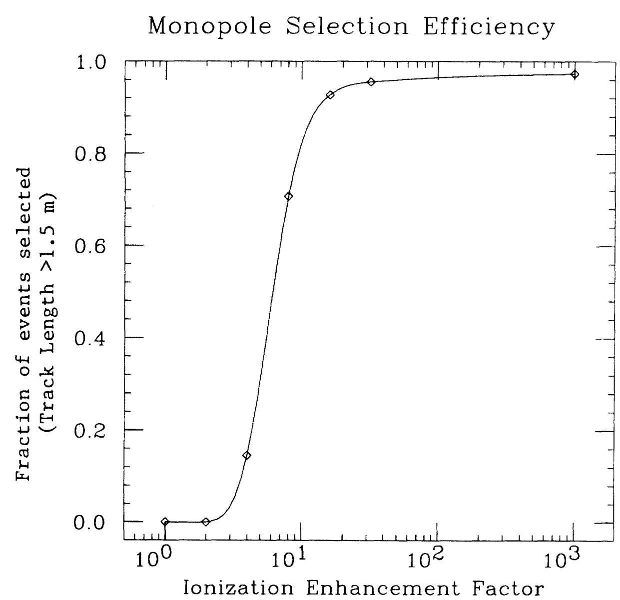

FIG. 6. Fraction of fake monopoles, with track length >1.5 m, passing a summed pulse height cut as a function of the ionization enhancement factor (the curve is only to guide the eye).

the real data. Account was taken of the bilinearity and the saturation of the ADC's in the readout electronics. These fake monopole tracks were then inserted into the analysis chain to determine what fraction would be selected by the software.

Figure 6 shows the fraction of fake monopole tracks which were selected ($> 4\times$ average muon ionization) as a function of their ionization enhancement factor. These results were used to determine the efficiency of the filter for accepting monopoles as a function of monopole ionization (e.g., for an enhancement factor of 10, 90% of the fake monopole tracks passed). Knowing the ionization as a function of β allows the software selection efficiency to be expressed as a function of β (although with increased uncertainty at the lower values of β).

To test the scanning efficiency, a number of these fake monopole tracks with ionizations of $32\times$ that of average muons were included in the set of events that were scanned; all of them were flagged by the physicist scanner as potential monopole tracks.

V. EXPOSURE

To determine the exposure of the detector both the spatial and the temporal acceptances of the detector were calculated. The geometry of the detector changed, in steps, as more of it was installed. For each configuration the area-solid angle product of the detector for isotropically arriving tracks was calculated by two methods. The first was a Monte Carlo approach which found the cross-sectional area of the detector for randomly chosen directions. An independent, analytical geometric calculation confirmed this result. During the time of the data taking the detector grew from 716 to 1329 m^2sr. These figures were then reduced to include the effect of the 1.5-m track length cut. Although in principle this was a purely geometric cut the determination of the track length by the track-finding programs was not perfect and therefore the correction was determined from the fraction of fake monopoles which failed this cut. A correction was also made for the variation of the trigger efficiency with angle.

For every data run (approximately 1.5 h of data taking) the duration of the run was recorded. A total of 4.99×10^7 s of data was analyzed, spanning the period from 21 January 1989 to 6 January 1992. This was then corrected for the average event readout dead time. The total exposure was calculated by summing the product of the corrected live time and the corrected geometric acceptance for each run. This gave an exposure of 2.64×10^{14} cm^2sr s.

VI. RESULTS

The efficiency with respect to β was multiplied by the exposure of the detector to provide the effective exposure as a function of β. Since no monopole tracks were identified, the resulting limit on the monopole flux was

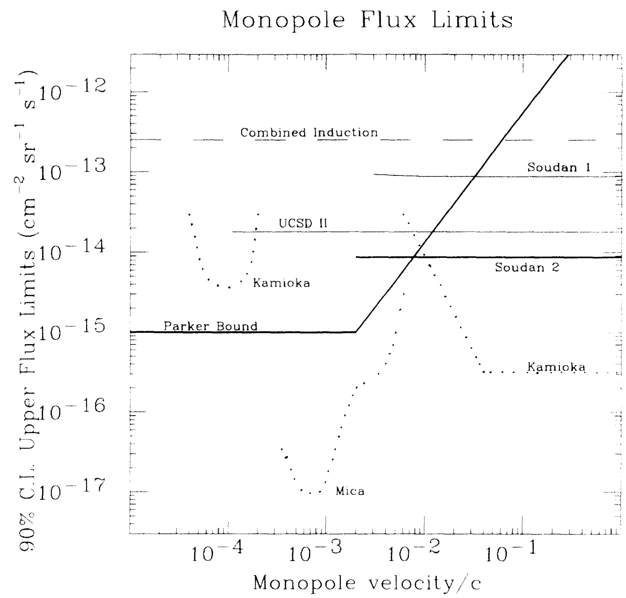

FIG. 7. Recent published monopole flux limits. Several techniques are shown. Magnetic induction (dashed line)[9,10]; track etch (dotted lines): Kamioka [4], mica [7]; Gas ionization (solid lines): UCSD II[8], Soudan 1 [14], and Soudan 2 (this work). The Parker bound [22] upper limit, from galactic magnetic field considerations, is also shown.

8.7×10^{-15} $cm^{-2}s^{-1}sr^{-1}$ for $\beta > 2 \times 10^{-3}$ (90% confidence level).

A summary of published monopole flux limits obtained by various techniques is shown in Fig. 7. Also included is the Parker bound [22], which is the upper limit on the average monopole flux imposed by the value and rate of regeneration of the galactic magnetic field and the extent to which monopoles would remove energy from this field. The present Soudan 2 limit is lower than previously published limits for gas ionization detectors.

This search was not designed to find monopole catalyzed proton decays [23]. In fact, any such events would have been rejected since they would have had tracks in the event other than the track from the monopole.

ACKNOWLEDGMENTS

This work was supported by the U.S. Department of Energy, the U.K. Science and Engineering Research Council, the State of Minnesota, and Oxford University. We wish to thank the staffs of the collaborating institutions, the Minnesota Department of Natural Resources for allowing use of the facilities at the Soudan Underground Mine State Park, the staff of the park for their support and the Soudan 2 mine crew: B. Anderson, J. Beaty, G. Benson, D. Carlson, B. Dahlin, J. Eininger and J. Meier.

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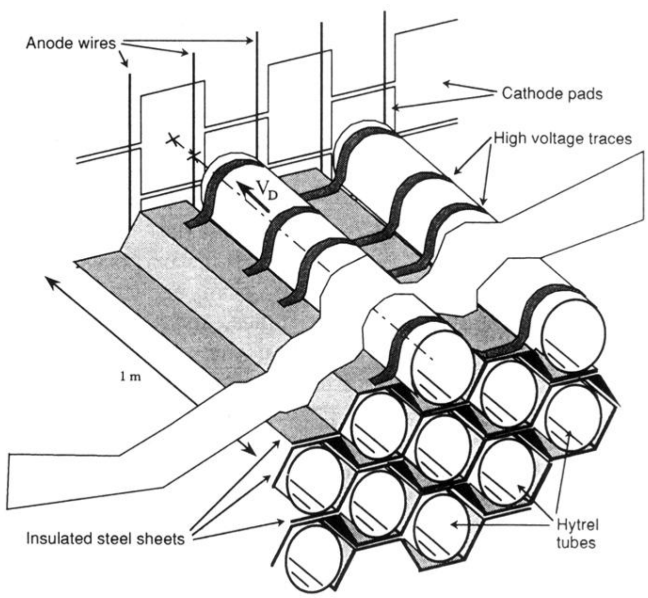
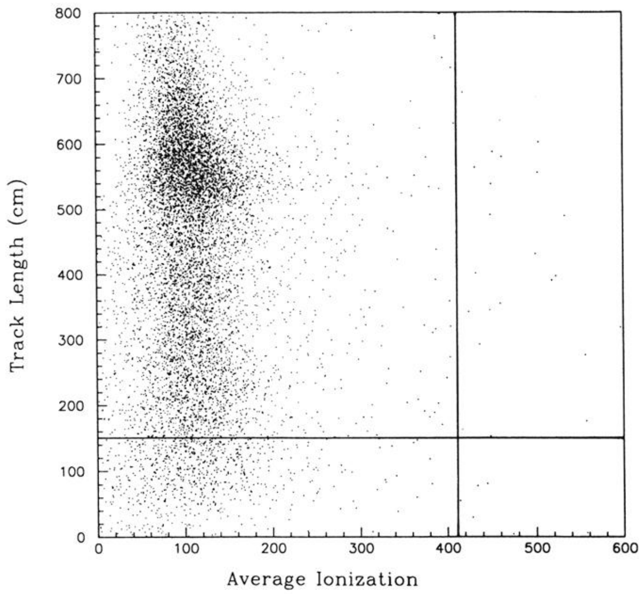


FIG. 2. Section of the detector showing drift tubes in the corrugated steel stack.



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