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Proposal to Develop an Integrated High-Rate Transition Radiation Detector and Tracking Chamber for the SSC

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Authorized Boston University Signature:

Name: John F. Imbergamo

Title: Comptroller

Signature: John F. Imbergamo

Certification Regarding Drug-Free Workplace Requirements
Grantees Other Than Individuals

This certification is required by the regulations implementing the Drug-Free Workplace Act of 1988, 34 CFR Part 85, Subpart F. The regulations, published in the January 31, 1989 Federal Register, require certification by grantees, prior to award, that they will maintain a drug-free workplace. The certification set out below is a material representation of fact upon which reliance will be placed when the agency determines to award the grant. False certification or violation of the certification shall be grounds for suspension of payments, suspension or termination of grants, or governmentwide suspension or debarment (see 34 CFR Part 85, Sections 85.615 and 85.620).

The grantee certifies that it will provide a drug-free workplace by:

(a) Publishing a statement notifying employees that the unlawful manufacture, distribution, dispensing, possession or use of a controlled substance is prohibited in the grantee's workplace and specifying the actions that will be taken against employees for violation of such prohibition;

(b) Establishing a drug-free awareness program to inform employees about--

(1) The dangers of drug abuse in the workplace;
(2) The grantee's policy of maintaining a drug-free workplace;
(3) Any available drug counseling, rehabilitation, and employee assistance programs; and
(4) The penalties that may be imposed upon employees for drug abuse violations occurring in the workplace;

(c) Making it a requirement that each employee to be engaged in the performance of the grant be given a copy of the statement required by paragraph (a);

(d) Notifying the employee in the statement required by paragraph (a) that, as a condition of employment under the grant, the employee will--

(1) Abide by the terms of the statement; and
(2) Notify the employer of any criminal drug statute conviction for a violation occurring in the workplace no later than five days after such conviction;

(e) Notifying the agency within ten days after receiving notice under subparagraph (d)(2) from an employee or otherwise receiving actual notice of such conviction;

(f) Taking one of the following actions, within 30 days of receiving notice under subparagraph (d)(2), with respect to any employee who is so convicted--

(1) Taking appropriate personnel action against such an employee, up to and including termination; or
(2) Requiring such employee to participate satisfactorily in a drug abuse assistance or rehabilitation program approved for such purposes by a Federal, State, or local health, law enforcement, or other appropriate agency;

(g) Making a good faith effort to continue to maintain a drug-free workplace through implementation of paragraphs (a), (b), (c), (d), (e) and (f).

Trustees of Boston University
Organization Name

Proposal to Develop an Integrated High-Rate TRD
PR/Award Number or Project Name

John F. Imbergamo, Comptroller
Name and Title of Authorized Representative

John F. Imbergamo
Signature

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Proposal to Develop an Integrated High-Rate Transition Radiation Detector and Tracking Chamber for the SSC

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SUMMARY

We propose to develop an integrated transition radiation detector and charged particle tracker for use in an SSC detector. This detector aims to discriminate between electrons and hadrons and to identify rare high energy charged particles. A low-mass structure of radiator materials and proportional straws will generate and detect transition radiation x-rays and will track charged particles. High performance VLSI electronics will be developed for the readout and processing of the proportional straw signals. A small prototype, sufficient to contain a high energy jet and followed by a fine-grained calorimeter, will be tested. An engineering prototype will be constructed to verify the design for a large detector.

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1. Introduction

It is well established that much of the interesting physics to be studied at the SSC is most accessible through study of leptonic channels. The massive particles that should occur at or before the TeV scale of electroweak symmetry breaking are expected to have significant branching fractions for channels including high energy electrons or muons. These may be direct decay products, as in the case of a massive $Z' \rightarrow e^+e^-$, or they may arise from decays of W and Z bosons produced in the primary decay. Efficient lepton identification over large solid angle and down to low momenta will be essential for good acceptance for these multileptonic decays. Heavy quark decays can be tagged by the electrons from the decay cascade; good electron identification in a dense track environment will be necessary to exploit this signature.

The observation of transition radiation can provide valuable information for particle identification. The radiation process is a negligible perturbation to the particle, and so the information is complementary and supplemental to calorimetric measurements. The practical theory of transition radiation is well understood,[1] and reliable calculations can be made for the performance of a system design. A number of TRD's have been proposed [2-10] and used in accelerator experiments [11,12,13], and a number of studies have considered the inclusion of transition radiation detectors in SSC detectors.[14,15,16] Adequate performance of a TRD system requires that the thickness of the detector package be ~50 cm.[13,17] It will be vital that sufficient space be allocated to a TRD system so that the system performance is maintained under variations of the SSC operating environment. The usual contention for detector space that a TRD system must face is with the charged particle tracking system.

We propose to resolve this contention and optimize system performance by combining the two functions in an integrated transition radiation detector and charged particle tracker. Proportional straw chambers filled with a xenon-enriched gas will detect x-rays from transition radiation as well as the ionization of passing charged particles. The radiator materials will provide mechanical support and rigidity for the straws. This approach has the advantages of very high-rate capability, modular construction, and robust performance.

Experiments at the SSC will require use of as much information in real time as possible, in order to achieve the large reduction factor necessary between the raw event rate of 10^8/sec and the number of events that can reasonably be expected to be recorded for later study. Active devices with local reduction of raw data to physically meaningful quantities will be particularly important in this regard. It is our intention to equip the TRD/tracking device with local "feature extraction" hardware that will contribute to the formation of a refined electron trigger.

The development efforts will include:

- Detailed Monte Carlo studies of the performance of the proposed system in a realistic representation of the SSC environment;
- studies of mechanical support, gas manifolding, heat flow, and signal routing;
- An extensive effort in VLSI electronics to develop high-sensitivity, low-noise amplifiers integrated with a pipeline delay structure in the low-power dense packaging required for this application;
- Detailed studies of proportional straw performance, including pulse shapes and drift times in various gases, irradiation tolerance, and x-ray response;
- Development and characterization of various materials for the transition radiators;
- An exploratory project to implement, embedded in the electronics and readout system, the algorithms allowing optimal use of the TRD and tracking information on a timescale suitable for event triggering, using massively parallel and/or pipelined processors.
- The construction and test of prototypes, in three stages:
  1) Several 100-straw detectors for single particles in a test beam;
  2) A 1500-straw detector for studies of jets produced by 0.45 TeV protons;
  3) An engineering prototype representing the smallest symmetry element of a final detector, *e.g.* half a polygonal sector, with about 15,000 straws, integrated electronics, and tested in a realistic environment with a detector system including a segmented pad chamber and a finely-segmented calorimeter.

The proposed program draws on the experience and expertise of groups with well-established performance records in the technologies under consideration. The effort is expected to require four years, at the end of which we will have developed fully the designs and technology to build an SSC detector system and will have built and tested a large engineering-prototype detector to verify the approach. Milestones for the project are presented later in this document.

2. Role of a TRD/Tracker

Our TRD/tracker concept has three functions. In a detector with no central magnetic field, or with a small magnetic field, it can function as a central tracking system with sufficient resolution to establish event topology and associate tracks with primary events. The TRD system provides electron identification to augment the calorimetric selection of electron candidates. The proportional straws determine a track position extrapolated to the calorimeter face and provide the matchup of particle track and calorimeter shower centroid.

Furthermore, the detailed information of TRD response from many independent straw layers is potentially useful for tagging high momentum muons and hadrons. The TRD response is a function only of the Lorentz γ of the particles passing through it: electrons above one GeV give a saturated response, and muons and pions above 100 GeV or so are starting to radiate. The capability to tag high-momentum particles could prove to be extremely useful in matching muons and in characterizing jet fragmentation.

We have studied the required TRD performance for two cases:

a) the identification of so-called "isolated electrons". This is the case for decays of heavy objects such as
   - Higgs decay: $H \to ZZ$, $WW \to$ electrons,
   - new quarks: heavy t or heavier $D \to tW \to$ electrons,
   - SUSY particles,
   - new W', Z' and other high-mass particle decays.

   We discuss below the validity of the supposition that these electrons are indeed <u>effectively</u> isolated.

b) The identification of non-isolated electrons within or near jets. This can be important
   - to give a better understanding of background processes,
   - in the case of decays of heavy particles with b-quarks in the final state,
   - to have a detector capable of recognizing surprises.

We have done extensive Monte Carlo calculations to understand the necessary level of electron-hadron discrimination. For an example of type (a) above, we have considered the detection of a 400 GeV Higgs boson in the decay mode $H \to WW \to e\nu +$ 2 jets. We have chosen this reaction because it is a well-defined process leading to one high p_T "isolated" electron. We take a detector geometry corresponding to a TRD extending between r1 = 20 cm and r2 = 70 cm. The radiator thickness is 4% of a radiation length. The electromagnetic calorimeter is located at r2 = 70 cm and has a tower structure of 2 cm by 2 cm; we assume a standard deviation of 1 mm for location of the electromagnetic shower centroid.

Cross-sections for (<u>detected</u> electron plus jets) for the Higgs process and the relevant backgrounds are plotted versus the size ΔR of the jet isolation cone in figure (1). The desired signal is the lowest curve on this figure. The next largest rates shown are due to $pp \to W$ + jets and $pp \to t\bar{t}$ and ($b\bar{b}$ + $c\bar{c}$). These processes have the same final state particle content as the signal, and must be separated by their kinematical characteristics. Instead of pursuing these "physics" backgrounds, we have studied the sources of <u>false</u> electrons. Here, the dominant sources are

A) the overlap of an energetic photon and a charged particle from a jet in a two-jet event (the highest curve);

B) the overlap of a direct high p_T photon with a charged hadron from the underlying event.

In both cases, we have defined overlap as coincidence within ± two standard deviations of the expected particle-shower spatial matching in a calorimeter.

Examining the curves for these two backgrounds, we see that their relative importance depends on the range of the "isolation cone" ΔR that is chosen. A cut $\Delta R \geq 0.15$ loses 30% of the signal; whether that cut brings the two-jet background below the direct photon depends on (unknown) fragmentation functions. Even for a high cut in ΔR, the background is at least 500 times the signal. In this sense, we are not confident that it is safe to speak of "isolated" electrons. Accordingly, we aim for a rejection of false electrons by 10^{-3}, recognizing that kinematic cuts needed to suppress physical backgrounds may also suppress false electrons.

For electrons inside jets, the backgrounds far exceed the Higgs signal. It happens that reduction of the background to below the level of real electrons from (b + c) decays also requires hadron rejection of order 10^{-2}. For this case, the calorimeter offers little further rejection.

For a process of type (b) above, we studied events with jets of 500 GeV transverse energy. Jets and electrons were accepted inside $30° < \theta < 150°$. A threshold transverse energy for electron candidates (selected on the basis of calorimeter response) of 25 GeV or 50 GeV was applied. In Table (1) we show, for the two energy thresholds and for various ranges for θ, the number of real electrons and the number of false electron candidates from various sources; no TRD information has yet been used. As can be seen from table (1), hadron rejection by the TRD inside the jet is required at the level of $< 10^{-2}$ to assure a background of $< 20\%$ in the real electron sample.

From these two examples and from other studies that we and others have conducted, we conclude that hadron rejection at the level of 10^{-2} to 10^{-3} (following calorimetric selection of electron candidates) will be required to study some particularly interesting physics channels at the SSC. Below, we will describe a TRD/tracker system that will provide this capability. We note that the hadrons to be rejected are predominantly low energy – a few GeV. In effect, a TRD replaces one function of a high central magnetic field.

3. The Straw Design

We will pursue several options in the development of the radiators and the proportional straws, as discussed in more detail below. The basic approach[16] uses the cluster counting method for transition radiation detection.[13] We have studied several possible concepts.

One "straw design" is shown in figure (2). The proportional straw chambers are imbedded in radiator material. Another possibility is shown in figure (3). This approach uses "multi-straws" which have the radiator material forming concentric cylinders about the proportional straws. The full detector will be constructed from a number of independent modules, for which we are considering several different layouts. One possibility is indicated in figures (4). A module of the multi-straws is shown in figure (5). We are also studying the "pinwheel" design, figure (6). Positive features of this design are that the radial intermodule gaps are eliminated and all straws are accessible from the outer circumference. Disadvantages of this design include increased occupancy for the inner straws and large variation in track obliquity to the straws. Extensive modeling and engineering studies will be required to evaluate the relative merits of these alternatives.

In each of these concepts, the straws are oriented perpendicularly to the beam, in an azimuthal sense. They provide tracking in the $r-z$ plane and constitute the x-ray detector of the TRD. This configuration has major advantages over axial straws:

a) the straws are shorter, and hence occupancy is low;

b) straws at a fixed distance from the beamline subtend a fixed interval of rapidity and so have a fixed occupancy independent of their z position along the beamline;

c) the azimuthal straw array gives excellent pointing to the beamline for track association with the correct primary vertex;

d) there is reduction in layer-to-layer occupancy correlations due to particles from different interactions that are separated from the interaction of interest by more than a few millimeters along the beam line.

e) The e/π discrimination depends on the polar angle θ as $(\sin\theta)^{-1}$. It is approximately constant for particles with a given P_t, independent of θ.

f) The average response from straws in different parts of the detector varies only at the 10% level, due to the $\pm 22.5°$ variation of azimuthal angle within an octant; there is no polar angle dependence.

Based on the design shown in figure (4), we determine the typical parameters of such a system. The proportional straws are 4 mm in diameter. We plan to use a gas mixture of approximately 50% xenon, 30% CO_2, and 20% neon, resulting in a maximum drift time of 40 ns. Addition of CF_4 would further reduce the drift time.[18] In the central region there are 48 layers of straws, distributed from 35 cm to 77 cm from the beamline. The radiators are slabs of polyethylene foam, 1 cm thick and 5% of bulk density; they form planes parallel to the beamline and lie between pairs of straw planes. For the region below 30° the straw structure is similar but the radiator planes are rotated to be perpendicular to the beam line.

A total of 330,000 straws cover the range $|\eta| < 2.5$. The thickness through a sector center is 4% of a radiation length. At 1.4 interactions per crossing and 8 charged particles per unit of rapidity, the mean number of charged particles from beam-beam interactions per straw per crossing is .016 for the straws at a radius of 35 cm and .007 for straws at 77 cm radius. The shaped pulses have a duration of 10–20 ns, so the resolving time of a straw is three to four times the 16ns bunch spacing. The occupancy of the straws is expected to be dominated by event-associated particles[19]; it is .06 for the inner straws and .03 for the straws at the outer radius. There are ~70 electrons on average for each particle traversal. With gas gain of 1×10^4, standing currents are 0.05 to 0.1 μA, giving acceptably low integrated charge doses on the wires of $\leq$ .04 Coulomb/cm per 10^7 seconds of running at design luminosity.

We have also studied the performance of the radiator arrangement shown in figure (3), with the detector starting at radius of 20 cm and extending to 70 cm. The rapidity coverage considered was $|\eta| < 1.3$. We recognize that it is important to cover $|\eta| \leq 2.5$, but we have not yet studied in detail a possible layout and its performance. The total number of straws is ~130,000 for $|\eta| \leq 1.3$. The thickness through a sector center is 4% of a radiation length. The occupancy by charged particles, inside and outside high-energy jets, is shown in figure (7). The occupancy by TR x-rays is approximately one order of magnitude less.

Measurement of the $r - \phi$ position of tracks in the TRD/tracker is provided by a system of interpolating readout gas "pad" chambers. Resistive interpolation between amplifier taps spaced along an azimuthal cathode strip will give $r-\phi$ resolution of 150 microns. A single layer of chambers at a radius of 33 cm for the central region and with pad sizes of $(\Delta\phi \approx 2.8°) \times (\Delta\eta \approx 0.015)$ will provide better than millimeter precision for the track position extrapolated to the calorimeter. Several layers of pads might be desirable to assist pattern recognition. For the forward systems, pad chambers would be mounted on the faces of the modules. The total thickness of the pad chamber is $\leq$0.01 radiation lengths. There are ~50,000 pad channels per layer. Occupancy per channel (including multiple events and track obliquity) would be at the percent level. Simulation of such chambers will be included in the MC simulations of system performance, but the development of these chambers is not a part of the current proposal. Our collaboration includes groups at BNL and at CERN that are working to make large low-mass chambers of this type.

4. Test Beam Measurements of Transition Radiation Yield

Two different radiators were investigated in a 3 GeV/c beam at Serpukhov. A stack of regularly spaced polypropylene foils (20 μm thick, 280 μm spacing) and a polyethylene foam of unusual structure (figure (8)) were measured. The setup is shown schematically in figure (9).

The results are summarized in table (2). The foam produces 75–80% of the yield obtained with a periodic foil radiator. Based on these test results we estimate that the detector structure proposed here will yield 0.27 detected x-rays per centimeter of electron track, to be compared with the best-yet result of 0.20 as obtained by the Helios Collaboration.[13] These results were used as input in Monte Carlo performance studies as described below. We show in figure (10) the calculated pion rejection, at 90% electron efficiency, for isolated particles as a function of the pion energy and polar angle. A 50 cm thick TRD system was assumed.

5. Monte Carlo Studies of System Performance

Tracking Performance

We have conducted Monte Carlo studies of several variations of the basic conceptual design. Figure (11) shows an ISAJET[20] event as it would appear in the detector in figure (4). The central detector octagon has been unfurled and each octant is viewed from the side. There are three symbols for hits to the straws, with larger symbols corresponding to higher energy thresholds. The event is a 500 GeV Higgs particle decaying to Z^0Z^0 with each Z^0 subsequently decaying to e^+e^-. The electrons are clearly identifiable. Photon conversions are readily identified, and the tracking capability of the detector is evident. We calculate that individual tracks are projected back to the beam line with < 1 mm uncertainty in position along the beam line.

TRD Performance in Jets

Pion rejection was studied as a function of the angle α between the pion trajectory and the jet direction, for different values of the jet polar angle θ. ISAJET events were thrown as above, and combined with "minimum-bias" events to represent pileup. The results are given in figure (12), where we plot the probability P (per jet and per straw sector) that a hadron will satisfy electron selection criteria that give 90% electron efficiency; a), b), and c) correspond to different values of θ. The probability of misidentification is about 10^{-2} to 10^{-3} for angles larger than 5° with respect to the jet axis. At smaller angles, the background level increases slowly, reaching a few per cent at the jet core. The main reason for this is that the pions at the jet core are more energetic and start to radiate. Despite difficulties at the jet core, the overall result is satisfactory: a rejection factor of 10^{-2} is achieved as close as 5° to the jet axis.

Recognition of Photon Coversions

We also studied the performance of this detector in identifying photon conversions. Photon conversions can be recognized in the TRD/tracker by three signatures:

a) except for Dalitz pairs, the conversion will occur at some depth in the system, and straws along the trajectory and preceeding the conversion point will be hit only at the level of the random occupancy;
b) straws after the conversion will have energy depositions typically twice minimum ionizing;
c) there will be twice as many TR x-rays detected per radiator along the path after the conversion compared to the case for electrons.

These three signatures can be combined to give a very powerful rejection for photon conversions, as will be described below. The pad chamber, of course, will give a precision point on a charged particle track to provide further rejection of conversion/charged-particle overlap background.

The spatial size of a TR x-ray ionization cluster is about .5 mm; this corresponds to about 10 ns drift time. With 20 ns pulse shaping time, we find the pulse-height distributions shown in figure (13a): shown are the distributions of the energy depositions for one minimum ionizing particle (π), two pions, and electrons (dE/dx + TR clusters). To study the use of the energy deposition information in particle identification, we choose three thresholds for the detection of ionization clusters in each straw. The first threshold level (TH1 at 0.2 keV) gives about 80% efficiency for relativistic particles (this threshold would be used for tracking). The second threshold level (TH2 at 1.0 keV) is located between one- and two-particle energy clusters distribution; it has ~50% efficiency for minimum-ionizing particles and ~90% efficiency for conversions. The third threshold level (TH3 at 4.5 keV) corresponds to ~ 80% efficiency for TR x-rays.

The analysis power of this method is demonstrated in figure (13b–f). The abscissa of each scatterplot indicates for a given particle the number of straws with energy deposition above TH3; the ordinate exhibits the number of straws with energy deposition between TH1 and TH2. The criteria for 90% electron acceptance are also indicated. This simple algorithm then permits not only efficient discrimination between electrons and single pions, figures (13b) and (13c), but also between multiple overlapping pions, figures (13d) and (13e). Similarly, photon conversions before the TRD are easily recognized and rejected, figure (13f).

We consider using a slightly more elaborate algorithm to reject photon conversions in the TRD. In this case, the TRD is subdivided into several parts (*e.g.* i=1,...5) along the track and for each part we measure the dispersions

$$DN_3 = \Sigma(N_3^i - \bar{N}_3^i(e))^2$$

$$DN_{12} = \Sigma(N_{12}^i - \bar{N}_{12}^i(e))^2.$$

Here N_{12}^i and N_3^i are the measured number of threshold crossings in detector part i; $\bar{N}_{12}^i(e)$ and $\bar{N}_3^i(e)$ represent the expected number of hits produced by a single electron in the corresponding detector part. In figure (14) we show scatterplots for three different cases: single electrons, conversions anywhere in the TRD, and conversions overlapping with one pion. This algorithm achieves powerful discrimination between electrons and conversion electrons.

Tagging of Particles with Large Lorentz Factors

With the aid of the TRD it is possible to identify not only electrons but also other charged particles with $\gamma \geq 10^3$. This is possible even inside jets, since the typical pion momentum is a few GeV. Of particular interest is muon tagging by the TRD, to link up to tracks from the muon spectrometer. The achievable hadron rejection factor, for 90% muon acceptance, is shown in figure (15) as a function of the muon energy for two values of the polar angle.

These Monte Carlo results, while not exhaustive, are very encouraging in their demonstration of the depth and the flexibility of the integrated TRD/tracker approach in identifying electrons and in rejecting a variety of potentially troublesome backgrounds.

6. Principal Development Efforts

The technical developments needed to realize the TRD/tracker concept are challenging. We describe below the principal areas where R&D will be focused.

Electronics Development

The readout electronics and its interface to trigger processors represent the key developments that will determine the performance of the detector system. State-of-the-art performance will be necessary in the following areas:

→ front end sensitivity, speed, and noise
→ data storage (analog or digital) during trigger decision
→ channel density
→ power dissipation
→ an architecture allowing high-speed data processing and communication with the trigger processor for particle identification purposes (electrons or high p_T particles, background rejection).

A block diagram of one approach is given in figure (16). The signal from a straw is amplified and shaped. A few-bit FADC (two of three bits) would digitize the signal, synchronized to the 16 ns bunch crossings. The thresholds of the FADC would be optimized as discussed above in the MC study of electron identification. We plan also to evaluate the possible performance advantages of an analog pipeline with digitization only after the Level-1 decision.

Once digitized, we envisage to use the information for local feature extraction, forming a fast-response trigger after ~10 μseconds. Detailed architectural studies and simulation are required. A pipelined approach is possible, using fast global memory modules with a 'region-of-interest option' controlled by calorimetric first-level trigger information. Alternatively, a massively parallel mesh of simple processors may be used[21] to determine simultaneously all high-p_t tracks, leaving association with calorimeters to a later stage or executing only a very coarse association.

The performance of the TRD/tracker concept can only be correctly evaluated if systems tests are carried out with close-to-final readout electronics and trigger capability. For this reason we wish to start quickly on the system definition and design considerations. We also wish to provide our engineers with adequate training in new design methodologies including ASIC implementation of the electronics and systems simulation.

The development of the electronics system is the most challenging part of this detector project. It will require professional design tools and a commitment of several electronics engineers over a period of three to four years, by which time a useable circuit could be available for prototype detectors. A radiation-hard design would be done in a subsequent step.

Mechanical Developments

Structural supports and stability studies for the straws and radiator must be an engineering priority. Gaps between the modules must be minimized. The modules themselves are quite light – one hundred kilograms for each octant. Another problem will be in managing the necessary gas flow and heat flow through the system. Temperature gradients must be sufficiently small to ensure gas gain uniformity at the level of 10%. In addition, cooling of the electronics will impose further constraints. The challenge here is to furnish the necessary utilities within a minimal intermodule gap. Study of the systems engineering issues will be led by the Boston University group; they will direct a subcontract with the Westinghouse Science and Technology Center, which has excellent design resources and an extensive engineering staff that will be available for consultation.

Development of technology for the multistraws must be pursued. Extensive tests of

pulse shapes, drift times, irradiation tolerance, and other properties will be required for the various options in straws and gases. This work will be pursued at Moscow and at Boston University, drawing upon broad experience in building and operating proportional straw tracking devices[22],[23],[24].

Continuing study is required on foams for the radiator material. Foams have been used in some experiments before [25]. Foam is very appealing for the simplicity of the radiator structure, for the mechanical support and rigidity it can lend to the straw assembly, and because its TR response is independent of the direction of the incident particle. Foams are available with a wide variety of physical characteristics[26]; the challenge is to find a material with sufficiently regular cell size and wall thickness in the sizes appropriate for the SSC regime. The Moscow groups will continue their work in this area. Open-cell foams for the radiators could be interesting as a way to address cooling problems.

Simulation of Detector Systems

Complete simulations of the various options in detector configuration, straw operation, electronics, and triggers will be necessary to evaluate the advantages and disadvantages of each feature and to assess system performance in the SSC environment. We have already developed at Moscow and at Boston University some Monte Carlo programs to simulate the TRD/tracker. These will require further work to provide the accurate performance evaluation that will be necessary to optimizing the design of the system. Simulation at the signal level will be an absolute necessity for the development of electronic and triggering components.

7. Milestones

The milestones of this development project are presented on a page following. For the first year we have indicated in some detail the specific work to be undertaken and the institutions that will be mostly involved in each task, although of course there will be broad involvement by all the collaborators in most stages. Subsequent years are presented in somewhat less detail.

We anticipate by early 1991 to have a test detector with of order 10^3 straws and borrowed, discrete electronics ready for beam tests in a 450 GeV beam at CERN. The purpose here will be to verify TRD and tracking performance and to test engineering concepts for manifolding and support. By mid-1993 we plan to have a full-scale prototype of a trd/tracker half-sector, with VLSI electronics and associated trigger processors. This will be installed in the test area

together with a pad chamber and the BNL/CERN liquid argon calorimeter and subjected to full system performance tests.

8. Budgets

Following the list of milestones, we present the first-year budgets for the US groups participating in this collaborative effort. These budgets represent increments requested to the normal operating budgets of these groups (the Columbia project is a new activity, and a separate request will be made for an operations base). After the budgets, we include the proposal from the Westinghouse Electric Corporation's Science and Technology Center for a subcontract (to be directed by Boston University, and included in the BU budget) to provide mechanical design and analysis assistance.

The CERN and Moscow groups will request funding for their participation through their respective institutions.

We anticipate that the operations budgets for subsequent years will increase in response to the need for increased scientific staff for the analysis and design stages. In the case of the VLSI tools, the equipment costs are being spread over the first two years to reduce front-loading. Requirements for equipment funds will rise significantly for years three and four when we are designing and constructing the 15,000-straw engineering prototype system.

Milestones for the TRD/Tracker Development Project

Goals for 1990 (first year):

- Preparation of VLSI design tools necessary for electronics development (Columbia, CERN).
- Assessment of mechanical engineering issues: structural support of the modules, gas manifolding, heat flow (BU).
- Monte Carlo study of the performance of the system, and refinement of the conceptual design (BU, Moscow).
- Laboratory tests of straw performance with xenon mixtures, including drift times, and signal shape (BU, BNL, Moscow).
- Design and tests of different radiators (Moscow).
- Radiation damage studies of straw/radiator assemblies (Moscow, BU).
- Study of readout architecture and triggering requirements, in conjunction with SSC calorimeter R& D groups (BNL, CERN, Columbia)
- Construction of a pad chamber prototype, and analysis of performance (CERN: this activity is pursued by members of the CERN group as an independently funded activity)
- Beam tests of 3-threshold algorithm with 100-straw prototype (CERN, Moscow)
- Preparation of a 1000-straw test module
  - mechanics (BU, Moscow)
  - electronics (BNL, Columbia)
  - test facilities (CERN)

Goals for 1991 (second year):

- Simulation of front-end chip following related designs
- Design and simulation of 3-bit pipeline
- Start silicon processing
- Set up test station for trigger development tests
- Set up, run, and analyze 1000-straw test system

Goals for 1992 (third year):

- Complete silicon processing, for test quantities
- run 1000-straw test with pad chamber and calorimeter
- test VLSI electronics on a (second) 1000-straw system
- Design and start construction of 15,000-straw prototype detector system.
- Engineer trigger processor for 15,000-straw system

Goals for 1993 (fourth year):

- Complete trigger processor for 15,000-straw system
- Test 15,000-straw prototype detector system, with pad chamber and calorimeter
- Analyze 15,000-straw test results and compare with simulations
- Iterate design for final detector

BOSTON UNIVERSITY

1 January 1990 through 31 December 1990

1. SALARIES AND WAGES	$55,700
Faculty:	
S. Ahlen†	$7,256
J. Beatty†	4,444
Postdoctoral research associate:	
J. Shank	32,000
Undergraduate research assistants (3)	12,000
2. FRINGE BENEFITS	10,660
24.4% of professional salaries	
TOTAL SALARIES AND BENEFITS	66,360
3. TRAVEL AND SUBSISTENCE	31,000
Domestic	19,000
Foreign	12,000
4. SUPPLIES AND SERVICES	32,000
TRD gases	15,000
Materials, supplies	11,000
Computer services	4,000
Telecommunications	2,000
5. SUBCONTRACT	115,680
Subcontract to Westinghouse Science and Technology Center for systems engineering	
TOTAL DIRECT COSTS	245,040
6. INDIRECT COSTS*	69,460
TOTAL OPERATIONS REQUEST	$314,500
7. EQUIPMENT (details on following page)	158,500
A. Radiation Damage System	$27,000
B. Preprototype Test Bed	37,500
C. Mechanical fabrication & assembly, 1000-straw prototype	70,000
D. Vax workstation for simulations	24,000
TOTAL REQUEST	$473,000

†One month summer salary.
*Calculated as a composite of 35% on campus @ 73.0%, 65% off campus @ 47.0% of MTDC, minus underrecovery.

BOSTON UNIVERSITY

Equipment Details

1. Radiation Damage System		27,000
gas system		3,000
regulators, filters, fittings	500	
flow controllers	2000	
fabrication	500	
radioactive sources		1,500
data acquisition system and electronics		21,500
computer, printer	5,500	
CAMAC crate, controller	5,000	
32-ch low-voltage ADC	3,000	
NIM crate, modules	3,500	
High voltage power supplies	2,500	
I, P, T monitors	2,000	
Test chamber fabrication		1,000
2. Preprototype test bed		37,500
gas system		3,000
oscilloscope		4,500
power supplies, modular electronics		5,500
readout: 50 channels @ $250/channel for amp, shaper, ADC		12,500
straws, radiator materials		4,000
design and fabrication		8,000
engineering	1,000	
mechanical fabrication	3,000	
materials	2,000	
electronics fabrication	2,000	
3. Prototype 1000-straw system		70,000
gas system		5,000
engineering		5,000
mechanical fabrication and assembly: 10^3 channels @ $60/channel endplates, manifolds, endplugs, ferrules, stringing, and mechanical assembly; cost based on per-channel charges of comparable systems built at BU		60,000

BROOKHAVEN NATIONAL LABORATORY

1 January 1990 through 31 December 1990

1. SALARIES AND WAGES	$118,000
Electronics engineer	90,000
Electronics technician (50%)	28,000
2. TRAVEL AND SUBSISTENCE	25,000
3. SUPPLIES AND SERVICES	25,000
TOTAL OPERATIONS COSTS	168,000
4. EQUIPMENT	60,000
Test station for trigger processor	
TOTAL REQUEST	$228,000

(Fringe benefits and IDC @ 46.5% included in each item as appropriate.)

ER F 4620.1
(7-85)

U.S. Department of Energy

Grant Application Budget Period Summary

(See Reverse for Definitions and Instructions)

OMB Approval No. 1910-1400

Please Print or Type

Organization: The Trustees of Columbia University in the City of New York	Period Covering: From: 1/1/90 To: 12/31/90	FOR DOE USE ONLY Proposal No: Award No.:
Principal Investigator (P.I.)/Project Director (P.D.): Prof. F. Sciulli		

SENIOR PERSONNEL PI/PD Co PIs, Faculty and Other Senior Associates (List each separately with title. A.6 show number in brackets. Attach separate sheet, if required.)	DOE Funded Person-Mos. Cal.	Acad.	Sumr.	Funds Requested By Applicant $
1.				
2. F. Sciulli				0
3.				
4.				
5.				
6. (1) TOTAL SENIOR PERSONNEL				
OTHER PERSONNEL (SHOW NUMBERS IN BRACKETS)				
1. ( ) POST DOCTORAL ASSOCIATES				
2. (3) OTHER PROFESSIONALS (TECHNICIAN, PROGRAMMER, ETC.)	36			150,000
3. ( ) GRADUATE STUDENTS				
4. ( ) UNDERGRADUATE STUDENTS				
5. (.5) SECRETARIAL-CLERICAL				10,000
6. ( ) OTHER				
TOTAL SALARIES AND WAGES (A + B)				160,000
FRINGE BENEFITS (IF CHARGED AS DIRECT COSTS) 27%				43,200
TOTAL SALARIES, WAGES AND FRINGE BENEFITS (A + B + C)				203,200
EQUIPMENT (LIST ITEM AND DOLLAR AMOUNT FOR EACH ITEM) 1. VLSI design tools: $200,000 2. Test equipment: 40,000 3. Test data acquisition system: 50,000				
TOTAL EQUIPMENT				290,000
TRAVEL 1. DOMESTIC (INCL. CANADA AND U.S. POSSESSIONS)				30,000
2. FOREIGN				
F. OTHER DIRECT COSTS				
1. MATERIALS AND SUPPLIES				30,000
2. PUBLICATION COSTS/PAGE CHARGES				
3. CONSULTANT SERVICES				25,000
4. COMPUTER (ADPE) SERVICES				4,000
5. CONTRACTS AND SUBGRANTS				
6. OTHER				4,000
TOTAL OTHER DIRECT COSTS				93,000
TOTAL DIRECT COSTS (A THROUGH F)				586,200
INDIRECT COSTS (SPECIFY RATE AND BASE) 74.1%				
TOTAL INDIRECT COSTS				118,115
TOTAL DIRECT AND INDIRECT COSTS (G & H)				704,315
APPLICANT'S COST SHARING (IF ANY)				
TOTAL AMOUNT OF THIS REQUEST (ITEM I LESS ITEM J)				704,315

PI/PD TYPED NAME & SIGNATURE	DATE 9/28/89
INST. REP. TYPED NAME & SIGNATURE	DATE

Westinghouse
Electric Corporation

Science & Technology Center

1310 Beulah Road
Pittsburgh, Pennsylvania 15235
(412) 256 1000

September 27, 1989

Dr. Scott Whitaker
Physics Department - Boston University
590 Commonwealth Avenue
Boston, Massachusetts 02215

Subject: Westinghouse Proposal 89M844-4
"Mechanical Design and Analysis Assistance for TRD Tracking Sub-System"

Dear Dr. Whitaker:

The Westinghouse Science and Technology Center is pleased to participate with Boston University in proposing a collaborative R&D program to the Department of Energy under the auspicies of its Generic SSC Detector R&D Program.

The enclosed proposal describes a 12-month research program, entitled "Mechanical Design and Analysis Assistance for TRD Tracking Sub-System". A summary of the cost information for this program is as follows:

FY 1990	$ 87,247
FY 1991	$ 28,433
TOTAL PROGRAM . . .	$115,680

Westinghouse will provide formal cost information for the FY 1990 estimated costs in Standard Form 1411 format upon request. Westinghouse submits this proposal anticipating the negotiation of a cost-type, DOE-funded, Federal Procurement-Regulated, contract or subcontract containing mutually-agreeable terms and conditions.

Hopefully this information will aid you in preparing your proposal. If you need additional information or have any questions, please contact Mr. D.T. Hackworth (412-256-2296) for technical matters or the undersigned (412-256-2736) for administrative matters.

Very truly yours,

Claire A. Halucka
Marketing Representative
STC Proposals Group

gt

Enclosures

cc: (W) STC - Mr. D.T. Hackworth, Manager Electromechanics

89M844-4

Proposal to

Physics Department
Boston University
590 Commonwealth Avenue
Boston, Massachusetts

Mechanical Design and Analysis Assistance for TDR Tracking Subsystem

STATEMENT OF WORK

September 1989

Approved:

F. T. Thompson

F. T. Thompson, General Manager
Engineering Technology Division
Westinghouse Science and Technology Center

TRANSITION RADIATION DETECTOR AND TRACKING CHAMBER FOR THE SSC

— STATEMENT OF WORK —

The Westinghouse Electric Corporation proposes a 12-month program to perform the preliminary mechanical design and analysis of a transition radiation detector and tracking chamber (TRD/Tracker) for the superconducting supercollider (SSC). The work will be carried out at the Westinghouse Science & Technology Center (STC) in Pittsburgh, Pa. Upon completion of the proposed program, necessary detail and assembly drawings for manufacture and testing of the tracking module components will be delivered to Boston University in Boston, Massachusetts.

The program is divided into three specific areas of performance:

- Mechanical design
- Thermal management
- Manufacturability

These three areas have been divided into eight tasks. Each task is described in the following pages.

TASK 1. TRANSITION RADIATION DETECTOR AND TRACKING DEFINITION AND SPECIFICATION

In Task 1, Westinghouse STC will work with Boston University to specify the functional design requirements for the detector. Physical constraints, such as size, weight, length, and detector geometry, will be identified as well as electrical leads and cooling requirements. In Figure 1, this effort is shown as lasting most of the first year of the program. This time frame will be required in order to make specification modifications as the concept progresses over the first year.

TASK 2. MECHANICAL DESIGN AND ANALYSIS

In Task 2, the preliminary design of the TRD/tracker assembly will be performed. Concepts proposed by the working group of STC and Boston University will be reviewed and evaluated. The final selected concept will be analyzed for structural adequacy to ensure sufficient stability and rigidity so that alignment requirements can be maintained over the design life of the device. Routing and connections of power, cooling, and instrumentation cabling and hoses will be conceptualized. Materials selection for construction of the detector will be based on input from Boston University.

TASK 3. FABRICATION DRAWINGS AND INTERFACES

Layout drawings of concepts proposed and studied in Task 2 will be prepared. Concept drawings of the selected transition radiation detector for a 1000 straw tube module configuration will be prepared in sufficient detail to obtain costing and scheduling information. Assembly drawings will be developed as necessary to assist in the fabrication and assembly procedure as well as interfaces with adjacent subsystems.

TASK 4. FABRICATION/ASSEMBLY PROCEDURES

The purpose of this task is to specify in sufficient detail the fabrication processes and assembly procedures required of the concept selected. These procedures will include such items as the following:

- Straw tube module mounting procedure
- Straw tube module assembly procedure
- Structural support fabrication method
- Module assembly sequence
- Electrical cable routing procedure
- Cooling hose routing procedure

These procedures will be prepared in a form to match the concept detail and costing estimate requirements for construction of a device.

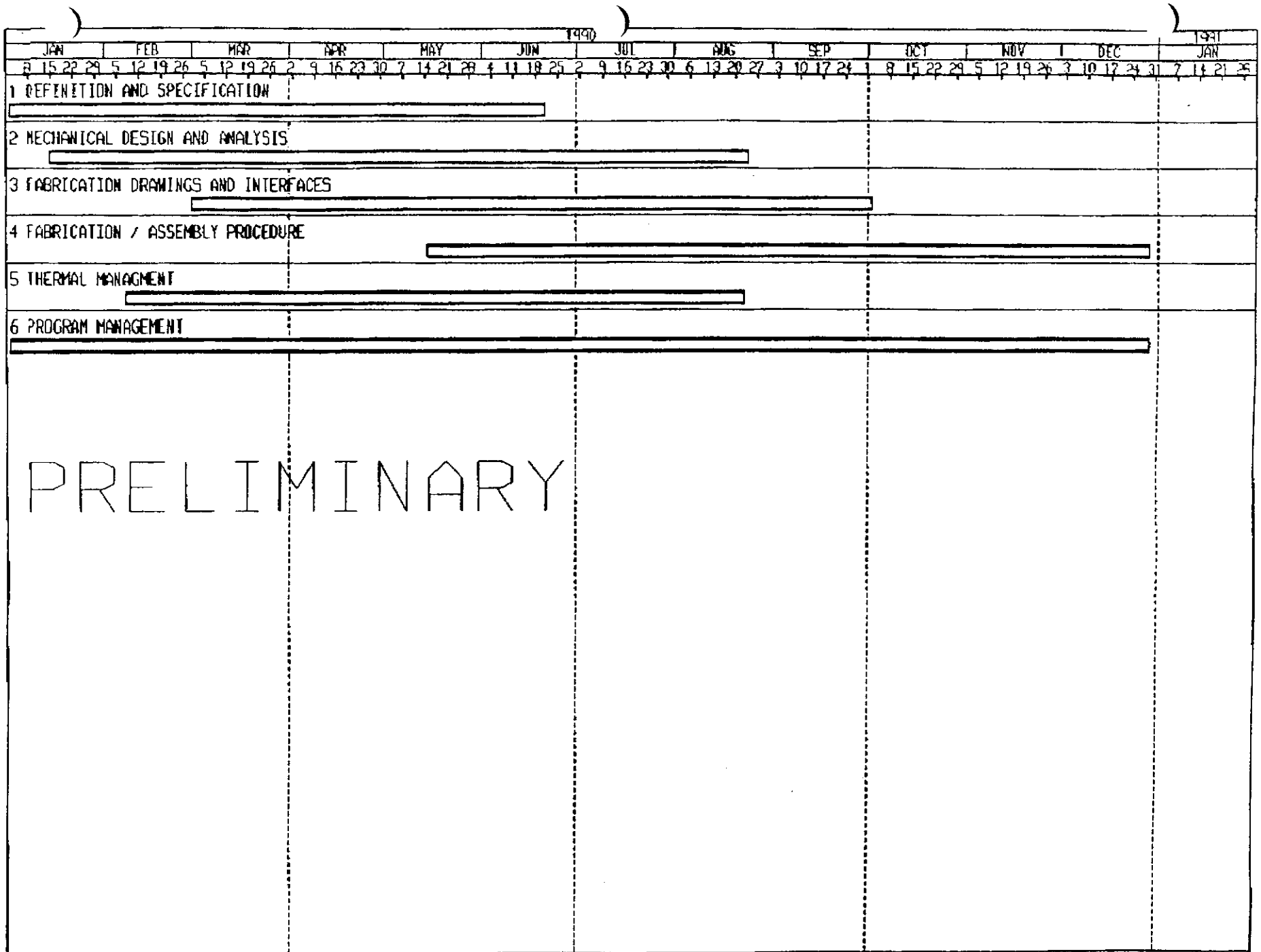
TASK 5. THERMAL MANAGEMENT

Thermal management will address cooling methodologies for removing the heat generated within the modules. All known sources of heat, both internal and external to the straw tube, will be determined and evaluated for the effect on detector performance. A scheme will be proposed for maintaining the detector modules at a uniform operating temperature with minimum compromise on the overall performance of the straw tube drift chamber.

TASK 6. PROGRAM MANAGEMENT

The program management task consists of the preparation of reports, design reviews, general meetings, and cost reporting to the overall program manager. Estimates of the Westinghouse effort are based on the following activities:

- Monthly progress and cost letter reports for 12 months
- Group meetings at Boston University every 6 weeks
- Yearly report to DOE describing technical progress



Summary Bar/ Early Dates
Critical Designator
Progress Bar

Primavera Systems, Inc. 1984-1989

WESTINGHOUSE ELECTRIC CORPORATION
Transition Radiation Detector
W3: SUMMARY BY TASK

Sheet 1 of 1

Project Start : 1JAN90
Project Finish: 22DEC91

Data Date: 1JAN90
Plot Date: 28SEP89

TRDP- Transition Radiation Detector Program

Date	Revision	Checked	Approved

References

[1] See for example: M.L. Cherry *et al.*, Physical Review D10, 3594, (1974); X. Artu *et al.*, Physical Review D12, 1289, (1975); G.M. Garibian *et al.*, Nuclear Instruments and Methods, 125 (1975) 133.

[2] T. Ludlam *et. al.*, Nucl. Instr. and Meth. 180 (1981) 413.

[3] C. W. Fabjan *et. al.*, Nucl. Instr. and Meth. 185 (1981) 119.

[4] J. F. Detoeuf *et. al.*, Nucl. Instr. and Meth. 265 (1988) 157.

[5] M. Holder and H. Suhr, Nucl. Instr. and Meth. 263 (1988) 319.

[6] R. Ansari *et. al.*, Nucl. Instr. and Meth. 263 (1988) 51.

[7] Y. Watase *et. al.*, Nucl. Instr. and Meth. 248 (1986) 379; Transition Radiation Detector for VENUS Experiment at TRISTAN (1987), KEK preprint 87-29.

[8] H. J. Butt *et. al.*, Nucl. Instr. and Meth. 252 (1986) 483.

[9] R. D. Apphun *et. al.*, Nucl. Instr. and Meth. 263 (1988) 309.

[10] A. Vacchi, Nucl. Instr. and Meth. A252 (1986) 498.

[11] J. Cobb *et. al.*, Nucl. Instr. and Meth. 140 (1977) 413.

[12] I. A. Denisov *et. al.*, preprint FNAL 84/134-E (1984).

[13] B. Dolgoshein, Nucl. Inst. and Meth. 252 (1986) 137.

[14] Snowmass 1984, Report of the Electron Identification Group, G. B. Yodh *et. al.*.

[15] Snowmass 1986, Identification of Electrons at the SSC, G. Brandenburg *et. al.*.

[16] T. Akesson *et al.*, in *Experiments, Detectors, and Experimental Areas for the Supercolider.*, R. Donaldson and M.G.D. Gilchriese, ed., Berkeley, 1987, p.472.
T. Akesson, C.W. Fabjan, F. Sauli, J. Schukraft (CERN), V. Chernyatin, B. Dolgoshein (Moscow Phys. Eng. Inst.), 1988. CERN GENEVA - CERN 88-02 (88,REC.MAY) 31-38. Estimate of a Transition Radiation Detector's Performance as Part of an Electron Identification Scheme.

[17] H. Grassler *et. al.*, "Simultaneous Track Reconstruction and Electron Identification in the H1 Radial Drift Chambers"; paper presented by J. B. Dainton at the Workshop on 4-Pi Tracking Systems for the Superconducting Supercollider, Vancouver, July, 1989.

[18] J. Fisher *et. al.*, Nucl. Instr. and Meth. !238 (1985) 249.

[19] Radiation Effects at the SSC, section 2.1, SSC-SR-1035 (1986).

[20] F.E. Paige and S.D. Protopopescu, Brookhaven Report BNL-38034, (1986).

[21] S. Lone, R. K. Bock, Y. Ermolin, W. Krischer, C. Ljuslin, K. Zografos. Fine-grain Parallel Computer Architectures in Future Triggers. Submitted to Nucl. Instr. Meth.

[22] A. Tomasch et al., Nucl. Instr. Meth. A241(1987)265. Response of High Resolution Drift Tubes to Relativistic Heavy Ions.

[23] S. Ahlen et al., Phys. ReV. Lett. 61(1988)145. New Limit on the Low-Energy Antiproton/Proton Ratio in the Galactic Cosmic Radiation.

[24] B. Zhou et al., Nucl. Instr. Meth. in press (1989). Using Dimethylether as a Drift Gas in a High Precision Drift Tube Detector.

[25] See for example, M. L. Cherry, Phys. Rev. D17 (1978) 2245 and references therein.

[26] D. A. Wrobleski *et. al.*, Los Alamos National Laboratory report LA-11271-MS, July, 1988.

Tables

Table (1) - Results from Monte Carlo simulation jets with 500 GeV transverse energy as observed in the TRD/tracker. The numbers of real electrons and of false electron candidates from various sources are given for two thresholds in electron transverse energy and for several bins in polar angle.

Table (2) - Results from beam tests at Serpukhov, comparing transition radiation yield from periodic polyethylene foil radiators and from polyethylene foam.

Table 1. MC study of real and false electrons found inside 3847 jets with 500 GeV transverse energy.

Source	A		B		C		D		E		F	
E_e	25	50	25	50	25	50	25	50	25	50	25	50
total	148	70	715	171	1252	661	75	38	339	123	80	31
$70° < \theta < 90°$	56	27	212	40	372	193	21	11	101	41	25	10
$50° < \theta < 70°$	44	20	223	72	422	230	24	13	113	46	26	10
$30° < \theta < 50°$	48	23	280	59	458	238	30	14	125	46	29	11

Sources of detected electron candidates:
A: Real electrons from c or b decays
B: Hadrons with energy deposition in the e.m. calorimeter
C: π^0 or γ matched with track within 4 mm × 4 mm in e.m. calorimeter
D: Photon conversion in radiator matched with track within 4 mm × 4 mm in e.m. calorimeter
E: Photon conversions in the radiator
F: Dalitz e^+e^-

Table 2. Summary of test results on transition radiation yield from regular foils and foam.

Thr. (KeV)	Number of Clusters per straw. pions	electrons Regular Foils	Foam 6.7% of bulk density
4.0	0.07	0.38	0.30
4.5	0.06	0.35	0.27
5.0	0.05	0.32	0.24

Figure Captions

(1) - Cross sections for different processes for real and false electrons as a function of an isolation cut ΔR. False electrons originate from the spatial overlap of γ's with hadrons, assuming a spatial accuracy of σ=1 mm, and using a 2σ cut.

(2) - Cross section through a conceptual TRD. Straws are imbedded in radiator material, e.g. polyethylene foam.

(3) - The "multistraw" concept. Each proportional straw is surrounded by several concentric radiators. The TRD is assembled in hexagonal close packing.

(4) - Layout of an octagonal structure of TRD modules with layered straws and radiators.

(5) - Conceptual view of a multistraw TRD module.

(6) - The "pinwheel" layout of TRD modules. Electronics and gas manifolding are accessible from the periphery.

(7) - Occupancy of straws by charged particles as a function of the angular separation from the jet axis. The occupancy due to TRD clusters is approximately an order of magnitude less.

(8) - Micrograph of the polyethylene foam that was tested at Serpukhov. The cell diameter is 200 ± 70 μm, and the wall thickness is15 ± 5 μm. The foam density is ~ 67mg/cm^3.

(9) - Layout of the Serpukhov test to measure TR yield from foam and from periodic foil radiators.

(10) - Rejection factor for charged pions as a function of pion energy in a 50 cm-thick TRD. This performance estimate is based on test beam measurements.

(11) - Display of a simulation of an ISAJET event as observed in the TRD/tracker. The event is the decay of a 500 GeV Higgs to ZZ and then to four electrons. Three sizes of symbols mark three thresholds for straw energy depositions.

(12) - Probability that charged pions may simulate an electron as a function of the angular separation α between the jet axis and the pion. Jet energy is 500 GeV.

(13) - a) energy deposition in a single straw by one and two pions and by TR photons plus dE/dx for electrons.
- b-f) acceptance of electrons and rejection of different sources of background.

(14) - Results of an algorithm used to reject photon conversions in the TRD. See text for explanation.

(15) - Rejection of typical pions as a function of muon energy, for criteria that give 90% muon acceptance, demonstrating the powerful "muon-tagging" capability of the proposed TRD/tracker.

(16) - Conceptual functional diagram of the front-end electronics for the TRD/tracker.

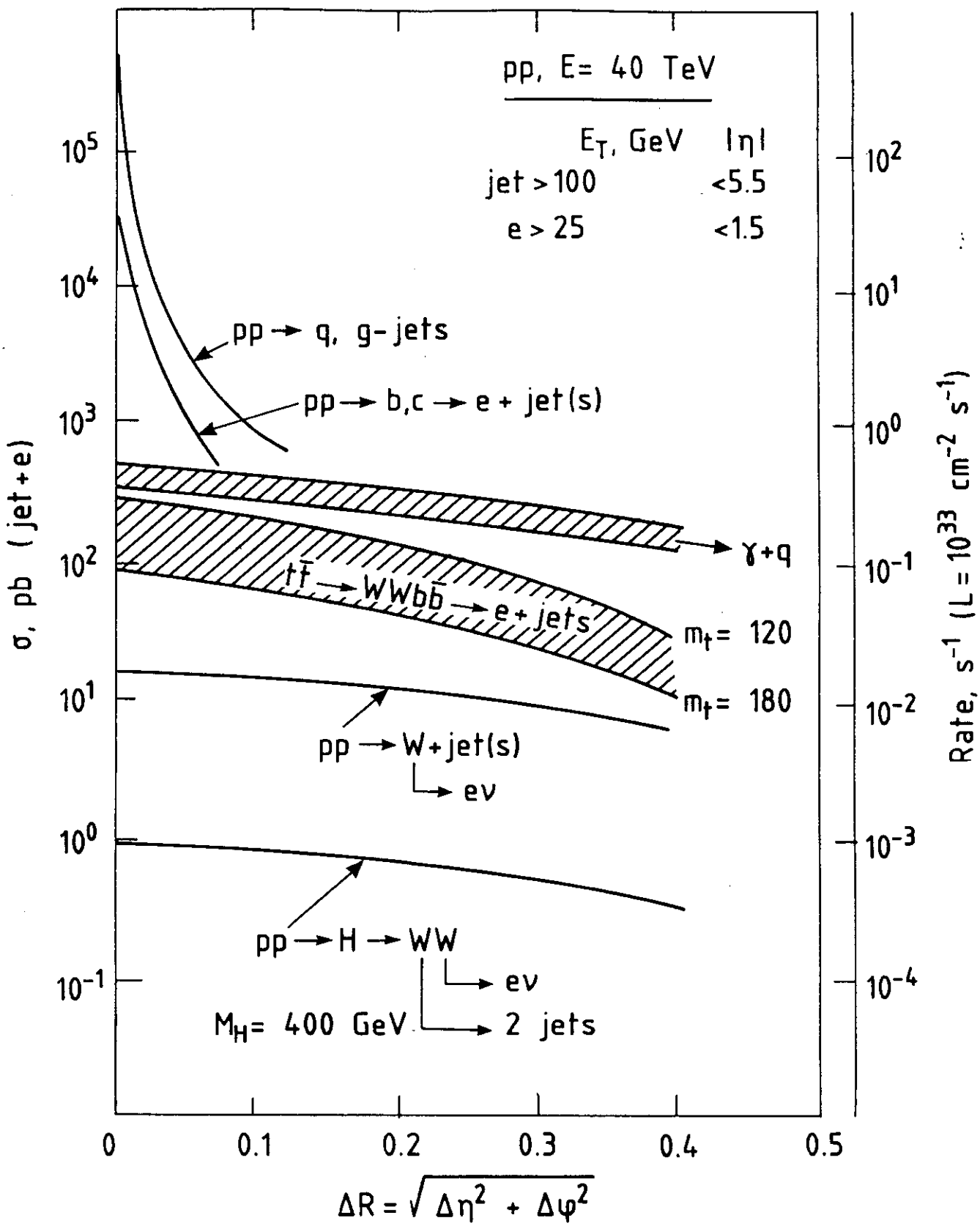

pp, E= 40 TeV
E_T, GeV
|η|
jet > 100
<5.5
e > 25
<1.5
pp → q, g-jets
pp → b,c → e + jet(s)
γ+q
tt̄ → WWbb̄ → e+jets
m_t = 120
m_t = 180
pp → W+jet(s)
→ eν
pp → H → WW
→ eν
→ 2 jets
M_H = 400 GeV
σ, pb (jet+e)
Rate, s^-1 (L = 10^33 cm^-2 s^-1)
ΔR = √(Δη² + Δφ²)

Fig 1

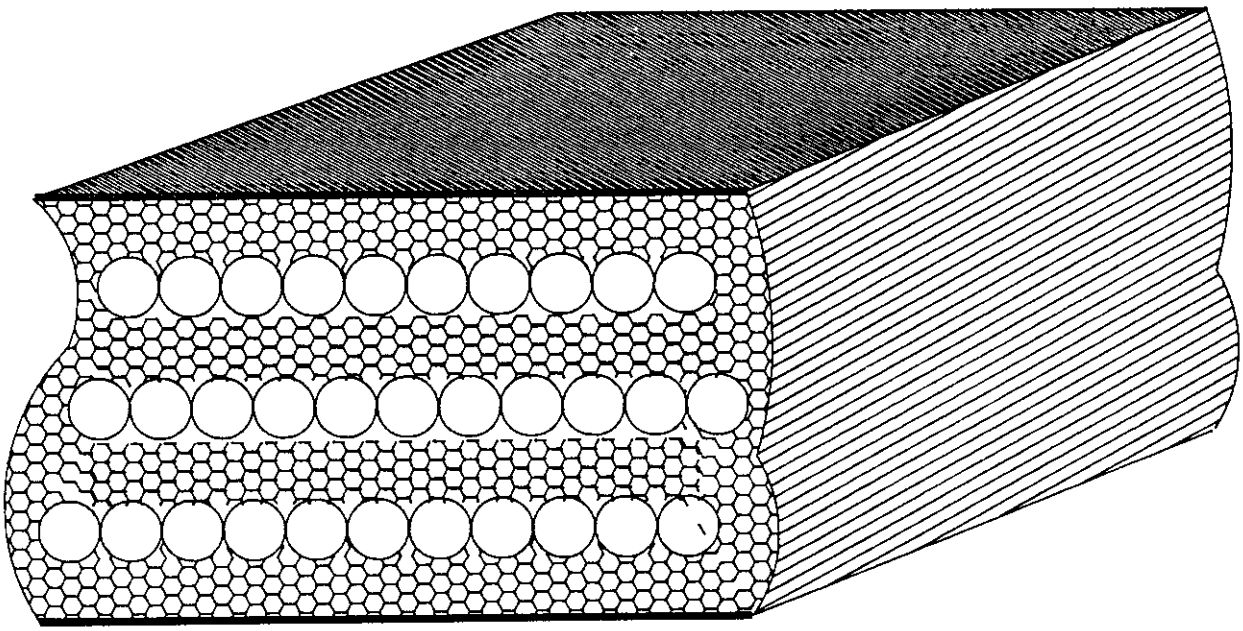


Fig. 2

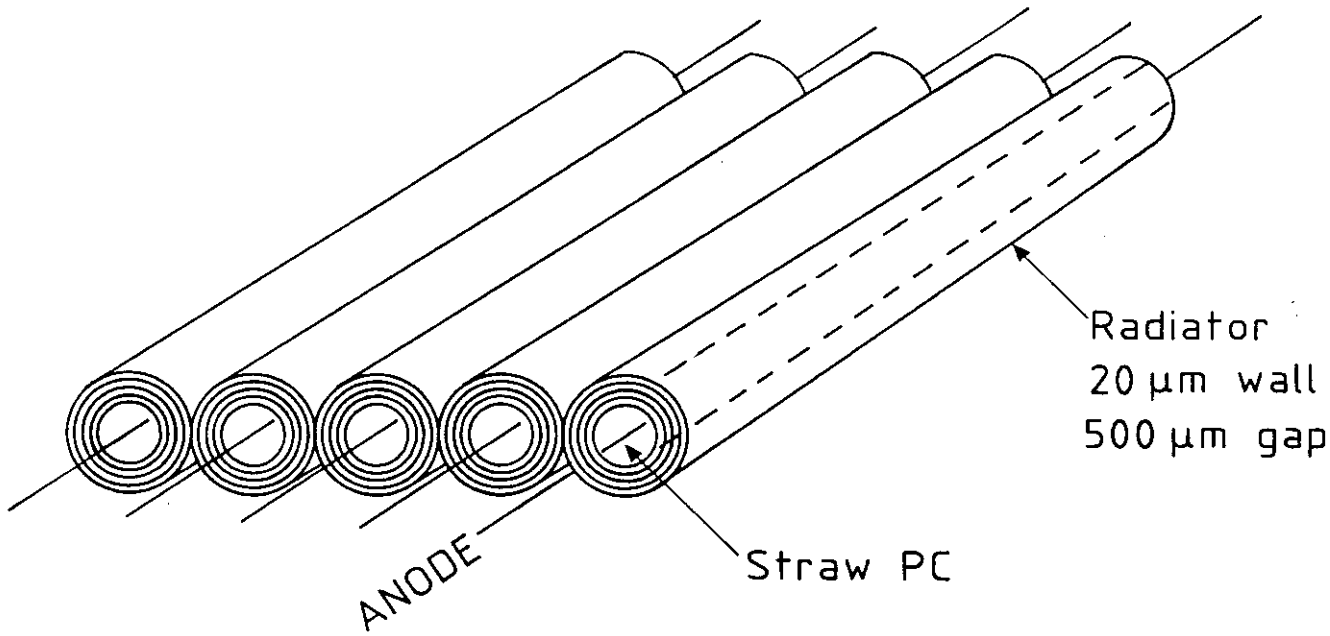


Fig. 3

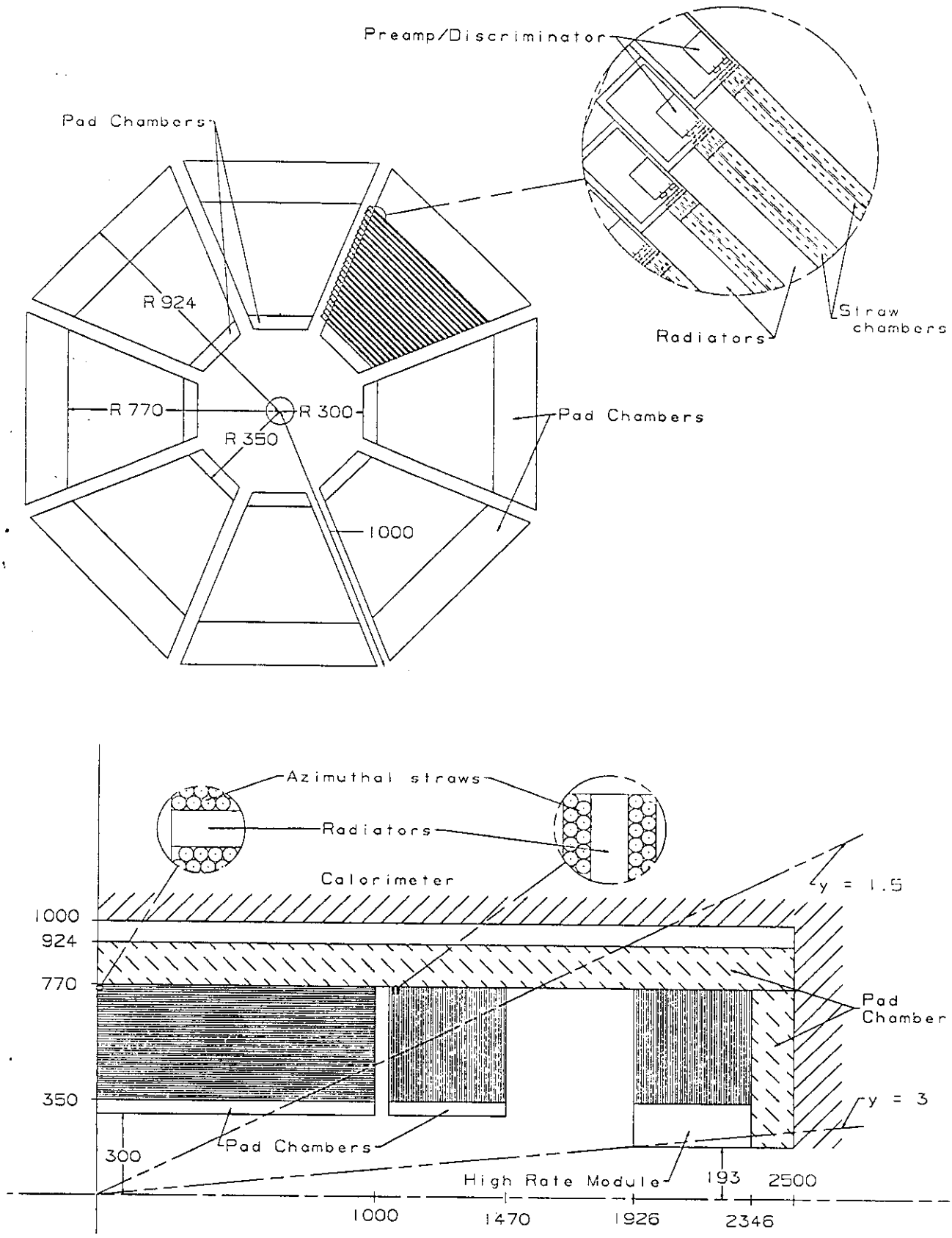

Preamp/Discriminator
Pad Chambers
R 924
R 770
R 300
R 350
1000
Pad Chambers
Radiators
Straw chambers
Azimuthal straws
Radiators
Calorimeter
y = 1.5
1000
924
770
350
300
Pad Chamber
y = 3
Pad Chambers
High Rate Module
193
2500
1000
1470
1926
2346

Fig. 4

One segment of TRD

(Straw stack)

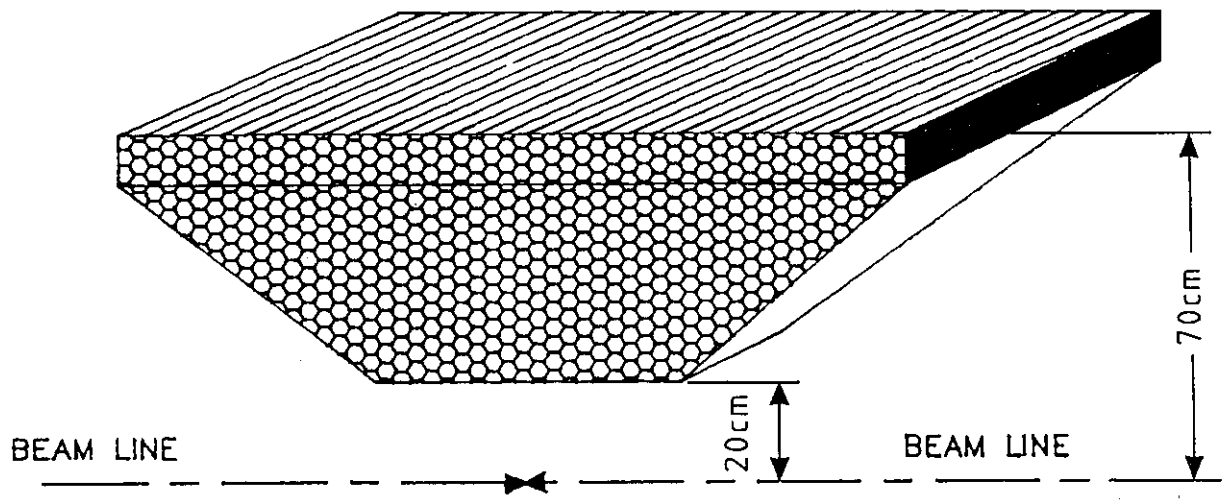


Fig. 5

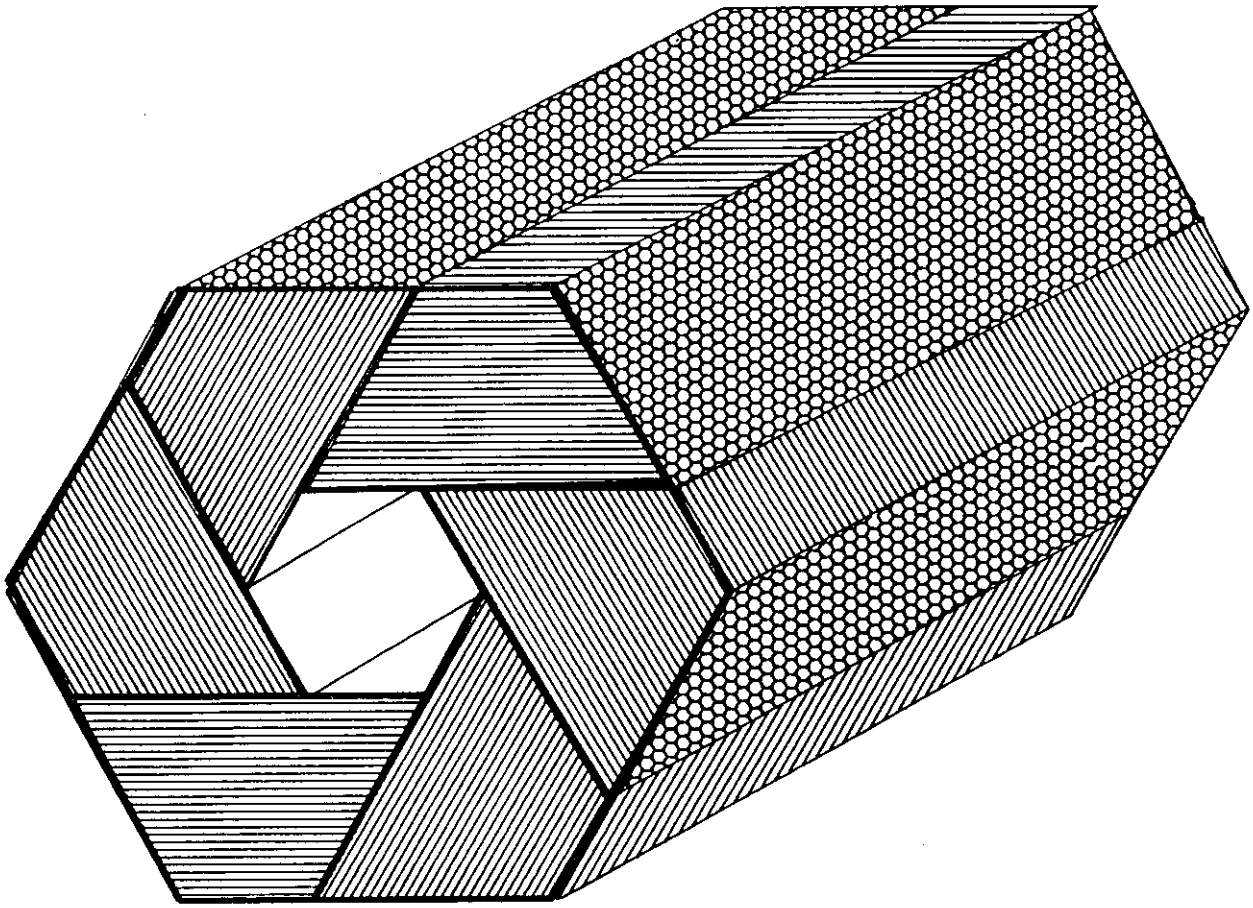


Fig. 6

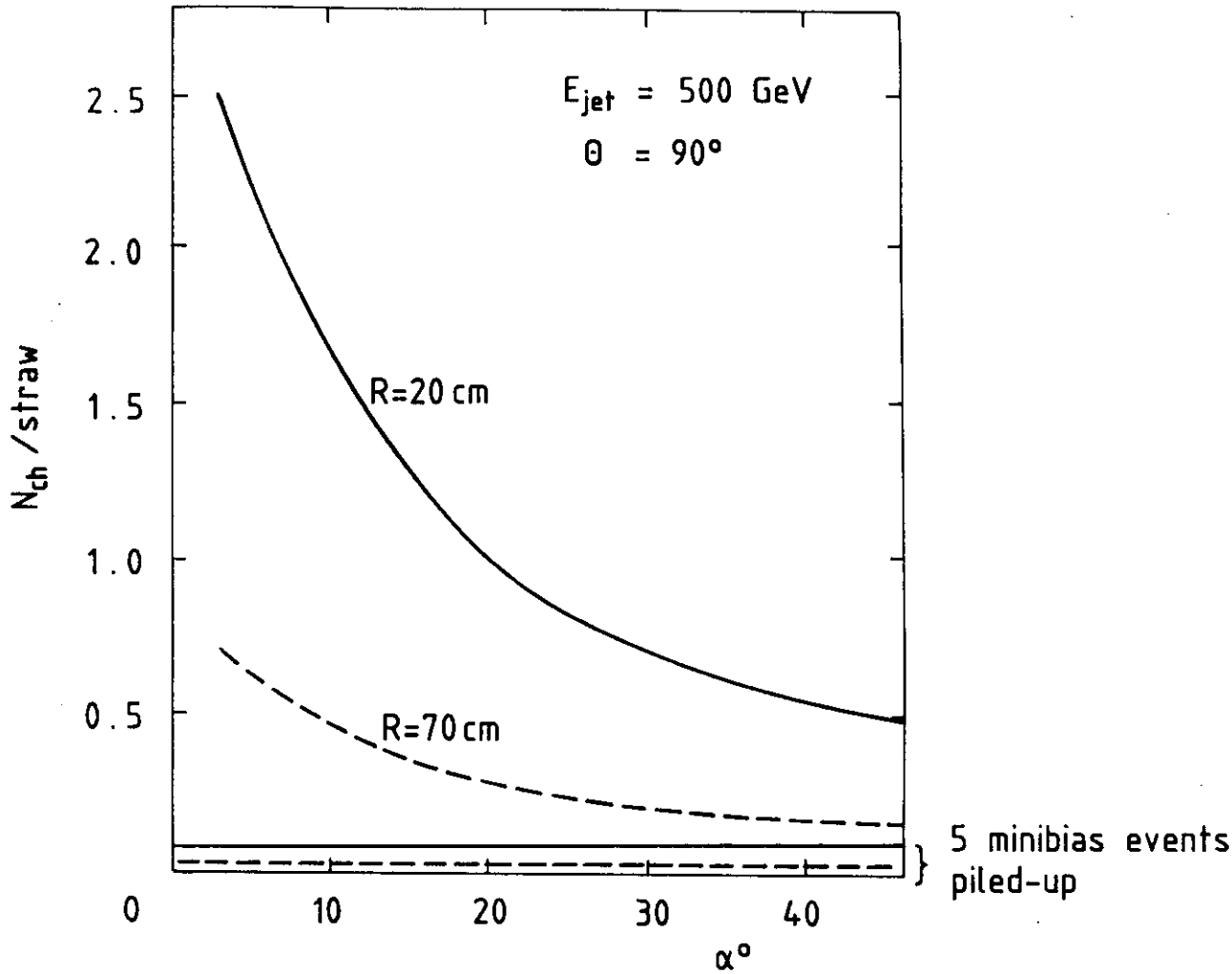

E_{jet} = 500 GeV
θ = 90°
R=20 cm
R=70 cm
N_{ch} /straw
2.5
2.0
1.5
1.0
0.5
0
10
20
30
40
α°
5 minibias events piled-up

Fig. 7

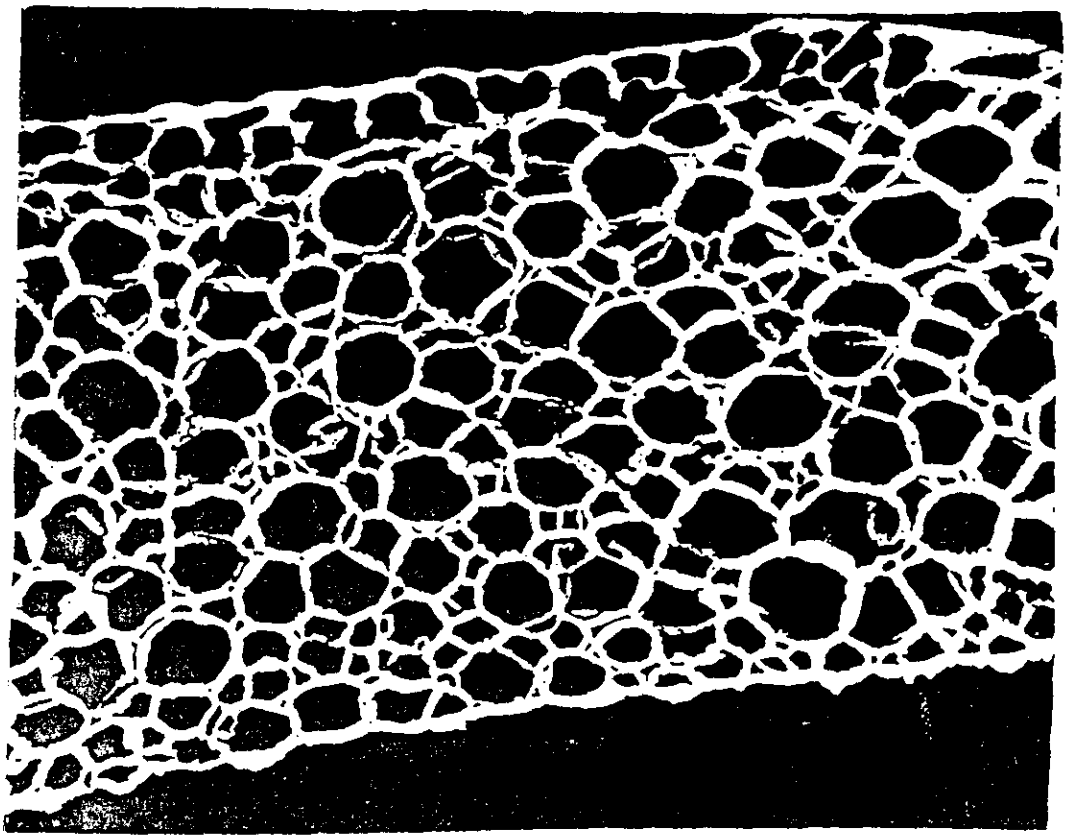


Fig. 8

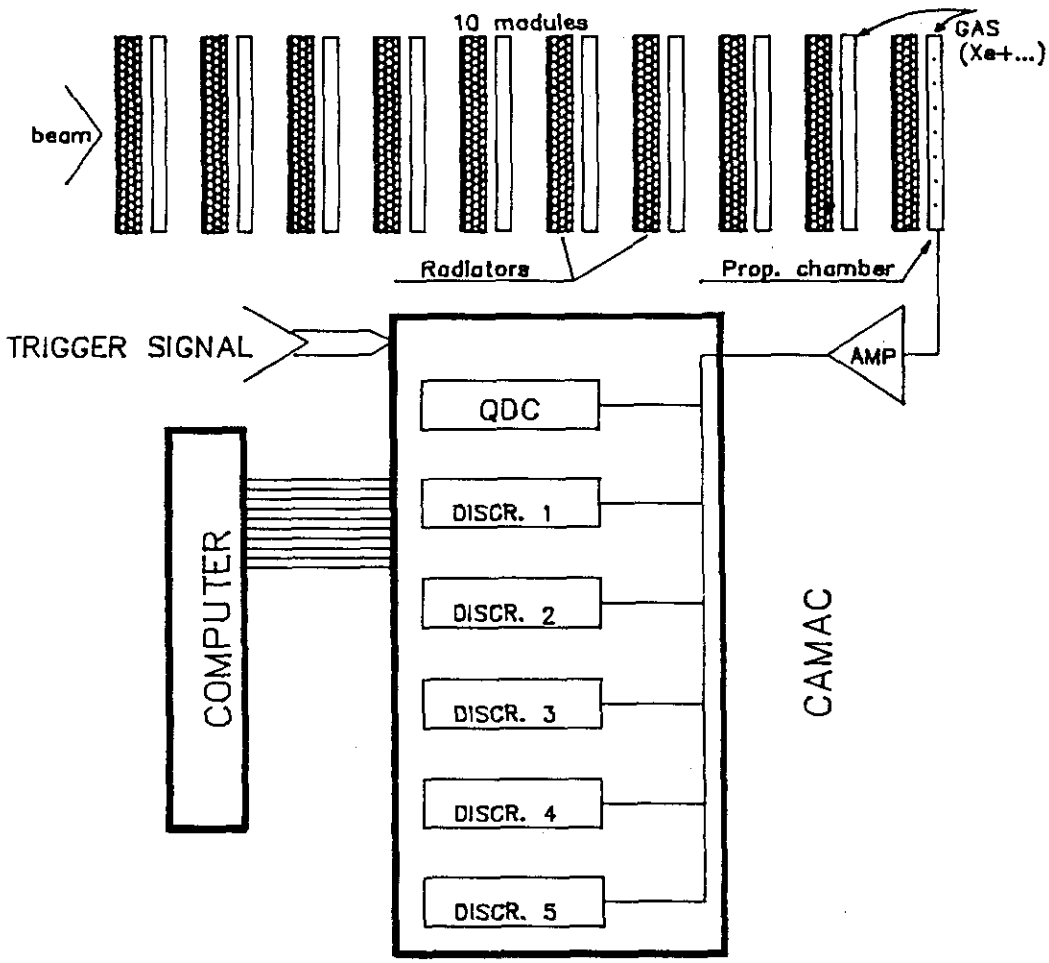

10 modules
GAS
(Xe+...)
beam
Radiators
Prop. chamber
TRIGGER SIGNAL
AMP
QDC
DISCR. 1
DISCR. 2
DISCR. 3
DISCR. 4
DISCR. 5
COMPUTER
CAMAC

Fig. 9

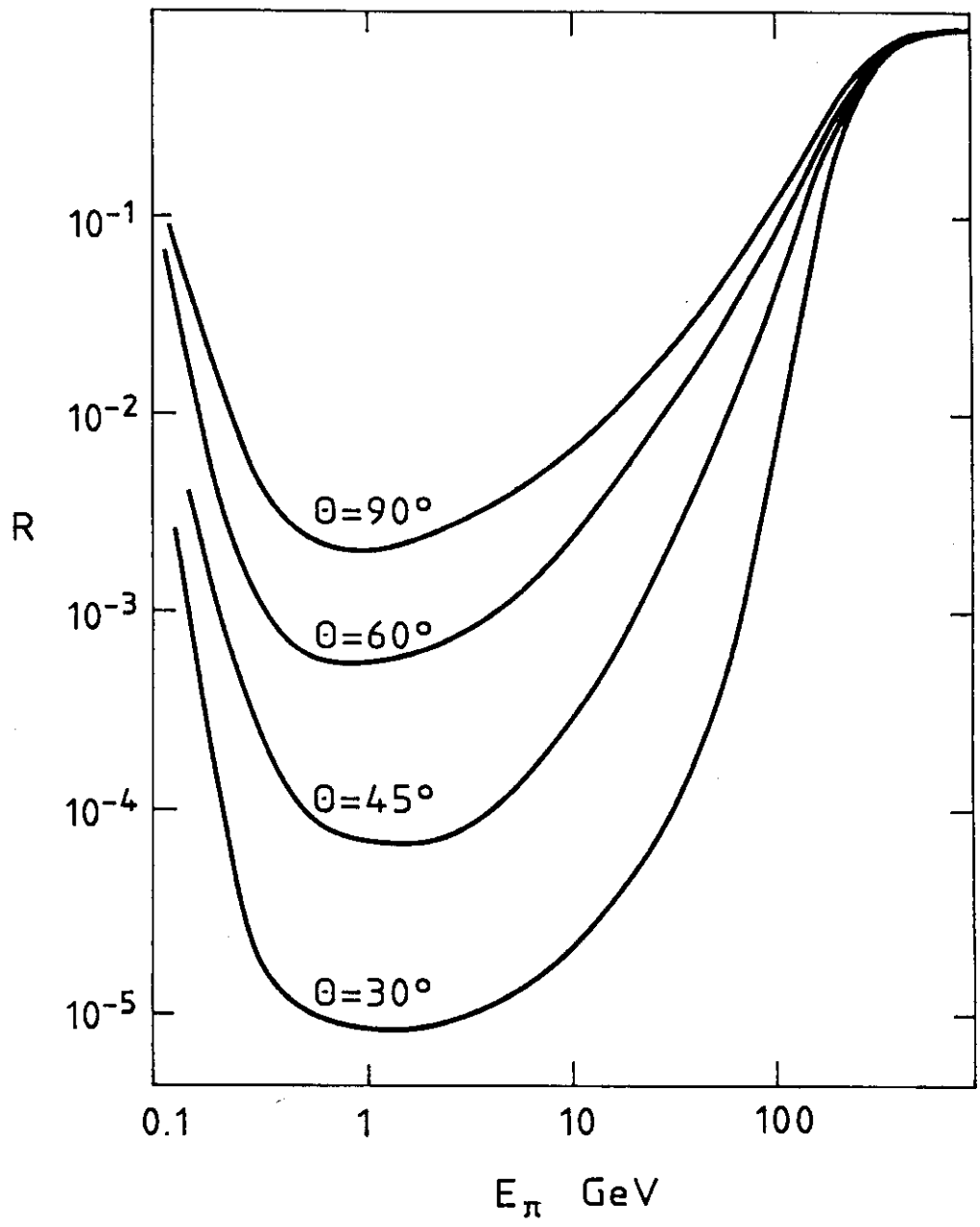


Fig. 10

Central TRD/Tracker Hits

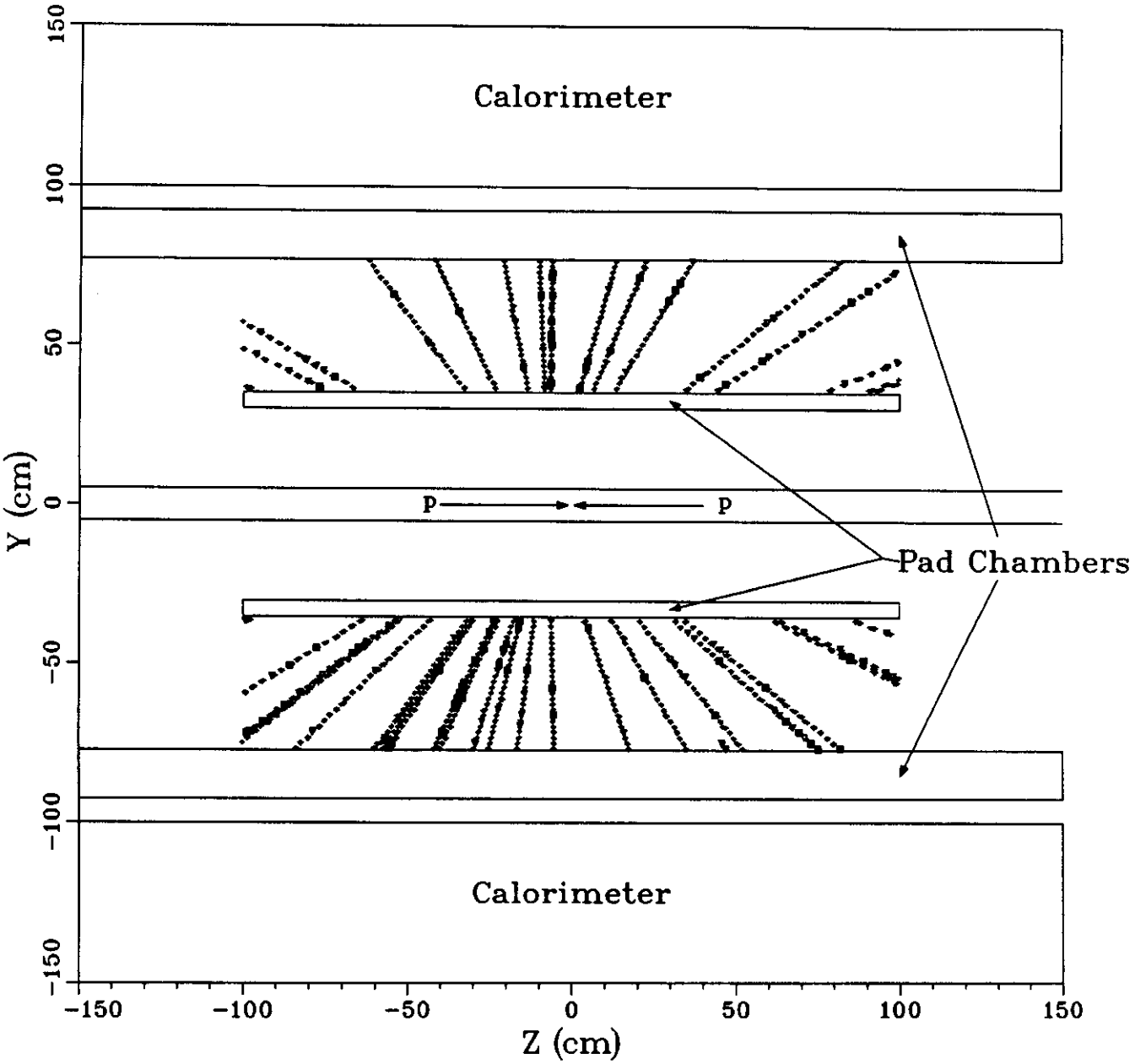


Fig. 11

PLOT 3)3.51 THUR 28 SEP, 1989 JOB-BATCH7791 Boston University DISSPLA 11.0)

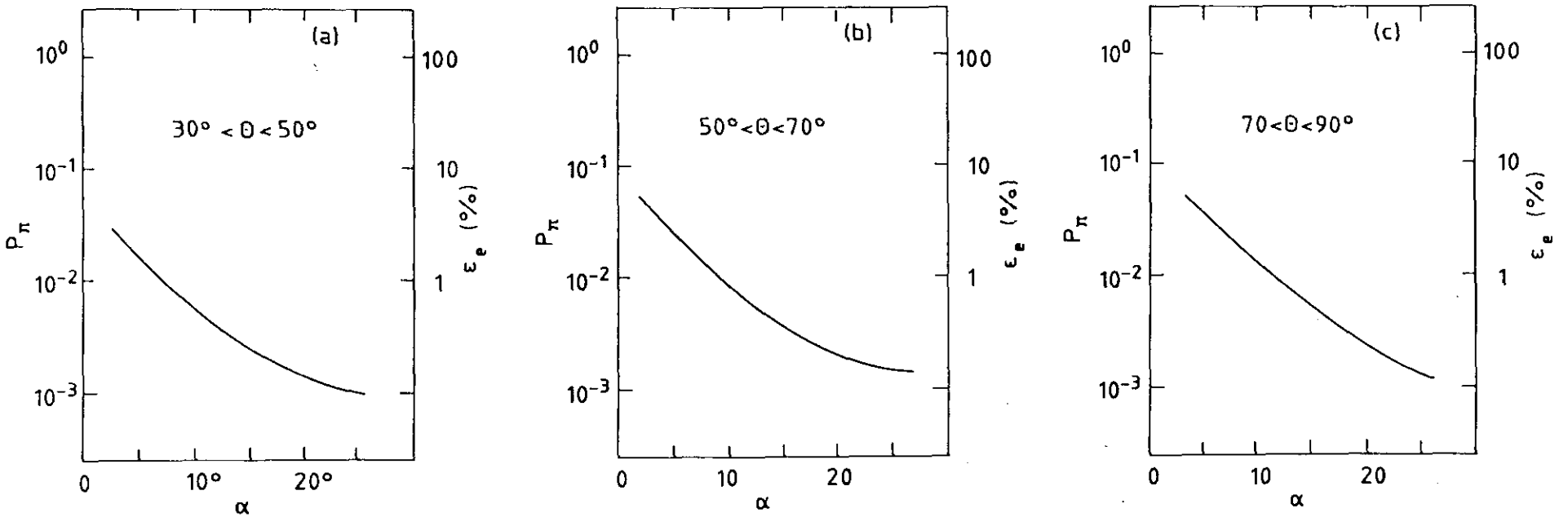

(a)
30° < Θ < 50°
(b)
50°<Θ<70°
(c)
70<Θ<90°
P_π
ε_e (%)
α
10^0
10^{-1}
10^{-2}
10^{-3}
100
10
1
0
10°
20°
10
20

Fig. 12

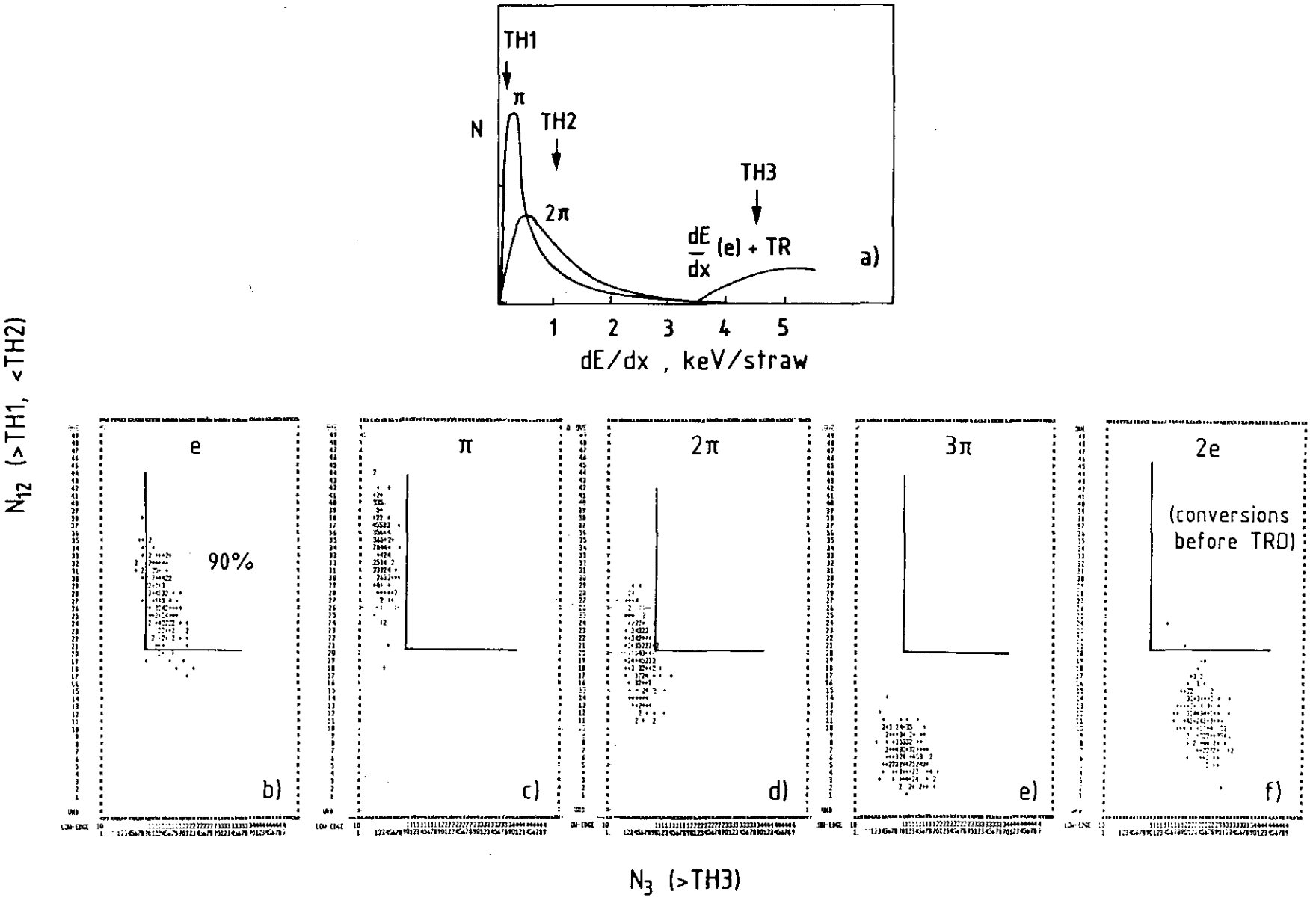
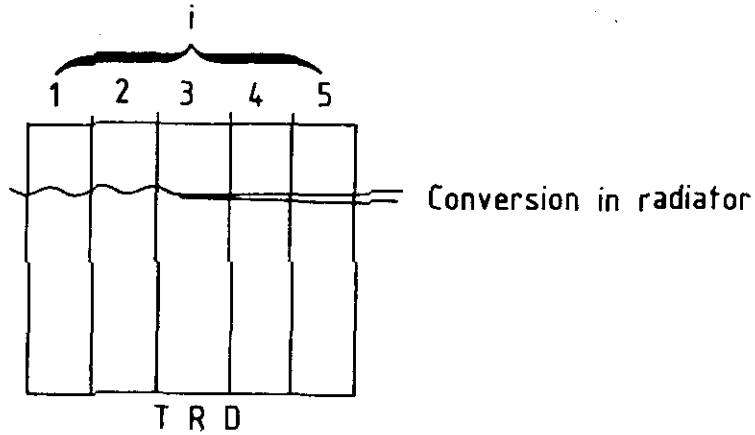
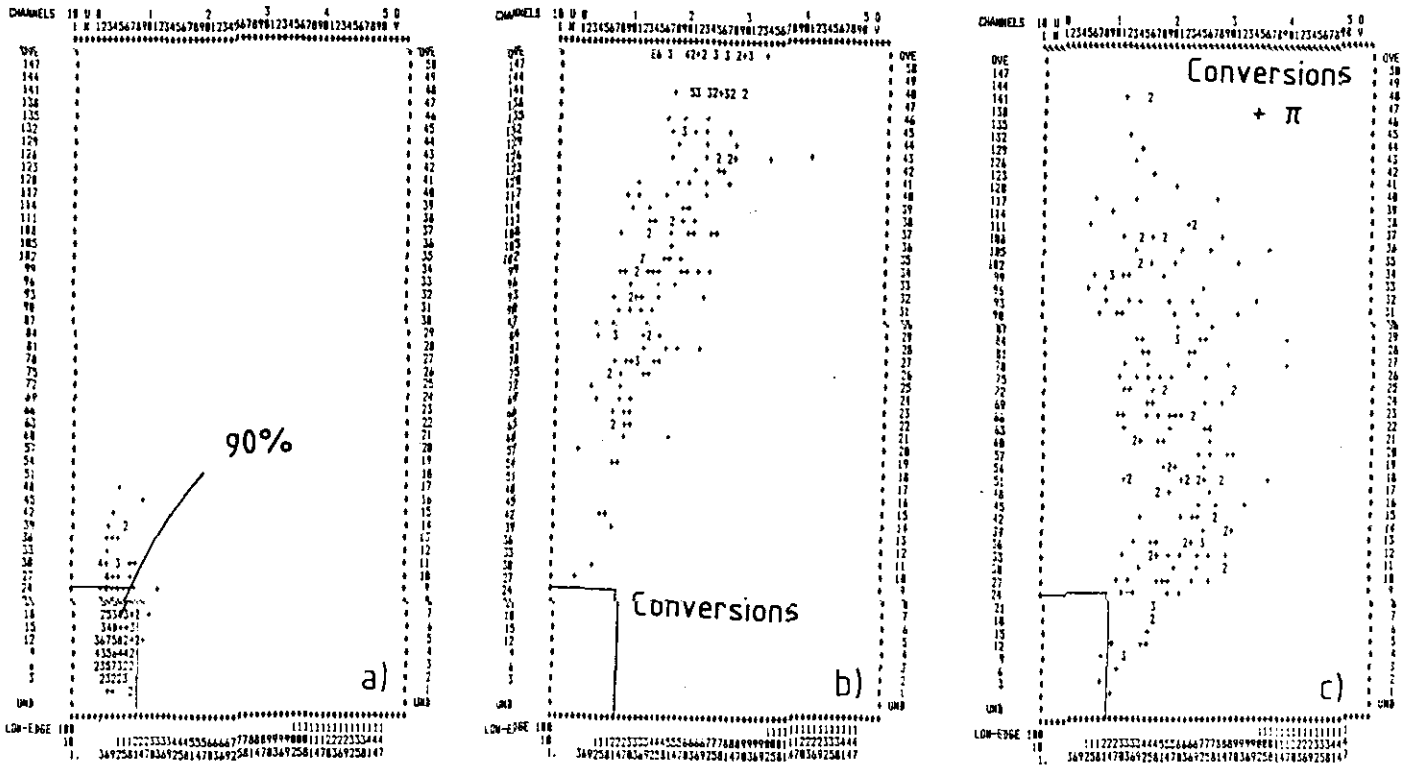

TH1
π
N
TH2
TH3
2π
dE/dx (e) + TR
a)
1 2 3 4 5
dE/dx , keV/straw
N12 (>TH1, <TH2)
e
90%
b)
π
c)
2π
d)
3π
e)
2e
(conversions before TRD)
f)
N3 (>TH3)

Fig. 13



$$DN_{12} = \sum_i \left[N_{12}^i - \overline{N}_{12}^i (e) \right]^2$$



$$DN_3 = \sum_i \left[N_3^i - \overline{N}_3^i (e) \right]^2$$

Fig. 14

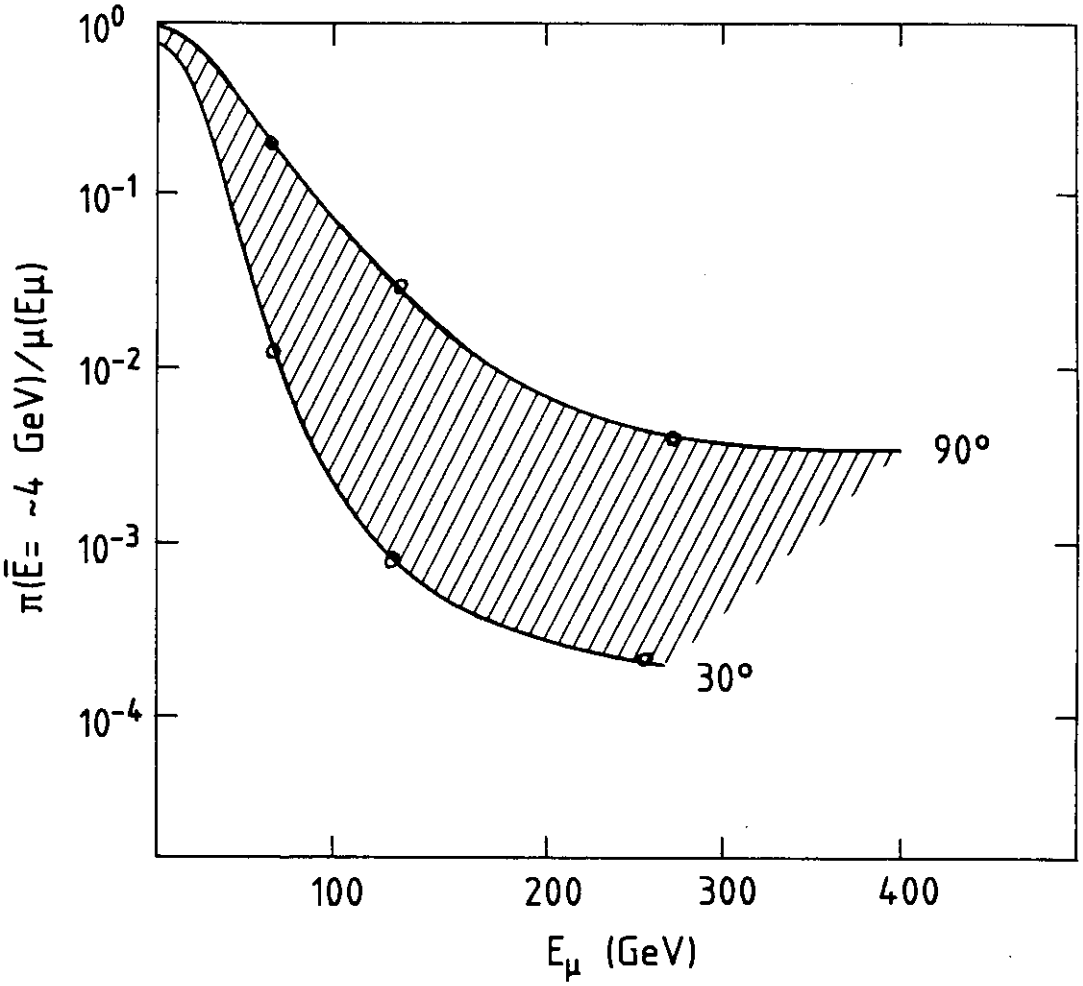

10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
$\pi(\bar{E} = \sim 4$ GeV$)/\mu(E\mu)$
90°
30°
100
200
300
400
E_μ (GeV)

Fig. 15

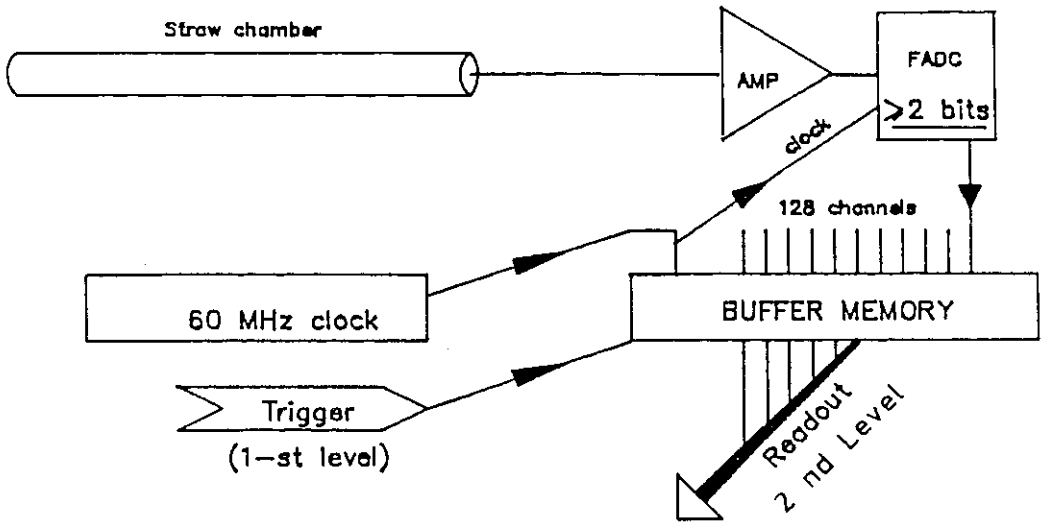

Straw chamber
AMP
FADC
≥2 bits
clock
128 channels
60 MHz clock
BUFFER MEMORY
Trigger
(1–st level)
Readout
2 nd Level

Fig. 16