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TRACKING TECHNIQUES IN UNDERGROUND PHYSICS

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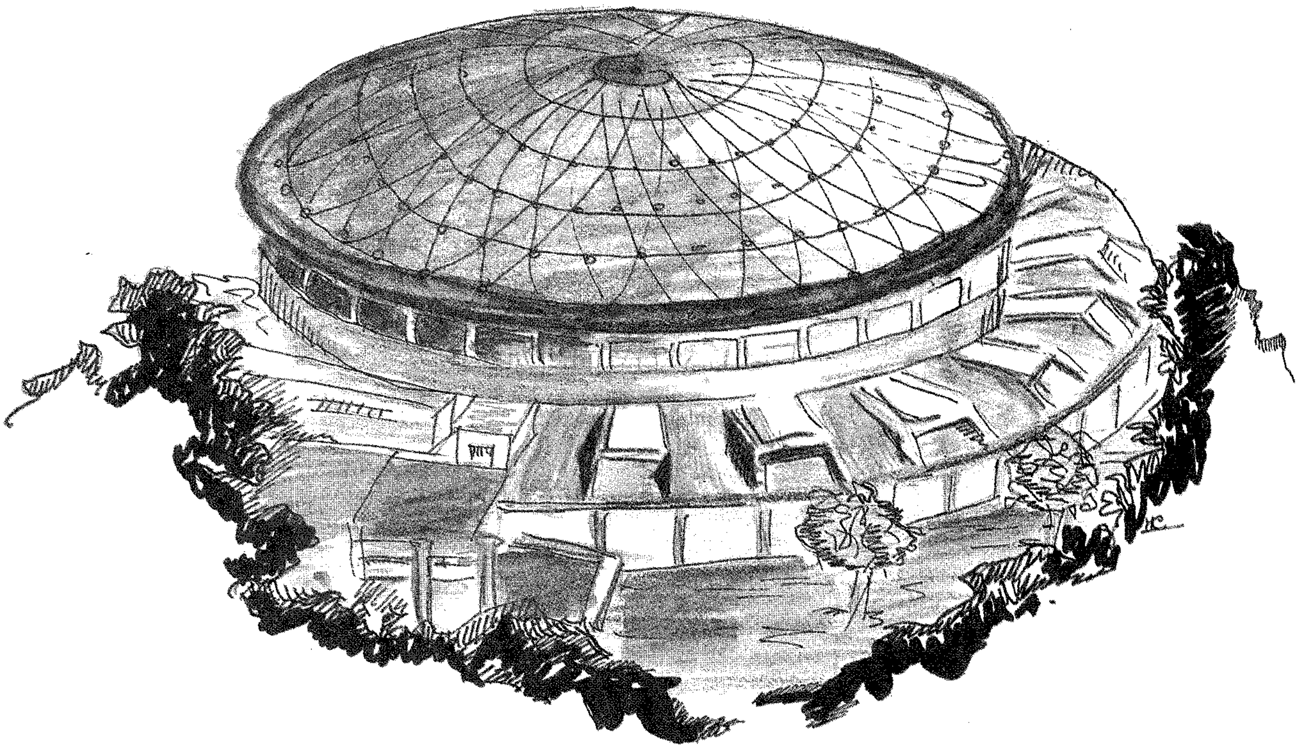

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TRACKING TECHNIQUES IN UNDERGROUND PHYSICS

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Abstract

Tracking of penetrating particles in underground experiments is discussed. The application to this field of the streamer tube technology is reviewed, with a particular reference to the MACRO experiment at Gran Sasso and its collaboration with industry. Other tracking technologies for large area detectors are presented.

Introduction

Starting around 1980, various underground experiments to search for nucleon decay were designed and put into operation in different countries. They followed two different competing technologies: the water Cherenkov detectors[1,2,3] and the fine grain calorimeters[4,5,6].

They could not succeed in giving a positive answer on the nucleon decay problem, but, besides a more precise understanding of the detection features for the second generation experiments, they opened new and unexpected goals for the underground physics. The present or proposed experiments cover the range from the few MeV energy region of low energy neutrinos from supernovae or from the sun, to UHE cosmic muon physics.

A relevant interest has grown in the high energy muon detection underground, due to the convergence of astrophysical and particle physics trends. The search for celestial point sources, through the production of muons by high energy gammas in the atmosphere or by neutrino interaction in the rock, is not only a fundamental task for cosmic ray physics, but could also provide a powerful tool for high energy physics by allowing the exploration of an energy region not yet accessible to accelerators[7]. However, the study of the high energy muons produced by the interaction of the ordinary cosmic primaries is also important to determine the cosmic ray chemical composition[8], and, at the same time, to study high-p_t interactions, new particle production, etc. In parallel to these aspects, the same underground experiments designed for muon tracking can search for exotic supermassive relic particles, such as the GUT monopoles[9], which is in turn a determinant objective both for cosmology and particle physics.

In this work the present detection technology for muon-tracking experiments is discussed, pointing out also the connections between research groups and industry.

Tracking of penetrating particles underground

A muon tracking apparatus has the primary need to reconstruct the trajectory of particles, at least in two projective views. The angular resolution needed is fixed by the physical limit due to the muon deflection by the geomagnetic field and the multiple scattering in the rock. This turns out to be $\sim 0.6^{o}$[10].

A two track resolution capability of a few cm is recommended for the study of multimuon events. The above requirements can be matched by a device with a space accuracy of ~ 1 cm, and a track reconstruction over a few meters. Since high energy muons (>100 GeV) have a probability of about 10% to undergo large e.m. interactions in most detector materials, a pattern recognition capability is very useful to reconstruct correctly the direction of the event. This puts a limit to the minimum number of samplings in a tracking apparatus. Low energy hadrons produced by muon interactions in the rock must be separated from muons; this can be easily accomplished by means of absorbers, giving rise to a minimum energy threshold for through-going tracks.

The system must be able to distinguish upward- from downward-going muons, in order to select the events due to neutrino interaction in the rock. This can be performed by a time of flight system with a rejection power of at least 10^6. If the track is reconstructed with a lever arm of a few meters such a discrimination can be achieved with time accuracies of the order of 1 ns.

An absolute timing (universal time) of the events is necessary for the gamma and neutrino astronomy. The precision of the order of 1 ms is easily achievable, and allows the detection of sources with duty cycles at the level of seconds.

In order to be sensitive to supermassive penetrating particles, the ionization threshold of the detector must be as low as possible. In the particular case of the search for magnetic monopoles, a gaseous detector can exploit the Drell effect[11] by using a suitable gas mixture. Since the expected velocities are low (down to 10^{-4} c), the readout memory time can be as long as hundreds of μs. In this case, the use of a tracking device allows the rejection of accidentals, generally due to the radioactivity background, by asking the alignment in space of the candidate events. The possibility of measuring the ionization loss also gives important information. The design of the apparatus must give an isotropic acceptance for tracking, and a sensitive area greater or equal to 1000 m^2 is necessary to have a sensitivity comparable to the astrophysical limits. However, it must be pointed out that, in the search for monopoles, a redundancy of techniques is extremely important to have a reliable rejection of accidentals.

Finally, the tracking detector must be operated for many years continuously, thus requiring high reliability and easy monitoring.

The streamer tubes of the MACRO experiment

At the Gran Sasso underground laboratory a relevant number of experiments is scheduled[12], and MACRO, which is now in installation, is an example of multi-purpose detector optimized for monopole search and cosmic muon physics. Details of the apparatus are given in ref. [13]. It has a large acceptance for isotropic particles (~10000 m^2 sr), and will detect ~10^7 cosmic ray events/yr. The tracking devices chosen for this experiment are the plastic streamer tubes[14]. This technology was introduced in underground physics with the NUSEX experiment[5]. The obtained results have shown that these detectors are well suited for the physical goals of this class of experiments; the reliability of streamer tubes turned out to be particularly good for the operation during several years in a low counting rate environment[15]. The thermoplastic technology allows an easy development of large area apparata, and the large signals typical of streamer mode give the possibility of using a simple read-out electronics. The technical aspects of the plastic streamer tube construction (9x9 mm^2 cell) have been further developed in the last few years by different groups using these detectors in large hadron calorimeters for LEP[16,17,18], neutrino[19] and collider experiments[40].

The MACRO group has developed a new design of plastic streamer tubes, which is particularly optimized for muon tracking underground in a large area, and whose construction technology is completely transferred to industry. The streamer tube devices used in MACRO have been described elsewhere[20]. Briefly they are 8-tube PVC chambers, with dimensions 25 x 3 cm^2 x 12 m. The individual cell cross section is 3 x 3 cm^2, with 100 μm anode wire and graphite cathode (see Fig.1). All the components of the chambers, shown in Fig. 2, are constructed in thermoplastic material by moulding or extrusion[21]. A low resistivity graphite varnish[22] has been adopted for the 8-cell profile, asking only for an upper limit of about 1000 Ω/square. This allows the painting of the profile directly on the extrusion line, just after the cooling section (see Fig. 3). The choice of low resistivity is particularly advantageous since it does not require any particular control or resistivity measurement, provided the varnishing system has the proper reliability. The failure probability has been drastically reduced by using a double varnishing system: two painting stations one after the other in the extrusion line, each one followed by a drying aspirator. This solution has allowed the commitment of this operation to non-specialized manpower, and the discarded material is reduced to a negligible level.

The assembling and testing of the streamer tube chambers has been committed to a firm[23], (see Fig. 4). Here the chambers can be produced at a maximum rate of ~20/day. Particular care has been devoted to the sealing of the chambers, since they must be operated with a Helium based gas mixture. The leakage test is performed under vacuum by the firm personnel. The same manpower is also in charge of the quality test, which is performed by measuring the current of each chamber at fixed high voltage, using an Argon 10% +CO_2 90% gas mixture to flux the chambers. The fraction of failures turned out to be about 1% of the total production.

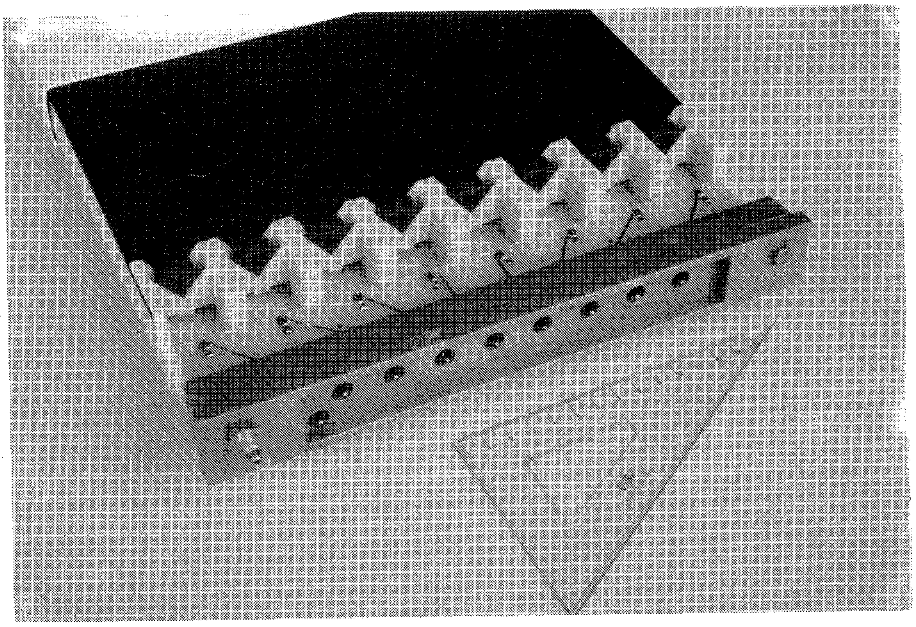

FIG. 1 - Streamer tube chamber shown open at one end.

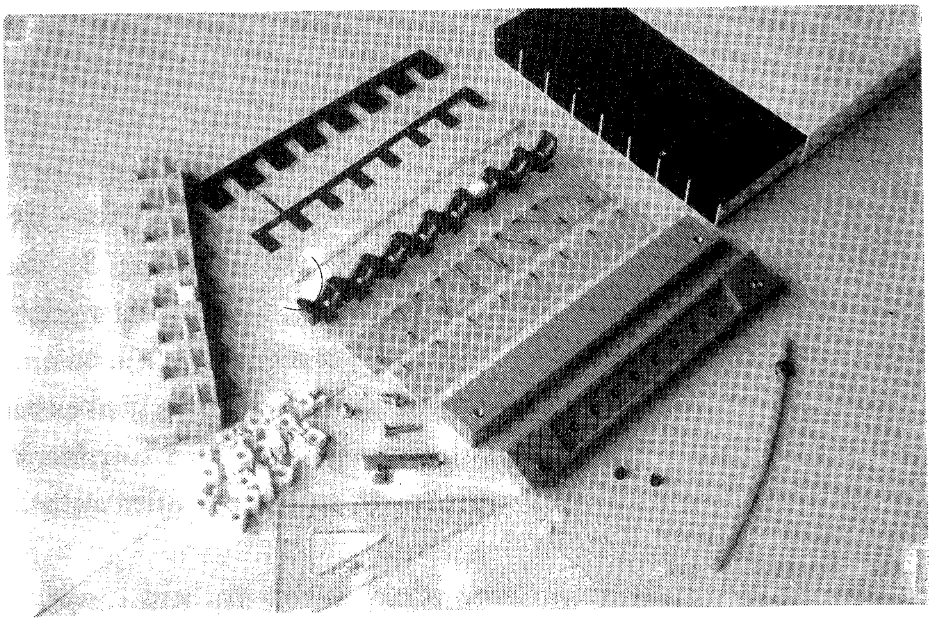

FIG. 2 - The components of a streamer tube chamber.

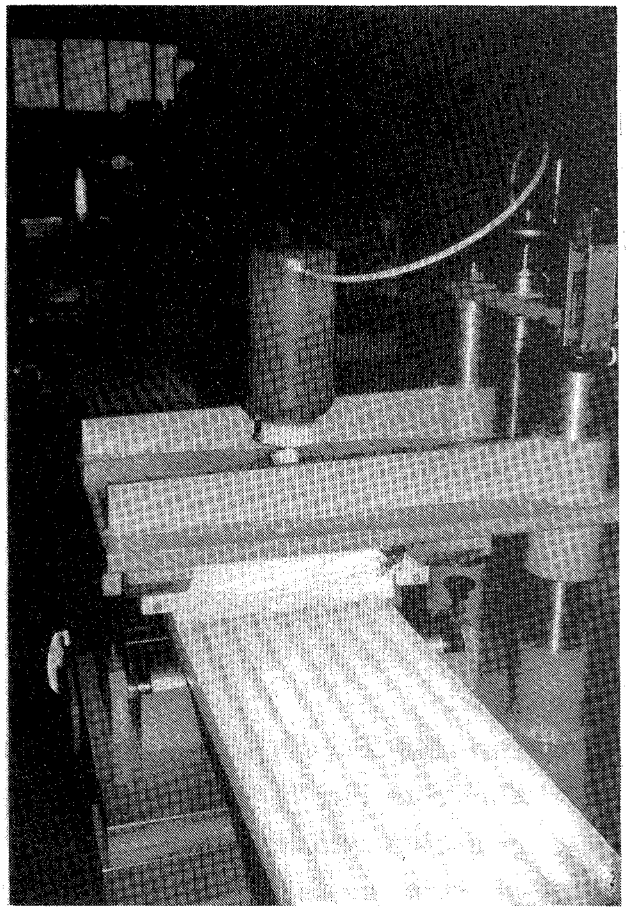

FIG. 3 - Varnishing of the 8-cell profile during extrusion[21].

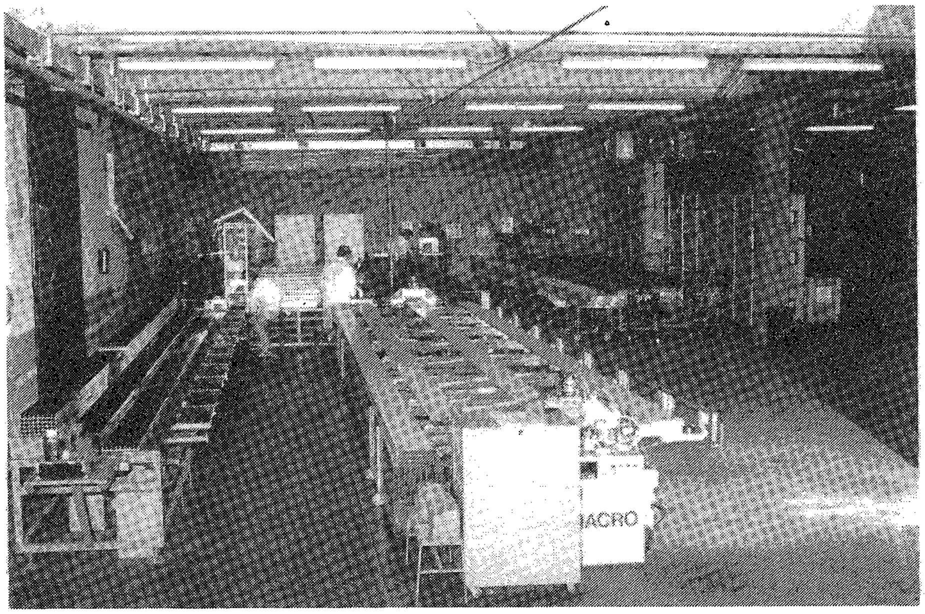

FIG. 4 - Assembling and testing facility for the MACRO streamer tube chambers[23]. Most of the machines were built by the firm of ref. [21]. The machine to stretch the wires was built by the INFN-Bari collaborators of MACRO.

The streamer tube chambers are equipped with digital readout in two coordinates. One coordinate is provided by the wires, while the other is provided by 3 cm wide pick-up strips, placed in MACRO at an angle of.about 30° with respect to the wires. Such strips are produced by the same firm which assembles the chambers, and are made out of an aluminum ribbon (40 μm thick) attached to a PVC foil (1 mm thick); on the other side of the plastic foil an aluminum sheet (40 μm thick) provides the ground reference electrode.

Fig. 5 and 6 show the 8-wire readout card and the 32-channel strip readout card[24]. Each readout channel consists of a discriminator with two outputs with different shaping times: 10 μs for relativistic particles and 600 μs for slow particle identification. A serial readout through two parallel shift register chains is performed by CAMAC processors[25]. Fast-Or signals are available for triggering purposes. In ref. [26] the slow monopole trigger is described in detail. The wire readout card gives also an analogical OR signal which is used to obtain charge and timing information by a FADC system[27].

The tubes will be operated in MACRO with a Helium + CO_2 +nPentane (or nHexane[28]) gas mixture. Due to the large volume of gas in the apparatus (~560 m^3), a recirculating system will be used[29], providing also the automatic control of the mixture.

The detection features of the streamer tube system in MACRO can be summarized as follows. They exhibit a wide noiseless operation range (~1000 V, see Fig. 7), where only particles are counted. The HV value at which the full efficiency region is achieved depends on the particular gas mixture and on the primary ionization: single primary electrons are detected with full efficiency at ~400 V above the knee of the plateau for minimum ionizing particles. The space accuracy is ~1 cm in both coordinates, resulting in an angular resolution of $\sim 0.2^{\circ}$, the time accuracy for through-going tracks is 50 ns, and the ionization threshold is below 1% min. ion.[30] The streamer tubes can also measure large ionization losses, as resulting from tests on relativistic ion beams[31]. The overall streamer charge response to ionization is summarized in Fig. 8. The logarithmic rise above the minimum ionization loss is well suited to the extremely wide energy loss range which is predicted for slow monopoles. The upward muon discrimination is performed in MACRO by a system of liquid scintillation counters, providing a time accuracy of about 1 ns[32].

The streamer tube chamber here described will be also used in the EAS-TOP experiment[33] for muon and hadron tracking in extensive air showers. The LVD experiment at Gran Sasso[34] will employ instead the usual 9x9 mm^2 cell streamer tube chambers.

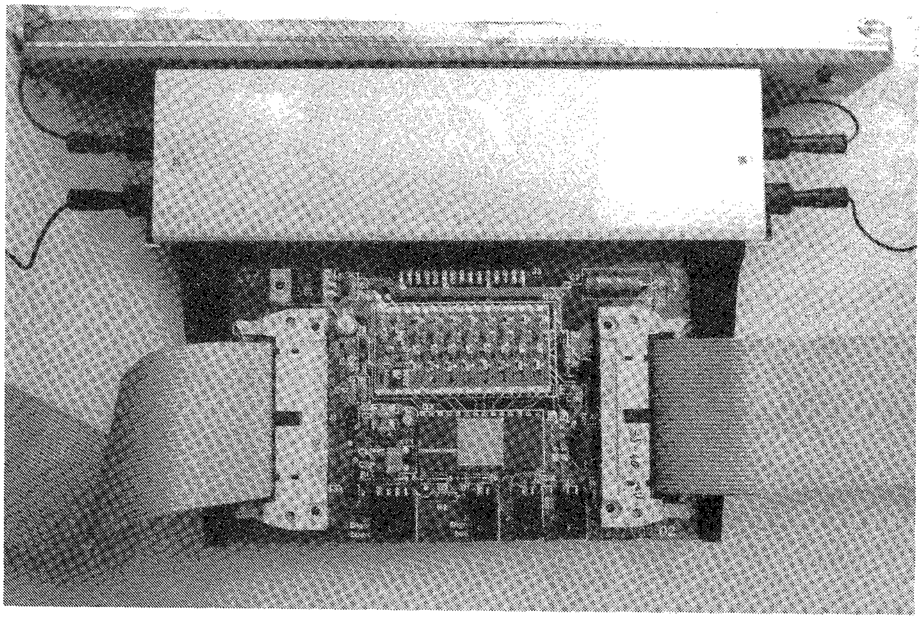

FIG. 5 - Wire readout card[24] (8 channels) connected to a streamer tube chamber through the HV distribution.

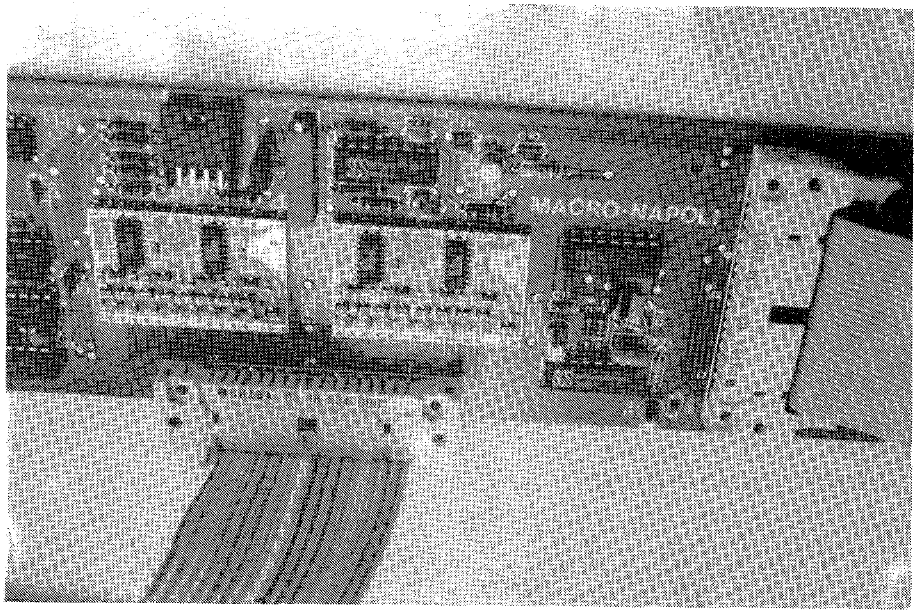

FIG. 6 - Particular of a strip readout card[24] (32 channels).

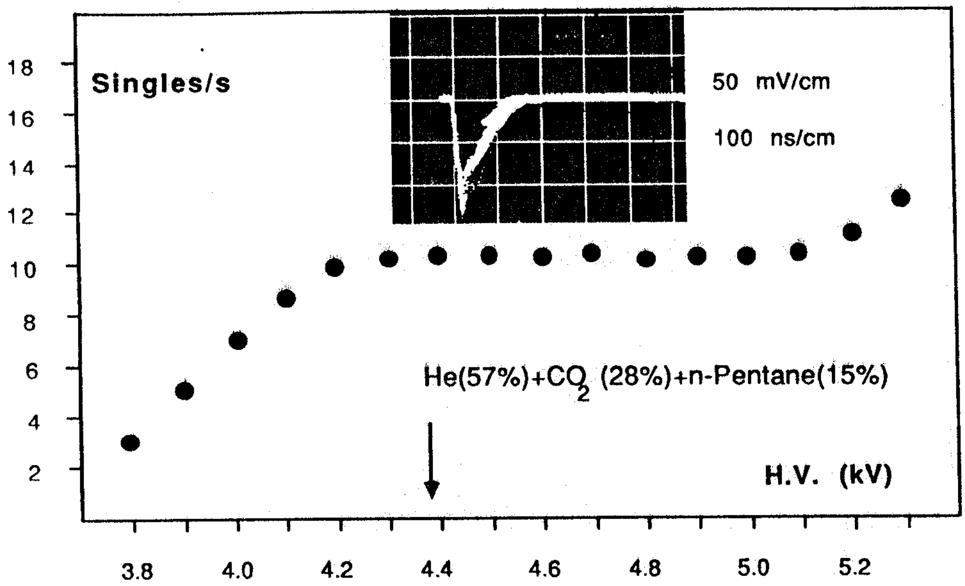

FIG. 7 - Singles rate as a function of high voltage and pulses on a single wire 4.4 kV, as measured with minimu ionizing particles, for a MACRO streamer tube chamber.

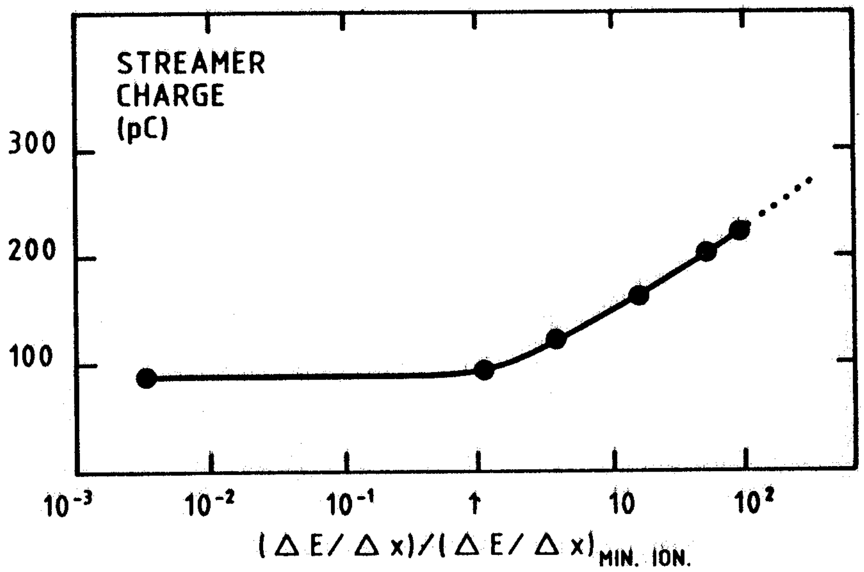

FIG. 8 - Streamer charge response as a function of ionization loss. The experimental points have been obtained with (from the left) single photoelectrons, muons, relativistic ions.

Other possible large scale technologies

From the above discussion it appears that the streamer tube technology has now reached a definitive development. There are other detection technologies that have promising features, and can be transferred to industry as well. One possibility is given by the Resistive Plate Counters[35], which are a cheaper and simpler version of the Pestov and Fedovitch device[36]. They would give good space and time accuracy, without the help of other detectors in the same apparatus. They consist of a 2 mm gap between two bakelite (phenolic resin) parallel plate electrodes. A gas mixture generally composed of Argon, isobutane and Freon is fluxed in the sensitive volume. A DC high voltage of the order of 10 kV is applied. When a particle crosses the gap a breakdown is generated. The discharge, however, is prevented from propagating through the whole gas volume because of the high resistivity of the electrodes ($10^{10} \div 10^{12}\ \Omega\cdot$cm): the electric field is suddenly switched off in a limited area around the point where the discharge occurred. The pulse can be localized in two dimension by external pick-up strips. The time resolution can be better than 1 ns, while the space accuracy can be of the order of a few mm. At present they can be produced in single and double gap modules (2 x 1 m^2) at a production rate of ~100 m^2/day. They have been used in the NADIR experiment[37], and will be soon operational in the FENICE experiment[38].

A similar device has been tested in Frascati[39], the main difference with respect to RPCs being the use of commercial plasticized PVC as resistive electrodes (~$10^{12}\ \Omega\cdot$cm). One of the advantages of this solution is the possibility of exploiting the thermoplastic technologies (bakelite is termosetting), which would allow better flexibility in producing detectors for large area experiments. Another interesting feature is the resulting noiseless operation, which allows easy monitoring and calibration. The other detection features are of the same order of those of RPCs.

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