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DETECTOR PROBLEMS AT THE SSC*

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1. Detector Problems at the SSC

Introduction

During the last couple of years there has been considerable concern expressed among the US high energy community as to whether detector limitations would prevent one from being able to fully exploit a luminosity of 10^{33} cm^{-2} sec^{-1} at a hadron-hadron high energy collider. As a result of these concerns, a considerable amount of work has been done recently in trying to understand the nature of potential difficulties and the required R& D that needs to be performed. A lot of this work has been summarized in the 1984 DPF Summer Study at Snowmass.1) This paper attempts to review some of these results.

This work is limited to the discussion of detector problems associated with the study of high energy hadron-hadron collisions. Even though there have been considerations of other possible future options for the SSC, like e^-p and fixed target capability, the detector questions for these options are quite different, and will not be considered here.

We shall start with the discussion of the desirable features of the detectors and of the SSC environment in which they will have to work. After a brief discussion of the model 4π detectors, we shall discuss specific detector aspects: lepton identification, tracking, calorimetry and computing and triggering. We shall end with some remarks about possible future course of events.

Desirable features

There are a number of characteristics that we would like to see in the SSC detectors. We enumerate them briefly below:

a) Diversity. The SSC will hopefully be the first machine in a totally new energy regime. Thus since it will be exploring a "terra incognita," we want to be prepared for any potential surprise. This, of necessity, will require certain diversity in detectors since one cannot predict *a priori* the necessary features. More specifically, it is generally agreed that both magnetic and non-magnetic 4π detectors should be built. Furthermore, specialized experiments will require special purpose experimental setups.

b) Capability to withstand high rate environment. The 10^8 interactions per second will severely tax the detectors. One should mention here several specific requirements necessary to cope with those rates: ability to withstand potential radiation damage, good time resolution, and ability to make quick trigger decisions.

c) Hermeticity. The experience of the CERN $\bar{p}p$ collider clearly demonstrates that a lot of new physics may be signalled by missing transverse energy.2) Theoretical considerations for the SSC energy regime reinforce this view.3) This need in turn imposes two requirements on the detectors: minimization of cracks and identification and energy measurement of all the muons.

d) Lepton identification. Here again we are guided by the CERN experience4) and the theoretical forecasts for the SSC.3)

e) Good granularity. At these energies, the jets will be composed of very closely spaced tracks. Thus identification of leptons within, or in the neighborhood of jets, demands good granularity. Good jet energy measurement also requires good granularity.

f) Reasonable cost. The detector architecture and parameters will be, in the end, a compromise between the available funds and the desires of their proponents. It is important that these trade-offs be well thought out.

g) Integrated approach. The problems we are dealing with are sufficiently complex and interrelated that we have to consider all of the detector aspects together in the design. More specifically, the detector hardware, detector software and machine parameters affect each other quite closely.

Machine environment

There is no doubt that the SSC will present quite a hostile environment to its detectors. For a bunch spacing of 10 m (33 nsec separation in time), we can expect for each crossing about 3-4 interactions that will give tracks in the detectors. This is based on the assumption of a total inelastic cross section of 90-120 mb$^{5)}$ and supposition that the detectors will not see any of the elastic scattering events.

The bunch spacing is a machine parameter that can be adjusted within some limits. The possible trade-offs$^{6)}$ are indicated in Fig. 1. Larger total beam current increases costs (synchrotron radiation, safety considerations) and thus must be kept in bounds. It is clear that a factor of two or so leeway exists, but not much more than that.

The multiplicity in typical events will be high; the present estimate$^{7)}$ gives $\frac{dn}{dy}|_{y=o} \approx 6$. In addition, the jets will have their tracks close together. These factors will make track reconstruction difficult unless good granularity and sufficient redundancy are provided.

Finally, the high energy of the tracks imposes stringent requirements on the resolution, if curvature measurements are to be used for track momentum determination.

4π Detectors

We have already mentioned that both magnetic and non-magnetic 4π detectors have some special advantages of their own. It might be worthwhile to enumerate them briefly.

Advantages of non-magnetic detectors:

a) Tracking is considerably simpler.

b) As a result of (a), the calorimeter can be brought considerably closer and hence becomes cheaper.

c) The absence of coil makes apparatus simpler and removes "inert" coil material.

d) Components of jets stay together. Thus calorimetric energy measurement is easier.

On the other hand, in favor of magnetic detectors one can mention:

a) Lepton identification is improved since its momentum measurement from curvature can be cross-checked with other information.

b) The sign of electron's (and all hadrons') charge can be measured.

c) Invariant mass measurements are possible.

d) Momentum of all individual tracks can be measured.

e) Magnetic field spreads out the jets and the additional separation may be helpful in track separation.

The characteristics of possible 4π detectors were studied in detail at the 1984 Snowmass meeting. Paper designs of three possible detectors were generated and costed.$^{8)}$ The first two, one magnetic, the other non-magnetic are rather conventional insofar that they do not introduce any new technology. The third one, relying on the scintillating fibers as the main tracking medium, employs as yet unproven technology and hence is more speculative. The three detectors are displayed in Fig. 2, reproduced from the Snowmass report. The relevant parameters of those three detectors (also from the Snowmass report) are shown in Tables I, II, and III which give the parameters of their tracking systems, parameters of their calorimeters, and their costs, respectively.

Lepton Identification

We start out by making a case for the necessity of having the capability to identify the leptons. Some of the arguments are:

a) New physics is very likely associated with leptons.

b) Since the muon energy is not included in the total calorimetric energy measurement, the requirement of total jet energy measurement, as well as that of hermeticity, can be achieved only if muons are identified and measured.

c) Heavy quark jets can be tagged frequently by the presence of energetic leptons.

d) Presence of energetic leptons can be a very useful element of level 1 trigger.

We proceed next to discuss specific details and problems of electron and muon identification. Beginning with the muons,$^{9)}$ the sources of backgrounds are hadronic punch-through's and μ's from π and K decay. Those are illustrated in Fig. 3 which shows the rate of punch through's at $L = 10^{33}$ as a function of p_T and the rate of the decay muons (assuming 1 m of flight path before the absorber) as a function of amount of iron filter material (and thus effectively of minimum p_μ). The typical detector probably will have in excess of 3 m of iron equivalent in the absorber; thus the muon background rate will be below 10^5. As we shall see later, this is probably low enough to be used directly in the level 1 trigger.

The resolution for muon momentum measurement is illustrated in Fig. 4. The assumption made is that the spatial resolution in the three gaps between the iron layers is 300 μ. The length indicated (2 m and 4 m) is the total length of the magnetized iron. For comparison, the advertised momentum resolution of both the L3 detector$^{10)}$ at LEP, and the SciFiD SSC detector (third 4π detector discussed above) are also shown.

The problems with the electron identification and measurement$^{11)}$ are quite different. The energy can be measured with a very high degree of accuracy in the electromagnetic calorimeter. The calculations indicate that a 1000:1 hadron rejection can be obtained at the SSC energies if the calorimeter is subdivided at least into three longitudinal segments. Some of the obvious backgrounds are the π°(or η) $\rightarrow 2\gamma$ decays with one of the γ's either converting internally or in the beam pipe, and a γ-hadron overlap in the same calorimeter cell. The first background represents real electrons. Thus it can be eliminated only either by detecting the other electron (in a magnetic detector) or by measuring dE/dx and thus discriminating between 1 or 2 tracks (in a non-magnetic detector).

The other background can be reduced by a P vs E measurement comparison in a magnetic detector or by a transition radiation detector (TRD) in a non-magnetic detector. The latter will work at electron energies below 200 GeV. One of its drawbacks is the fact that to obtain high enough conversion efficiency for the transition radiation x-rays, a layer of gas about 2 cm thick is required. This, in turn, will necessitate long enough gate-time so that the problem with accidentals can become quite severe. This can, in turn, be alleviated by providing and reading-out cathode pads near the anode wires; the cost of this solution, however, is many more channels of required electronics. A possible schematic of a TRD is illustrated in Fig. 5.

Finally, one should mention the possibility of detecting electrons of very high energies by synchrotron radiation. In a strong field (B $\gtrsim$ 1 Tesla) significant number of photons above e^+e^- threshold will be generated. Their conversion early in the calorimeter will give a very large pulseheight in the initial layers of the calorimeter. Whether this technique will work in practice needs to be verified experimentally; the relevant numbers are illustrated in Table IV.

Table IV

Synchrotron Radiation Parameters

$Bl = 3$ Tesla meters, $B = 1.5$ Tesla

E(GeV)	E_c(MeV)	ΔE(MeV)	$x^{\min} = \frac{5\text{MeV}}{\epsilon_c}$	N($\epsilon > 5$MeV)
50	5	14.6	1.0	.41
100	20	58	.25	3.4
200	81	229	.062	7.8
500	506	1430	.010	12.3
1000	2025	5715	.0025	16.5

Tracking

We should consider here both the standard central tracking chambers as well as the vertex detectors.[12)] The limitations on these systems at the SSC will be imposed by:

a) Radiation damage considerations,

b) instantaneous rate considerations (current drawn, space charge),

c) occupancy rate, and

d) reconstruction possibility.

We shall consider each one of these factors in turn. To review the radiation damage question, we must recall that 1 rad corresponds approximately to 3.5×10^7 mip/cm^2. The tolerance of different components to high radiation levels is known reasonably well and is displayed in Fig. 6 as a function of minimum radius at which the components could survive at the SSC.

The performance of the central tracker can be considered by taking a specific example. We assume that we want to cover $|y| \leq 1.5$, with a detector that starts at r = 20 cm, has 600 cells with 2 mm spacing and 1 m long wires. With our previously stated assumptions about cross-sections and multiplicities we obtain a following comparison between the expected performance and our present ideas of the values that can be tolerated.

Table V

Performance of a central tracker (described above)

	Estimated	Allowed limit
Maximum drift time	20(gas) + 7(wire) ns	33 ns
Occupancy	15%	?
Efficiency	92%	?
Current	0.5μa	1μa
Particles/mm/sec	3×10^3	10^4
Electrons/mm/yr.	3×10^{16}	10^{18}

The Table assumes a rather low gain yielding 10^6 electrons/particle and the only considered mechanism for efficiency loss is due to double hits in a single cell (we shall count the "right" hit 50% of the time in such cases). Even though these parameters push the state of the art, there is no obvious reason why such a system should not work.

The question of tracking has not been sufficiently investigated. Some preliminary calculations by H. H. Williams on $t\bar{t}$ jets of 500 GeV/c indicate that the losses due to finite double-hit resolution are not prohibitive. However, more detailed work is needed on interference from other interactions in the same crossing.

For completeness, we reproduce in Fig. 7 the three central tracking systems discussed at the last Snowmass meeting. One should note that the wires in the D1 detector (no magnetic field) run transversely to the beam axis.

The possibilities for the vertex detector are: drift chamber, scintillating fibers, and Si strips. Because of the futuristic aspects of the scintillating fiber technology, most of the work so far has been done with the other two techniques. Because of the radiation damage, however, most of the discussed designs are limited to the luminosity of $10^{32}\text{cm}^{-2}\,\text{sec}^{-1}$. One such design, for that luminosity, is displayed in Fig. 8.

Calorimetry

Some of the obvious motivations for the importance of calorimetry[13)] in the SSC detectors are:

a) it provides a natural way to measure jet energy

b) the resolution improves with energy

c) the required depth grows only logarithmically with energy.

d) it can provide a level 1 trigger capability

e) it automatically becomes the front part of the muon detection system.

The obvious questions that need to be addressed in designing the calorimeter are:

a) Materials to be used. Some considerations that are relevant here are compactness, cost, integration time, ease of calibration, and similarity in response to the hadronic and electromagnetic components.

b) Granularity. This has to be well matched to the rates expected and the nature of the physics to be investigated.

c) Hermeticity. It is important to cover as large an area as possible with a minimum number of cracks. The relevant question is how much of a departure form a perfect system we can tolerate.

Regarding the material of the calorimeter, there is at present a strong preference in the community for the uranium-liquid argon mix. Some of the advantages here are: equality of hadronic and electromagnetic response, no radiation damage, high density and hence good compactness, and relative ease of calibration.

One of the difficulties of this system is its relatively long charge collection time. For a 2 mm gap, 150 ns collection time is required, resulting in a high fraction of cells having some remnant of previous shower. Thus time measurement of the leading edge of the pulse will be necessary to discriminate against unrelated energy. This system would perform best with a minimum bunch spacing.

Other possible calorimetric media are warm liquids, iron and gas, heavy glass, silicon and barium fluoride. They all appear to have serious disadvantages and/or require still intensive development.

The granularity choice has to be considered both in light of the nature of the showers and the nature of the physics studied. For electrons, the width of the shower is characterized by Moliere radius, r_m given by

$$r_m = \frac{21\mathrm{MeV}}{\epsilon_c} X_\circ$$

where ϵ_c is the critical energy and $X_\circ$ is the radiation length. Experimentally a sandwich of 2 *mm* U and 2 *mm* Ar will contain 95% of the shower in 2 cm. The hadronic shower width is proportional to interaction length λ_o , with typically 95% of the shower energy being contained within a cylinder of that radius.

Regarding physics considerations the Snowmass study looked at two specific cases. The resolution of the W mass, if W decays via $W \rightarrow q\bar{q}$, improves down to granularity of $\Delta\eta \simeq \Delta\varphi \approx 0.03$. For t quark decay by the electronic mode, 80% of the time the electron is isolated from the rest of the jet if $\Delta\eta = \Delta\varphi = 0.02$. Since a typical calorimeter will start about 1-2 m away from the interaction point, these physics considerations lead to parameters that are comparable to those imposed by the requirements of the electromagnetic shower criteria.

Hermeticity

There are three obvious experimental sources that can generate spurious missing transverse energy. These are the aperture provided by the beam pipe, cracks in calorimeter associated with boundaries of various subsystems, and the finite energy and position resolution. The calorimeter should be designed optimally in such a way that the contribution to the missing energy from those is not larger than the amount of missing transverse energy carried off by the neutrinos from the heavy quark decays.$^{13)}$

The effect of the beam pipe is illustrated in Fig. 9, where the effective missing energy cross section is shown for three different beam pipe apertures. The resulting curves are compared with the size of the contribution due to neutrinos.

The effect of the cracks was investigated by replacing "live" material with some "inert" material in the calorimeter. The resulting "missing" energy was calculated for two different fractional dead areas and again compared with the neutrino cross section. The results are displayed in Fig. 10.

Finally, the effect of resolution was also studied. The conclusion was that the assumed calorimetric resolution, i.e., $\delta E_{\text{had}} = 0.35\sqrt{E}$ and $\delta E_{\text{em}} = 0.15\sqrt{E}$ does not contribute at any significant level to an increase in events with missing P_T.

Electronics, Computing, Trigger

Traditionally these functions have been rather decoupled, but it is quite clear that for the SSC detectors they have to be integrated and designed in a coherent manner.14) The data rates at the SSC will be staggering: in excess of 10^8 events/sec, with each event possibly encompassing about 10^6 bytes. Thus even one event recorded every second, if recorded without any preprocessing, would result in writing on a 6250 BPI tape at its maximum possible speed (8×10^5 bytes/sec). Independent of the recording medium, however, the data rate is so large that a significant amount of on-line event preselection and processing will be required.

The fundamental difficulty in the trigger is the requirement of reducing the raw event by about 10^8. This is difficult but probably not impossible technically. The real difficulty may, however, lie in doing this without losing any significant new physics. It is clear that the trigger and data acquisition architecture will require a considerable amount of flexibility built into it so that a variety of different topologies can be explored.

The extrapolations from the existing experiments, both of fixed target and colliding beam varieties, leads one to believe that 50 sec of IBM 3081K time will be required to process one event.14) Thus each 4π detector would require computing capability that is equivalent to about 2 1/2 times the projected Fermilab required computing power.

Very roughly, the present ideas about triggering rely on having several different trigger levels, each one of increasing complexity. Level 1 trigger should be deadtimeless and require no more than about 200 nsec for the decision. Some possibilities are a muon or electron of 5 GeV or higher, or some amount of missing energy. It is estimated that these requirements would generate a rate of about 10^5 Hz.

Additional, more sophisticated, hardware processing would be required at this stage to reduce the event rate to no more than 1 KHz. Such rates would make it feasible to have a bank of parallel processors to select roughly one event/second that has the highest probability of being of interest. Clearly, this would require about 1000 processors, capable of making a decision in 1 sec. The task is certainly formidable.

The schematic computer architecture being discussed, as well as the cost estimates, rely heavily on the assumption that significant technology progress will be made in the field in the next decade. Thus for example the estimate of Snowmass 1984 Computing Group of about $50 M/detector in computing costs assumed a gain of a factor or 8 in compute power per dollar in the next five years.

There is no doubt that these ideas will evolve greatly during the next few years and that technology will progress. Today, however, the triggering and computing questions appear to present some of the most formidable problems for the SSC detectors.

Special Purpose Detectors

We shall limit this discussion to a few relatively obvious comments. First of all, there is no doubt that some experiments need special purpose, relatively small scale detectors. It is highly likely that these experiments will also require special interaction region configurations. Some examples of such experiments are elastic *pp* scattering, searches for monopoles, and searches for new heavy long lived particles.

In addition there may be another class of experiments that may also need special purpose detectors but larger in scope.15) At least a part of their rationale is that they would be cheaper than the multi-purpose 4π detectors. Some examples of such detectors would be diffractive dissociation, study of details of jets and CP violation experiments. There have been some investigations in this area at Snowmass, but I do not believe that as yet a convincing case has been made for their necessity.

Finally, we should emphasize that because of its high rates the SSC is inherently different from e^+e^- machines as far as its possible potential for special purpose experiments. Since the datataking capability of the 4π detectors is way below the total SSC event rate, the general purpose detectors simply will not be able to do all the physics. Thus in a certain way SSC is half-way between e^+e^- storage rings and hadronic fixed target situation. Whether this special situation will justify non-4π detectors is still an open question.

Plans for the Future

Judging from the LEP experience, it is not too early to begin thinking about the detector problems. On the other hand, the machine testing and construction must have top priority.

Some of the obvious detector R&D that should commence soon must address such generic questions as radiation hardening of electronics, rapid and cheap computing, new calorimetric media and improvement of the existing ones, and new tracking techniques (e.g., scintillating fibers).

In parallel, work has to be done on realistic Monte Carlo calculations so that the effects of pileup on triggers and tracking become well understood. Furthermore one should investigate to what extent the n'th level accidentals could simulate (or provide serious backgrounds) for events of interest.

Finally we should start thinking about new and innovative ways of solving the problem of detector and beam time approval mechanisms.

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Table I

	D1	SCD	SciFiD
Type	Wire chambers	Wire chambers[a]	Scintillating glass optical fibers
Principal coordinate	z	ϕ	ϕ
Secondary coordinate measurement technique	Charge division	Small angle stereo and cathode strips	Small angle stereo
Radial extent (z=0)	50 to 100 cm	25 to 235 cm	10 to 100 cm
Rapidity range	0 to 4.7	0 to 1.5 (central) 1.5 to 5.0 (endcap)	0 to 1.5
Cell spacing	5 mm	1 to 4 mm	25 mm
Number of hits per track	20	100 (wires) 6 (strips)	130
Number of dE/dx layers	20	10	none
Number of channels	184.5 k	100 k wires[b] 32 k strips	150 M fibers 38 M cells[c] 920 CCD's
Resolutions:[d]			
principal coordinate	200 μm	200 μm	10 μm
secondary coordinate	1 cm	1 mm	70 μm/su per layer
track pair	5 mm	1-4 mm	50 μm
momentum	none	$3\ 10^{-4}p$	$2.5\ 10^{-4}p \oplus 0.031$

[a] Inner silicon strip detectors are omitted from this table.
[b] There are an additional 30 k channels in the endcap tracking system.
[c] Cells are defined by the image intensifier resolution.
[d] Spatial resolutions are per measurement unless stated otherwise.

Table II

	D1	SCD	SciFiD
Type			
electromagnetic	U-Cu/liquid Argon	U-Cu/liquid Argon	U-Cu/liquid Argon
hadronic	U-Cu/liquid Argon	U-Cu/liquid Argon[*]	U-Cu/liquid Argon
catcher/flux return	Fe/wire chambers	Fe/wire chambers	Fe/wire chambers
Thickness			
electromagnetic	30 X_0(1.4 λ)	40 X_0(1.2 λ)	40 X_0(1.5 λ)
hadronic	5.6 λ	4.0 λ	8.5 to 13 λ
catcher/flux return	5.0 λ	9.0 λ	5 to 8 λ
Rapidity range	0 to 5.5	0 to 5.0	0 to 5.0
Sampling thickness			
electromagnetic	0.6 X_0	0.5 X_0	0.5 X_0
hadronic	0.03 λ	0.03 λ	0.03 λ
catcher/flux return	0.3 λ	0.3 λ	0.3 λ
Longitudinal segments	5 (3 in EM)	5 (3 in EM)	5 (3 in EM)
Tower size ($\Delta\eta = \Delta\phi$)			
electromagnetic	0.04	0.02 to 0.1	0.03
hadronic and catcher	0.04	0.04 to 0.2	0.06
Number of towers			
electromagnetic	31.5 k	45 k	48 k
hadronic and catcher	31.5 k	11 k	12 k
Number of channels	157.5 k	166 k	180 k
Mass			
U-liquid Ar	1330 T	2440 T	2400 T
Fe-gas	1780 T	6900 T	6300 T

[*] The forward hadronic calorimeter is constructed from iron-gas tubes sandwiches.

Table III

	D1		SCD		SciFiD	
Tracking system		37.0		28.8		26
mechanical costs	18.5		11.6		10	
electronics costs	18.5		17.2		16	
Transition radiation detectors		25.6		—		15
mechanical costs	9.2		—		2	
electronics costs	16.4		—		13	
U-liquid argon calorimeters		39.5		81.0		68
mechanical costs	33.2		73.7		60	
electronics costs	6.3		7.3		8	
Iron-gas calorimeters		17.0		21.4		14
mechanical costs	15.4		20.4		13	
electronics costs	1.6		1.0		1	
Superconducting coil		—		19.0		31
Muon detection system		35.3		49.5		16
mechanical costs	28.8		41.5		8	
electronics costs	6.5		8.0		8	
Trigger and data acquisition		9.9		10.0		10
Totals (before contingency)		164.3		209.7		180
mechanical total	105.1		166.2		124	
electronics total	59.2		43.5		56	
Contingency (25%)		41.1		52.4		45
Total[a]		205.4		262.1		225

[a] Offline computing costs have not been included in this table. The Computing Working Group estimated that these costs would be about 40 M$ for a magnetic detector. They should be considerably less for a non-magnetic detector.

FIGURE CAPTIONS

1. Plot of the average number of interactions per bunch crossing ($\langle n \rangle$), number of protons per bunch (N_B), linear tune shift due to single bunch collisions ($\Delta\nu$) and total number of protons in each ring ($N_{\rm tot}$) as a function of the bunch spacing (S_B). The data used correspond to the Reference Design A parameters.

2. Schematic drawing of (a) the non-magnetic detector, referred to as D1, (b) "conventional" magnetic detector, called SCD, and (c) the scintillating fiber detector (SciFiD). (from Ref. 8)

3. Integrated rate of μ's from π and K decay as a function of hadron transverse momentum. A decay path of 1 m and luminosity of 10^{33} are assumed. The arrows indicate the muon range in iron. The dashed curve is the rate of pions which punch through ten interaction lengths of iron. (from Ref. 9)

4. Comparison of four different momentum resolution functions for muons. The top two curves (marked 2 m and 4 m) correspond to tracking muons through 1 m thick magnetized iron slabs (B = 1.8 T). Input and output slopes are assumed known to $\delta\theta = \pm 0.15$ mrad and spatial resolution is taken to be 300 μ. The curve marked A is the resolution calculated for the scintillating fiber detector discussed above (with B = 1.5 T). Curve marked B is the expected resolution from the $L3$ detector at LEP. (from Ref. 9)

5. Sketch of a possible TRD module. (from Ref. 11)

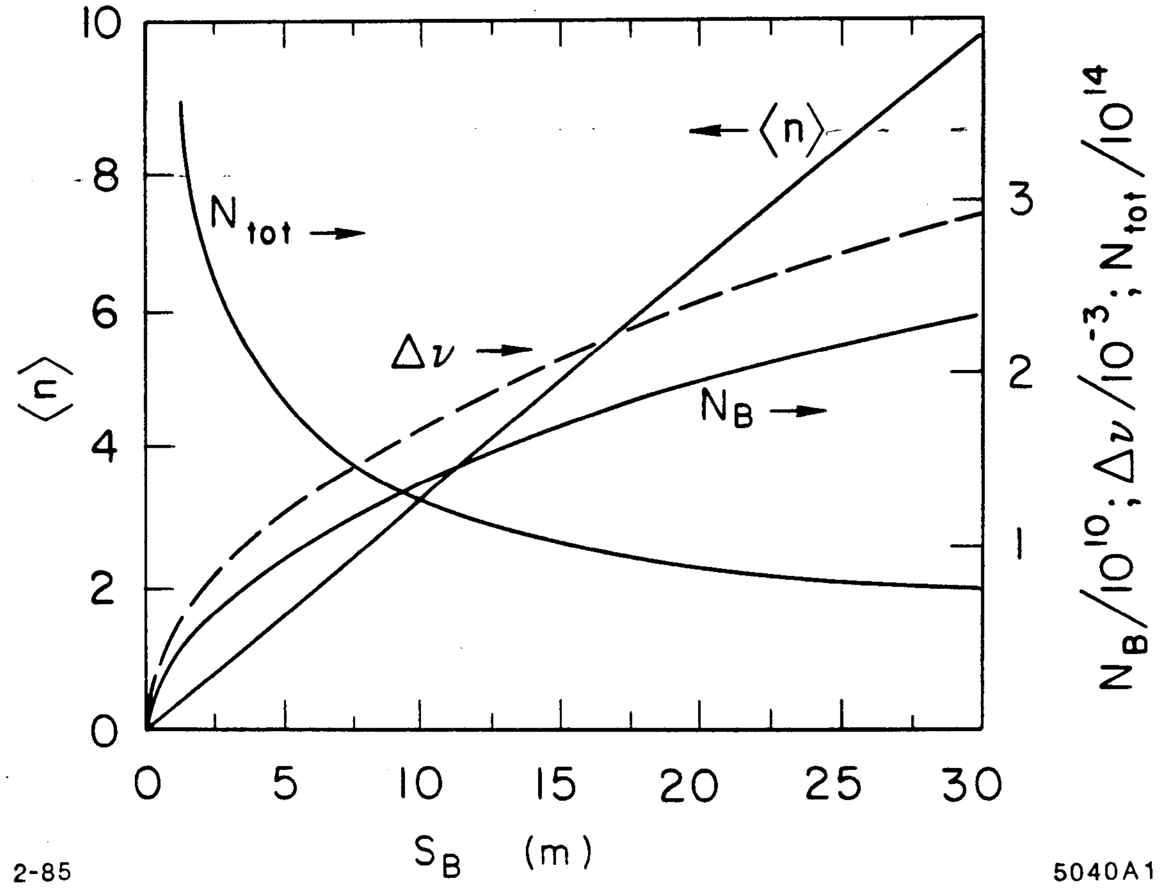
6. Minimum component radii for radiation damage at luminosities of 10^{32} and 10^{33} cm^{-2} sec^{-1}. (from Ref. 12)

7. The central tracking systems discussed at Snowmass for (a) the D1 detector, (b) the SCD detector, and (c) the SciFiD detector. (from Refs. 8 and 12)

8. A possible vertex detector system for use at a luminosity of 10^{32} cm^{-2} sec^{-1}. (from Ref. 12)

9. Contribution to the differential missing p_T cross section due to neutrino production from heavy quark decays (solid line) and due to incomplete coverage within beam holes of several sizes. The top quark mass is taken as 45 GeV/c^2. (from Ref. 13)

10. Differential missing p_T cross section due to azimuthally directed cracks in the calorimetry between $\theta = 30°$ and $\theta = 150°$. The cracks represent 1.3% (dotted) and 4.0% (dashed) of the area for the two cases shown. The cross section due to neutrinos from heavy quark decays is shown as a solid line. A beam hole of $\theta < 0.3°$ is used. (from Ref. 13)



10
8
6
4
2
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⟨n⟩
0
5
10
15
20
25
30
S_B (m)
3
2
1
N_B/10^10; Δν/10^-3; N_tot/10^14
N_tot →
Δν →
N_B →
← ⟨n⟩
2-85
5040A1

Fig. 1

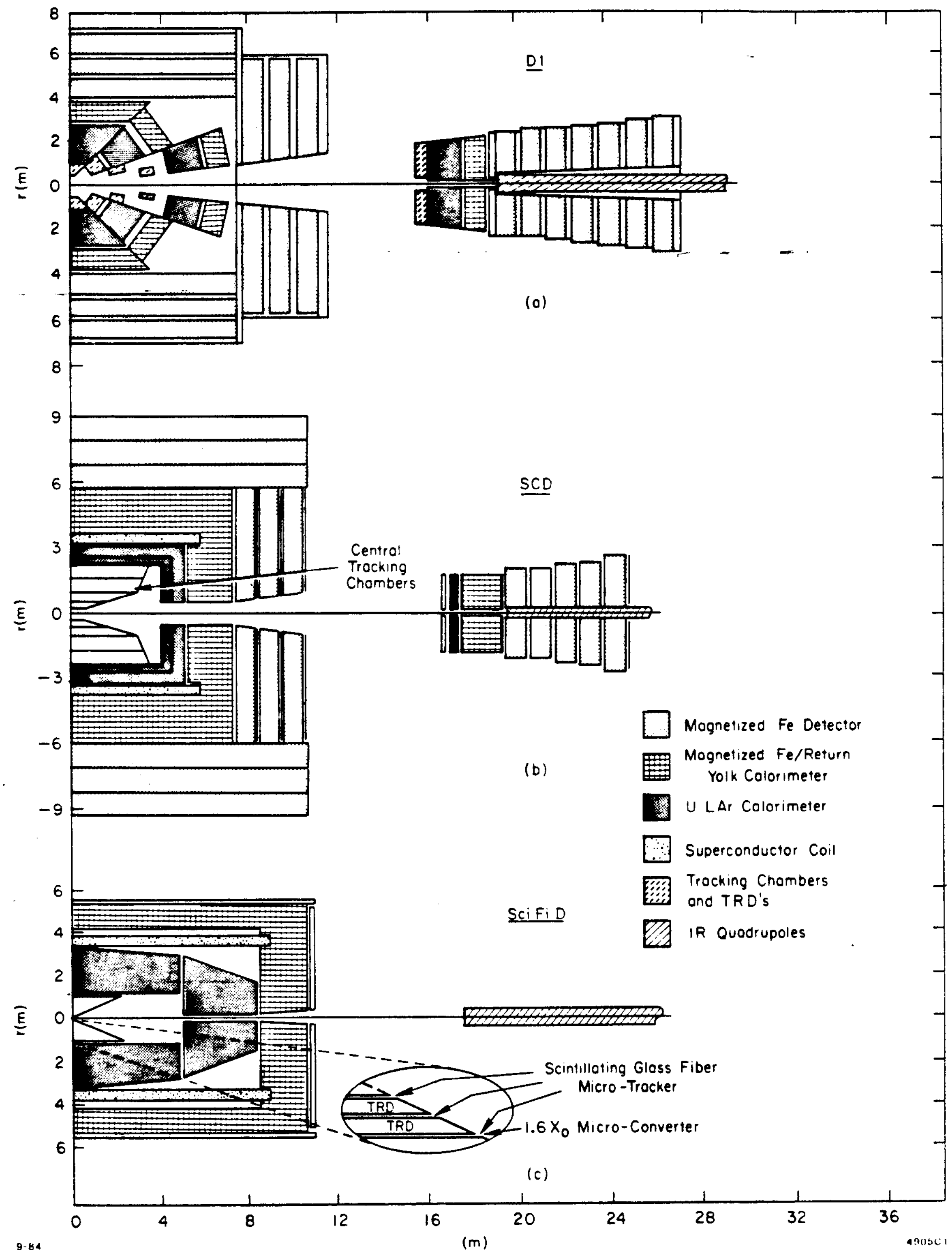
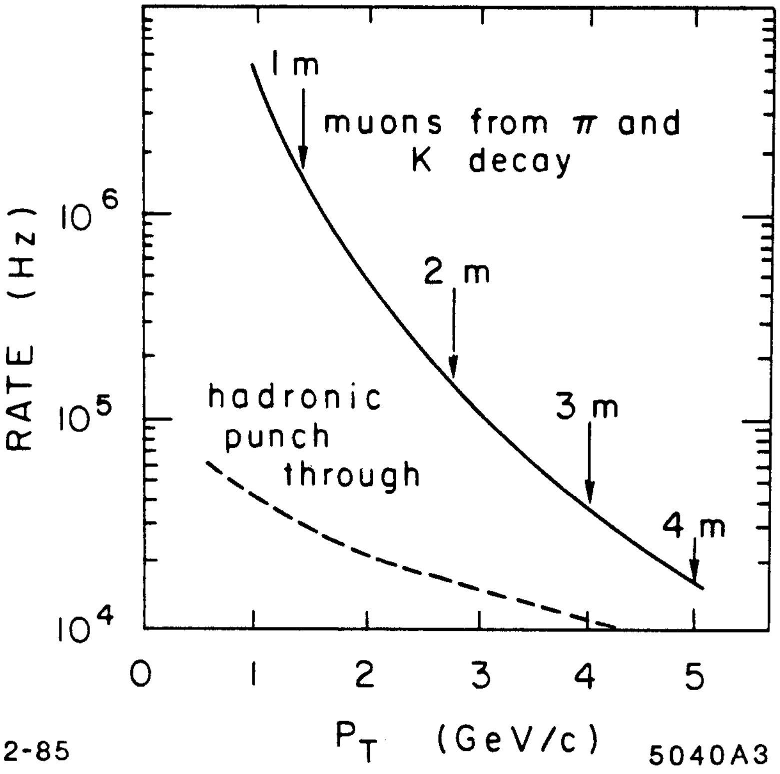
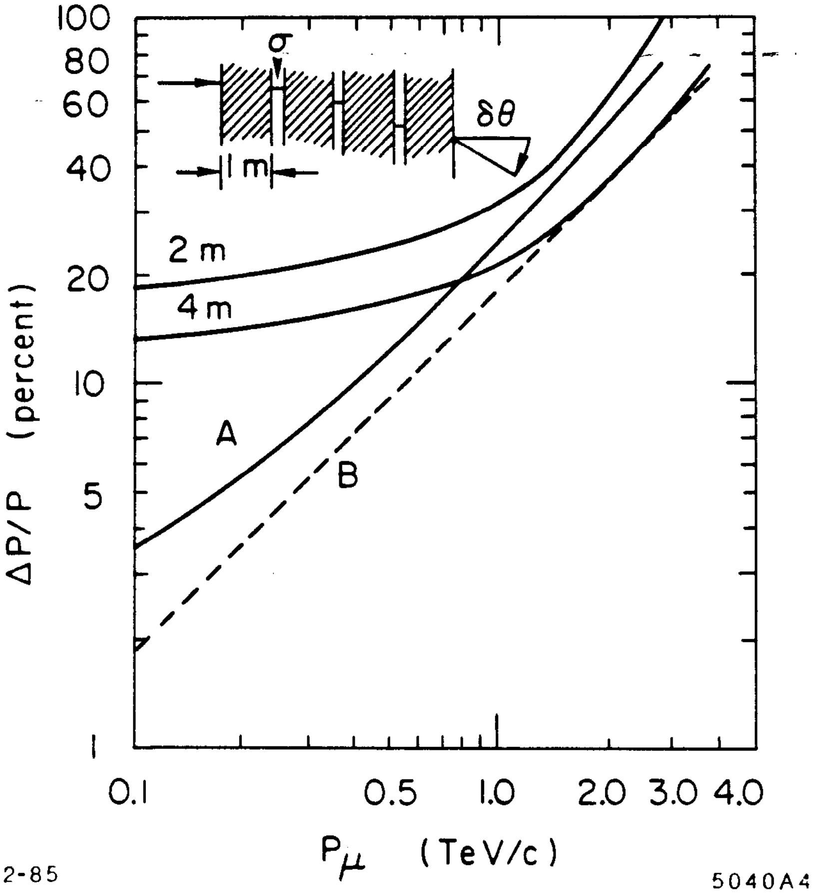

D1
(a)
SCD
Central Tracking Chambers
(b)
Sci Fi D
Magnetized Fe Detector
Magnetized Fe/Return Yolk Calorimeter
U LAr Calorimeter
Superconductor Coil
Tracking Chambers and TRD's
IR Quadrupoles
Scintillating Glass Fiber Micro-Tracker
TRD
TRD
1.6 X_0 Micro-Converter
(c)
r(m)
8
6
4
2
0
2
4
6
8
9
6
3
0
−3
−6
−9
6
4
2
0
2
4
6
0
4
8
12
16
20
24
28
32
36
(m)
9-84
4905C1

Fig. 2



1 m
muons from π and K decay
2 m
3 m
4 m
hadronic punch through
RATE (Hz)
10^6
10^5
10^4
0
1
2
3
4
5
P_T (GeV/c)
2-85
5040A3

Fig. 3



100
80
60
40
20
10
5
1
σ
δθ
1 m
2 m
4 m
A
B
ΔP/P (percent)
0.1
0.5
1.0
2.0
3.0
4.0
Pμ (TeV/c)
2-85
5040A4

Fig. 4

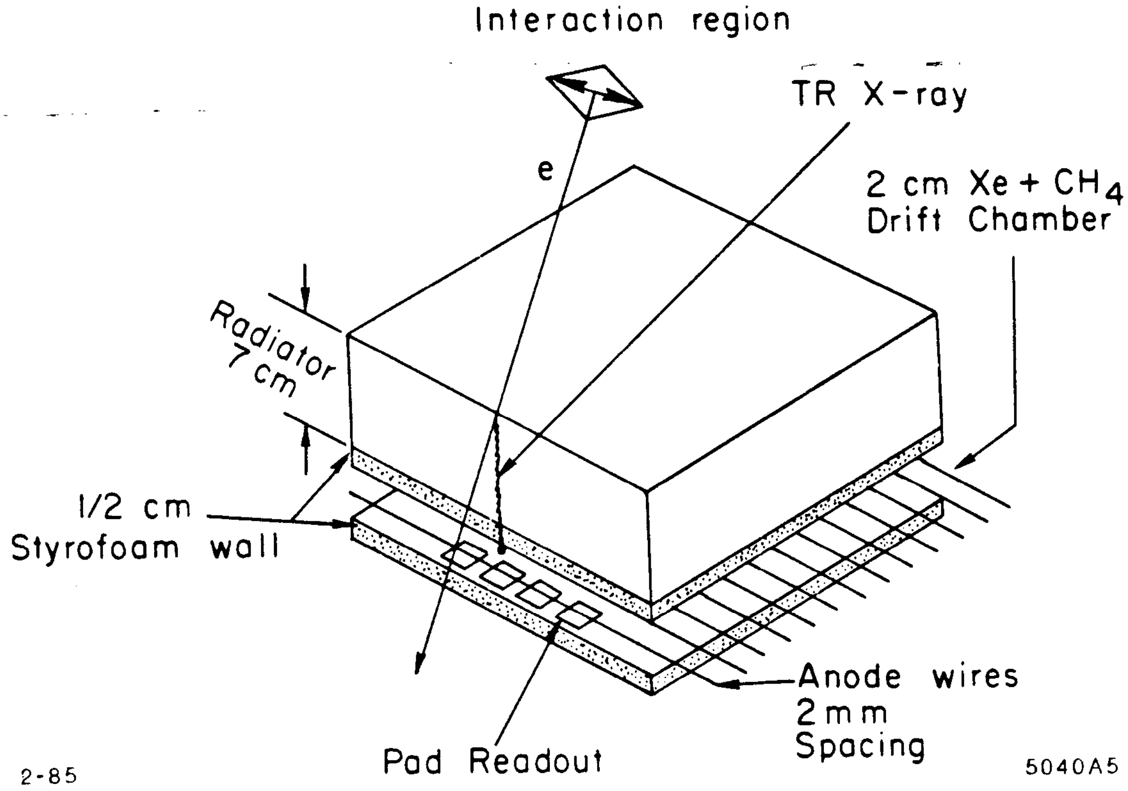

Interaction region
TR X-ray
e
2 cm Xe + CH$_4$
Drift Chamber
Radiator
7 cm
1/2 cm
Styrofoam wall
Anode wires
2 mm
Spacing
Pad Readout
2-85
5040A5

Fig. 5

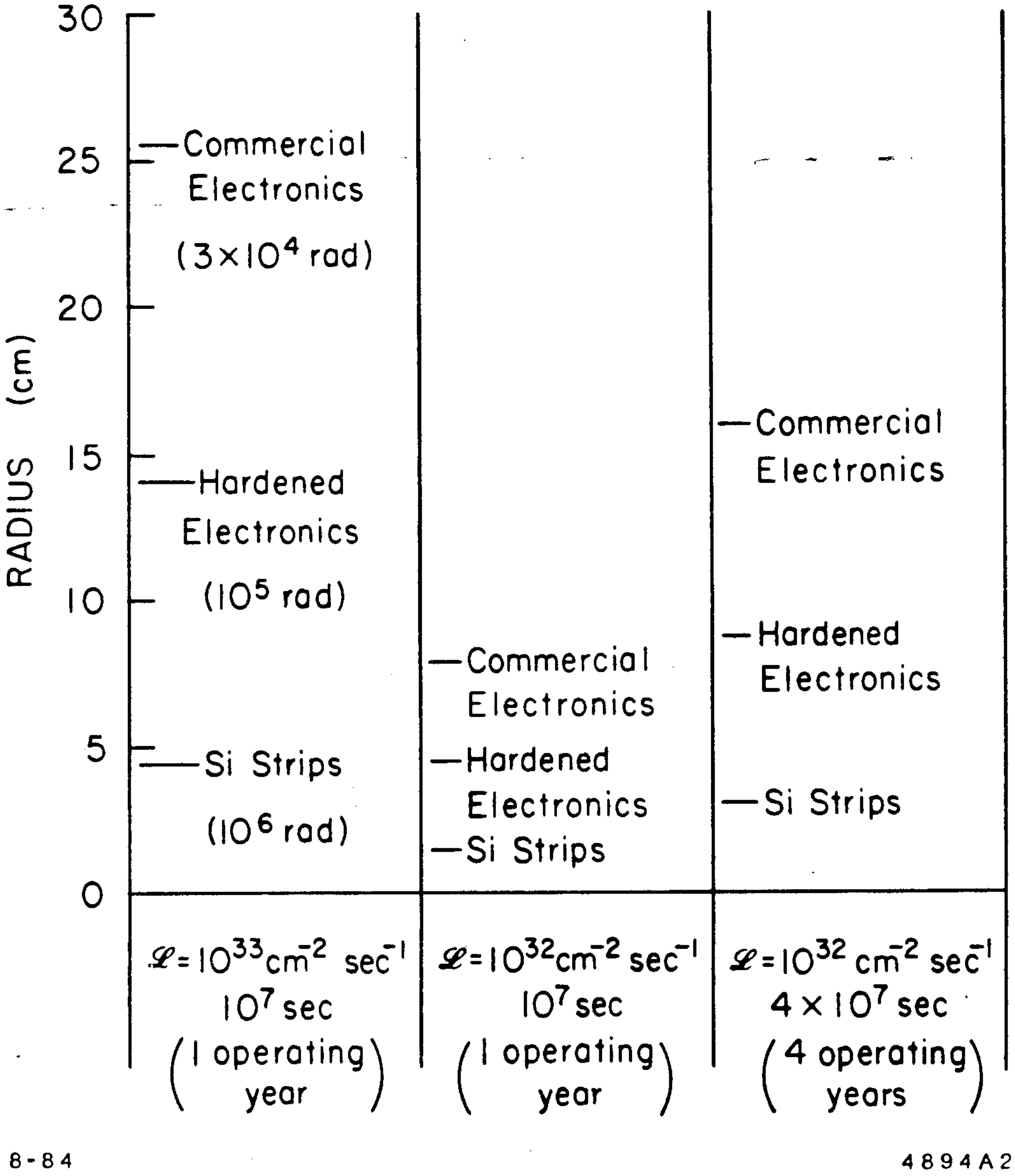

30
25
20
15
10
5
0
RADIUS (cm)
Commercial Electronics (3×10^4 rad)
Hardened Electronics (10^5 rad)
Si Strips (10^6 rad)
Commercial Electronics
Hardened Electronics
Si Strips
Commercial Electronics
Hardened Electronics
Si Strips
$\mathcal{L} = 10^{33} cm^{-2} sec^{-1}$
10^7 sec
(1 operating year)
$\mathcal{L} = 10^{32} cm^{-2} sec^{-1}$
10^7 sec
(1 operating year)
$\mathcal{L} = 10^{32} cm^{-2} sec^{-1}$
4×10^7 sec
(4 operating years)
8-84
4894A2

Fig. 6

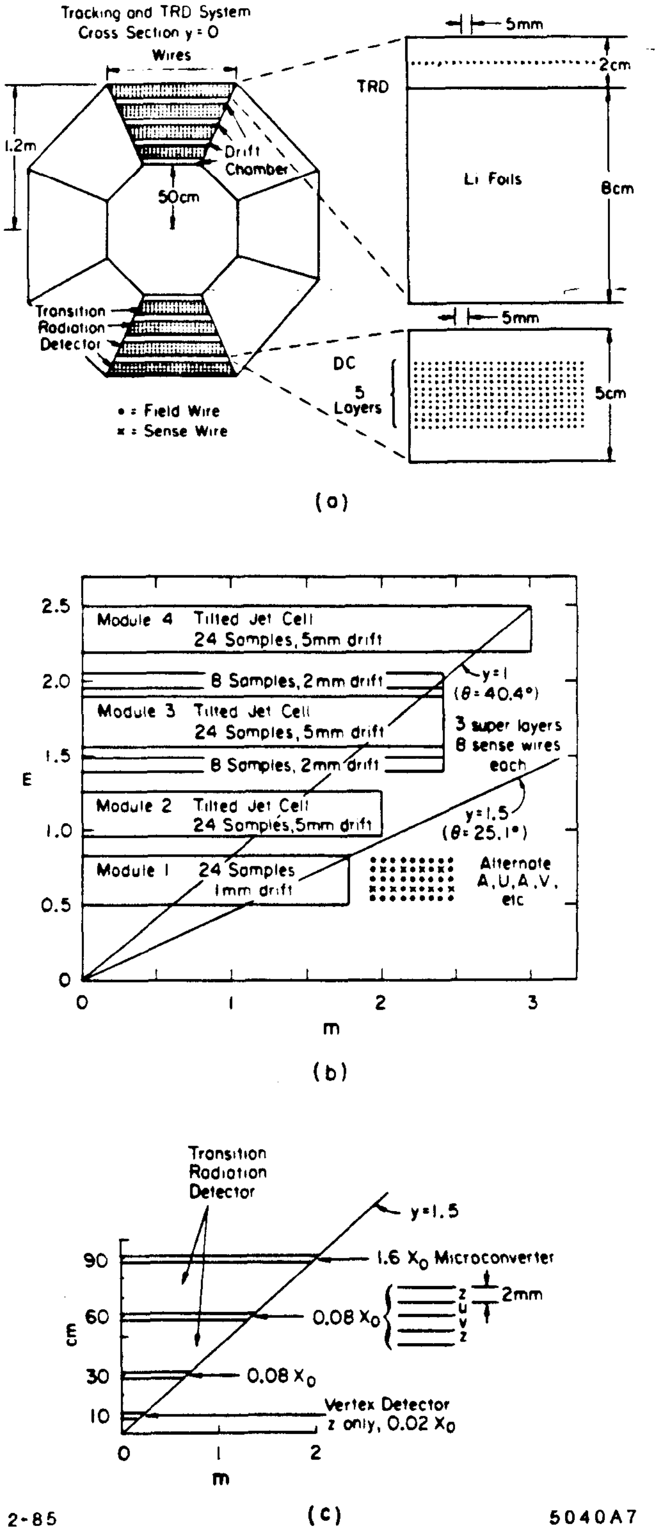

Tracking and TRD System
Cross Section y = 0
Wires
1.2m
Drift
Chamber
50cm
Transition
Radiation
Detector
• = Field Wire
× = Sense Wire
5mm
2cm
TRD
Li Foils
8cm
5mm
DC
5
Layers
5cm
(a)
2.5
2.0
1.5
1.0
0.5
0
E
Module 4 Tilted Jet Cell
24 Samples, 5mm drift
8 Samples, 2mm drift
Module 3 Tilted Jet Cell
24 Samples, 5mm drift
8 Samples, 2mm drift
Module 2 Tilted Jet Cell
24 Samples, 5mm drift
Module 1 24 Samples
1mm drift
y=1
(θ=40.4°)
3 super layers
8 sense wires
each
y=1.5
(θ=25.1°)
Alternate
A, U, A, V,
etc
0
1
2
3
m
(b)
Transition
Radiation
Detector
y=1.5
90
60
30
10
cm
1.6 X0 Microconverter
0.08 X0
z
u
v
z
2mm
0.08 X0
Vertex Detector
z only, 0.02 X0
0
1
2
m
2-85
(c)
5040A7

Fig. 7

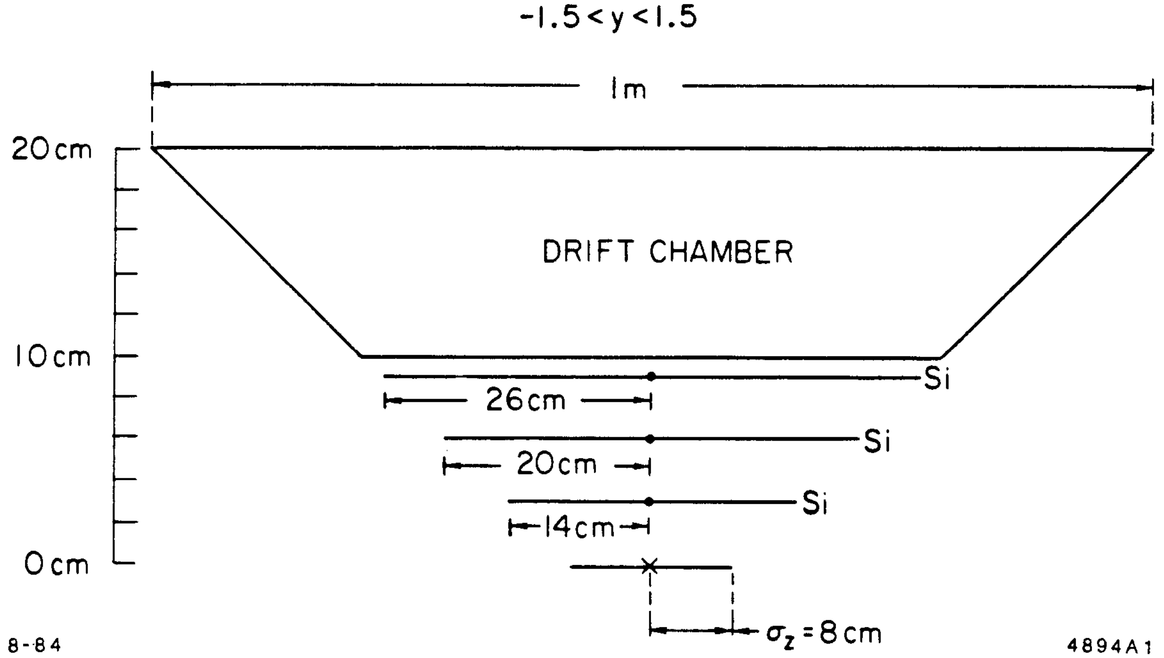
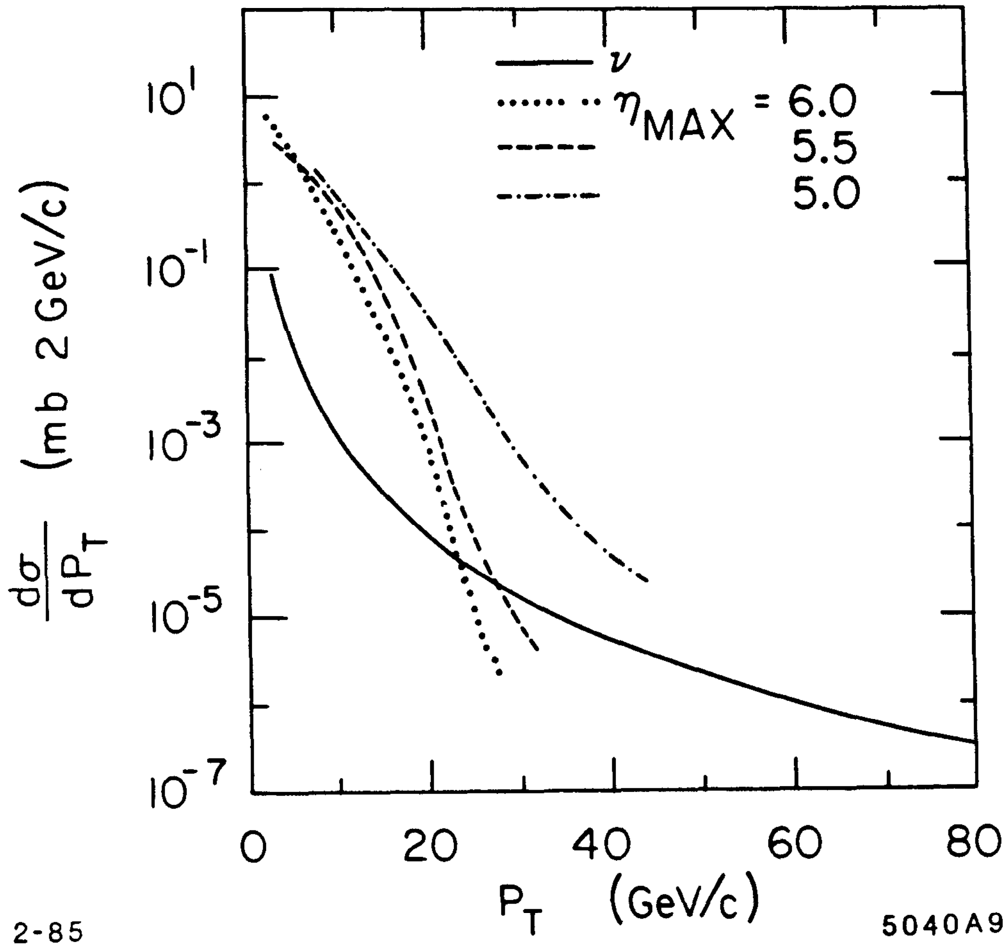

-1.5<y<1.5
1m
20cm
10cm
0cm
DRIFT CHAMBER
Si
26cm
Si
20cm
Si
14cm
σz = 8cm
8-84
4894A1

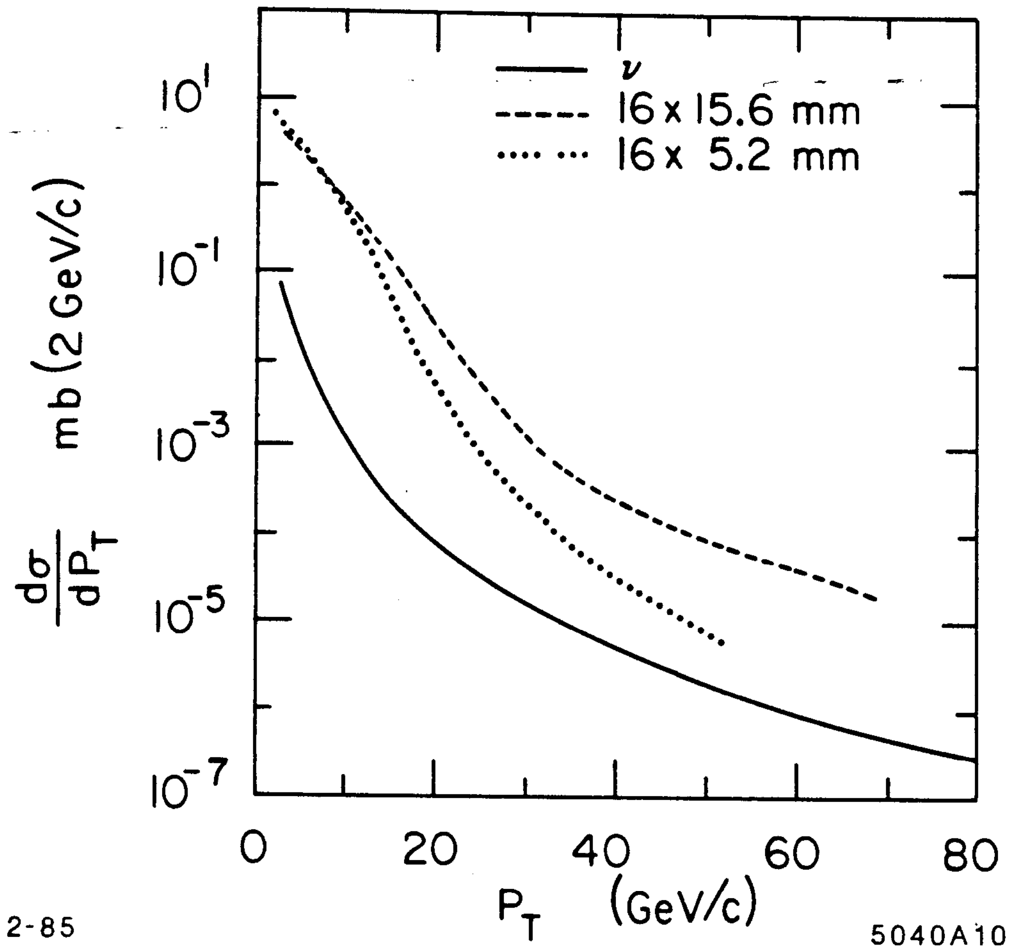
Fig. 8



2-85

5040A9

Fig. 9



ν
16 x 15.6 mm
16 x 5.2 mm
10^1
10^{-1}
10^{-3}
10^{-5}
10^{-7}
$\frac{d\sigma}{dP_T}$ mb (2 GeV/c)
0
20
40
60
80
P_T (GeV/c)
2-85
5040A10

Fig. 10