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PARTICLE IDENTIFICATION FOR BEAUTY PHYSICS

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Summary of the Particle Identification Group

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Workshop on High Sensitivity Beauty Physics at Fermilab
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I. Ground Rules

For this workshop the Particle Identification Group took on the task of examining some practical detector solutions for a few of the problems which are central to high-statistics B-meson spectroscopy. Our approach was to try to understand the technological state-of-the-art for detectors which could satisfy the needs of a spectrometer system capable of exploiting the full power of the Tevatron as a B-meson factory, either in the collider or the fixed target mode. Such spectrometer systems were sketched by the "architecture" groups at the workshop. We were particularly interested in identifying the detector technologies best suited to such systems, evaluating the limits imposed by detector performance on the sensitivity to interesting B-meson signatures, and delineating areas where detector R&D work is most needed to support a B-physics research program.

As a matter of practical expediency for a few-day workshop we quickly distilled our definitions of a generalized B-meson experiment to the following simple terms:

1. The detector system, whether for fixed target or colliding beams consists of a high-resolution vertex detector (silicon) close to the interaction point, surrounded by a volume of non-destructive particle identification (which may be immersed in a magnetic field), and this is followed by electromagnetic calorimetry.

2. The goals of particle identification are
   a. Viable selection of prompt, single leptons at the trigger level. We chose to focus on the electron case.
   b. Separation of pions, kaons and protons at the abstraction level.

3. The required coverage in solid angle, particle momenta and interaction rates for the two kinds of experiments are as follows:

<u>"Collider":</u>

$Y_{Lab} \lesssim 2$

$P_{Lab} \approx 0.5 - 5$ GeV/c

Int. rate $\lesssim 1.0 \times 10^{6} \mathrm{sec}^{-1}$

<u>"Fixed Target"</u>:

$Y_{Lab} \gtrsim 2$

$P_{Lab} \approx 5 - 100$ GeV/c

Int. rate $\approx 10^{6} - 10^{9} \mathrm{sec}^{-1}$

An example of the kind of fixed target detector configuration which would be appropriate for high sensitivity B physics at the Tevatron is given by the beauty spectrometer designed for the SSC at last year's Snowmass Workshop.[1] A possible collider detector was presented by Lockyer[2] at the opening session of this meeting. Both of these concepts have been given further development by the architecture groups here.

Whether collider or fixed target, the central difficulty for detector design is that an experiment sensitive to CP violation in the B system must be capable of recognizing rare and complicated signatures (fully reconstructed B-meson pairs) against the full background of low p_T phenomena, with rates and efficiencies which allow the accumulation of $\approx 10^7$ reconstructed events per experiment.[3]

With the problem defined as above, the most difficult issue for a collider experiment (no "easy" issues were identified!) appears to be that of providing an adequate lepton (electron) trigger in the central region where momenta of $\lesssim 1$ GeV/c must be handled with good hadron rejection. For a fixed target experiment at the Tevatron the feasibility hinges on the issue of whether an experiment can be done at interaction rates approaching $10^{9} \mathrm{sec}^{-1}$. Our short survey of detectors for particle identification focussed mainly on these two issues. Figs. 1 and 2 illustrate the detector architectures which we took for our considerations.

II. Electron Detection

A fast and efficient electron signature provides an effective means of quickly reducing the full hadronic interaction rate to a level where more complete event reconstruction can be undertaken, while at the same time substantially enriching the B sample (≈40% semileptonic branching ratio). References 1 and 4 give an analysis for the SSC case. For our purposes we need ultimately a hadron rejection factor [R (e/π) = electron efficiency/hadron efficiency] ≈ 10^4, with electron efficiency ≳ 90%, for the kinematic range and rate capability requirements given in Section I.

Schemes to realize such a trigger have been proposed in which a system of detectors is used to provide information at increasing levels of processing sophistication (and time):

Detector	Hadron Rejection Factor	On-line Processing Time
EM Calorimeter	100 - 1000	≲ 100 ns
TRD	10 - 100	≲ 100 ns
Tracking (Fast Reconstruction)	Photon and Pair Rejection	~ 10 μs
Tracking (Full Reconstruction)	Momentum-energy Match	≳ ms

Fairly detailed estimates of the performance of such a detector system have been made by several groups. It is instructive to look at the particular case of the NA34 (HELIOS) experiment[5] at the CERN SPS, which relies on precisely this kind of a trigger, and for which the system of detectors has been built and preliminary tests carried out.

The HELIOS detector system is shown in Fig. 3. This is a fixed target experiment, designed for proton beams at 450 GeV/c, with interaction rates of ≈10^5 sec^{-1}. The electron detector system covers the forward 6° cone, and consists of a silicon pad detector, tracking via high precision drift chambers and silicon strips, a transition radiation detector with both anode and segmented cathode readout, and a uranium/liquid argon calorimeter whose EM section is segmented into 2 × 2 cm^2 towers at a distance of approximately 3 meters from the target. The system was designed, with a careful Monte Carlo simulation, to provide hadron rejection factors > 10^5 offline, with a factor of 10^4 at the trigger level, for electrons with energy greater than 10 GeV for singles, and lower values (5-6 GeV) for pairs. Fig. 4a, b, c show the segmentation of EM calorimeter, the TRD readout, and the silicon pad plane. The trigger logic correlates a shower in the calorimeter with the pulse-heights at the corresponding positions in the TRD and silicon detectors. The pulse-height in the silicon pads is used to reject Bethe-Heitler conversion pairs: the logic distinguishes 0-, 1-, 2-times minimum ionizing. The spectrometer incorporates a weak magnetic field (approximately 0.5 Tesla-meter) and drift chambers which achieve good spatial and two-track resolution. The TRD is a compact device with 8 layers of radiator/detector, each segmented as shown in Fig. 4b. The readout is designed to use the TR-cluster counting method,[6] in which separation between the ionization energy loss and the localized energy deposit due to transition radiation is achieved by analyzing the time-dependence of the induced charge signal on the anode wires. Each of the 8 TRD layers consists of a radiator of polypropylene foils with a thickness of approximately 1% R.L, with a total length of radiator equal to 6.2 cm per layer. The TR efficiency of the radatior is approximately 0.3 TR quanta/cm of radiator.The TR detector is designed to achieve a hadron rejection factor > 10^2 in a first-level trigger, for p > 5 GeV/c.

The HELIOS detector has been assembled and has taken data. Analysis is still in progress, and final performance data are not yet available. However, results of test beam studies carried out this past summer are instructive.[7] The system was exposed to non-interacting beams of electrons and pions at 17 and 45 GeV. For the electromagneic calorimeter alone, by selecting on shower energy, shower radius, and the energy deposited in each of two layers in depth of the EM calorimeter, a rejection factor of about 100 was achieved at both energies, for 90% electron efficiency. If tracking information is used to match particle momentum with the shower energy, this result improves by about a factor of 10. In these tests the TRD detector measured typically 11 photons per view (x and y) for electrons. The match between measured position in the TRD and the shower position in the EM calorimeter was accurate to 2.5 mm in x and 3.5 mm in y. The preliminary result is that the TRD provides an additional rejection factor of about 300 at 90% electron efficiency.

These results are consistent with the design criteria and are very promising for our B-physics goals. They do not yet represent a demonstration of on-line rejection in real events. The measured noise per tower in the HELIOS electromagnetic calorimeter is 15 MeV. Each electron shower spreads over about 18 towers (3 × 3 in each of two layers). Assuming the hadron rejection factor is limited by noise, the device should perform well at electron energies ≈ 1 GeV, at least on well-isolated tracks.

III. Further Prospects for Transition Radiation Detectors

Techniques of transition radiation detection have been developed to the point where thin, compact modules can be envisioned which are powerful tracking devices, efficient for electrons and virtually blind to hadrons. The HELIOS detectors embrace this concept, and point the way toward more ambitious developments.[8,9] Fig 5 shows a proposed module of a "high granualarity" TRD detector (Ref. 9). Many such sets can be ganged together to provide the full detector. Readout from the Xenon MWPC's has a threshold to exclude the minimum-ionizing dE/dx signal, and provide "cluster counting" for transition radiation x-ray signals, with good spatial resolution and a very high degree of segmentation. The readout is also fast: maximum drift time in the Xenon MWPC is about 40 nanoseconds. A simulation of the performance of such a device as a function of the length of detector and electron energy is shown in Fig. 6. Rejection factors in the range 100-1000, for 90% electron efficiency, are feasible for electron energies from 1 GeV to 100 GeV. (At lower energies the efficiency for electrons falls off. At higher energies, pions begin to radiate transition quanta.)

IV. Highly Segmented Position Sensitive Detectors: Cathode Pad Readout for High Rates

The transition radiation detectors described above are inherently fast, but at extremely high rates many events will be seen simultaneously in any practical detector. For the extreme case where each strobe of the detector finds, say, 20 events superimposed, the only defense is a very high degree of segmentation. The readout configuration should be such that high local multiplicities of tracks can be treated. Developments are presently under way in which a thin, planar wire chamber (such as the readout plane for a TRD module) is equipped with highly segmented pad readout.

The "pad chamber" concept calls for a detector with a cathode area subdivided into a very large number of pixel-like elements such that a charged particle traversing the detector at normal incidence leaves an induced signal on a few localized pads. The pads are interconnected by a resistive strip, and readout amplifiers are connected to the resistive strip at small intervals. Fig. 7 depicts the structure of a small prototype.[10] Fig. 8 shows schematically the response of such a chamber to a large number of particles. The pattern of tracks is easily recognized. and a centroid-finding readout system[11] allows position determination accurate to a small fraction of the basic cell size. It should be possible, in the near future, to produce practical devices capable of covering very large areas (square meters) with $\lesssim 10^5$ detection elements per m^2. The realization this presupposes the development of monolithic circuits which integrate fast preamplifiers, analog memory units and a multiplexed output to facilitate fast, low-noise signal processing for a very large number of detection elements (pixels) at practical cost and without overwhelming masses of cables and connectors. A first step in this direction has been taken in the development of so-called "microplex" chips for readout of silicon microstrip detectors.[12] Substantial R&D effort has been proposed (and some work is in progress) to develop integrated circuits, using analog MOS technology, which would allow high speed miltiplexed readout electronics to be distributed in small, low-mass chips over the cathode plane of a pad chamber detector.[13]

V. Ring Imaging Cerenkov Counters

In order to study B meson production and decay we need a means of distinguishing pions from kaons over a wide range of momentum with a high degree of segmentation and high rate capability. The imaging Cerenkov technique has been brought to an advanced state of development through intense efforts for several large experiments, in particular the SLD[14] group at SLAC and DELPHI[15] at LEP. Recently design and development work has been done to push these techniques to the high rate environment of hadron machines.[16,17,18] These developments were discussed in our group, and a two-stage RICH detector system was sketched which could be incorporated either in the fixed target or collider mode (See Figs. 1,2).

The scheme calls for two independent RICH detectors with the following properties:

1. Gas radiator: $n \approx 1.001$, $\gamma_T \approx 25$, mirror focussed, radiative length ≈ 40 cm.

2. Liquid radiator: $n \approx 1.2$, $\gamma_T \approx 1$, proximity focussed.

The readout for these devices is via UV photon detection in a low-pressure multiwire proportional chamber with TMAE as the active photoionizing gas. This kind of readout is illustrated in Fig. 9 (from Ref. 18). Photoelectrons produced in the 30 mm conversion gap are amplified and transferred to the MWPC sage, where the position of each converted photon is read out on anode wires and/or induced charge on cathode segments. The detector is operated at a pressure of approximately 40 torr with a saturated mixture of C_2H_6 + TMAE at 30°C. We envision the readout to be a pad plane segmented in two dimensions using the techniques discussed above in Section IV. The detector sketched in Fig. 2 would have a total readout area of approximately $10 m^2$. If each pad is 1×1 cm^2, which we calculate will give sufficient resolution in the angular diameter of measured rings, the total readout is approximately 10^5 channels. The RICH detector for E665 (Ref. 16), described for us by Satish Dhawan, incorporates a similar detection scheme, with pad readout comprising 10,800 channels. This system was built at a cost of approximately $5 per channel. Our system would require an order-of-magnitude extrapolation, but it does not appear that there are fundamental obstacles to be encountered.

A key question is whether such a system could be designed to sustain the very high interaction rates required for a fixed-target B-physics experiment at the Tevatron. The model for this is that 20 events appear simultaneously in the detector every 20 nanoseconds. For this we need to shorten the drift time in the photon detector (the conversion gap in Fig. 8), without reducing efficiency. Results from Woody and Holroyd at BNL[19] indicate that the TMAE mixture could be operated at a temperature of 80°C and still be chemically stable. AT this temperature the mean free path for photon conversion is 1.24 mm, corresponding to a drift time of 20 nanoseconds. This needs to be confirmed in tests, and the question of radiation hardness at such an elevated temperature has not been addressed.

With these caveats, the detector could in principle sustain the required rate. It would have to be capable of resolving approximately 200 tracks simultaneously, calling for some 5×10^4 read-out pads per plane, which is consistent with the requirement discussed above for adequate resolution of Cerenkov rings.

The remaining problem for very high rates in such a detector is the electronic signal processing and readout. Here again a fast multiplexed system of pad readout is called for. In our discussions, S. Dhawan conjectured a scheme with fast analog CCD buffer on each pad, with sparse data selection similar to what is done in E665 (Ref. 16), and 50 ns shaping time prior to digitization. For such a system with a total of 100 output busses, an "event" with hits on 100 pads would require 500 nanoseconds to read out. With a reasonable pre-trigger, this should be acceptable. Alternatively, future developments of segmented phototubes, or photodiodes, may replace the MWPC pad readout for very high rates.

VI. Electromagnetic Calorimetry at Very High Rates

We have seen that the science of EM calorimetry includes techniques, which have either been demonstrated or are in some stage of development, which could satisfy the needs of Tevatron B-physics at interaction rates $\lesssim 10^6 \text{sec}^{-1}$. Some of the options are briefly described as follows (Z refers to heavy metal absorber):

Z-Liquid Argon:
- O.K. at ≈ 1 MHz interaction rate
- Good segmentation
- Radiation Hard
- Large body of expertise exists

Z-Silicon:
- Very compact
- Shower size (Moliere radius) ≈ 5 mm

BaF_2:
- Very fast
- Radiation Hard Crystal
- Good segmentation: UV component
- Can be read out with wire chamber (TMAE)

Z-Scintillating Fiber:
- Fast
- Good Segmentation
- Needs R&D

For the giga hertz interaction rates of our extreme fixed target scenario, only barium fluodide (BaF_2) has properties which can inspire some hope. Barium Fluoride is a scintillating crystal which emits UV light with a decay time of less than one nanosecond. In addition, highly pure BaF_2 is the most radiation resistent scintillating material known, showing little effect of radiation damage with doses of up to 10^8 rads.

Because the fast component of scintillation light appears as UV photons an array of BaF_2 crystals can be read out by the same techniques of photosensitive MWPC, using TMAE, as was discussed in the previous section. This approach was pioneered several years ago by D. Anderson, working with the Charpak group at CERN. This BaF_2 approach has undergone considerable development in recent years, both at CERN and at Brookhaven. At Brookhaven, C. Woody and co-workers, using specially designed fast electronics and pulse-shaping, have obtained an output pulse from the wire chamber with a baseline width of 20 ns, operating at rates up to 10^7 Hz per readout element.

With this kind of performance, one could imagine a forward calorimeter array such as that illustrated in Fig. 10, which could handle the extreme conditions of the fixed target spectrometer. This array could occupy the shaded portion of the EM calorimeter wall in Fig. 2.

Unfortuanately, the state of the art is not quite ready to produce such a detector, and there are major uncertainties to be resolved. First, it has proven very difficult to grow pure BaF_2 crystals with acceptable transmission properties for the fast scintillation component. The quantities are small and the process is time-consuming: the array shown in Fig. 9 would require a volume of crystal which exceeds the world production over the past four years. Secondly, the readout system with TMAE has drawbacks: TMAE is very bad to work with, and has a low quatum yield. Of greatest concern for this application is the radiation hardness of TMAE. Some recent results have shown dramatic evidence of effects at high rates,[20] although little is actually known at this point. Work is in progress at SLAC, Brookhaven and Fermilab to study this problem in more detail.

VII. Conclusions

We have looked briefly at the requirements for particle identification for possible beauty experiments at the Tevatron, both in the fixed target and the collider mode. Techniques presently in use in high energy physics experiments, and under development, should make sensitive experiments feasible. However, in all cases the present state of the art must be advanced to meet the necessary requirements for segmentation and/or rate capability. The most fundamentally difficult challenges appear to be the efficient tagging of soft electrons (for the collider experiment) and the need to handle interaction rates up to $\approx 10^9$ Hz in the fixed target mode. In both cases we can find "in principle" demonstrations that the requirements can be met. We have considered only the most basic properties of detectors, however, and the real answers will come from careful studies of details.

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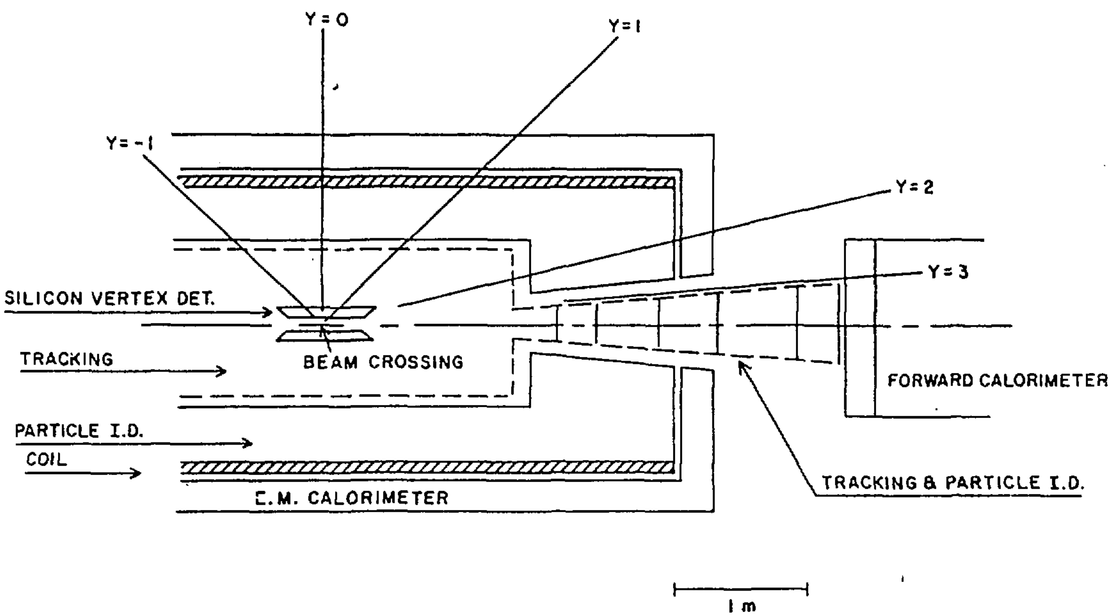


Fig. 1 Detector layout for a B-physics experiment in a collider.

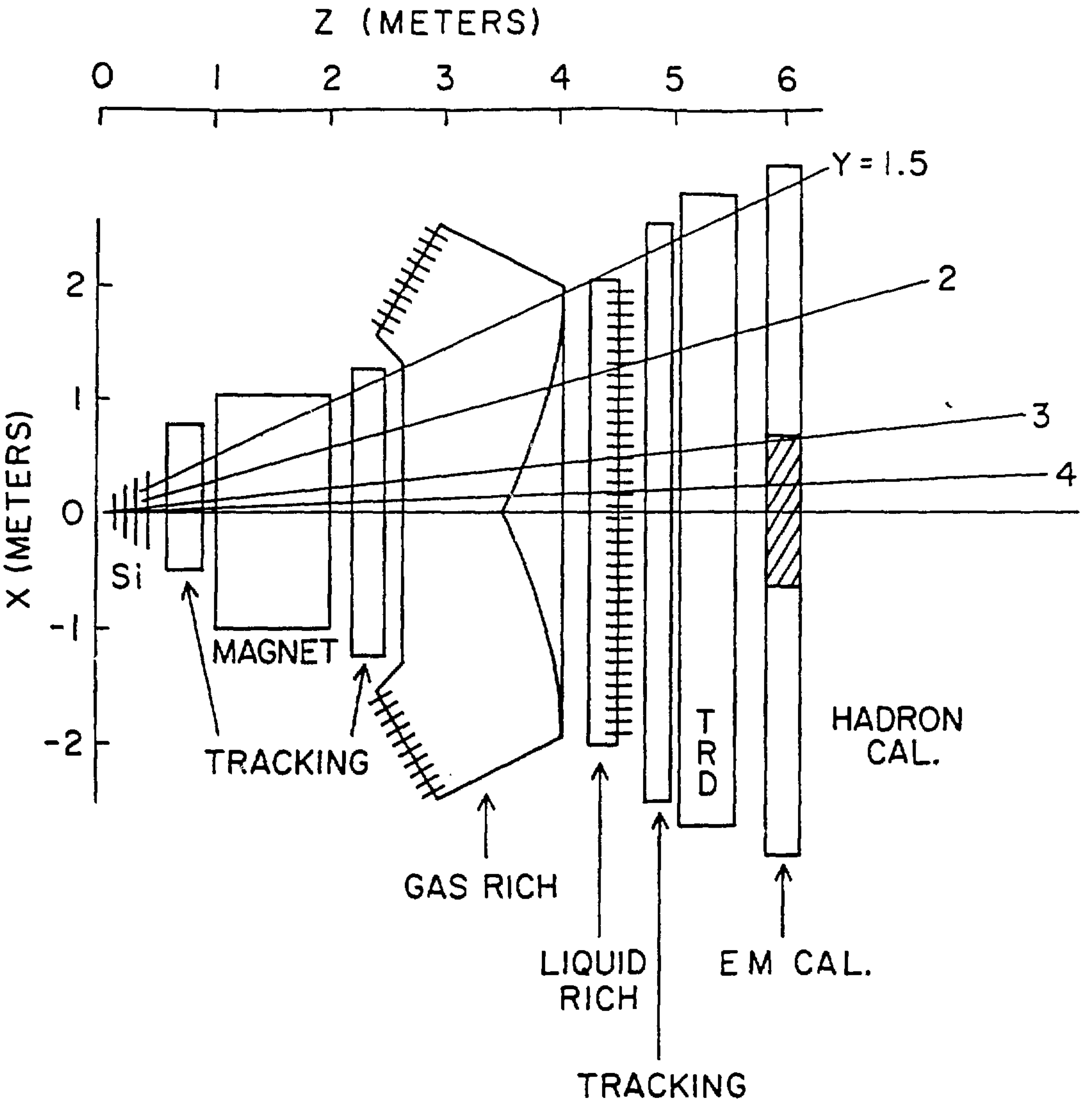


Fig. 2 Layout of a fixed target experiment. The hash-marks on the Ring Imaging Cerenkov (RICH) counters indicate read-out planes. The shaded portion of the EM calorimeter requires special technology for very intense radiation environments.

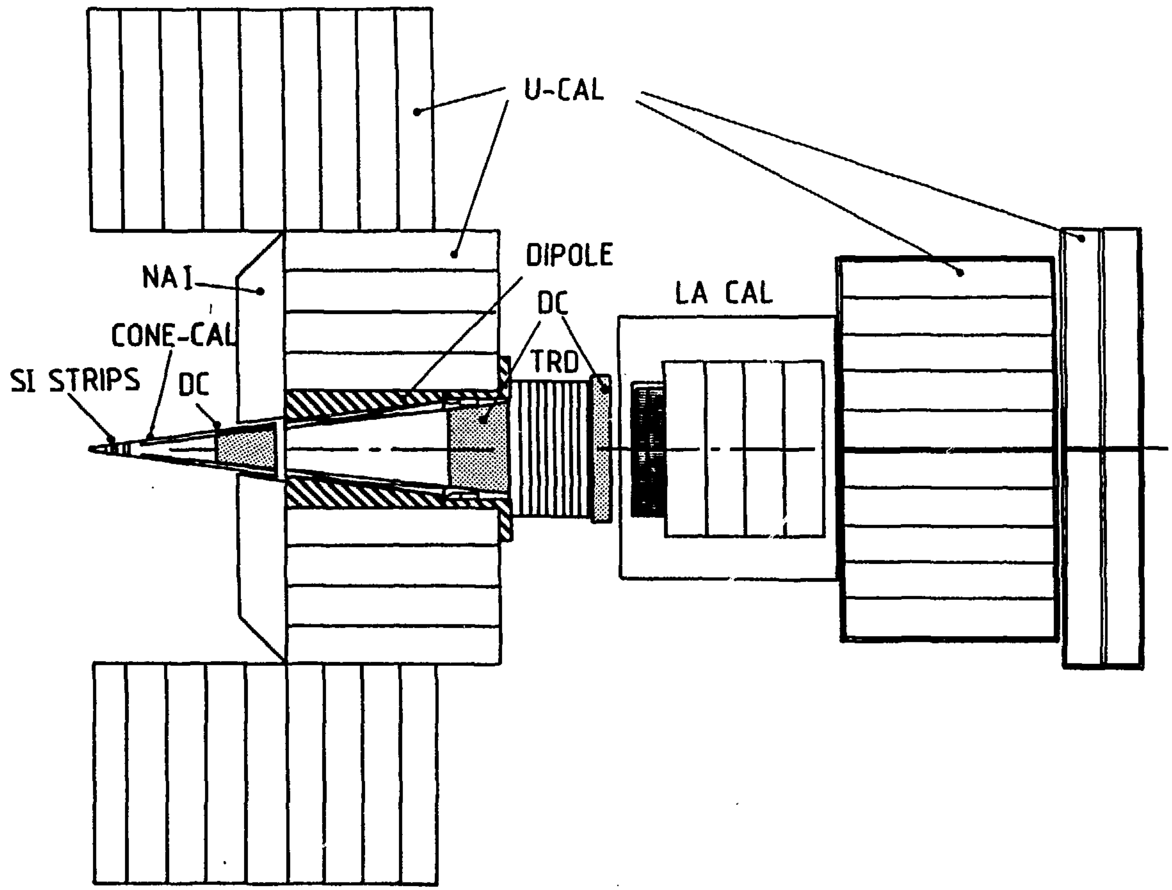


Fig. 3 The HELIOS detector system at the CERN SPS.

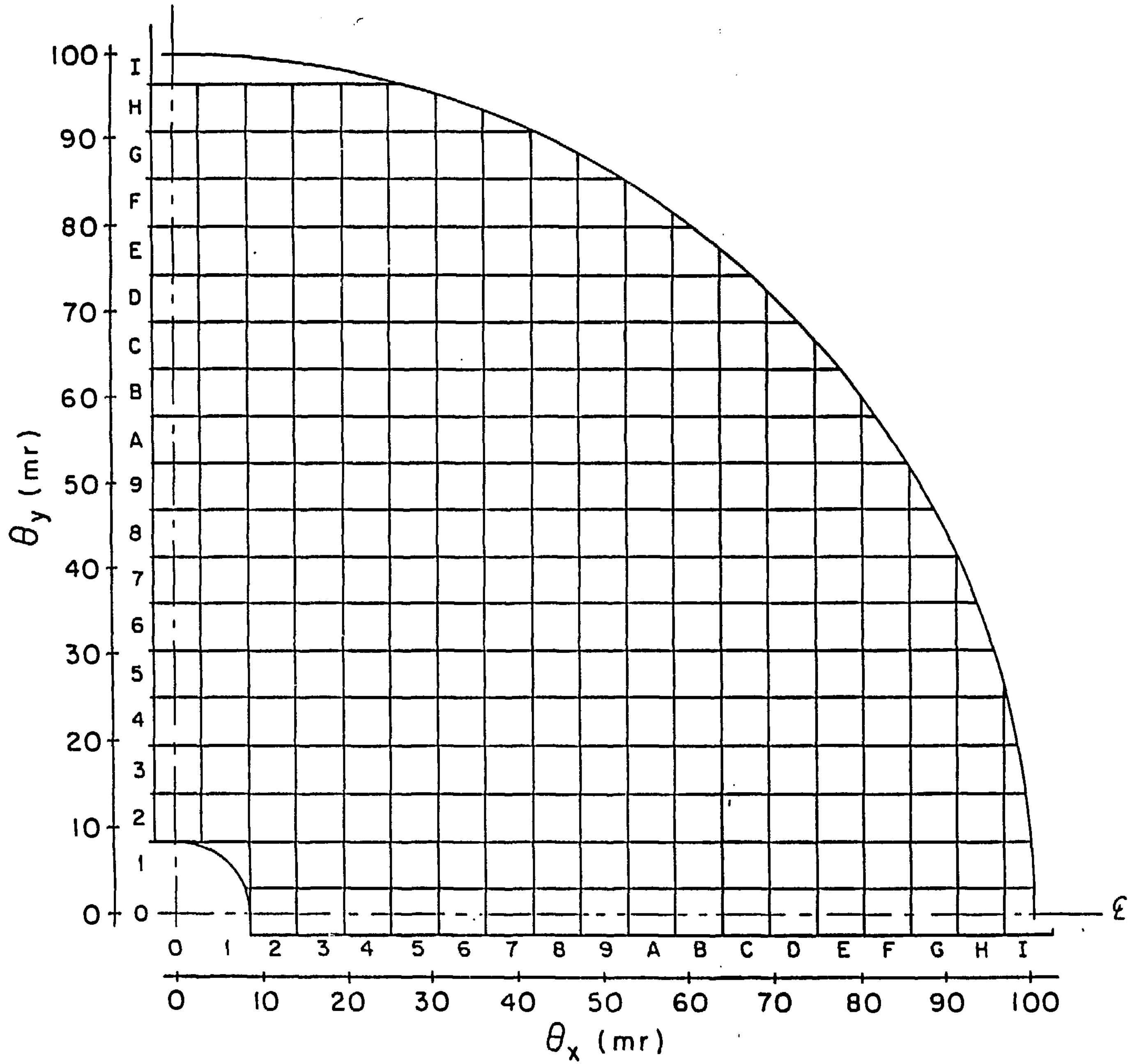


Fig. 4a Segmentation of the electromagnetic portion of the HELIOS uranium/liquid argon calorimeter.

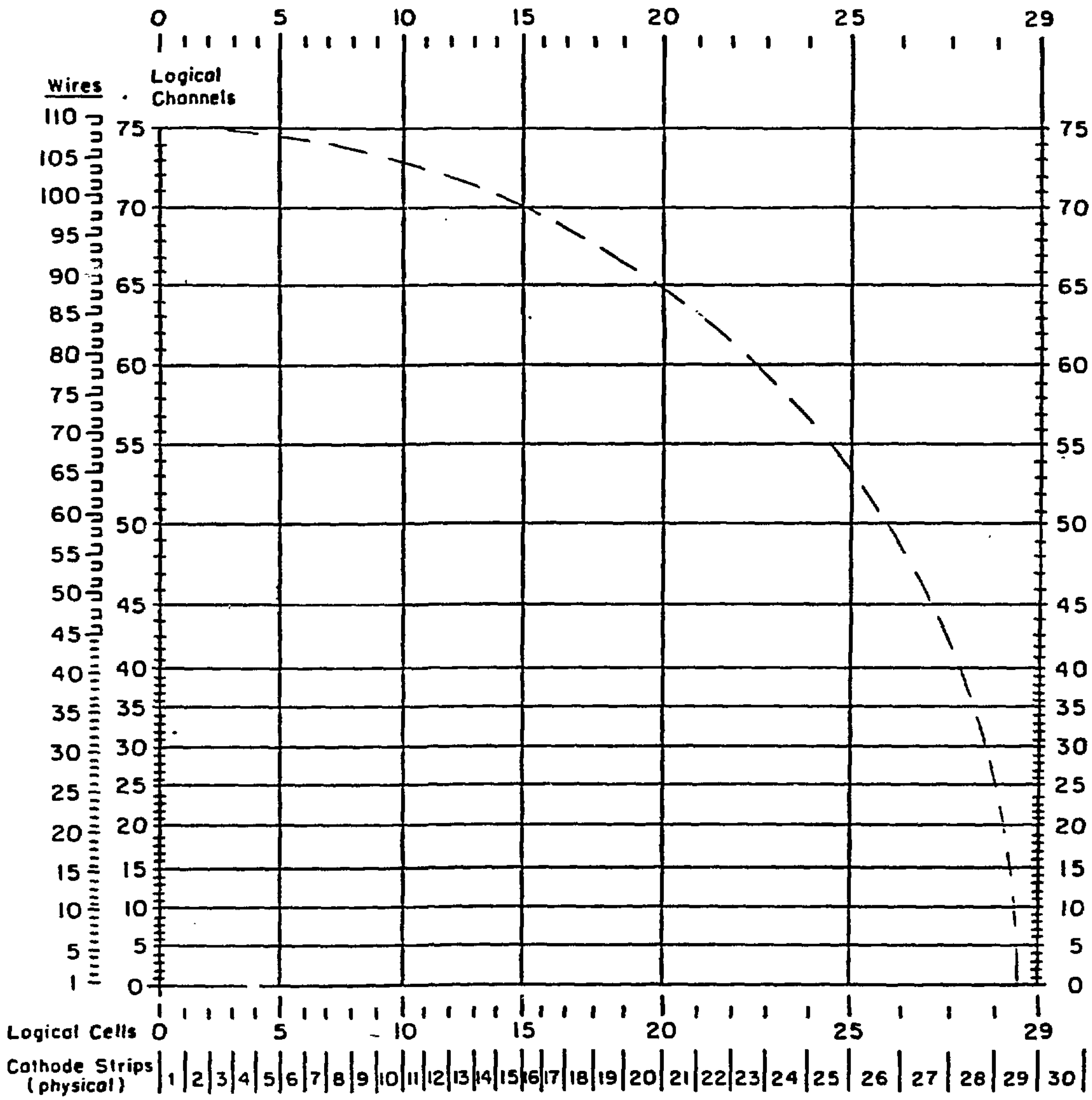


Fig. 4b Segmentation of the HELIOS Transition Radiation Detector readout.

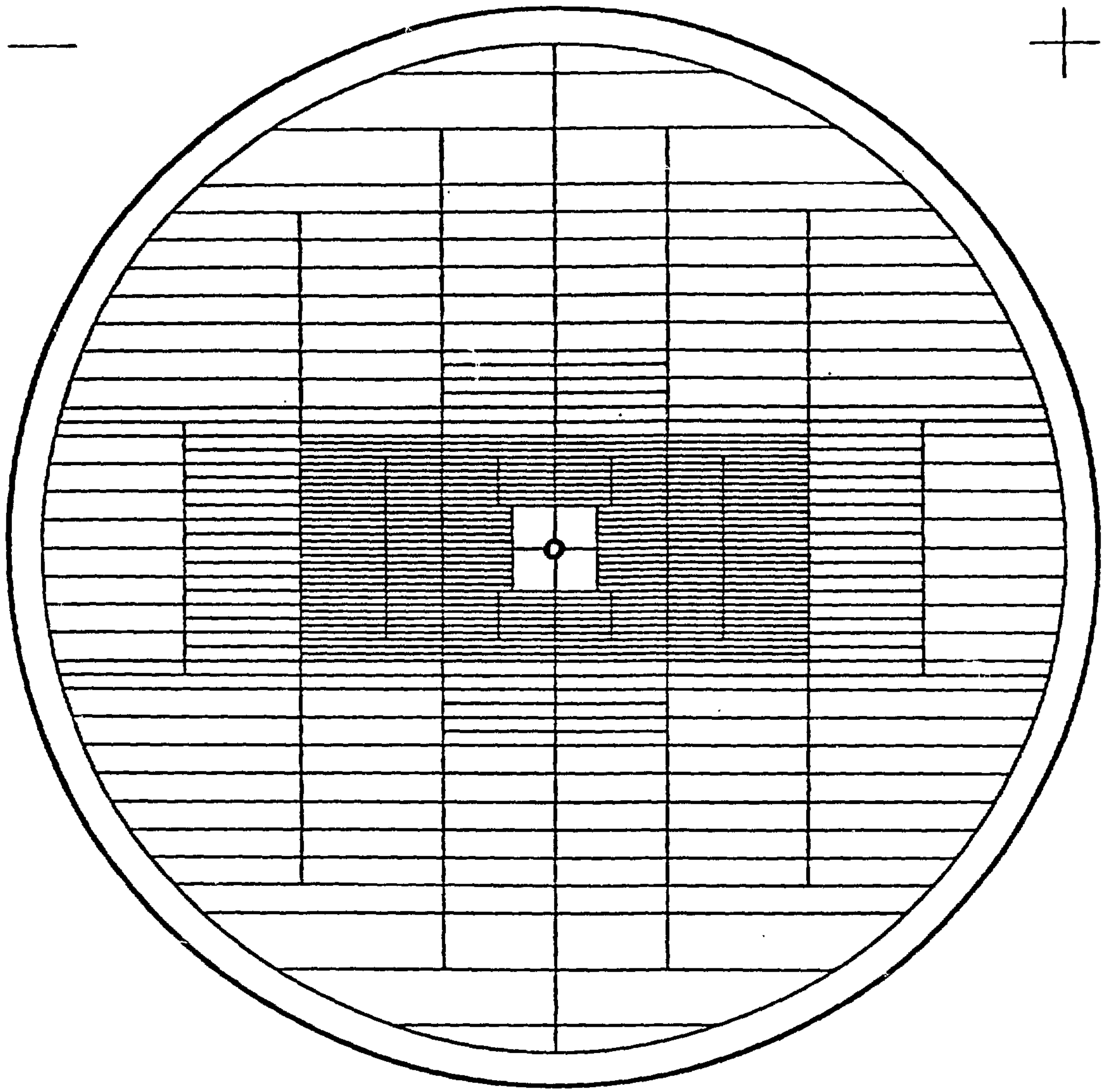


Fig. 4c Segmentation of the HELIOS silicon pad plane.

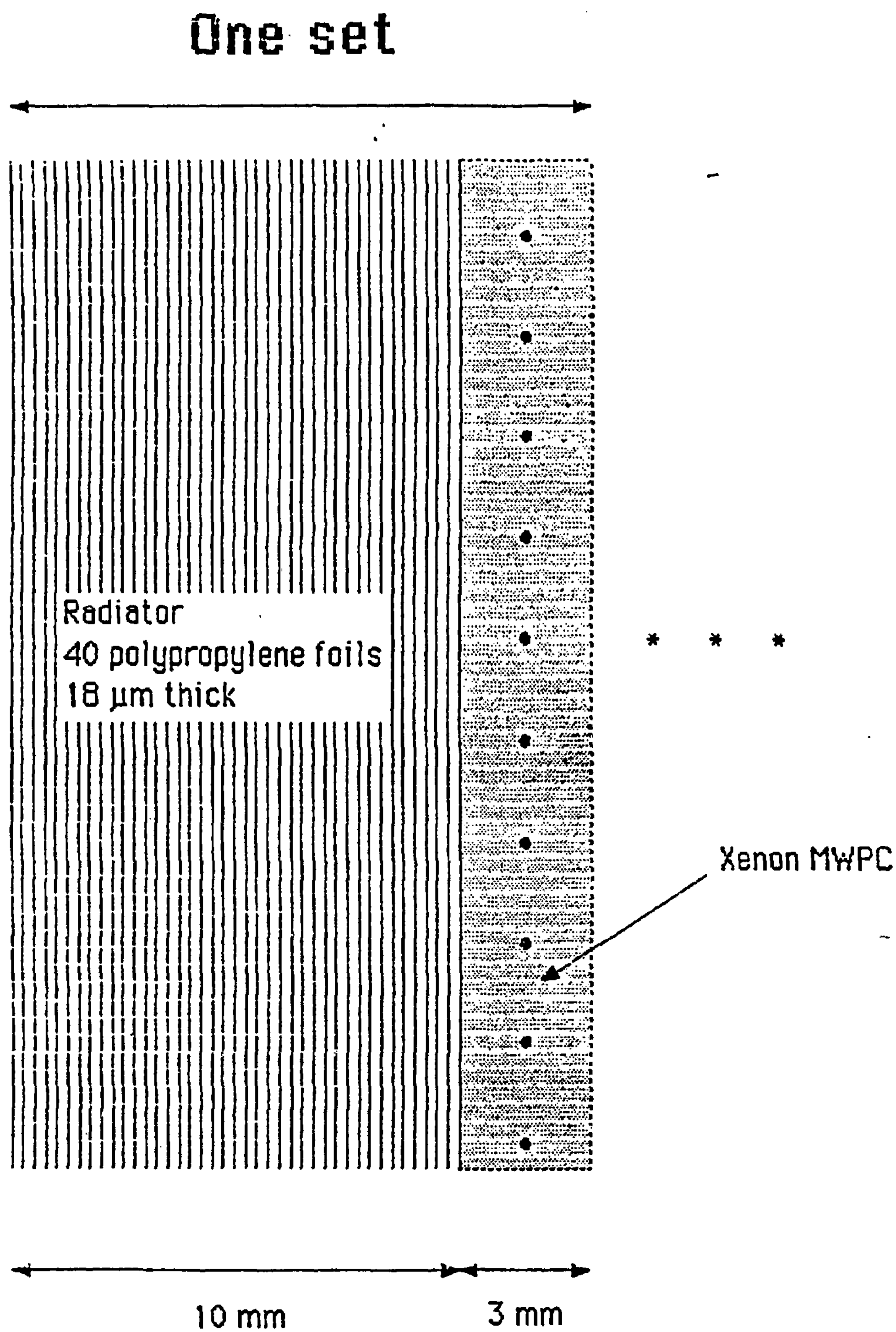
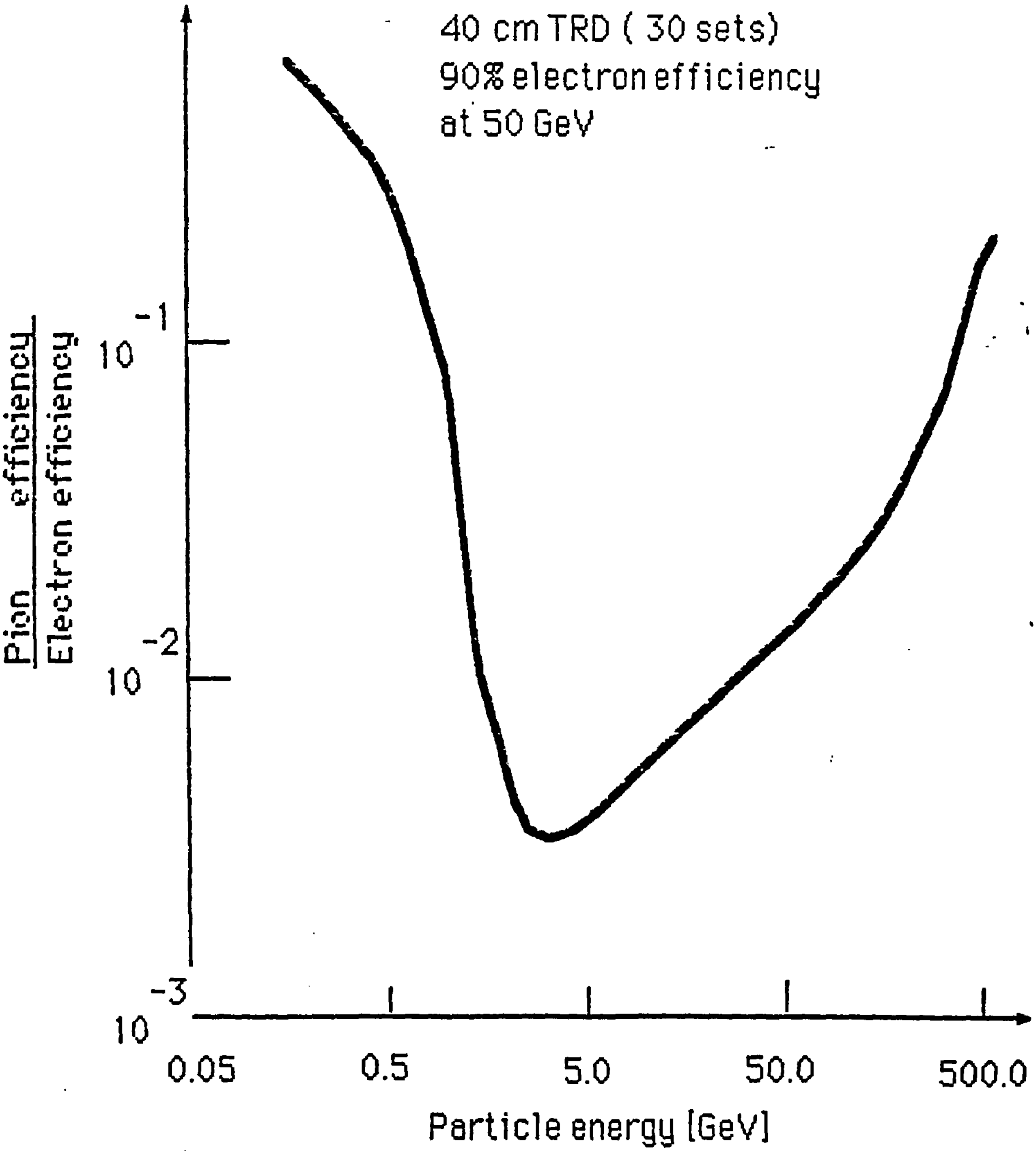


Fig. 5 Schematic layout of a high-granularity cluster-counting TRD (Ref. 9).



<u>Fig. 6</u> Hadron rejection power of a 40 cm long TRD made up of modules as shown in Fig. 5 (Ref. 9)

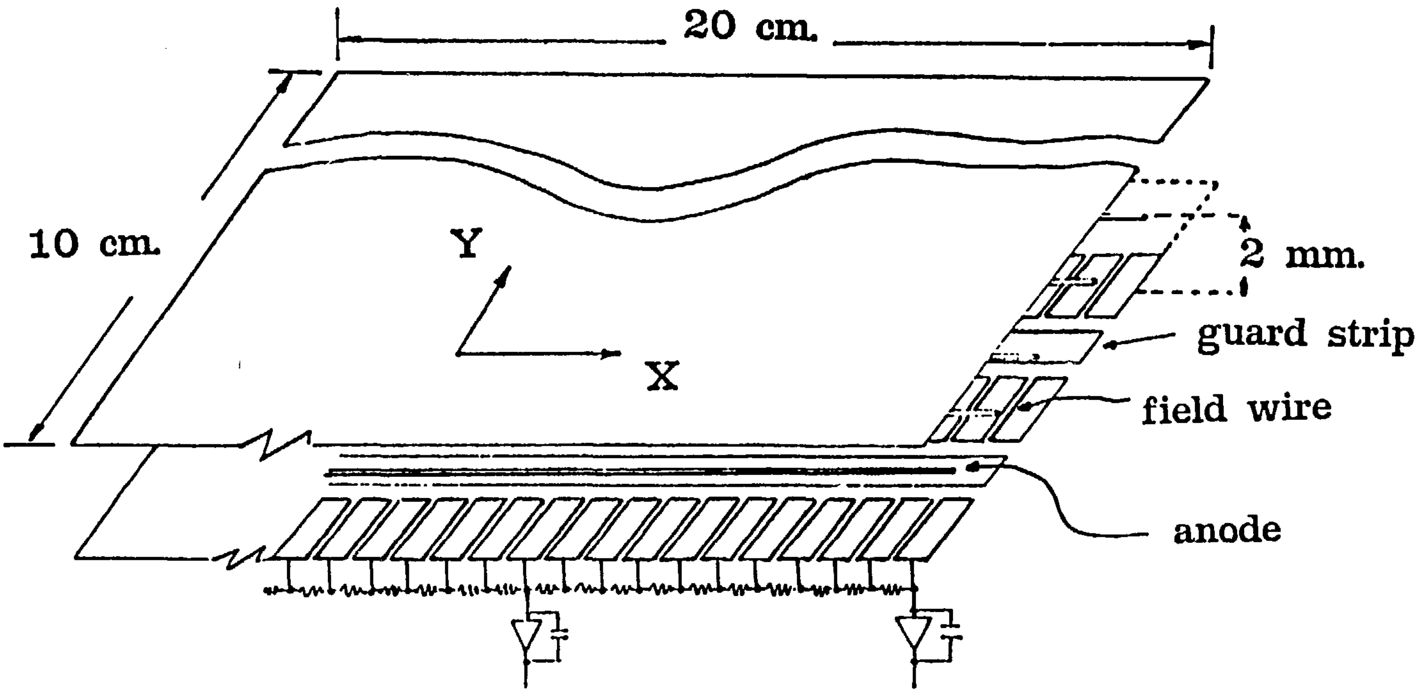


Fig. 7 Schematic representation of a small pad chamber, with 2 mm cell size and a total of 500 signal channels.

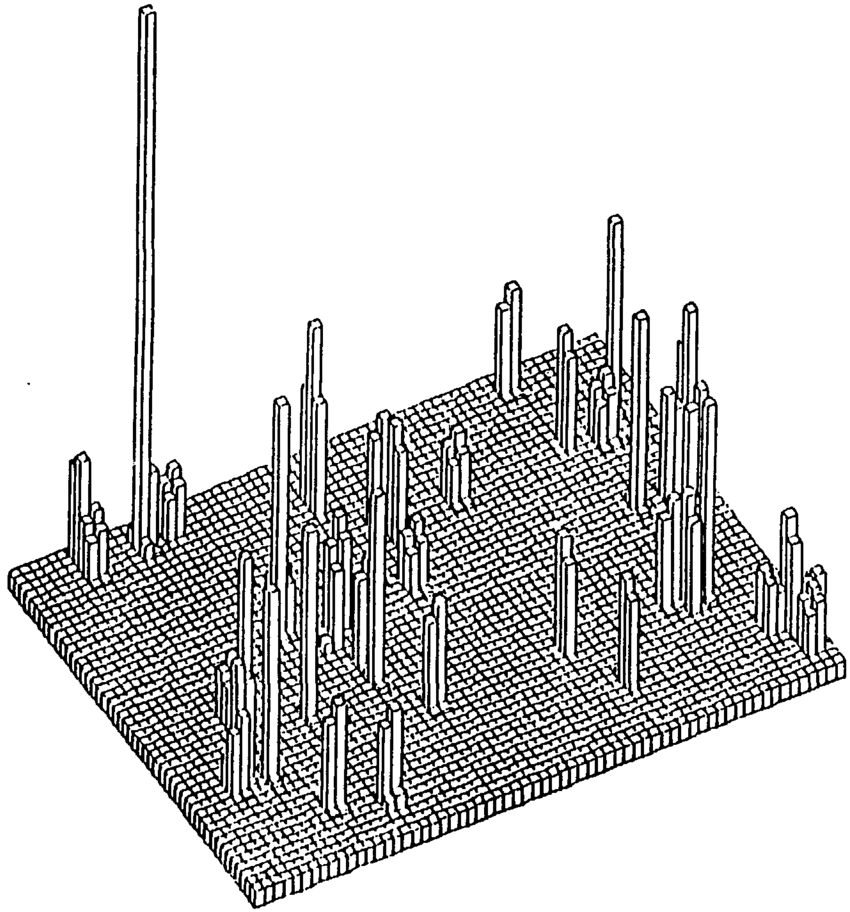


Fig. 8 A Monte Carlo Simulation of 40 minimum ionizing tracks traversing a thin gas chamber with induced charge readout in 3000 pixel-like 2 × 2 mm^2 elements for an anode-cathode spacing of 2 mm. The effect of delta rays is included.

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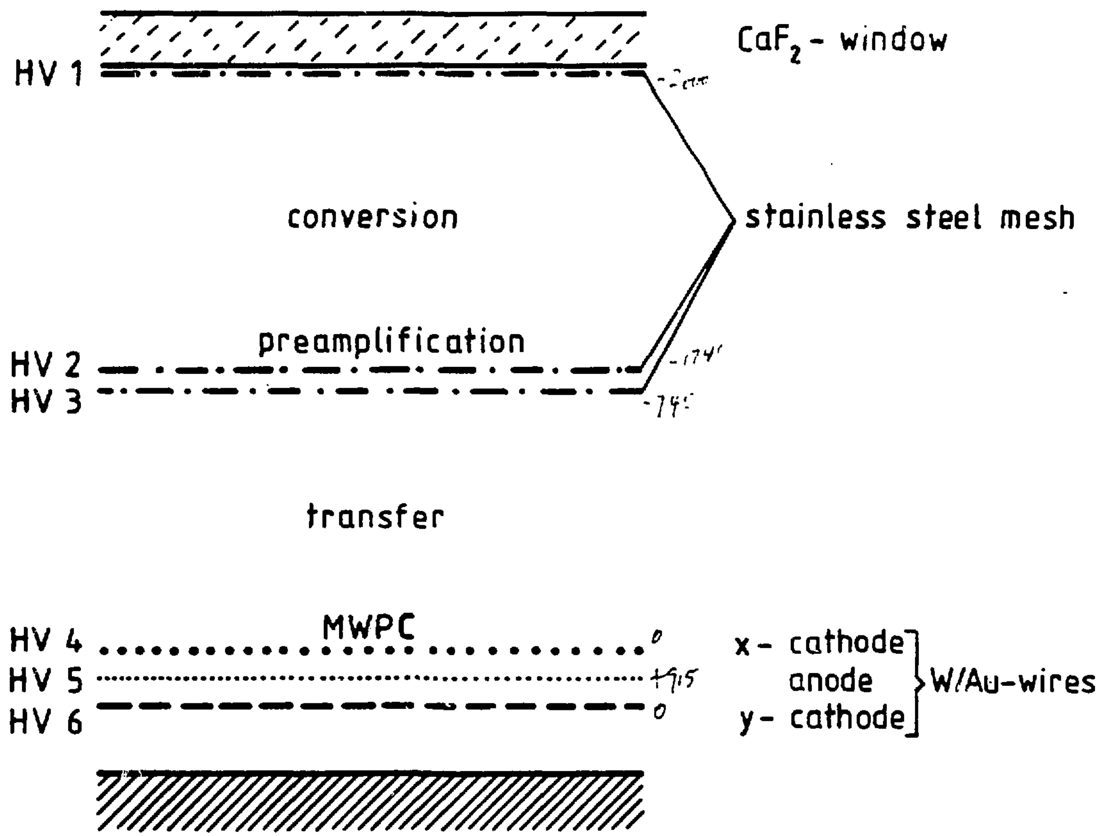

Fig. 9 UV photon conversion and MWPC readout for a Ring Imaging Cerenkov Counter (Ref. 18).

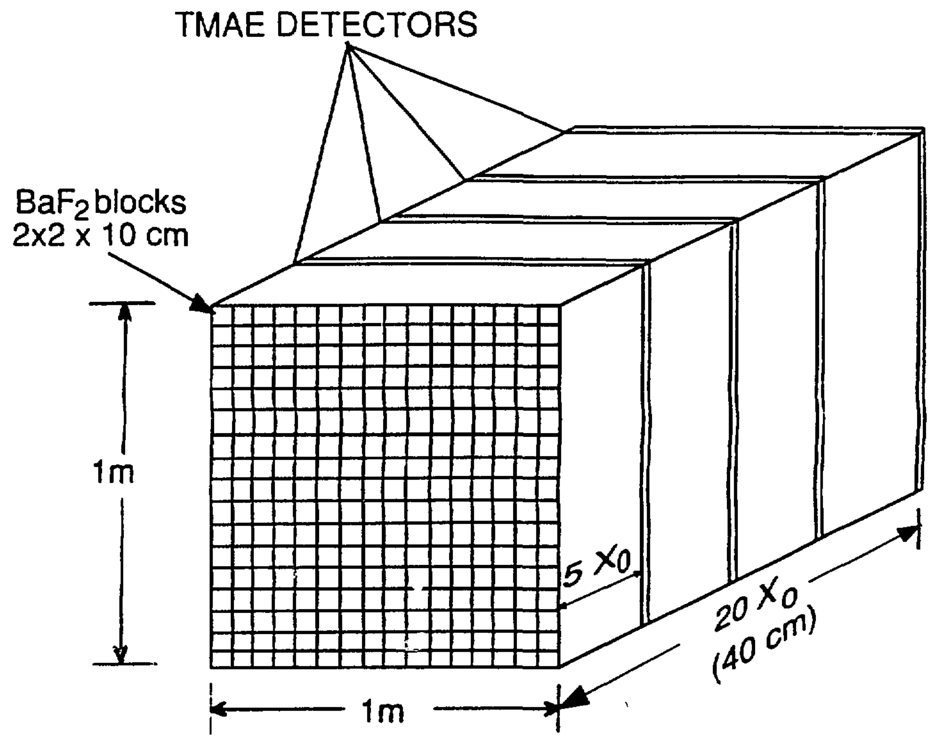

Fig. 10 An electromagnetic shower detector array consisting of 4 10,000 barium fluoride crystals with MWPC readout.