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PROPOSAL TO DEVELOP A HIGH-RATE TRACKING DETECTOR SUBSYSTEM FOR THE SSC USING SCINTILLATING FIBERS

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ABSTRACT

We propose to develop a high rate tracking subsystem appropriate for SSC experiments, based on scintillating fiber technology. The use of scintillating fibers as a detection medium affords the prospect for tracking particles with high resolution, low occupancy, and very short resolving time. It is the objective of this proposal to develop a prototype detector with up to 10^4 fibers for beam tracking tests to determine the utility of the technique. The program will establish a strong collaborative effort between university-based groups, laboratory groups, and research groups in private industry. We expect that it will take 3 years of intensive effort to complete the tasks of this proposal.

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I. INTRODUCTION

An important challenge for any SSC experiment is the provision of an effective tracking detector. Because of the high luminosity environment and the short bunch separation at the SSC, any tracking detector must have fast response, low occupancy, good spatial resolution, and good resistance to radiation damage.

A central tracking system should be capable of reconstructing low-mass states such as the Z^o with a precision of 1-2%, and should enable cross-checks of the electromagnetic and hadronic calorimeter calibration over a wide momentum range. Further, expected topologies such as the Higgs boson, detected via the decay $H \rightarrow Z^oZ^o \rightarrow qq\,l\,l$ and the decay $H \rightarrow Z^oZ^o \rightarrow$ 4 leptons, should be identifiable, with at least a 3σ charge sign determination for tracks of $p_T \leq 1$ TeV/c.

At an SSC detector operating at machine luminosities $L = 10^{33}$ cm^{-2} sec^{-1}, any viable tracking device must operate reliably in a high radiation environment (typically 10^5 rad/yr at a radius r = 50 cm from the interaction region due to beam interactions and neutron albedo). The tracking system, which must have low material thickness, should be capable of reconstructing all tracks, have good rejection against spurious tracks, and should be capable of separating tracks resulting from multiple interactions in a bunch crossing. A number of tracking options are being considered, but so far no technique has been proven. At small radii (typically r < 50 cm) silicon-strip detectors and/or pixel detectors are being considered for track reconstruction. At larger radii, the possibility of a stand-alone scintillating fiber tracker is potentially very attractive. It should be noted that the advantages of these two detector types are complementary.

Since the first successful use of fiber tracking in a collider environment [1], significant progress has been made [2]. Fiber trackers have the following attractive features:

[i] good tracking precision: multilayer structures of 500μm diameter fibers can result in a measurement resolution of 150μm per layer and provide good two track resolution.

[ii] fine granularity: for fibers of 500μm diameter placed at radii r ≥ 50cm, the occupancy from all sources is expected to be < 1% per fiber, per bunch crossing;

[iii] good time resolution: an intrinsically prompt response;

[iv] insensitivity to magnetic fields and to RF noise;

[v] simple electronics if a binary (yes/no) readout is used;

and [vi] no power dissipation in the tracking volume.

However, several technological developments are required before a realistic scintillating fiber central tracker for SSC detectors can be claimed. Figures 1 and 2 show hypothetical central tracking systems which cover the kinematic range $\eta \leq 3$. For $\eta \leq 1.5$ the geometry is cylindrical. For $1.5 \leq \eta \leq 3$, various configurations of forward detectors are planned. The basic detection element is an active scintillator fiber of ≤ 4m length, coupled by a 4m-to-6m long, clear fiber waveguide to a high-rate photodetector. The performance goals are: the detection of minimum ionizing particles resulting from a beam-beam collision with an efficiency exceeding 95% per layer; the determination of the longitudinal coordinate and impact parameter to 1mm for each track; unambiguous asignment of each track to a beam crossing (16 nsec spacing); momentum resolution sufficient to reconstruct the mass of the Z^0 to < 2% in a leptonic decay; momentum resolution sufficient to make a 3σ determination of the charge of a 1 TeV/c particle; and radiation resistance adequate for all components to survive for several years of beam without significant degradation of capabilities. As discussed in Appendix A below, the major initial effort of this proposal will be the development of:

[i] a fast scintillator having a peak emission wavelength in the spectral range $530 \leq \lambda \leq 650$nm, having an acceptably long attenuation length and insensitivity to radiation damage;

[ii] clear fiber waveguides of good collection efficiency, adequate radiation hardness and long attenuation length, and good coupling techniques between scintillator and waveguide;

[iii] photo-detectors that have good quantum efficiency in the spectral reqion in [i] above (for example the solid-state photomultiplier (SSPM) being developed by the Rockwell International Science Center and avalanche photodiodes (APD) from companies such as RCA and Hamamatsu) ;

and [iv] fast, low-noise preamplifiers and discriminators followed by a pipelined readout and a p_T - sensitive track capability in the trigger.

As shown in Figure 1, some superlayers of the detector could include a large-area pad device to make the task of pattern recognition easier. This technique has been used successfully by the UA2 Collaboration [1]. We propose to investigate, through simulation, the mechanical and electronic readout implications of including pad layers and to study the potential advantages of such structures for fast pattern recognition.

Lastly, during the course of this subsystem development, we will investigate different aspects of mechanical support, alignment accuracy, and optimal fiber configuration for good pattern recognition while striving to maintain minimal material thickness. Such studies are essential for the design of a final detector. Successful completion of development work on scintillating fibers, waveguide fibers, and photodetectors will demonstrate the feasibility of a realistic fiber tracking detector for the SSC.

References

[1] J. Allitti, et al, IEEE Transactions on Nuclear Science, Vol. 36, No. 1(1989)

[2] For a comprehensive review of the field and recent progress see: The Proceedings of the Workshop on Scintillating Fiber Detectors for the SSC, Fermilab, November 14-16, 1988, S. Reucroft and R. Ruchti, eds.

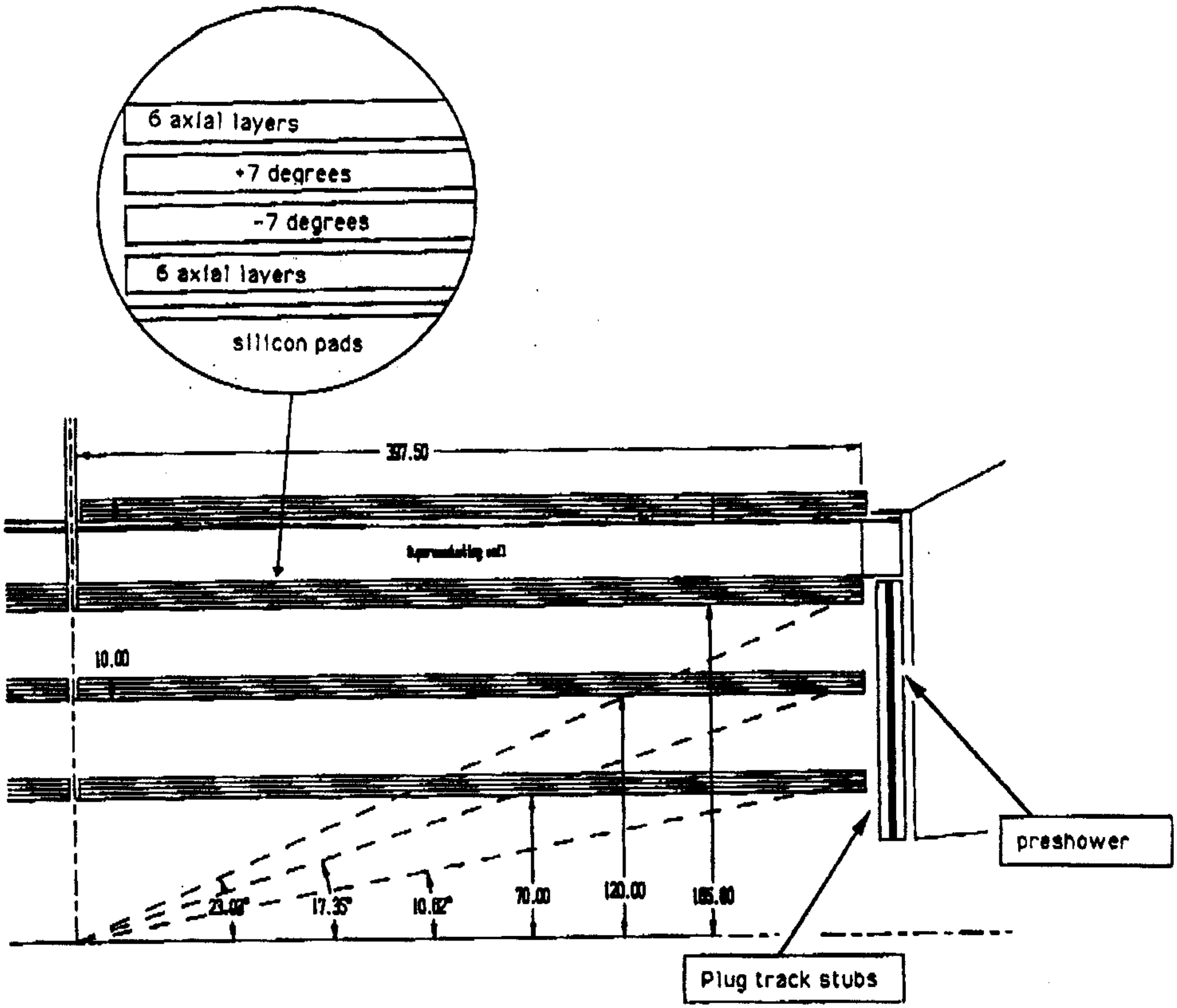


Figure 1. Hypothetical Tracking Detectors Based on Scintillating Fibers
(Central Region, $\eta \leq 3$)

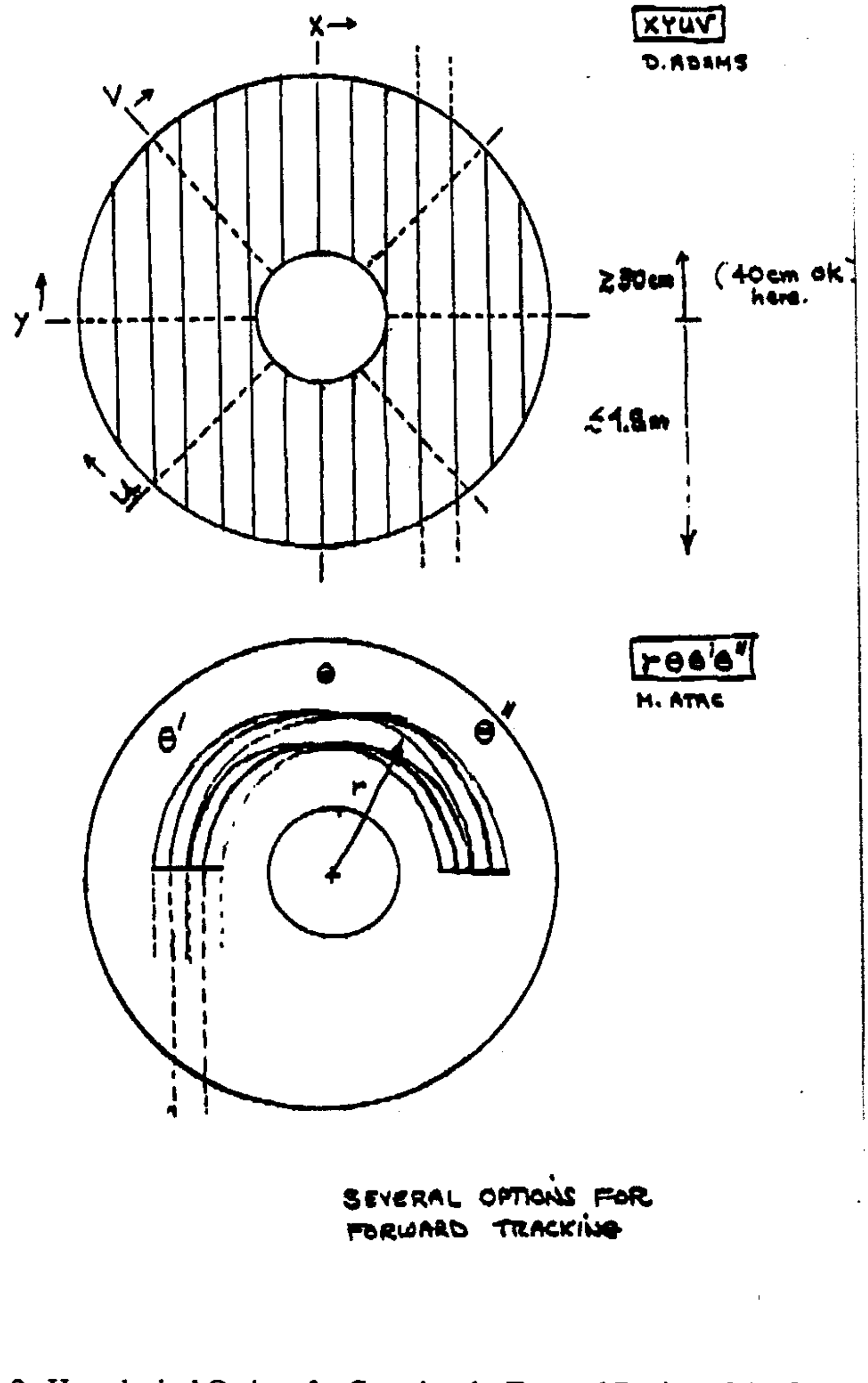


Figure 2. Hypothetical Options for Covering the Forward Region of the Central Tracker Using Scintillating Fibers ($1.5 \leq \eta \leq 3$)

II. SCOPE OF WORK

In order to develop a prototype tracking detector a large number of tasks must be addressed, requiring a strong collaborative effort between university groups, national and international laboratory groups, and private industry. These tasks are enumerated below. Supporting information for each task is provided in Appendix A.

A. Fibers

1. Scintillating fiber: the development of fluors for operation at wavelengths in the range $530 \leq \lambda \leq 650$nm; the development and optimization of claddings for scintillating fibers; and cross section profile studies for optimal performance.

2. Clear optical waveguide: the development of claddings, cross-section profiles and coupling techniques, with the aim of achieving high coupling efficiency and long attenuation length.

B. Photodetectors

1. Solid state photomultipliers (SSPM): the optimization of this device for high-rate, single photon counting in the spectral range of interest.

2. Avalanche photodiodes (APD): the development of pixel arrays with high quantum efficiency and adequate rate capability.

3. Vacuum photomultipliers: study of prismatic photocathodes, cathode materials, and amplification structures for improved quantum efficiency and spatial resolution for use in applications where light levels are not too low (such as in shower preconversion detectors) or where magnetic field effects are sufficiently controlled that a vacuum electron amplifier can be made to operate successfully.

C. Electronics

1. Front end electronics: the study of amplifier and discriminator technology capable of low-noise and high-frequency operation at 77 K.

2. Data acquisition and trigger: the design of architectures for data latching, pipeline storage, and vector trigger pattern recognition.

3. Integrated circuits: an investigation of the feasibility of integrated pixel structures which incorporate photodetection, amplification, and discrimination for single photon counting at high rates.

D. Radiation Hardness

1. Fibers: a measurement of the radiation damage characteristics (using charged particles, gammas, and neutrons) for candidate scintillating fibers and waveguides.

2. Photodetectors: a determination of the radiation damage characteristics of photodetectors and of the associated electronics.

E. Simulation

1. Tracking Structures: optimization of the fiber configuration for pattern recognition, good track resolution and two track separation, for acceptance, and for fast trigger decisions.

2. Pad layers: study of the use of Si pad layers to facilitate track reconstruction algorithms and provide sufficient granularity for complete pattern recognition.

3. Backgrounds: a study of neutron-albedo hit rates, conversions in superlayers, low momentum spirals, and effects of Cerenkov light in waveguides.

F. Cryogenics Systems

1. The construction of small cryostats for initial studies of devices and fibers at LHe and LN_2 temperatures.

2. The design of optical penetrations to minimize heat transfer via thermal conduction through waveguide and conductor materials, and to minimize the effects of thermal transfer through photons (infrared component) generated in the waveguides at the ambient temperature of the fiber detector.

3. The design of electrical connections between photodetectors, preamps, and external circuitry to minimize heat transfer and heat loads.

3. The design and construction of large scale distributed cryostats for the prototype detector.

G. Mechanical Engineering

1. Fiber Support Structure: the design and fabrication of low mass cylindrical supports for superlayers of scintillating fibers with couplings to clear fiber waveguides.

2. Fiber Layers: a study of techniques for the fabrication of axial and stereo superlayers with adequate mechanical precision and interlayer registry.

3. Cryostat Support Structure: the design of supports for photodetector cryostats taking account of the need for waveguide penetrations and strain relief.

A brief description of the work to be performed in each of these tasks is presented in Appendix A below.

III. MILESTONES

YEAR I

1. Construction of several optical cryostats capable of supporting the operation of SSPMs and/or APDs at a level of several hundred channels.

2. Identify and survey:
   (i) radiation hard scintillators having good quantum efficiency and long attenuation length;
   (ii) coupling techniques between scintillating and waveguide fibers;
   (iii) other options for optical imaging, including multianode PMTs and other technologies.

3. Design of a preamplifier/discriminator capable of operating at liquid nitrogen temperature.

4. Development of a simulation package to optimize the geometry of the prototype detector for fast pattern recognition and rapid trigger decisions.

5. Development of DAQ and vector/trigger processing algorithms and formulation of an electronics design strategy.

YEAR II

1. Working SSPMs (several hundred channels) coupled to scintillating fibers and preliminary tests with sources and cosmic rays.

2. Working APDs (several hundred channels) coupled to scintillating fibers and preliminary tests with sources and cosmic rays.

3. The production of radiation resistant scintillating fibers, and the initiation of procurement procedures necessary for prototype construction.

4. The completion of a conceptual design study for a prototype detector suitable for beam tests.

5. Prototype DAQ circuits fabricated and tested initially with simulated inputs and later with real signals from the photodetectors and associated ancillary electronics.

6. The initiation of a conceptual design study for a distributed cryostat system.

YEAR III

1. Construction of the prototype scintillating fiber tracking with 10^3 - 10^4 channels and full data acquisition system.

2. Cosmic ray tests followed by beam tests.

3. Completion of the conceptual design study of a distributed cryostat system.

IV. DISTRIBUTION OF RESPONSIBILITIES

This collaboration represents a merger of two strong groups, one an association of universities and ORNL, the other from Fermilab and Japan, each of which originally had independent interests in developing a scintillating fiber tracker for the Supercollider and each of which has proponents who made fundamental contributions to the field of scintillation fiber detectors. We list below the distribution of responsibilities among the participating institutions.

A. Fibers	
1. Scintillators	Notre Dame, Fermilab, Tsukuba
2. Waveguides and splicing	Notre Dame, Fermilab, UCLA, Purdue, Tsukuba
B. Photodetectors	
1. SSPMs*	UCLA, Rockwell, Notre Dame, UT Dallas
2. APDs	Rice, Fermilab, UI Urbana, Osaka, Tsukuba
3. Vacuum photomultipliers	Fermilab, UCLA, Notre Dame, Tsukuba
C. Electronics	
1. Front End Preamps	UT Dallas, ORNL
2. DAQ and Front-end triggering	Penn State, ORNL, Fermilab, UI Urbana
D. Radiation Damage Studies	
1. Fiber Detectors	Purdue, UI Chicago, Tsukuba
2. Photomultipliers and Electronics	ORNL, Purdue, UI Chicago
E. Simulation:	UCLA, Penn State, Rice, Purdue, Fermilab, Tsukuba, Notre Dame
F. Cryogenics:	
1. Small Cryostats	UCLA, Notre Dame, UI Chicago, Fermilab
2. Large Distributed Cryostats	UI Chicago, Fermilab, Industry
G. Mechanical Engineering Designs:	ORNL

*See Section XI for regulations on SSPM development.

V. MANPOWER

In this section we list the manpower contributed to the program from the participating institutions. Further documentation of this participation by institution is included in Appendix B.

	INSTITUTION	PERSONNEL	FTE
A.	UCLA	M. Atac	0.25
		Post Doc	1.0
		Technician	0.5
		Students	1.0
B.	Notre Dame	R. Ruchti	0.3
		V. P. Kenney	0.25
		N. Biswas	0.25
		Faculty Fellow	0.25
		Post Doc	0.5
		Engineer	1.0
		Technician	0.5
		Students	2.5
C.	UT Dallas	E. Fenyves	0.1
		R. Chaney	0.25
		H. Hammack	0.25
		Students	0.25
D.	Rice	D. Adams	0.25
		Post Doc	1.0
		Students	2.0
E.	UI Chicago	H. Goldberg	0.25
		S. Margulies	0.25
		J. Solomon	0.25
		Post Doc	1.0
		Students	2.0

	INSTITUTION	PERSONNEL	FTE
F.	ORNL	Engineering	1.5
G.	Penn State	G. Smith	0.25
		R. Lewis	0.25
		B. Oh	0.2
		W. Toothacker	0.1
		S. Heppelmann	0.1
		J. Whitmore	0.1
		Post Doc	1.0
		Electrical Engineer	0.5
		Technician	1.0
H.	Purdue	D. Koltick	0.25
		E. Shibata	0.25
		Post Doc	0.5
		Students	1.0
I.	Fermilab	M. Atac	0.25
		P. Berge	0.2
		M. Binkley	0.2
		A. Bross	0.2
		A. Clark (FNAL visitor)	0.3
		J. Elias	0.3
		G. Foster	0.2
		J-M Gaillard (FNAL visitor)	0.3
		R. Kephart	0.2
		S. Tkaczyk	0.2
		R. Wagner	0.2
		Technicians	1.0
J.	UI Urbana	S. Errede	0.25
		J. Thaler	0.25
		Electronic Engineer	0.5

Programmer	0.6
TOTAL FTE FOR SENIOR AND PROFESSIONAL STAFF	19.8
TOTAL FTE FOR STUDENTS	8.8
TOTAL FTE ALL PERSONNEL	28.6

VI. BUDGET REQUEST

Scintillating fibers constitute a principal candidate technology for use in a central tracker at the SSC. Since a central tracker is an important component of most proposed SSC detectors, it is important that the development work discussed in this proposal be adequately funded so that the feasibility of the technology is determined sufficiently early to be useful in SSC detector design.

This program is expected to require three years for completion. We request funds in the amount of $1969K in the first year and estimate that the project will require $2500K in the second year and $3000K in the third year. The first year budget request is presented in Sections VII, VIII, and IX below and individual itemized budgets for participating institutions are presented in Appendix B.

Finally we note that, pending successful funding of this proposal, substantial matching funds ($294K) will be contributed by several universities in support of their participation, and important facilities will made available at ORNL and Fermilab in support of this SSC subsystem program.

VII. SUMMARY FIRST YEAR BUDGET *
(By Task, in US Dollars)

Task	Total
A. Fibers	330K
B. Photomultipliers	670K
C. Electronics	401K
D. Radiation Damage	169K
E. Simulation	214K
F. Cryogenics	126K
G. Mechanical Engineering	59K
Total	1969K

* Funding request for the first year of a three year program.

VIII. SUMMARY FIRST YEAR BUDGET*
(By Institution, in U.S.Dollars)

Institution	Request	Matching Funds@	Net Request
UCLA	270K	37K	233K
Notre Dame	310K	65K	245K
UT Dallas	96K	30K	66K
Rice	142K	36K	106K
UI Chicago	186K	31K	155K
UI Urbana	110K		110K
Penn State	245K	45K	200K
ORNL	178K	**	178K
Purdue	185K	50K	135K
Fermilab	178K	**	178K
Tsukuba***			
Osaka City***			
Group subcontracts	363K		363K
Totals	2263K	294K	1969K

* Funding request for the first year of a three year program.

Individual budgets from participating institutions are included in Appendix B below.

@ Matching funds in the amount of $294K will be available to the various University groups contingent upon successful funding of this proposal.

** Fermilab and ORNL are making significant contribution to this program by making a number of essential facilities available to this program. See Appendices B and C.

*** Tsukuba University and Osaka City University will request funds for this project separately from the U.S. - Japan accord.

IX. BUDGET TABLE

On the next two pages are a table, breaking down the costs for the first year of the program by project and institution. All entries are in thousands of US Dollars. The budgets listed in Sections VI and VII above represent the vertical and horizontal projections of this table respectively.

An important column in the table is Column L which shows expenses which are not necessarily specific to a given collaboration group but are to be subcontracted by the collaboration. These include:

L4 Order for scintillation fiber from which the prototype detector will be made. ($10K. To be implemented in Year 2 of the program.)

L5 Order for waveguide fiber from which the prototype detector will be made. ($10K. To be implemented in Year 2 of the program.)

L8 Subcontract through UCLA to Rockwell for SSPMs. ($183K to be spent in Year 1, $258 to be spent in Year 2. See Appendix B)

L9 Subcontract(s) through the collaboration for APDs. ($80K. Vendor(s) to be determined in Year 1.)

L10 Subcontract(s) through the collaboration for Vacuum PMTs. ($50K Vendor(s) to be determined in Year 1.)

L12 Subcontract through UT Dallas and ORNL for liquid nitrogen temperature VLSI preamplifier chip with 128 channels. ($50K. Vendor(s) to be determined in Year 1.)

L23 Subcontract through UI Chicago for conceptual design study for a distributed cyogenics system. ($50K. Vendor to be determined in Year 2.)

FIBER SU YSTEM

	A	B	C	D	E	F	G
1	TASK	UCLA	NOTRE DAME	UT DALLAS	RICE	UI CHICAGO	PENN STATE
2							
3	A. FIBERS						
4	SCINTILLATOR		90				
5	WAVEGUIDES		75				
6							
7	B.PHOTODETECTORS						
8	SSPM	148					
9	APD				37		
10	VAC PMT	30	45				
11							
12	C. ELECTRONICS						
13	PREAMPS			66			
14	TRIGGER/PIPELINE						121
15	VLSI/ASIC						
16							
17	D. RADIATION DAMAGE						
18	FIBERS					84	
19	ELECTRONICS						
20							
21	E. SIMULATION	35			69		79
22							
23	F. CRYOGENICS	20	35			71	
24							
25	G. MECHANICAL ENGINEERING						
26							
27							
28							
29	COLUMN TOTAL	233	245	66	106	155	200
30	ROW TOTAL						

	H	I	J	K	L	M	N	O
1	OAK RIDGE	PURDUE	FERMILAB	UI URBANA	GROUP WIDE	TOTAL	DEFER TO	TOTAL BUDGET
2							YR2	YR1
3								
4		25	60		10	185	10	175
5		25	55		10	165	10	155
6								
7								
8					441	589	258	331
9			31	35	80	183		183
10			31		50	156		156
11								
12								
13	59		0		50	175		175
14	30		0	75		226		226
15			0			0		0
16								
17								
18		55				139		139
19	30					30		30
20								
21		30	1			214		214
22								
23			0		50	176	50	126
24								
25	59					59		59
26								
27								
28								
29	178	135	178	110	691	2297	328	1969
30						2297		1969

X. REQUEST FOR SSC LABORATORY SUPPORT

In the third year of this program we will require access to test beam facilities (for example at Fermilab) in order to study high-rate tracking properties of the prototype scintillating fiber tracker. At that time, we intend to request assistance from the SSC laboratory for installation of equipment in an appropriate test beam, for assistance in obtaining the necessary test beam time and for the usual necessary support associated with beam operation required to carry out our studies.

For initial demonstration of the effectiveness of scintillating fiber tracking techniques, any beam capable of several GeV/c of momentum would be sufficient. However tests of two track (and multitrack) resolution and momentum measurement would be most usefully performed in a high energy beam and with magnetic fields up to 2 Tesla. Since Fermilab is making a significant contribution to this program in manpower and resources, a logical choice of site for beam tests would be one of the fixed-target beam lines or test beams at Fermilab. However this choice depends critically on scheduling for the Tevatron and hence careful coordination is required. It is essential that SSC testing requests such as ours be presented to Fermilab through the SSC laboratory, so that a coherent plan for scheduling and support can be developed.

XI. REGULATIONS AND RESTRICTIONS

This collaboration agrees to respect the ITAR restrictions governing the use of and dissemination of information about SSPM devices to be developed by Rockwell in collaboration with UCLA, Notre Dame and UT Dallas groups. These groups have separately submitted letters to Rockwell and DOE formally agreeing to ITAR policy.

The implications of this policy and its restrictions should be reviewed and/or amended once new, high-speed, infrared-insensitive (IRI) devices are fabricated under funding provided through this program.

APPENDIX A
DISCUSSION OF THE TASKS IN THE SCOPE OF WORK

A. FIBERS

The utilization of fiber detectors for tracking applications depends critically on several factors:

[i] the quantum efficiency of the scintillator within given critical dimensions;
[ii] the optical self-absorption properties of the scintillation material, and in particular the Stokes' shift between absorption and emission spectra;
[iii] the properties of the scintillation waveguide for light trapping (total internal reflection), light transmission (reflection coefficient and optical absorption), and cross talk;
[iv] the radiation resistance of the scintillator material and optical waveguides;
and [v] the coupling efficiency to, and the quantum efficiency of the photodetector for wavelengths of interest.

We examine each of these in turn:

[i] The quantum efficiency of the scintillator. For a variety of reasons, organic plastics and liquids are the most desirable materials for the construction of a tracking detector. Firstly, fluorescence yields in the order of 70%-80% of anthracene are routinely obtained. Secondly, the materials have low density, 1 g cm^{-3}, a radiation length of 42cm and an absorption length of 79cm. Such properties are well matched for tracking applications. The scintillation efficiency does depend, however, on a critical dimension - the distance scale over which the scintillation process occurs. For binary scintillators, this critical scale is given by the range of Forster Transfer which is tens of Angstroms. For ternary and quaternary scintillators, the scale is set by the mean free path for wave shifting between dyes and is typically 250μm or greater, depending upon dye concentration. This has the consequence of a minimal radial dimension for scintillating fibers which is set by this critical scale.

[ii] The self-absorption process. In conventional ternary and quaternary scintillators, self absorption is reduced by using a very low concentration (0.01%-0.1%) of final dye. In binary scintillators, a large Stokes' shift is an essential property required of

the dye material, since 1% concentrations of the dye are necessary for Forster Transfer between the solvent (for example polystyrene) and solute (dye). Measurements of polystyrene indicate that optical transmission is best for wavelengths $530 \leq \lambda \leq 650$ nm (see Figure A1). Hence it is important to select a scintillator with fast fluorescence in this region.

[iii] Waveguide properties: For plastic fibers, typical refractive indices $n = 1.59$ and $n=1.49$ are obtainable for the core and cladding respectively. There are also claddings of lower refractive index (down to $n=1.40$) which warrant study. These indices provide for 6% light trapping in a fiber guide (3% of the light trapped in each direction in the guide). Reflection coefficients of 0.999 have been achieved with plastic materials, having polystyrene core and acrylic cladding). It would be of great benefit if this could be improved.

The physical properties described in [ii] and [iii] above dictate the attenuation length for light in fibers. For fiber diameters of 0.5mm - 1mm, this is typically in the 1m-2m range. This situation can be improved by careful work on dye materials and dye purity, on the purity and optimization of core and cladding materials of a fiber (a chemistry issue) and by improvements in the interface between core and cladding materials (a mechanical issue).

[iv] Radiation Resistance: Measurements have been reported on polystyrene-based plastic scintillator and non-scintillator samples which indicate that optical transmission properties, for wavelengths $\lambda \geq 500$nm, survive for gamma doses of 10Mrad administered over short time intervals [see Figure A2]. The effects of long-term damage to core materials, cladding materials, and fiber structures are not yet well understood. However it is clear that scintillation fluorescence at wavelengths greater than 500nm is desirable. Conventional bialkali photocathodes are inefficient at these wavelengths. Hence it is essential to develop photodetectors with high quantum efficiency at long wavelengths. Appendix A, Sections B and D, outlines our plans for photodetection and radiation damage studies.

[v] Coupling to the detector readout. There will always be a coupling loss between the fiber detector and the imaging system, because of mismatches in alignment of fiber scintillators to fiber light guides, and of fiber light guides to the pixel elements of the imaging system. These result from cladding mismatches, interstices between fibers,

refractive index mismatches, and diffractive effects. After careful alignment and bonding, one has to live with the result.

There are several options for fiber splicing. An obvious choice is to couple a scintillating fiber of a given diameter to a waveguide fiber of slightly larger diameter, thus avoiding a cladding misalignment. There are several possibilities for optical coupling including optical grease or oil, gluing, dissolving/melting, UV polymerization, and ultrasonic bonding. The latter method is a particularly promising option.

Amazingly, it has been observed that polystyrene fibers may be cycled to cryogenic temperatures (7 K) numerous times without apparent damage to the fibers. We intend to study this systematically for fibers of various cladding thicknesses and cladding materials, in order to select an optimal configuration for light transmission from ambient temperature to the 7 K environment for SSPM operation and the 77 K environment for APD operation.

Goals: We will continue our program of dye development for fibers which has thus far been very productive [ref] and more recently has included the development of syntheses for the large Stokes dye bipyridine diol (BPD) at Aldrich and Bicron and several new large Stokes primaries MOPOM and di-t-butyl-MOPOM synthesized by Philadelphia College of Pharmacy and Medicine (J. Kauffman). BPD has properties similar to the dye 3HF with fluorescence in the green, but is potentially a more stable molecule. The MOPOM structures have the high molar extinction coefficient characteristic of the familiar POPOP, but have substantially larger Stokes' Shift and improved solubility. They may be a good bridge to longer wavelength ternary and quaternary scintillators.

Additionally we will in collaboration with industry:

[i] work on polymer and cladding purity as well as dye purity to improve light efficiency and optical transmission in the produced fibers;

[ii] study effects of the molecular weight of polystyrene on boule preparation, and the nature of the core cladding interface;

[iii] investigate cladding materials and cladding thickness for acrylics, polyvinylacetate, and fluoridated hydrocarbons for compatability with polystyrene core material, and for good visible wavelength and infrared poor transmission;

[iv] investigate extramural absorbers (overcoatings) for fibers such as aluminization, TiO_2 and opaque materials to minimize crosstalk;

[v] investigate the systematics of fiber drawing in single strands, ribbons, and multifibers;

[vi] investigate radiation resistant adhesives to bond fibers into ribbons and onto support structure, so that degraded adhesives will not damage fibers or their alignment. Polysiloxane based adhesives are one of the possibilities;

[vii] investigate coupling techniques for fiber splicing and coupling to photodetectors as discussed above;

[viii] investigate the behavior of polystyrene fibers in a cryogenic environment and under temperature cycling;

and [ix] investigate coupling strategies for fibers to solid state photodetectors which will work reliably under temperature cycling.

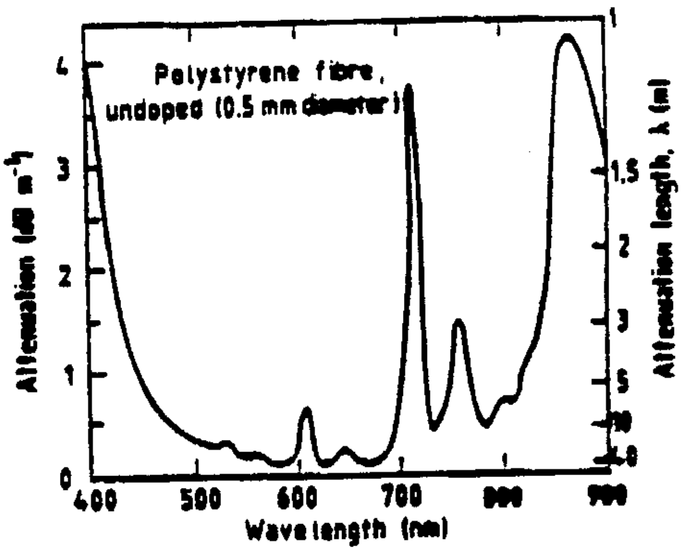


Figure A1. Optical Transmission in Polystyrene as a Function of Wavelength

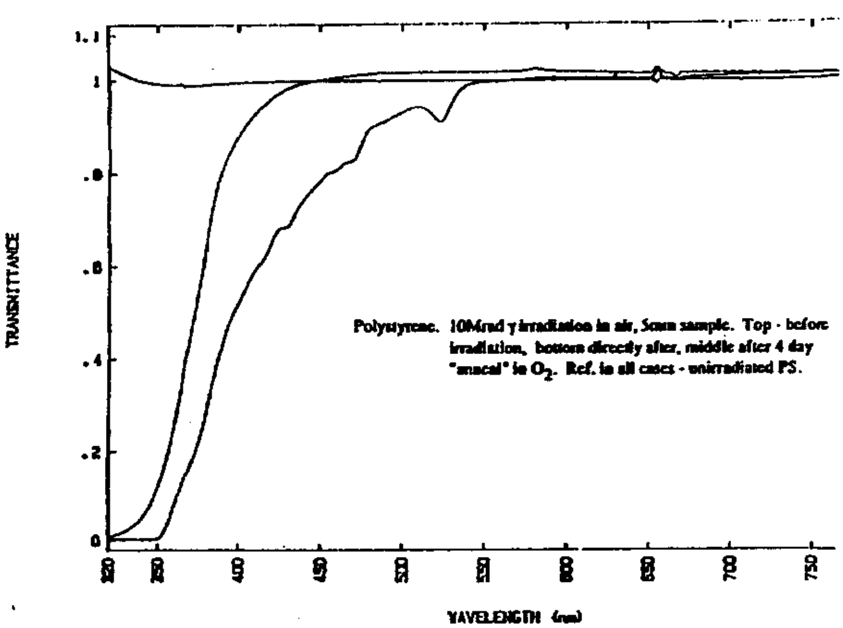


Figure A2. Optical Transmission in Polystyrene as a Function of Radiation Dose (Cobalt 60 Gamma Source)

B. PHOTODETECTORS

Since a high detection efficiency per fiber is essential for good pattern recognition and for minimizing the amount of material in the tracking volume, the principal readout requirement of the scintillating fiber tracking technique is that of photodetection with single photon counting at high rate. Additional important requirements for any photodetector include fast time response, low dark current, high quantum efficiency in the wavelength region of light output from the fibers, and low per channel cost. Our proposed development of long wavelength fibers with emission in the range $530 \leq \lambda \leq 670$ nm as needed for radiation hardness and attenuation length reasons is also advantageous for solid state photodetection. In such devices, quantum efficiencies exceeding 0.5 have already been achieved in this spectral range.

Although no fully acceptable photodetector presently exists, there are several possibilities. Our intention is to explore and develop as thoroughly as possible the most promising options. These options include:

[i] The solid state photomultiplier (SSPM) under development by the Rockwell International Science Center [see Appendix C];

[ii] Avalanche photodiodes (APD) being developed by RCA and Hamamatsu, and others;

and [iii] Position sensitive vacuum photocathode devices available from a variety of manufacturers or under development.

The solid state photomultiplier development is described in detail in Appendix C. Quantum efficiencies as high as 60% have been demonstrated within a broad spectral range $400\text{nm} \leq \lambda \leq 28\mu\text{m}$, and devices have been fabricated with pixel structures of $250\mu\text{m} \times 250\mu\text{m}$ size and smaller. Single photon counting studies have been carried out at rates approaching 10^8 cm $^{-2}$ sec^{-1}. To achieve these levels of performance, the devices must be operated at cryogenic (7 K) temperatures.

To make these devices useful for SSC applications with scintillating fibers, we intend to work in collaboration with Rockwell to optimize the spectral response in the visible region and blind the infrared sensitivity. Along with this optimization we expect that the speed of the device will be improved still further, since hole collection times will be substantially reduced as the infrared sensitive region of the detector is made much thinner. The nature of the SSPM structure is discussed in Appendix C. Important subsidiary cryogenic developments are planned (Appendix A, Section F) for making optical connections to these devices for performance studies.

Existing avalanche photodiodes manufactured by RCA and Hamamatsu have quantum efficiencies exceeding 40% at a wavelength of 600nm and can be operated in either avalanche or breakdown mode by varying the applied voltage. When cooled to liquid nitrogen temperature, these devices have very low dark current, enabling practical single photon counting. For a practical APD fiber photodetector, improvements are desirable in the quantum efficiency and essential in the gain/rate capability. We have recently learned that the quantum efficiency of optical CCD devices can be improved by a factor of 1.5 through the addition of an anti-reflection coating. We intend to investigate this possibility for APDs. When operated in the avalanche region, gains ranging from 300 to a few thousand are achievable. However, the recovery time depends on the gain and may limit the rate capability. Together with industry, we propose to explore in detail the gain versus rate limitations and search for a solution. In particular, it may be possible to reduce the APD pixel size so that a number of cells view each fiber, and thus achieve both adequate gain and rate performance.

Vacuum photodetectors with transmission or absorption photocathodes are an existing mature technology that could also form the basis for fiber readout. High rate position sensitive structures already exist for a limited subset of these devices. Hamamatsu and Phillips each manufacture position sensitive photomultiplier tubes with either anode pads or crossed, multiwire anodes. These tubes provide position resolution in the range 1 to 3 mm. Another possible vacuum photodetector candidate makes use of proximity-focussed solid state (pixel) anode structures. Several approaches are currently under study using arrays of APDs, silicon pad detectors, CCDs or CIDs as the focal plane detector. We propose to encourage and participate in ongoing developments in industry, and to cooperate in tests using scintillating fibers whenever practicable.

For all vacuum photocathodes, a crucial restriction of their use results from the low (0.1-0.15) photocathode quantum efficiency at wavelengths $530 \leq \lambda \leq 670$ nm. To overcome this limitation, we intend to investigate alternate photoemitter materials (such as GaAs) and to develop new photocathode mechanical structures (for example prismatic photocathodes) which exploit the highly collimated nature of the light from fiber waveguides.

C. ELECTRONICS

[i] Front End Preamplifiers: We will pursue the development of front end electronics for both SSPM and APD structures. This includes the characterization of low temperature preamplifiers, capable of operation at liquid nitrogen temperatures. The primary thrust of this work will be the development of multichannel, low temperature electronics which are compatible with SSPMs and/or APDs. The first phase will be the development of a data acquisition and storage system using discrete electronics operating at room temperature. Parallel to this effort will be the development of devices to operate at liquid nitrogen temperatures. The low temperature technology already exists in connection with infrared detectors. Once the requirements of the devices and the cryogenic technology are understood, a major emphasis on this project will be the development of a VLSI chip which will collect data from multiple photomultipliers and which will operate at LN_2 temperatures. State of the art VLSI design systems are available at several of our participating institutions and can be used in the design of this chip.

[ii] Data Acquisition Electronics: The high granularity and speed of the scintillating fibers and solid state photomultipliers requires careful design of a high-rate data acquisition system, yet also affords opportunities for pattern recognition and triggering.

The key element in the electronics is the storage device. Only low-power devices have been considered thus far since heat dissipation will be a problem for a large number of readout channels. An attractive device for use in the prototype detector is the LRS MLL400, largely because of its track record in a TDC pipeline system. The redundancy afforded by its 250MHz capability would be useful in data compaction. Data on the input lines can be sampled once every 4 nsec. Since a 4 meter length of fiber corresponds to a time spread of 20 nsec, hence a 4 nsec time slice corresponds to 1/5 of the length of a fiber. This redundant information will be useful in matching the x, u, and v segments of a track. [The x coordinate refers to an $r\phi$ measurement, while u and v refer to narrow-angle stereo.]

We also plan to test an inexpensive variation of the shift register concept. In this application a RAM memory is used as a FIFO, by indexing a shift register rather than by shifting data from register to register. This scheme places the burden of high speed (16nsec) on the address register only rather than on the individual data registers. Details of this prototypical system are presented in Appendix C.

Lastly, it should be emphasized that the speed of the readout and the excellent two-track resolution of a scintillating fiber tracker provide opportunities for developing hardware tracking capability at the front end. This could include using fast electronics to form vector segments in a given superlayer - effectively measuring the angle of the segment relative to the intersection region. Such a strategy could permit the rejection of large angle tracks - corresponding to low momenta - at a first level trigger. By exploiting the vector-in-superlayer concept, we intend to develop the design of a fast trigger system to identify high P_T tracks in the central region, $\eta < 1.5$. A CAD/CAE system will be developed by the collaboration to design and simulate candidate architectures. Such work will be initiated in the first year of the program and is expected to be intensified in the second year when we have gained some understanding of the photodetectors and associated front end electronics.

D. RADIATION DAMAGE STUDIES

The elements of a central tracker at the SSC will be subjected to charged particle fluences ranging from 10^5 cm^{-2} s^{-1} at 20 cm from the beam axis to 10^3 cm^{-2} s^{-1} at 2 m. A fairly uniform neutron albedo of 2 x 10^{12} cm^{-2} yr^{-1} with an average energy of about 1 MeV is also expected. Gammas from π^0 decays and charged-particle bremsstrahlung will also be present. Thus a comprehensive examination of the radiation sensitivity of scintillating fiber assemblies requires exposures to all three types of particles.

Of particular interest are the radiation damage to the scintillation waveguides (core, scintillation components, cladding, and interface), the non-scintillating fiber guides (similar issues as well as optical coupling materials), adhesives and backing materials used to form the fibers into ribbons and layers, and damage to the the photomultiplier structures and associated electronics. Although the radiation level in the vicinity of the photomultipliers is expected to be low (in an actual experiment these are likely to be located in the region between the outer walls of the calorimetry and the inner walls of a muon detector), nevertheless radiation damage issues must be carefully investigated.

We intend to make measurements with neutrons, electrons, and gammas which are available at Argonne National Laboratory, Oak Ridge National Laboratory, and various university facilities, as well as under more realistic collider conditions - for example tests in the C0 region at the Tevatron might be a possibility.

E. SIMULATION

The design of an SSC tracking system must rely on the development of accurate simulation software at many different levels. With the exception of a few "gold-plated" events, the signature for most SSC physics will require detailed comparison with Monte Carlo predictions. The extent to which tracking can aid in uncovering physics processes must be studied within the context of a simulation program. Different geometries can be tested to optimize the detailed design of the tracking system. We plan to carry out such studies as part of this subsystem proposal.

The benefits of a tracking system include measurements of direction, momentum, multiplicity, and charge. These must be weighed against conversions, bremsstrahlung, and multiple scattering in materials as well as overall costs for construction of the tracking system. The parameters to vary include the size, number, and location of the fibers, the fiber cross sectional profile, the magnetic field, and the extent of the information to be read out and saved. We will vary these parameters in our simulations to achieve an optimal design.

We will also develop software appropriate for reconstructing the tracks in our detector. This requires that we be able to do pattern recognition to associate the individual hits with tracks and then use those hits to calculate direction, momentum and vertex (or impact parameter) for each reconstructed track. We will develop algorithms for quickly using a subset of the tracking information for triggering. The design of the hardware must be such that all the above can be performed in a rapid and accurate manner. One avenue of investigation in simulation will be the addition of one or more layers of pad detectors to enhance the speed and accuracy of the pattern recognition.

As the basis of our simulation program, we intend to make use of the CERN simulation package GEANT interfaced to the ISAJET or PYTHIA event generators. There is of course considerable effort required to incorporate a description of our tracking designs into the GEANT framework and to turn the GEANT output into hits in the simulated detector. Initial work is already underway at several institutions using standard VAX/VMS machines. In the near term we will want to study large event samples, for which the VMS machines are inadequate. Unix based RISC VAX workstations can provide this enhanced capability with an order of magnitude improvement in computing power. Further increases in CPU capability might come from additional RISC processors, mainframe computers or an ACP farm.

F. CRYOGENIC SYSTEMS

[i] SSPM Cryogenics: To limit thermal electron noise to an acceptable level, SSPMs must be maintained near 7 K (see Appendix C). Thus development of a cryogenic system is an essential task.

For a central tracker having between 10^6 and 10^7 fibers, one possible plan is to distribute the SSPMs among a hundred or so cryostats located in the space between the detector's calorimeter and flux-return yoke. Because the SSPMs are quite small, the 7 K volume would not be very large. For example, an 128-channel array is approximately 3cm long with a 0.5mm x 0.25mm cross section. Hence at 10^4 channel system could be imaged in a detector volume of approximately 3cm x 10cm x 0.25mm.

Scintillation light would enter each cryostat via an assembly of transition optical fibers connected to the tracker's non-scintillating optical fibers at ambient (room) temperature. Within the cryostats, the transition fibers would first be grounded at liquid nitrogen temperature and then would be optically coupled to an SSPM array maintained at 7 K. The SSPM signal outputs would, in turn, be connected to the front-end electronics contained within the same cryostat, but at liquid nitrogen temperature. Amplified outputs would then emerge from the cryostat into a room-temperature environment. Among the important parameters to be investigated are:

[a] heat load due to thermal conductivity of the optical fibers.

[b] heat load due to transmission of infrared light into the cryostat via the optical fibers. Polystyrene transmits poorly in the infrared and the cladding thicknesses are unfavorable for infrared transmission. Nevertheless this issue must be understood.

[c] thermal loading due to the SSPMs themselves.

[d] heat transfer due to wire bonding to preamps at liquid nitrogen temperature.

During the first two years of this proposal, initial testing of SSPMs will be performed first in units of 1-10 elements and then with a 192 channel device. During this period and in collaboration with industry, a design of a prototype cryostat will be undertaken, capable of supporting the operation of 10^3 - 10^4 SSPM channels and associated front-end electronics. This prototype unit will serve to test the cryogenic design concepts and is intended to be used with the prototype fiber tracker in beam tests. In addition, the cryogenics system required for a full-scale tracker of 10^6 - 10^7 elements will be investigated during the third year.

The design and construction of the prototype cryostat and the study of a full-scale cryogenics system will be performed with engineering assistance from national laboratories and industry. At this time, both Alabama Cryogenics (Huntsville) and Grumman Aerospace (Bethpage NY) have expressed interest in this project, and other companies will be contacted.

[ii] APD Cryogenics: Development of appropriate cryogenic systems for APD devices parallels that of the SSPM cryogenics discussed above, except that APD devices require liquid nitrogen temperature for noise-improved operation. This poses less difficulty and complexity in cryostat design. Nevertheless design of a prototype cryostat to support the operation of such devices will also be explored. Several small cryostats will be put into operation within the group capable of accomodating either APDs or SSPM devices.

G. MECHANICAL ENGINEERING

We will develop a detailed conceptual design for support of a central tracking system with a cylindrical central region, $\eta < 1.5$, and for forward tracking, $1.5 < \eta < 3$. Additionally a conceptual design for a support of distributed cryostats for the photodetectors will also be implemented. To this end a careful evaluation of the state-of-the-art, light-weight, composite materials will be made, drawing on the expertise at the Oak Ridge facilities where vast amounts of DOE dollars have been spent on such structures. Very large structures that are extremely rigid, yet light weight (and of low mass) and which have exceptional dimensional tolerance and creep factors can be designed. In addition, alignment techniques will be developed that will permit accurate positioning of the detector elements in layers, accurate registry of different superlayers, and subsequent monitoring of that alignment.

Consider the central portion of a fiber tracker. Here superlayers of scintillating fibers will be supported by a cylindrical structure that could, for example, be made of carbon filament - Rohacell or Kevlar-Rohacell composite material. The composite is formed by adhering very thin layers of cross-fiber carbon material to Rohafoam 31 cylindrical tube on the inner and outer surfaces. A thickness of Rohafoam of 0.6cm and 75μm thick filament can be formed into a tube having only 0.12% radiation lengths of material, yet having more than adequate rigidity to support a uniformly distributed load of scintillating fibers of 65.3 kg mass. Such a mass is based on a cylindrical superlayer of 500μm thick fibers arranged in 12 individual layers of fiber of 4 meter length and at a mean radius of 50cm. For outer layers one would increase the thickness of the Rohacell appropriately.

The fibers will most likely be made in the form of ribbons. Each ribbon may be made of several hundred fibers which are glued together precisely. These ribbons can be positioned and glued to the cylindrical support tube while using a laser beam for alignment. The scintillating fiber ribbons will be optically coupled to non-scintillating optical fibers at the end of the structural cylinder. These optical fibers will be of slightly larger diameter to improve optical coupling by avoiding cladding mismatches. The optical fibers then transport the photons to the photodetectors. Coupling fixtures to support joints between scintillating fibers and non-scintillating fibers must be designed as well as for interfacing the non-scintillating fibers to the optical cryostats.

The mechanical engineering challenge lies in producing a rigid, stable and light weight structure that can be easily aligned and that serves both as the mandrel for optical fiber assembly as well as the support structure of the complete tracking system within the confines of space allotted to the tracker and the optical coupling assemblies.

APPENDIX B
ITEMIZED BUDGETS FROM PARTICIPATING INSTITUTIONS

ITEMIZED PROPOSAL BUDGET FOR UCLA

	YEAR 1	YEAR 2
1.) Salaries & Wages		
Scientific Personnel		
M. Atac, Task Manager Adjunct Professor (proposed) 50% time for 12 months	-0-	-0-
Assistant Research Physicist I 100% time for 12 months Base salary 6/01/89: $ 3,142/month Anticipated 7/01/90: $ 3,299/month	$ 37,704	$ 39,588
Graduate Student Researcher II 50% time academic year, 100% time summer Base salary 6/01/89: $ 2,256/month Anticipated 7/01/90: $ 2,369/month	$ 16,920	$ 17,768
Support Personnel		
F. Chase, Senior Engineering Technician 25% time for 12 months Base salary 6/01/89: $ 3,880/month Anticipated 7/01/90: $ 4,074/month	$ 11,640	$ 12,222
J. Kolonko, Academic Specialist 5% time for 12 months Base salary 6/01/89: $ 5,838/month Anticipated 7/01/89: $ 6,130/month	$ 3,503	$ 3,678
Total Salaries:	$ 69,767	$ 73,256
2.) Employee Benefits		
Academic @ 24% - 1989, 25% - 1990,	$ 9,890	$ 10,817
Graduate Student Researcher @ 1.75% academic year and 3.47% summer	$ 413	$ 434
Staff @ 30% - 1989, 31% - 1990	$ 3,492	$ 3,789
Total Benefits:	$ 13,795	$ 15,040

ITEMIZED PROPOSAL BUDGET FOR UCLA

	YEAR 1	YEAR 2
3.) Supplies and Services		
Laboratory Tools: Test Supplies	$ 1,500	$ 1,000
Liquid Helium/ Liquid Nitrogen	$ 2,000	$ 2,000
Magnetic Tapes: Diskettes	$ 500	$ 550
Computer Maintenance	$ 500	$ 550
Freight & Postage	$ 300	$ 300
Telephone Expense	$ 900	$ 1,000
Total Supplies/ Services:	$ 5,700	$ 5,400
4.) Travel:		
Domestic Travel:		
Airfare - 15 RT/YR between UCLA, FNAL and and Notre Dame @ $500 each	$ 7,500	$ 7,500
Per Diem: 120 days/year @ $100/day	$ 12,000	$ 12,000
Car Rentals: 17 weeks @ $150/week	$ 2,550	$ 2,550
Total Travel:	$ 22,050	$ 22,050
5.) Equipment		
Electronic Instrumentation	$ 44,000	$ 10,000
Less: UCLA Contribution	$ (36,500)	$ -0-
Total Equipment:	$ 7,500	$ 10,000
6.) Fabrication		
High Rate Scintillating Fiber Test System to include amplifiers, cabling, connectors, coupling fixtures	$ 20,000	$ 20,000
Total Fabrication:	$ 20,000	$ 20,000

ITEMIZED PROPOSAL BUDGET FOR UCLA

	YEAR 1	YEAR 2
7.) Subcontracts		
Rockwell Science Center	$ 182,645*	$ 258,174*
Univ. of Texas at Dallas	$ 56,000+	$ 59,000+
Total Subcontracts	$ 238,645	$ 317,174
Total Direct Costs	$ 375,457	$ 462,920
8.) Indirect Costs:		
Overhead @ 27.8 % on MTDC Off-Campus	$ 44,845	$ 32,177
Total Budget	$ 420,302	$ 495,097

* See Page 7 of Appendix A

\+ .e Appendix B

ITEMIZED PROPOSAL BUDGET
for the
UNIVERSITY OF NOTRE DAME

(First Year of a Three Year Program)

A. 1. SENIOR PERSONNEL

R. Ruchti	(30% of time)
V. Kenney	(25% of time)
N. Biswas	(25% of time)
N. Cason	(10% of time)
W. Shephard	(10% of time)

2. OTHER PERSONNEL

Research Engineer	(100% of time)	$ 33,915
Faculty Fellow	(25% of time)	$ 10,000
Post Doctoral Fellow	(50% of time)	$ 15,000
Technician	(50% of time)	$ 6,100
Graduate Students	(2 @ full year)	$ 21,847
Undergraduates		$ 2,500

B.	FRINGE BENEFITS	$ 15,019
C.	PERMANENT EQUIPMENT (See Itemized List)	$130,896
D.	MATERIALS AND SUPPLIES	$ 15,000
E.	TRAVEL	$ 20,000
TOTAL DIRECT COSTS		$270,277
INDIRECT COSTS (28.9% of total direct costs less permanent equipment under D)		$ 39,723
TOTAL PROJECT COST		$310,000
NOTRE DAME MATCHING FUNDS FOR PERMANENT EQUIPMENT		$ 65,000
TOTAL REQUEST FROM SSC/DOE		$245,000

ITEMIZED LIST OF PERMANENT EQUIPMENT for the UNIVERSITY OF NOTRE DAME

(First Year of a Three Year Program)

1.	FIBERS	
	a. Dye Synthesis and purification	$ 30,000
	b. Fiber cladding tooling and fabrication	$ 15,000
	c. Fiber Manufacture (Ribbons, Strips, Multis)	$ 10,000
	d. Boule Preparation Studies	$ 10,000
	e. Splicing Hardware	$ 5,000
2.	VACUUM PMTS	
	a. High strip current MCP structures	$ 25,000
	b. Cathode faceplate fabrication	$ 15,000
3.	CRYOSTAT CONSTRUCTION FOR SSPM AND APD TESTS WITH FIBERS	
	a. Small test cryostat	$ 10,000
	b. Ancillary hardware	$ 5,000
4.	LABORATORY TEST EQUIPMENT	$ 5,896
TOTAL		$130,896

ITEMIZED FIRST YEAR BUDGET

UNIVERSITY OF TEXAS AT DALLAS

I.	DIRECT COSTS	
	A. SALARIES AND WAGES	
	Dr. E.J.Fenyves (10%)	$ 8,477
	Dr. R.C. Chaney (10%)	$ 5,278
	Hilton Hammack (25%)	$ 11,441
	Research Assistant (25%)	$ 3,132
	Total Wages and Salaries	$ 28,328
	B. FRINGE BENEFITS (25%)	$ 7,082
	C. TRAVEL	$ 1,995
	D. M AND O	$ 1,484
	E. PERMANENT EQUIPMENT	$ 40,000
II.	INDIRECT COSTS (44%)	$ 17,111
TOTAL COST		$ 96,000
MATCHING FUNDS FROM UT DALLAS ON PERMANENT EQUIPMENT		$ 30,000
TOTAL REQUEST (FIRST YEAR)		$ 66,000

Rica 1990 Budget for SSC Tracking Subsystem Proposal

	Cost	Total
SALARIES		
1 Postdoc	$30,000	
2 Students	21,600	$51,600
FRINGE BENEFITS		
1 Postdoc (6 mos @ 19% and 6 @ 20%)	5,850	
2 Students (6 mos @ 24% and 6 @ 26%)	5,400	11,250
EQUIPMENT		
1 VAX/VMS 3100 Vaxstation	17,388	
1 HP plotter	4,700	
Fibers, readout devices and electronics	20,000	42,088
TRAVEL		
10 round trips group meetings @ $500 ea	5,000	5,000
INDIRECT		
Salary (6 mos @ 47.5% and 6 @ 49%)	30,325	
Travel (6 mos @ 27.5% and 6 @ 29%)	1,413	31,738
		141,676
University Contribution (25%)		-35,419
TOTAL		106,257

UNIVERSITY OF ILLINOIS AT CHICAGO

Budget Summary

28 Sept. 1989

Principal investigators: H. Goldberg
S. Margulies
J. Solomon

A. SENIOR PERSONNEL		000
B. OTHER PERSONNEL		
1 postdoctoral associate (100% for 12 months)	$ 34,000.	
2 undergraduate students (15 hrs/wk for academic yr. plus 40 hrs/wk for summer)	$ 11,500.	
		$ 45,500.
C. FRINGE BENEFITS (6.45% for postdoc, 0.2% for undergrads)		2,216.
TOTAL SALARIES, WAGES, & FRINGE BENEFITS		$ 47,716.
D. EQUIPMENT		
Spectrophotometer	15,000.	
LeCroy p.h.a. system, accessories, & interfaces	9,715.	
MacIIx data acquisition system & interfaces	11,540.	
Picoammeter	1,980.	
		38,235.
E. TRAVEL		
Domestic		18,000.
F. OTHER DIRECT COSTS		
1. Materials and supplies		
materials and supplies	10,000.	
radioactive sources	500.	
MacII software, including LabVIEW	3,000.	
		13,500.
2. Contracts		
sample irradiation fees	5,000.	
cryogenic study	10,000.	
		15,000.

G.	TOTAL DIRECT COSTS		$132,451.
H.	INDIRECT COSTS (57% of A,B,C,E, and F1; 57% of first $25,000 of F2)		53,703.
I.	TOTAL DIRECT & INDIRECT COSTS (G plus H)		186,154.
J.	UNIVERSITY COST SHARING To assist the proposd work, the University of Illinois at Chicago has agreed to reduce its indirect cost charge, normally 57% as indicated in H, to 24%.		
	1. INDIRECT COSTS @ 24%	22,612.	
	2. NET UNIVERSITY COST SHARING (H less J1)		(31,091)
K.	TOTAL AMOUNT OF REQUEST (I less J2)		$155,063.

ORNL Involvement In Tracking Detector Subsystem for the SSC Using Scintillating Fibers

CAPITAL EQUIPMENT - Most of the needed equipment such as CAD/CAE workstations are already in place, so no money is needed for major purchases.

PERSONNEL - Assignment of engineers to these tasks are expected to be ..
3 Electrical Engineers at 50% time
1 Mechanical Engineer 50% time.

BUDGET Year #1.
(Man months and $K)

Front End Electronics	6 mm	$56K
DAQ & Patern Analysis	3 mm	$28K
Radiation Damage	3 mm	$28K
Mech. Engineering	6 mm	$56K
Travel	____	$10K
	18 mm	$178K

BUDGET Year #2
(Man months and $K)

DAQ	6 mm	$58K
Pattern analysis	6 mm	$58K
Mechanical Engineering	6 mm	$58K
Harris Semiconductor runs		$50K
Machine shop time		$75K
Materials (Carbon fiber re-enforced)		$25K
Travel	____	$10K
	18 mm	$276K

BUDGET Year #3 (To be determined)

PENN STATE UNIVERSITY
DATA ACQUISITION & SIMULATION ACTIVITIES - FY90
(Official University approved budget will be provided upon request)

a)	<u>Labor</u>	
	1) Electrical engineer from Penn State EE Department and/or industry (DAQ)	$50,000
	2) Technician (DAQ)	15,000
	3) Research Associate (SIM)	30,000
b)	<u>Travel</u>	12,000
c)	<u>Fringe and Indirect Costs on a)-b)</u>	74,000
d)	<u>Equipment</u>	
	1) <u>Diagnostics</u> (DAQ)	
	1) LeCroy Model 9450 dual channel digital scope	$17,000
	2) Hewlett-Packard Model 1651A Multi-channel logic analyzer scope	7,000
	2) <u>VME System</u> (DAQ)	
	1) Motorola MVME147 Monoboard Microcomputer	$ 3,000
	2) Motorola MVME712M Transition Module	1,000
	3) Motorola MVME945lA1 crate	1,800
	4) SCSI disc system	1,000
	5) OS-9/146 Development Pak DEV-4700-30EL-58W7	2,000
	6) VME-buss diagnostic hardware	1,600
	3) <u>Prototype Boards</u> (DAQ)	
	1) XVME-085 prototype module (2)	$ 800
	2) XVME-081 INTEL prototype module	800
	3) XVME-090 extender board	500
	4) <u>Electronic Components</u> (DAQ)	
	1) 74F194 shift register, 74F289 RAM, MCM10470*15 RAM, pre-amps, discriminators, shapers, etc.	$ 2,500
	5) <u>Computations</u> (SIM)	
	1) RISC VAX Workstation	<u>$25,000</u>
	Total	$245,000
	Less Dept. of Physics (Laboratory for Elementary Particle Science) Contribution	<u>-45,000</u>
	Total Requested	$200,000

Purdue University
SSC
Project Budget

I.	Scientific Personnel	
	a. Senior Personnel: David S. Koltick Edward I. Shibata	0
	b. Research Associate 50% for 12 months	$15,000
	c. Graduate Researcher 6 man months	12,120
	d. Undergraduate Physics Majors 6 man months	5,000
	Total salaries and wages	32,120
	Grad fee remission	810
	Total compensation	32,930
III.	Fringe Benefits	
	Total fringe benefits	2,806
	Total compensation and fringe benefits	35,546
IV.	Travel: Domestic	
	a. Between Purdue, Fermilab and Notre Dame 60 @ $100 per trip	6,000
	b. Company Visits 10 trips @ $1000 per trip	4,000
V.	Equipment	
	a. GPIB NuBus Card for Mac II	695
	b. GPIB CAMAC Create Controller	2,100
	c. BNC Pulsar	1,295
	d. Multichannel Analyzer	3,500
	e. Laser	5,000

	f. Tek DSA 602	35,000
VI.	Supplies	
	a. Software, including Lab View for Mac II	2,500
	b. Radiation Sources	1,000
	c. Materials	10,000
		13,500
VII.	Total direct costs	106,861
VIII.	Indirect cost 0.490 of MTD cost	28,139
VIIII.	Total cost	135,000

X.	Purdue Contribution (Physics)	
	a. Equipment	50,000
	Total (Purdue)	50,000

FERMILAB PARTICIPATION IN FIBER TRACKING SUBSYSTEM PROPOSAL

Names:	M. Atac	Visitors:
	P. Berge	
	M. Binkley	A. Clark
	A. Bross	J.M. Gaillard
	J. Elias	
	G. Foster	
	R. Kephart	
	S. Tkaczyk	
	R. Wagner	

Resources:

- Physics Department plastics shop
- Laboratory and test areas
  - High rise chemistry lab
  - 14th floor west lab area
  - Lab 6 scintillator fabrication facility
  - CDF fiber test equipment - move to lab 6
- Computer time
- PREP electronics
- Existing equipment
  - Cordax measuring machine
  - Lab 6 winding and placement machines
  - Spectrophotometer
  - G C mass spectrograph
  - Dye laser
- Technician time (request funding in proposal)
  - 3 man-months ET for assembly
  - 3 man-months MT for cryo and mechanical
  - 6 man-months MT for plastic operations
- Shop time (request funding in proposal)
  - 6 to 7 machinist months

FIRST YEAR BUDGET

Item	*Salary*		*Operating*		*Equipment*	
Fibers	tech.	20 K$	mat'ls	25 K$		
	shop	5 K$	drawing	5 K$		
Waveguides	tech.	20 K$	mat'ls	15 K$		
	shop	5 K$	drawing	5 K$		
			splicing	5 K$		
Avalanch Photodiodes	tech.	10 K$	cryogens	1 K$	devices	5 K$
					electronics	10 K$
Vacuum Photodetectors	tech.	10 K$	cryogens	1 K$	devices	15 K$
Simulation			tapes	1 K$		
Travel				20 K$		
Totals:		70 K$		78 K$		30 K$

Note: acquisition of new photodetector devices per specifications developed during this work, estimated at 150 K$ to 200 K$, is a collaboration-wide cost item.

SSC Scintillating Fiber Tracker Subsystem Proposal - UI Participation

UI Personnel (6):

Robert Downing, Steven Errede, Michael Haney, Inga Karliner,
Vaidas Simaitis, Jon Thaler

N.B. Additional UI faculty and other personnel may join as time progresses.

The UI HEP group proposes to carry out the following research activities for the SSC Scintillating Fiber Tracker SubSystem Proposal:

1st Year UI Research Activities for SSC SciFi Tracker Subsystem:

1.) Development of CAD/CAE system to be used by collaboration to design/simulate candidate architectures for fast track vector processing trigger pattern recognition schemes and candidate data acquisition systems (latching, pipeline storage) for the SciFi tracker.

2.) Development of high quantum efficiency avalanche photodiode pixel arrays with adequate rate capabilities and radiation hardness.

3.) Simulation studies of various aspects of SSC SciFi Tracker, e.g. pattern recognition algorithms for track triggering and offline tracking, momentum resolution, track linking with e.g. external muon subsystem, EM calorimeter and electrons, etc.

UI Budget for First Year of SSC SciFi Tracker Project:

Electronic Engineer(s)	(1/2 FTE)	$50K
Programmer	(9 mos 1/2 FTE + FTE summer)	$25K
Materials and Supplies		$35K
TOTAL (Includes 49% Overhead)		$110K

Science Center
Rockwell International Corporation
1049 Camino Dos Rios
P.O. Box 1085
Thousand Oaks, California 91360

Rockwell International

In reply refer to SC61047

January 30, 1989

Fermi National Laboratory
Pine Street at Kirk Road
Batavia, Illinois 60510

Attention: Dr. M. Atac
(312) 840-4775

Subject: Science Center Proposal No. SC61047
High Rate Scintillating Fiber Tracking Experiment

Reference: Technical discussions between M. Atac, Fermi National Laboratory, and R. Florence/M. Petroff, Rockwell Science Center, on November 30, 1988

As the result of referenced discussions, Rockwell International Corporation, through its Science Center, is pleased to submit herewith its proposal for the subject program for your consideration.

Questions of a technical nature should be directed to Dr. Paul J. Besser at (714) 762-8751. Inquiries of a pricing or contractual nature should be directed to the undersigned or R. A. Johnson at (805) 373-4202 and 373-4415 respectively.

Rockwell International Corporation
Science Center

J. N. Ferrenberg, Manager
Contracts and Proposals

JNF/mds

Enclosures: 4 copies

COST PROPOSAL SC61047

Table Of Contents

Rockwell International
Science Center
Proposal SC61047

Statement of Work

Rockwell International Corporation, Science Center, proposes to furnish the necessary personnel, facilities, materials and services to conduct The High Rate Scintillating Fiber Tracking Experiment Program in accordance with the Statement of Work contained in Technical Proposal SC61047T.

Type of Contract

Contractor proposes a CPFF contract.

Estimated Cost	$408,997
Fixed Fee	31,822
Total Estimated Price	$440,819

Terms

As mutually agreed.

Schedule

01 May 1989 through 30 September 1990.

Proposal Validity

This proposal is valid through 01 May 1989.

Government-Owned Facilities

The contractor does not intend to use Government-owned facilities, industrial equipment or special tooling in performance of a contract resulting from this proposal. Our DUNS number is 00-825-5523.

Administrative Offices

Government contracts are administered by DCASMA-Van Nuys, 6230 Van Nuys Boulevard, Van Nuys, California 91401-2713, telephone (818) 904-6311.

The cognizant DCAA is located at 6633 Canoga Avenue, Canoga Park, California, 91304. Contact Mr. Kenneth Solso, DCAA. He may be reached at (818) 710-2405.

Authorized Negotiators

Contract negotiations may be conducted by either J. N. Ferrenberg or R. A. Johnson, both of whom may be reached at the Science Center, 1049 Camino Dos Rios, Thousand Oaks, California 91360, telephone (805) 373-4202 and 373-4415 respectively.

ROCKWELL INTERNATIONAL CORPORATION
Science Center

R. A. Johnson, Director
Contracts and Pricing

SC61047

CONTRACT PRICING PROPOSAL COVER SHEET

1. SOLICITATION/CONTRACT/MODIFICATION NO. Unsolicited

FORM APPROVED OMB NO. 3090-0116

NOTE This form is used in contract actions if submission of cost or pricing data is required. (See FAR 15.804-6(b))

2. NAME AND ADDRESS OF OFFEROR (Include ZIP Code)
ROCKWELL INTERNATIONAL CORPORATICN
Science Center
1049 Camino Dos Rios; P.O. Box 1085
Thousand Oaks, CA 91360

3A. NAME AND TITLE OF OFFEROR'S POINT OF CONTACT
J. Ferrenberg, Manager
Contracts & Proposals

3B. TELEPHONE NO. (805) 373-4202

4. TYPE OF CONTRACT ACTION (Check)
[X] A. NEW CONTRACT
[ ] B. CHANGE ORDER
[ ] C. PRICE REVISION/REDETERMINATION
[ ] D. LETTER CONTRACT
[ ] E. UNPRICED ORDER
[ ] F. OTHER (Specify)

5. TYPE OF CONTRACT (Check)
[ ] FFP [XX] CPFF [ ] CPIF [ ] CPAF
[ ] FPI [ ] OTHER (Specify)

6. PROPOSED COST (A+B=C)

A. COST	B. PROFIT/FEE	C. TOTAL
$ 408,997	$ 31,822	$ 440,819

7. PLACE(S) AND PERIOD(S) OF PERFORMANCE
Science Center, Thousand Oaks, CA 05/01/89 through 09/30/90

8. List and reference the identification, quantity and total price proposed for each contract line item. A line item cost breakdown supporting this recap is required unless otherwise specified by the Contracting Officer. (Continue on reverse, and then on plain paper, if necessary. Use same headings.)

A. LINE ITEM NO.	B. IDENTIFICATION	C. QUANTITY	D. TOTAL PRICE	E. REF.
	High Rate Scintillating Fiber Tracking Experiment	Lot	$440,819	See Attached Cost Breakdowns

9. PROVIDE NAME, ADDRESS, AND TELEPHONE NUMBER FOR THE FOLLOWING (If available)

A. CONTRACT ADMINISTRATION OFFICE
DCASMA-Van Nuys
6230 Van Nuys Boulevard
Van Nuys, California 91401-2713

B. AUDIT OFFICE
DCAA-Rocketdyne
6633 Canoga Avenue
Canoga Park, California 91304

10. WILL YOU REQUIRE THE USE OF ANY GOVERNMENT PROPERTY IN THE PERFORMANCE OF THIS WORK? (If "Yes," identify)
[ ] YES [X] NO

11A. DO YOU REQUIRE GOVERNMENT CONTRACT FINANCING TO PERFORM THIS PROPOSED CONTRACT? (If "Yes," complete Item 11B)
[ ] YES [X] NO

11B. TYPE OF FINANCING (✓ one)
[ ] ADVANCE PAYMENTS [ ] PROGRESS PAYMENTS
[ ] GUARANTEED LOANS

12. HAVE YOU BEEN AWARDED ANY CONTRACTS OR SUBCONTRACTS FOR THE SAME OR SIMILAR ITEMS WITHIN THE PAST 3 YEARS? (If "Yes," identify item(s), customer(s) and contract number(s))
[ ] YES [X] NO

13. IS THIS PROPOSAL CONSISTENT WITH YOUR ESTABLISHED ESTIMATING AND ACCOUNTING PRACTICES AND PROCEDURES AND FAR PART 31 COST PRINCIPLES? (If "No," explain)
[X] YES [ ] NO

14. COST ACCOUNTING STANDARDS BOARD (CASB) DATA (Public Law 91-379 as amended and FAR PART 30)

A. WILL THIS CONTRACT ACTION BE SUBJECT TO CASB REGULATIONS? (If "No," explain in proposal)
[X] YES [ ] NO

B. HAVE YOU SUBMITTED A CASB DISCLOSURE STATEMENT (CASB DS-1 or 2)? (If "Yes," specify in proposal the office to which submitted and if determined to be adequate)
[X] YES [ ] NO DCASMA-Van Nuys, CA

C. HAVE YOU BEEN NOTIFIED THAT YOU ARE OR MAY BE IN NONCOMPLIANCE WITH YOUR DISCLOSURE STATEMENT OR COST ACCOUNTING STANDARDS? (If "Yes," explain in proposal)
[ ] YES [X] NO

D. IS ANY ASPECT OF THIS PROPOSAL INCONSISTENT WITH YOUR DISCLOSED PRACTICES OR APPLICABLE COST ACCOUNTING STANDARDS? (If "Yes," explain in proposal)
[ ] YES [X] NO

This proposal is submitted in response to the RFP contract, modification, etc. in Item 1 and reflects our best estimates and/or actual costs as of this date.

15. NAME AND TITLE (Type)
R. A. Johnson, Director
Contracts and Pricing

16. NAME OF FIRM
ROCKWELL INTERNATIONAL CORPORATION
Science Center

17. SIGNATURE
[signature]

18. DATE OF SUBMISSION

NSN 7540-01-142-9845

INFORMATION CONTAINED ... IS PRIVILEGED OR CONFIDENTIAL INFORMATION ... ROCKWELL INTERNATIONAL CORPORATION WITHIN THE MEANING OF 5 USC 552 AND AS SUCH IS EXEMPT FROM THE PUBLIC DISCLOSURE PROVISIONS THEREOF

1411-101

STANDARD FORM 1411 (10-83)
Prescribed by GSA
FAR (48 CFR) 53.215-2(c)

Rockwell International
Science Center
Proposal SC61047

ATTACHMENT TO STANDARD FORM 1411

Supporting Data

Part 1 - Materials

Description	Quantity	Cost	Source	Amount
FY1989				
1. Photomask - 5 layers	1	Lot	P.O.	$ 7,850
2. Liquid Helium	50L	2.95	P.O.	148
FY1990				
3. Liquid Helium	800L	2.95	P.O.	2,360
4. Misc. Material	Lot	Lot	E.E.	3,000
	Total Materials			$13,358

P.O. = Purchase Order
E.E. = Engineering Estimate

Supporting data relative to the material and/or subcontract prices resides in the contractor's Purchasing Department and will be made available to the DCAA during proposal audit or to the Government price/cost analysts upon request from the contracting officer.

Part 2 - Direct Labor - Engineering

The engineering direct labor rate is a weighted composite using the actual salaries of specific persons together with current projections during the planned period of performance. Data supporting actual labor rates of technical personnel comprising the weighted composite resides in the Accounting Department (Payroll Office). Data supporting projections of the weighted composite rate over the planned period of performance resides in the Contracts and Pricing Department. Upon request, this information will be made available to the Defense Contract Audit Agency.

The contractor has used 5% per annum for direct labor escalation. This escalation factor is based on our forecast of competitor salary increases and what we as an organization will be required to do to recruit as well as retain senior research managers and scientists. The information and data relative to our forecast resides in the Human Resources Department and will be made available to the DCAA upon request.

Rockwell International
Science Center
Proposal SC61047

Part 3 - Labor Overhead - General and Administrative Expense

	FY1989	FY1990
Indirect Cost	184.0%	184.0%
D/L Fringe	38.0%	40.0%
General & Adminis.	13.0%	12.8%

A copy of the contractor's forward pricing rate letter reflecting the projected overheads is attached as supporting pricing data. The projected overhead rates, which have been used in this proposal, have been reviewed and accepted for use in proposal forward pricing and for provisional billing purposes by the resident DCAA located at the contractor's Rocketdyne Division. The local ACO has made a copy of the audit report available to the contractor and, if requested, will make it available to the PCO.

Part 4 - Travel and Subsistence

Trip A: Two persons, four trips to Chicago, IL for program review, one day at destination each trip.

2 R/T Air Fare @ $480/trip	$ 960
*Subsistence - 1 day @ $117/day X 2	234
Auto rental - 1 day @ $35/day	35
Personal auto - LAX, $23/trip X 2	46
Parking - LAX, 1 day @ $5/day X 2	10

$1,285 X 4 trips = $5,140

Trip B: Two persons, two trips to Washington D.C. for technical conference, three days at destination each trip.

2 R/T Air Fare @ $529/trip	$1,058
*Subsistence - 3 days @ $121/day X 2	726
Auto rental - 3 days @ $35/day	105
Personal auto - LAX, $23/trip X 2	46
Parking - LAX, 3 days @ $5/day X 2	30

$1,965 X 2 trips = $3,930

*Per Federal Travel Regulations

Travel Summary

Trip A	$5,140
Trip B	3,930
Total	$9,070

Part 5 - Cost of Capital

Contractor has provided the following forms under the current DOD Profit Policy which reflects contractor's calculations of the contract facilities capital cost of money and the weighted guidelines program profit.

CASB-CHF and its attachments	(prepared by Accounting)
DD Form 1861-1	(prepared by Accounting)
DD Form 1861-2	(prepared by Pricing)
Contract Profit Calculation Format	(prepared by Pricing)

The calculations provided show an entitlement to cost of money of $19,722 and a weighted guideline profit entitlement of $72,172 (18%). However, contractor does not feel that it is in the best interest of the Government under the circumstances of the ongoing budget constraints to propose the total cost of money or the fee as reflected above and instead proposes cost of money at approximately 50% of the entitlement and a fixed fee at 8%, offering the residual cost of money and fixed fee as a contribution to the proposed effort.

Contractor has provided the data and information required under the new FAR Profit Policy in support of the proposed cost of money and fee. It is recognized that the treasury rate used in the calculation of the above data had recently changed from .09250 to .09750. We are however unable to integrate the new rate in our pricing system in time for use in this proposal. It is planned that the new rate will be reflected in any required update prior to negotiation.

Science Center
Proposal SC61047

Cost Breakdown(s)

FY 1989

	Hrs./$	Rate	Amount
Engineering	1324	32.03	$42,408
Direct Labor Fringe	$42,408	38.00%	16,115
Subtotal			58,523
Indirect Cost	$42,408	184.00%	78,031
Subcontracts			0
Material			7,998
Travel			1,285
Consultant			0
Subtotal			145,837
General & Administrative		13.00%	18,959
Subtotal			164,796
CAS 414			4,665
Interdivision Cost			0
Estimated Total Cost			169,461
Fixed Fee			13,184
Total Price			$182,645

FY 1990

	Hrs./$	Rate	Amount
Engineering	1800	33.16	$59,688
Direct Labor Fringe	$59,688	40.00%	23,875
Subtotal			83,563
Indirect Cost	$59,688	184.00%	109,826
Subcontracts			0
Material			5,360
Travel			7,785
Consultant			0
Subtotal			206,534
General & Administrative		12.80%	26,436
Subtotal			232,970
CAS 414			6,566
Interdivision Cost			0
Estimated Total Cost			239,536
Fixed Fee			18,638
Total Price			$258,174

Science Center
Proposal SC61047

Cost Breakdown(s)

Total Program

	Hrs./$	Rate	Amount
Engineering	3124	32.681	$102,096
Direct Labor Fringe	$102,096	39.17%	39,990
Subtotal			142,086
Indirect Cost	$102,096	184.00%	187,857
Subcontracts			0
Material			13,358
Travel			9,070
Consultant			0
Subtotal			352,371
General & Administrative		12.88%	45,395
Subtotal			397,766
CAS 414			11,231
Interdivision Cost			0
Estimated Total Cost			408,997
Fixed Fee			31,822
Total Price			$440,819

EXHIBIT C
Modified Form CASB-CMF
S.C. Rate: 0.21492 DL$
Plant - Anaheim: 0.17420 DL$
Plant - Palo Alto: 0.02765 DL$
Offsite: 0.00282 DL$

FACILITIES CAPITAL
COST OF MONEY FACTORS COMPUTATION
FISCAL YEAR 1989

CONTRACTOR: ROCKWELL INTERNATIONAL SCIENCE CENTER
BUSINESS UNIT:

COST ACCOUNTING PERIOD: FISCAL YEAR 1989	1. Applicable Cost of Money Rate: 9.375 %	2. Accumulation & Direct Dist. of NBV	3. Allocation of Undistributed	4. Total Net Book Value	5a. CAS 414 Cost of Money For Cost Acctg. Period	5b. Depr. of CAS 417 Cost of Money	5. Combined Cost of Money For the Period	6. Allocation Base for the Period ($ × 000)	7. Facilities Capital Cost of Money Factors
			Basis of Allocation	Columns 2 + 3	Column 1 × 4		Columns 5a + 5b	In Unit(s) of Measure	Columns 5 ÷ 6
BUSINESS UNIT FACILITIES	Recorded	$13,226,361							
	CAS 417 CON	$209,102							
	Leased Property								
	Corporate/Group	$660,000							
	Total	$14,095,463							
	Undistributed								
	Distributed								
OVERHEAD POOLS	ENG	$11,190,766		$11,190,766	$1,049,134	$16,670	$1,065,804	5,025 DL$	$0.21210 DL$
	COMMON	$184,975		$184,975	$17,341		$17,341	6,150 DL$	$0.00282 DL$
	PLANT-ANAHEIM	$1,629,675		$1,629,675	$152,782		$152,782	891 DL$	$0.17147 DL$
	PLANT-PALO ALTO	$64,083		$64,083	$6,000		$6,000	242 DL$	$0.02483 DL$
G & A EXPENSE POOLS		$1,025,964		$1,025,964	$96,184		$96,184	BASE (TCP) $ 20,281	$0.00474
TOTAL		$14,095,463		$14,095,463	$1,321,449	$16,670	$1,338,119		

FACILITIES CAPITAL
COST OF MONEY FACTORS COMPUTATION

GENERAL & ADMINISTRATIVE EXPENSE

FISCAL YEAR 1989

G & A EXPENSE POOL	(2) ACCUMULATION OF DIRECT DIST. OF NBV	(3) ALLOCATION OF UNDISTRIBUTED	(4) TOTAL NET BOOK VALUE	(5) COST OF MONEY FOR THE COST ACCTG. PERIOD	(6) ALLOCATION BASE FOR THE PERIOD ($=000)	(7) FACILITIES CAPITAL COS OF MONEY FA
CORPORATE ALLOCATION	$ 660,000		$ 660,000	$ 61,875		
B&P TRANSFERRED FROM ENG. O/H	365,964		365,964	34,309		
TOTAL	$ 1,025,964		$1,025,964	$ 96,184	BASE TWIP $ 20,281	$ 0.00474

10

FACILITIES CAPITAL COST OF MONEY DISTRIBUTION OF ASSET TYPES

Form Approved OMB No. 0704-0267 Expires Oct 31 1985

1. CONTRACTOR NAME	2. CONTRACTOR ADDRESS
ROCKWELL INTERNATIONAL CORPORATION	1049 Camino Dos Rios Thousand Oaks, CA 91360
3. BUSINESS UNIT SCIENCE CENTER DIVISION	
4. COST ACCOUNTING PERIOD FY 1989	5. APPLICABLE TREASURY RATE 9.375%

6. DISTRIBUTION OF FACILITIES CAPITAL BY ASSET TYPES

FACILITIES CAPITAL	Net Book Value (1)	Land (2)	Buildings (3)	Equipment (4)
a. RECORDED	13,435,463	836,226	3,020,233	9,579,004
b. LEASED				
c. CORPORATE/GROUP	660,000	10,000	230,000	420,000
d. TOTALS	14,095,463	846,226	3,250,233	9,999,004

7. DISTRIBUTION STATUS TO OVERHEAD AND G & A EXPENSE POOLS

a. UNDISTRIBUTED				
b. DISTRIBUTED				
c. TOTALS				

8. ASSIGNMENT TO OVERHEAD AND G & A EXPENSE POOLS

Pool (1)	Net Book Value (2)	PERCENT DISTRIBUTION (Nearest whole percentage) Land (%) (3)	Buildings (%) (4)	Equipment (%) (5)
ENG	11,190,766	7.39%	25.61%	67.00%
COMMON	184,975			100.00%
PLANT - ANAHEIM	1,629,675	0.58%	8.92%	90.50%
PLANT - PALO ALTO	64,083		13.37%	86.63%
G & A	1,025,964	0.97%	22.42%	76.61%
TOTALS	14,095,463	6.00%	23.06%	70.94

DD Form 1861-1, OCT 84 Replaces DD Form 1861 which is obsolete

CONTRACT FACILITIES CAPITAL COST OF MONEY

Rockwell International Corporation
Science Center-Anaheim

1049 Camino Dos Rios
Thousand Oaks, Calif. 91360

Proposal SC61047

FY 1989

Pool	Alloc Base	Factor	Amount	Land	Building	Equip.
Plant	$42,408	0.17147	$7,272	$606	$2,110	$4,556
Common	$42,408	0.00282	$120	$0	$0	$120
G & A	$145,837	0.00474	$691	$9	$138	$544
Totals			$8,083	$615	$2,248	$5,220
Tres Rate	9.375%		$86,219	$6,560	$23,979	$55,680

DD Form 1861-2

Anaheim FY 1989

WEIGHTED GUIDELINES PROFIT FACTORS

1. Performance Risk

$145.837	X	ave	4.50%	=	$6,563

2. Facilities Capital Employed

   a. Buildings

$23,979	X	15.00%	=	$3,597

   b. Equipment

$55,680	x	35.00%	=	$19,488

Total Weighted Guidelines Profit $29,648

EXHIBIT C
Modified Form CASB-CMF

S.C. Rate:	0.19711 DL$
Plant - Anaheim:	0.17080 DL$
Plant - Palo Alto:	0.02384 DL$
Offsite:	0.00275 DL$

FACILITIES CAPITAL
COST OF MONEY FACTORS COMPUTATION
FISCAL YEAR 1990

CONTRACTOR: ROCKWELL INTERNATIONAL SCIENCE CENTER
BUSINESS UNIT:

COST ACCOUNTING PERIOD: FISCAL YEAR 1990	1. Applicable Cost of Money Rate: 9.375 %	2. Accumulation & Direct Dist. of NBV	3. Allocation of Undistributed	4. Total Net Book Value	5a. CAS 414 Cost of Money For Cost Acctg. Period	5b. Depr. of CAS 417 Cost of Money	5. Combined Cost of Money For the Period	6. Allocation Base for the Period ($ = 000)	7. Facilities Capital Cost of Money Factors
			Basis of Allocation	Columns 2 + 3	Column 1 x 4		Columns 5a + 5b	In Unit(s) of Measure	Columns 5 - 6
BUSINESS UNIT FACILITIES	Recorded	$12,955,907							
	CAS 417 COM	$192,433							
	Leased Property								
	Corporate/Group	$660,000							
	Total	$13,808,340							
	Undistributed								
	Distributed								
OVERHEAD POOLS	ENG	$10,766,539		$10,766,539	$1,009,363	$16,670	$1,026,033	5,279 DL$	$0.19436 DL$
	COMMON	$192,084		$192,084	$18,008		$18,008	6,540 DL$	$0.00275 DL$
	PLANT-ANAHEIM	$1,735,938		$1,735,938	$162,744		$162,744	924 DL$	$0.17613 DL$
	PLANT-PALO ALTO	$75,826		$75,826	$7,109		$7,109	337 DL$	$0.02109 DL$
G & A EXPENSE POOLS		$1,037,953		$1,037,953	$97,308		$97,308	BASE (MIP) $ 20,896	$0.00466
TOTAL		$13,808,340		$13,808,340	$1,294,532	$16,670	$1,311,202		

FACILITIES CAPITAL
COST OF MONEY FACTORS COMPUTATION

GENERAL & ADMINISTRATIVE EXPENSE

FISCAL YEAR 1990

G & A EXPENSE POOL	(2) ACCUMULATION OF DIRECT DIST. OF NBV	(3) ALLOCATION OF UNDISTRIBUTED	(4) TOTAL NET BOOK VALUE	(5) COST OF MONEY FOR THE COST ACCTG. PERIOD	(6) ALLOCATION BASE FOR THE PERIOD ($-000)	(7) FACILITIE CAPITAL CO OF MONEY F
CORPORATE ALLOCATION	$ 660,000		$ 660,000	$ 61,875		
B&P TRANSFERRED FROM ENG. O/H	377,953		377,953	35,433		
TOTAL	$1,037,953		$1,037,953	$ 97,308	BASE IWIP $20,896	$ 0.00466

FACILITIES CAPITAL COST OF MONEY DISTRIBUTION OF ASSET TYPES

Form Approved
OMB No. 0704-0267
Expires Oct 31, 1989

1. CONTRACTOR NAME ROCKWELL INTERNATIONAL CORPORATION	2. CONTRACTOR ADDRESS 1049 Camino Dos Rios Thousand Oaks, CA 91360
3. BUSINESS UNIT SCIENCE CENTER DIVISION	
4. COST ACCOUNTING PERIOD FY 1990	5. APPLICABLE TREASURY RATE 9.375%

6. DISTRIBUTION OF FACILITIES CAPITAL BY ASSET TYPES

FACILITIES CAPITAL	Net Book Value (1)	Land (2)	Buildings (3)	Equipment (4)
a. RECORDED	13,148,340	841,735	3,038,367	9,268,238
b. LEASED				
c. CORPORATE/GROUP	660,000	10,000	230,000	420,000
d. TOTALS	13,808,340	851,735	3,268,367	9,688,238

7. DISTRIBUTION STATUS TO OVERHEAD AND G & A EXPENSE POOLS

a. UNDISTRIBUTED				
b. DISTRIBUTED				
c. TOTALS				

8. ASSIGNMENT TO OVERHEAD AND G & A EXPENSE POOLS

Pool (1)	Net Book Value (2)	PERCENT DISTRIBUTION (Nearest whole percentage) Land (%) (3)	Buildings (%) (4)	Equipment (%) (5)
ENG	10,766,539	7.73%	26.82%	65.45%
COMMON	192,084			100.00%
PLANT - ANAHEIM	1,735,938	0.54%	8.23%	91.23%
PLANT - PALO ALTO	75,826		10.97%	89.03%
G & A	1,037,953	0.96%	22.16%	76.88%
TOTALS	13,808,340	6.16%	23.67%	70.17%

CONTRACT FACILITIES CAPITAL COST OF MONEY

Rockwell International Corporation
Science Center-Anaheim

1049 Camino Dos Rios
Thousand Oaks, Calif. 91360

Proposal SC61047

FY 1990

Pool	Alloc Base	Factor	Amount	Land	Building	Equip.
Plant	$59,688	0.17613	$10,513	$861	$3,085	$6,567
Common	$59,688	0.00275	$164	$0	$0	$164
G & A	$206,534	0.00466	$962	$13	$177	$772
Totals			$11,639	$874	$3,262	$7,503
Tres Rate	9.375%		$124,149	$9,323	$34,795	$80,032

DD Form 1861-2

Anaheim FY 1990

WEIGHTED GUIDELINES PROFIT FACTORS

1. Performance Risk

$206,534	X	ave	4.50%	=	$9,294

2. Facilities Capital Employed

a. Buildings

$34,795	X	15.00%	=	$5,219

b. Equipment

$80,032	x	35.00%	=	$28,011

Total Weighted Guidelines Profit $42,524

Science Center
Rockwell International Corporation
1049 Camino Dos Rios
P.O. Box 1085
Thousand Oaks, California 91360

Rockwell International

November 1, 1988

Ms. Rita Bush
Administrative Contracting Officer
Defense Logistics Agency
Oxnard Multi-Functional Field Office
500 Esplanade Drive
Suite 990
Oxnard, California 93030 2119

Dear Ms. Bush:

The purpose of this letter is to request approval of the following Rockwell Science Center forward pricing rates.

The following rates have been developed by the Science Center for quoting effort with the Corporation and to outside customers:

	1989	1990	1991	1992
Common Overhead	44%	44%	44%	44%
Engineering Overhead	161%	158%	157%	157%
Plant Overhead	140%	140%	140%	140%
Palo Alto Research Lab	134%	130%	130%	130%
Fringe Benefits	38%	40%	42%	45%
General & Administrative	13.0%	12.8%	13.2%	13.1%

These rates are effective immediately and supersede all previously quoted rates. Attached are summary data supporting the above rates. Upon completion of government review, please contact me to discuss any questions.

ROCKWELL INTERNATIONAL
Science Center

J. I. McDonald
Controller

Attachments

cc: K. Solso, DCAA

COMPANY OFFICIAL
TO BE OPENED BY
ADDRESSEE ONLY

SC61047T

HIGH-RATE SCINTILLATING FIBER TRACKING EXPERIMENT

UNSOLICITED PROPOSAL

Submitted to

Fermi National Laboratory
P.O. Box 500
Batavia, Illinois 60510

Prepared by

Rockwell International Science Center
P.O. Box 3105
Anaheim, California 92803-3105

January 1989

Approved by:

R. Bharat, Director
Silicon Devices

SC61047T

STATEMENT OF WORK FOR

HIGH-RATE SCINTILLATING FIBER TRACKING EXPERIMENT

INTRODUCTION

Fermi National Laboratory (FNL) proposes to utilize Rockwell's Solid State Photomultiplier (SSPM) with scintillating fibers in particle tracking systems. Although tests have shown that, on the average, one photon is detectable from a normal incident minimum-ionizing particle at the end of a 180 μm thick, meter-long fiber, further demonstrations are required to establish the SSPM can provide time resolution of a few (<10) nanoseconds.

There are two indicated design changes for optimization of SSPMs for use in scintillating fiber tracking systems: 1) reduce contact resistance and 2) eliminate as much of the optically-active layer thickness as possible without affecting the quantum efficiency for visible light. The equivalent circuit of an SSPM consists of a contact resistance (between 2 and 5 kΩ for present designs) in series with a capacitance of about 0.2 pF with a current source in parallel. The current source is a short pulse of about 2.5×10^{-5} A for a period of about 5×10^{-11} s ($\sim 10^4$ electrons) followed by a 10^{-7} to 10^{-6} s current tail containing about 4×10^4 electron charges. Such a circuit is not matched to a wideband (100 MHz) amplifier with a 50 Ω input impedance. The shortest rise time with typically 10 to 20 pF at the input of a transimpedance amplifier is between 20 and 80 ns, consistent with the 2 to 4 kΩ contact resistance.

Reduction of the contact resistance to a value below 100 Ω is therefore indicated if nanosecond risetimes are to be obtained. Even if this is successfuly accomplished, however, the pulses (10^4 electrons) will barely exceed frequently-occuring noise excursion amplitudes of about five times the rms kTC noise charge of about 1000 electrons for an ideal 100 MHz amplifier at 300 K connected to an SSPM with a 50 Ω transmission line. In order to provide a larger signal-to-noise margin, the fast portion of the current pulse can be increased to contain about 3×10^4 electrons by thinning the SSPM's optically-active region to about 6 μm, which is the theoretical minimum thickness allowing unimpaired visible light SSPM response.

This statement of work describes a program in which Rockwells' Science Center, Anaheim, California, fabricates and evaluates SSPMs designed to provide the required response times. Rockwell will also conduct an experiment, using scintillating fibers excited by a beta source, to demonstrate this capability. A schedule for this proposed work is shown on Page 3.

DESIGN

Rockwell shall design a photomask set which will provide linear SSPM arrays suitable for mating with scintillating fiber tape provided by FNL. The arrays shall have the following characteristics:

No. of elements	50
Element area	9x9 sq mils
Element pitch	10 mils
Dies per wafer	80 (approx)

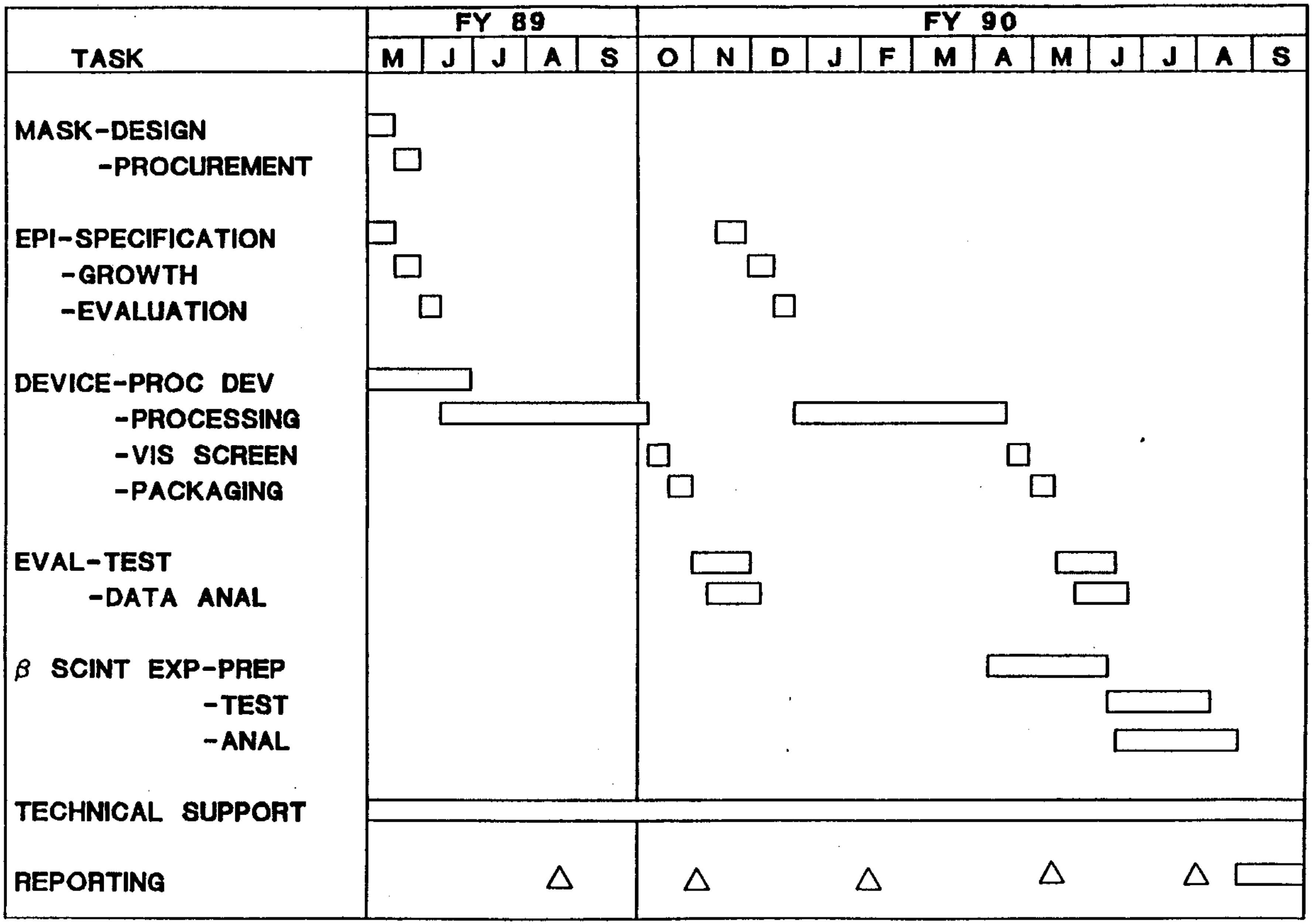
The photomasks will then be procured for use in array processing.

FABRICATION

Arrays will be fabricated with several variations in optically-active layer thickness and top contact process parameters in order to optimize the SSPM for particle tracking. Process development experiments will be performed as required to reduce the number of variations used in device processing. Epitaxy growth parameters (i.e.; thickness, donor and acceptor profiles) will be specified and the optically-active and blocking layers deposited on silicon wafers prepared for front-illumination. The grown material will be evaluated by visual, spreading resistance, and cryogenic capacitance vs voltage techniques prior to device processing.

An existing SSPM process lot follower will be modified to incorporate the desired top contact fabrication steps and a lot comprising at least three wafers of each variation (epitaxy and top contact) will be initiated. The processed wafers will be visually screened to generate a map of defect-free dies and arrays will be selected (2 from each variation) for dicing, mounting, and wire bonding.

SCINTILLATING FIBER TRACKING USING SSPMs



Following evaluation of Lot 1, epitaxy will be grown and wafers selected for a second lot which will be processed to further optimize SSPM performance.

EVALUATION

Evauation of the devices will include quantum efficiency for visible light detection, dark count rate density, saturation count rate density, avalanche gain, and gain dispersion as functions of bias at several temperatures. Selected devices will be measured using wideband amplifiers with 50 Ω input impedance supplied by Fermilab for evaluation of pulse rise time and width. Devices meeting time resolution requirements for Superconducting Supercollider (SSC) vertex particle tracking will be packaged for beta and accelerator particle scintillation experiments at Fermilab or other facilities.

DELIVERABLES

Rockwell will select for delivery to FNL four 50-element SSPM arrays which will be located adjacent or in close proximity to tested dies on the wafer. The selection will be made to provide arrays which are optimal for particle tracking experiments planned by FNL.

SCINTILLATION EXPERIMENTS

Several arrays will be selected for beta particle scintillation experiments using a strontium-90 source. Several detectors of a linear array will be coupled to scintillating fibers as in the initial feasibility test reported and demonstrated at the 1988 IEEE Nuclear Science Symposium held in Orlando, FA. Coincident photons from adjacent fibers traversed by beta particles will be detected. The experiments will emphasize time resolution and rate capability of the improved SSPMs for detection of such events.

TECHNICAL SUPPORT

Rockwell shall provide technical support to FNL in the form of analysis of SSPM performance, assistance in the design of FNL experiments, and preparation of technical papers.

APPENDIX C
OTHER SUPPORTING DOCUMENTATION

Development of High Rate Tracking Detectors for the SSC Using Scintillating Fibers and Solid State Photomultipliers

M. Atac[1,2], C. Anway[2], C. Buchanan[2], D. Chrisman[2], D. Cline[2], J. Kolonko[2]
1 Fermilab, Batavia, Illinois
2 UCLA, Los Angeles, California

B. Baumbaugh, V.P. Kenney and R. Ruchti
University Notre Dame, Notre Dame, Indiana

R. Florence and M. Petroff
Rockwell Science Center, Rockwell International
Anaheim, California

R.C. Chaney, E.J. Fenyves and H.D. Hammack
University of Texas at Dallas
Dallas, Texas

ABSTRACT

The Solid State Photomultiplier (SSPM)[1] recently developed by Rockwell International Science Center, coupled with fast scintillating fibers, can have a rate capability of higher than 10^8 tracks per cm^2 per second. The SSPM's, with gains approaching 5×10^4 are capable of single-photon counting with quantum efficiencies of ≈ 80 % for visible wavelengths. Using polystyrene with 3HF or Butyl PBD di-methyl POPOP scintillating fibers, a time resolution of better than 5 ns has been obtained with a SSPM. Scintillators having peak emission wavelength of ≥ 530 nm are known to be highly radiation resistant, and the spectral response of the SSPM is a good match for such wavelengths. The high rate capability, very good time resolution, and high quantum efficiency, suggest that scintillating fiber/SSPM detectors could be powerful components of a SSC tracking system. It is the objective of this proposal to develop a prototype detector with 192 SSPM/fiber channels for beam tracking tests to determine the utility of the technique. The program will establish a strong collaborative effort between University based physics groups and research groups in private industry in the development of these devices.

1.) Introduction

Using scintillating fibers for tracking is desirable especially to obtain fast timing with fine resolution. This is very much needed to cover the collision regions for high luminosity colliders like the SSC, which is being designed to operate at a luminosity of 10^{33} $cm^{-2}s^{-1}$ with a bunch spacing of 16 ns. Fibers with good time resolution can relate tracks to the bunch crossing. This was attempted earlier using avalanche photodiodes (APD's)[2] with disappointing results because the APD's went into breakdown before producing stable operating gains. Although scintillating fibers have been successfully used as active targets coupled to an image intensifier with CCD readout[3], the phosphor memory time and slow readout speed of CCD's (fast cameras are capable of 500 frames per second) make such an arrangement impractical at high rates.

Scintillating fibers have also been used for tracking in the UA2 experiment[4]. About 30 photons per mm were produced for a minimum ionizing particle with a step index fiber with scintillation fluorescence at $\lambda = 420$ nm. An attenuation length of 1.7 m was achieved through 1 mm diameter fibers. Photons were image-intensified and read out using CCD's, providing a track resolution of $\sigma = 0.35$ mm.

A solid-state device which is capable of counting single photons has recently been developed by researchers at the Rockwell International Science Center[1]. The device produces gains of 5×10^4 via impurity impact ionization in a solid-state photomultiplier that is sensitive to photons in the range from 400 nm to 28 μm. Square 50×50 μm^2 diode elements in both linear and area arrays have been fabricated and tested with success. A rate capability of more than 10^8 counts per cm^2 per second was measured using a 50×50 μm^2 device with a quantum efficiency exceeding 50 %. The device is appropriately called a Solid State Photomultiplier (SSPM). Figure 1 shows how well the single-, double-, and triple-photon pulses are resolved. Because the device is sensitive from visible wavelengths to infrared wavelengths of 28 μm ($h\nu =$ 0.05 eV), thermal electrons could result in a very large background unless the SSPM is operated at a sufficiently low temperature ($\leq 10°$ K). Figure 2 shows the SSPM's background rate and count rate capability as a function of temperature.

Scintillating fibers made from 3HF (3-hydroxyflavone) in polystyrene, Bipyridyl-diol (BPD) and other new dyes, would provide a good spectral match for the SSPM's because the fluorescence emission maxima in the range $500 \leq \lambda \leq 600$ nm correspond to an SSPM quantum efficiency of greater than 60% (Figure 3). For example, the 3HF fiber has a good light yield with a rise time of < 1 ns and a decay time of 3 ns. A fiber diameter of 250 μm may be sufficient to produce four detected photons in the SSPM for wavelengths of ~ 530 nm. The attenuation length for such a wavelength is expected to be long with a thin acrylic cladding. The refractive indices of polystyrene and acrylic are n = 1.59 and 1.49, respectively. Polystrene based scintillators can be highly radiation resistant[5] when appropriate dyes are used. An example is illustrated in Figure 4.

Why is the SSPM important for fiber tracking detectors?

1) The high quantum efficiency of the SSPM allows the use of fluorescent dyes with large Stokes' Shifts. These dyes, particularly those such as 3-HF and BPD which utilize intramolecular proton transfer, have lower fluorescence efficiency, $\sim \frac{1}{2}$ to $\frac{3}{4}$ that of NE110. The high QE of the SSPM helps to compensate for the lower scintillation efficiency.

2) The ability to use large Stokes dyes with emission in the 500 – 600 nm range, where the SSPM quantum efficiency is high, allows several additional advantages:

   a) radiation resistance of the overall system is greatly improved for $\lambda > 500$ nm;

   b) optical self-absorption problems are reduced substantially with the large Stokes materials;

   c) small diameter fibers (d $<<$ 250 μm) may be used as efficient scintillation detectors because secondary dyes are not needed.

3) The use of the SSPM obviates the need for high resolution image tubes utilizing phosphor screens. This point deserves emphasis: **there are no fast and efficient phosphors with time constants below 50 ns** (the speed of P-47). Phosphor persistance has been a recognized difficulty associated with high-resolution, fast imaging.

Caviat: The SSPM must be operated cryogenically at 7°K for successful performance. Hence these devices must be contained in a cryostat. Ultimately we will have to address the problem of the design of a thin cryostat carefully placed to interfere minimally with other detectors - this is a problem for overall design for an experiment. However, in this proposal we are taking the initial step: the development of a working SSPM/Scintillating fiber tracking detector to demonstrate the utility of the technique for SSC tracking applications.

2.) Recent Tests with Scintillating Fibers and Results

A preliminary test of the SSPM's effectiveness as a light detector for scintillating fibers was performed using square 0.225×0.225 mm^2 step-index-of-refraction fibers with a 0.18×0.18 mm^2 core. Two fibers[6] having different wavelengths, $\lambda = 440$ and $\lambda = 530$ nm, were investigated. The experiment[7], illustrated schematically in Figure 5, involved the exposure of two adjacent fibers to a partially-collimated beam of electrons from a strontium-90 beta source (2.25 MeV maximum energy). Coincident photon detection pulses were pulse-height-analyzed to obtain data which is plotted in Figure 6 for one of the fibers. The distributions are for two different lengths of fiber between the point irradiated and the SSPM. Because the amplitude of each SSPM pulse is proportional to the number of simultaneously-detected photons, with very little amplitude dispersion, such distributions allow determination of the average number of photons detected per electron hit (i.e., penetration through the fiber). The first n peaks correspond to 1, 2, .., n detected photons per hit, and their areas A(n) are expected to approximately follow the Poisson distribution,

$$p(n, \mu) = \frac{\mu^n \exp(-\mu)}{n!}$$

The average number of electrons detected per hit, μ, is therefore equal to the ratio

$$\mu = \frac{(n+1)A(n+1)}{A(n)}.$$

It is noted that the distribution for photon numbers greater than three may deviate from Poisson statistics due to a substantial contribution from electrons scattered through large angles, resulting in long paths in the fiber.

The first five columns of Table 1 give the parameters for two fibers of different wavelength coupled to an SSPM with no special provisions to reduce reflection losses. The parameter n_1 is the core index of refraction,

n_2 that of the cladding, and F is the percentage of isotropically-emitted photons that are within the angle for total internal reflection in one direction. The other columns give the average number of detected photons and the photon attenuation length from the pulse height data and expected number of detectable photons assuming that, on the average, about 400 eV of particle energy is consumed in a typical plastic scintillator while creating one photon. Some of the scattered electrons and the low energy (< 0.5 meV) part of the beta electron distribution may produce somewhat larger scintillations than those of minimum ioizing particles (MIP's) created in a collider.

TABLE 1

	$\lambda = 440$ (nm)	$\lambda = 530$ (nm)
SSPM Q.E. at λ	0.4	0.6
n_1	1.60	1.56
n_2	1.48	1.48
F (%)	3.5	2.6
Average Photons/e from Data	0.9	0.95
Measured Attenuation Length (m)	1.8	1.06
Calculated Detection Photons/MIP	1.08	0.90

These results may therefore exceed the average number of photons that would be detected if MIP's were used in the same experiment. Nevertheless, the photon yields in Table 1 are probably quite close to the yield per collider MIP in a system where the fibers would be aluminized, terminated with a reflecting surface, and optically matched to an SSPM. It should be noted that none of these provisions were employed in the experiment reported here.

The data for two scintillating fibers of different wavelengths indicates that meter-long fibers of this type, optimally coupled to SSPM's, can be effective in detecting minimum ionizing particles. The present SSPM's are not optimized for very high rates and for the wavelength of the scintillating plastics we would like to use for tracking. It is necessary that this work be performed jointly with the Rockwell International Science Center for optimizing SSPM's and scintillating fibers in order to provide more efficient tracking systems for future high-energy particle physics research.

3.) Proposed Research and Development

A joint research and development effort is being proposed between UCLA, Notre Dame, University of Texas at Dallas, and the Rockwell International Science Center to accomplish the following:

a) Optimize ohmic contact resistance of SSPM's to improve pulse rise time, and to reduce device thickness to minimize infrared response and improve device speed.

b) Search for ways to obtain good optical coupling between scintillating fibers and SSPM's.

c) Develop and incorporate high quantum efficiency long attenuation length scintillating fibers with the SSPM's

Tests using β-sources and high-energy particles are needed to find answers to such questions as: (1) How many photo-electrons are produced in the developed SSPM and the scintillating fibers? (2) What are the radiation resistance properties of these fibers and the attenuation length of the fibers?

4.) The Proposed Beam Test Device

A device will be constructed with 192 SSPM channels coupled to the same number of polystyrene scintillating fibers with step index acrylic cladding. Figure 7 shows a test apparatus for measuring scintillating fibers/SSPM properties. A small liquid helium cryostat maintains the SSPM at a temperature of 7° K. Rockwell will provide the SSPM devices to carry out the tests. Photons can be brought to the photosensitive surface or can be produced inside the dewar using a β-source. The scintillating fibers can be placed in a high-energy particle beam to study tracking.

References

1.) M.D. Petroff, M.G. Stapelbroek, W.A. Kleinhans, Appl. Phys. Lett., Vol. 51, No. 6 (Aug. 1987) 406.

2.) F. Capasso, J. Allam et.al., IEEE Trans. Electron Devices, ED-30, 381 (1983).

3.) R. Ruchti et. al., IEEE Trans. on Nucl Sci., Vol. NS-34, No. 1, Feb. 1987.

4.) S. Palanque, private communication, UA2 experiment at CERN. H. Blumenfeld, M. Bourdinaud, and J.C. Theoemin, Nucl. Instrum. Methods in Phys. Res. A257 (1987) 603.

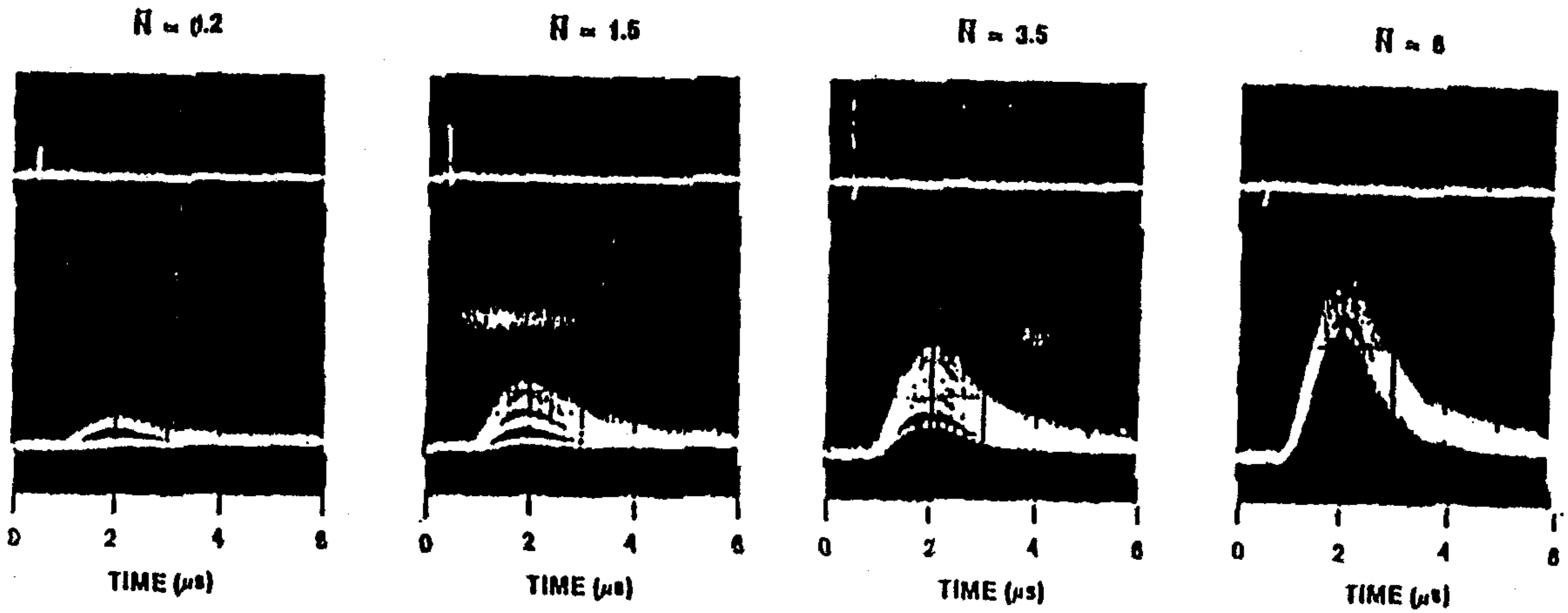
5.) F. Takasaki, KEK, 1988 Snowmass Workshop Proceedings.

6.) D.F. Anderson and A.D. Bross provided the scintillating fibers.

7.) M.D. Petroff and M. Atac, to be published in Proc. of 1988 Nucl. Sci. Symposium.

PULSES ARE DIRECT AND IMMEDIATE CONSEQUENCE OF THE DETECTION OF INDIVIDUAL PHOTONS

$\bar{N}$ = AVERAGE NUMBER OF DETECTED PHOTONS PER LED PULSE.



10,000 LED PULSES/S
0.1 S EXPOSURE

TOP TRACES: VOLTAGE APPLIED TO LED

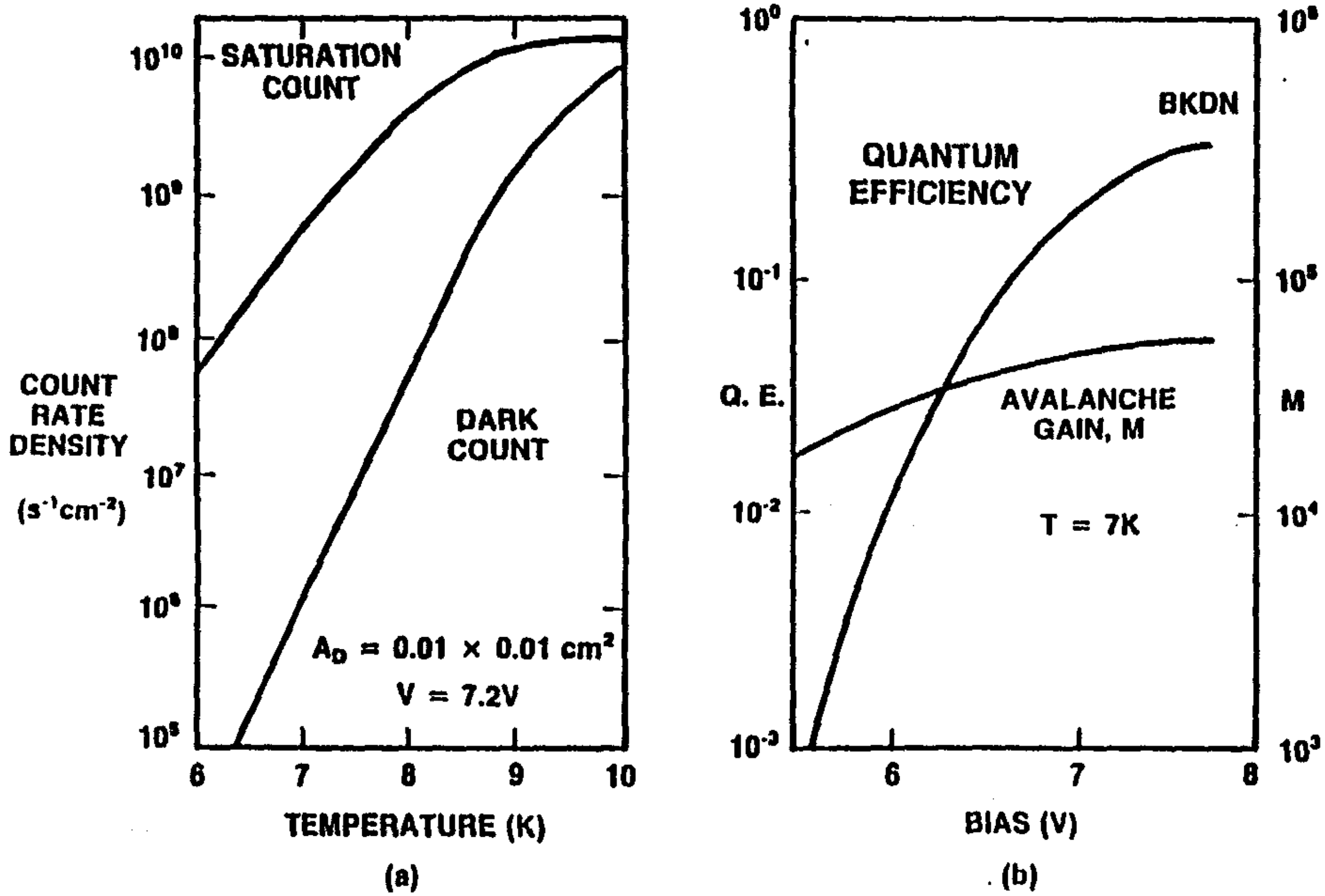
BOTTOM TRACES: SSPM RESPONSE

T = 8.0 K

Fig. 1 Well Resolved Single and Multiple Photoelectron Pulses

Rockwell

SSPM CHARACTERISTICS



(a) TEMPERATURE DEPENDENCE OF THE SSPM DARK-COUNT-RATE AND SATURATION-COUNT-RATE DENSITIES.
(b) BIAS DEPENDENCE OF GAIN, M, AND QUANTUM EFFICIENCY ($\lambda = 20\ \mu m$).

Rockwell International

Fig. 2

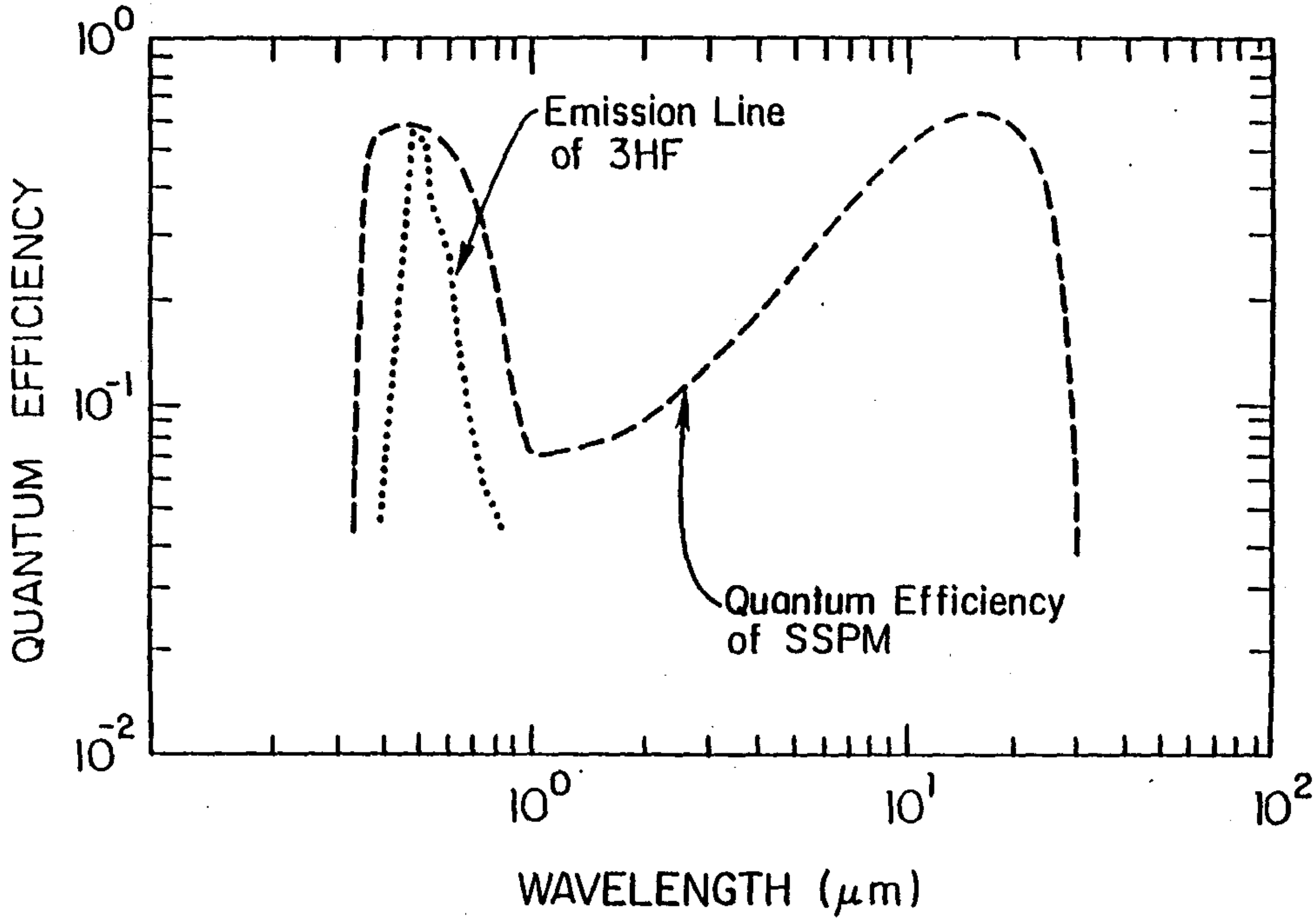


Fig. 3 Quantum efficiency

OPTICAL ATTENUATION LENGTH FOR A KYOWA SCINTILLATING FIBER SCSN 81 + Y7 FROM FUMIHIKO TAKASAKI, KEK, 1988 SNOWMASS WORKSHOP

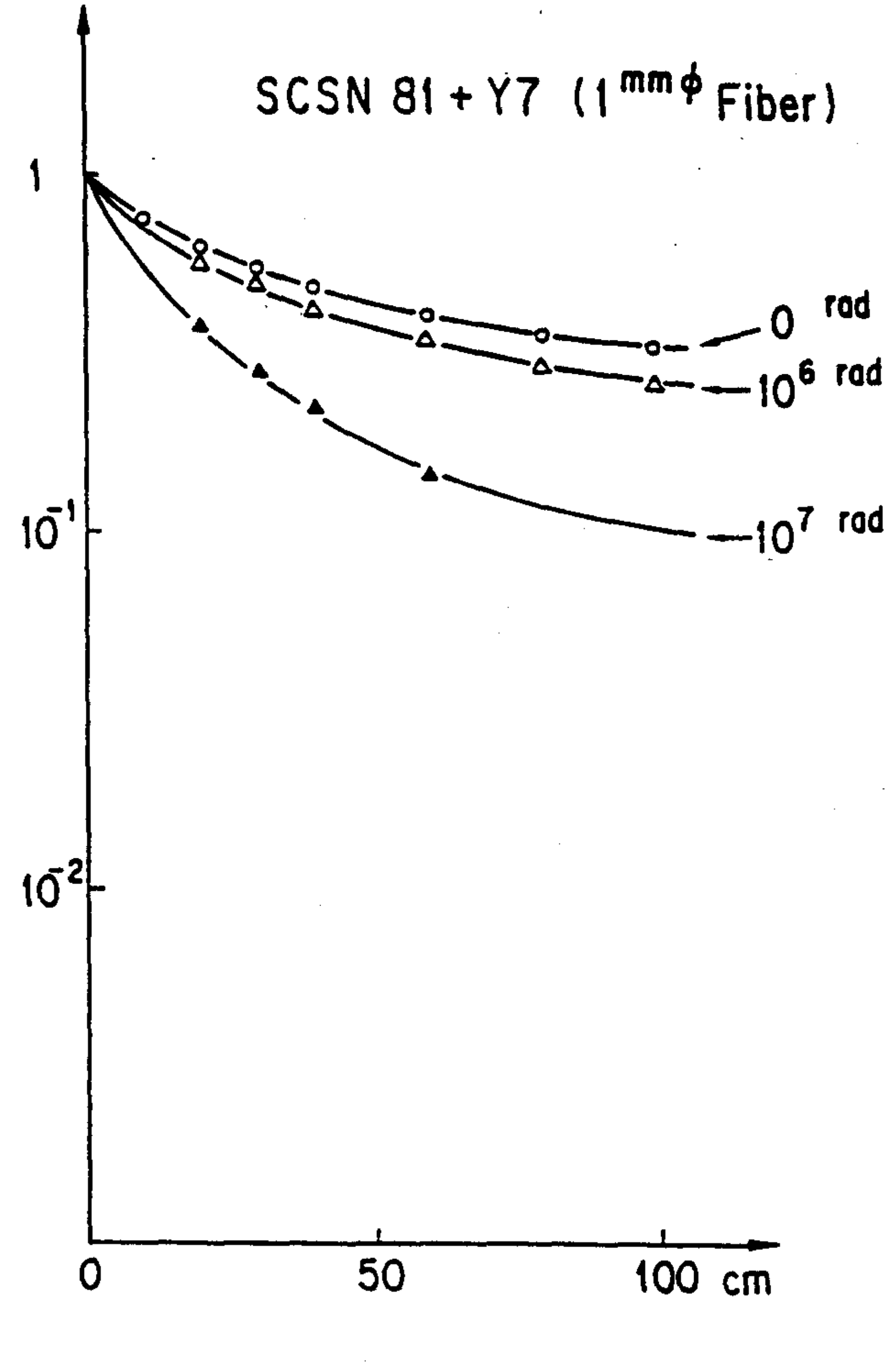


Fig. 4

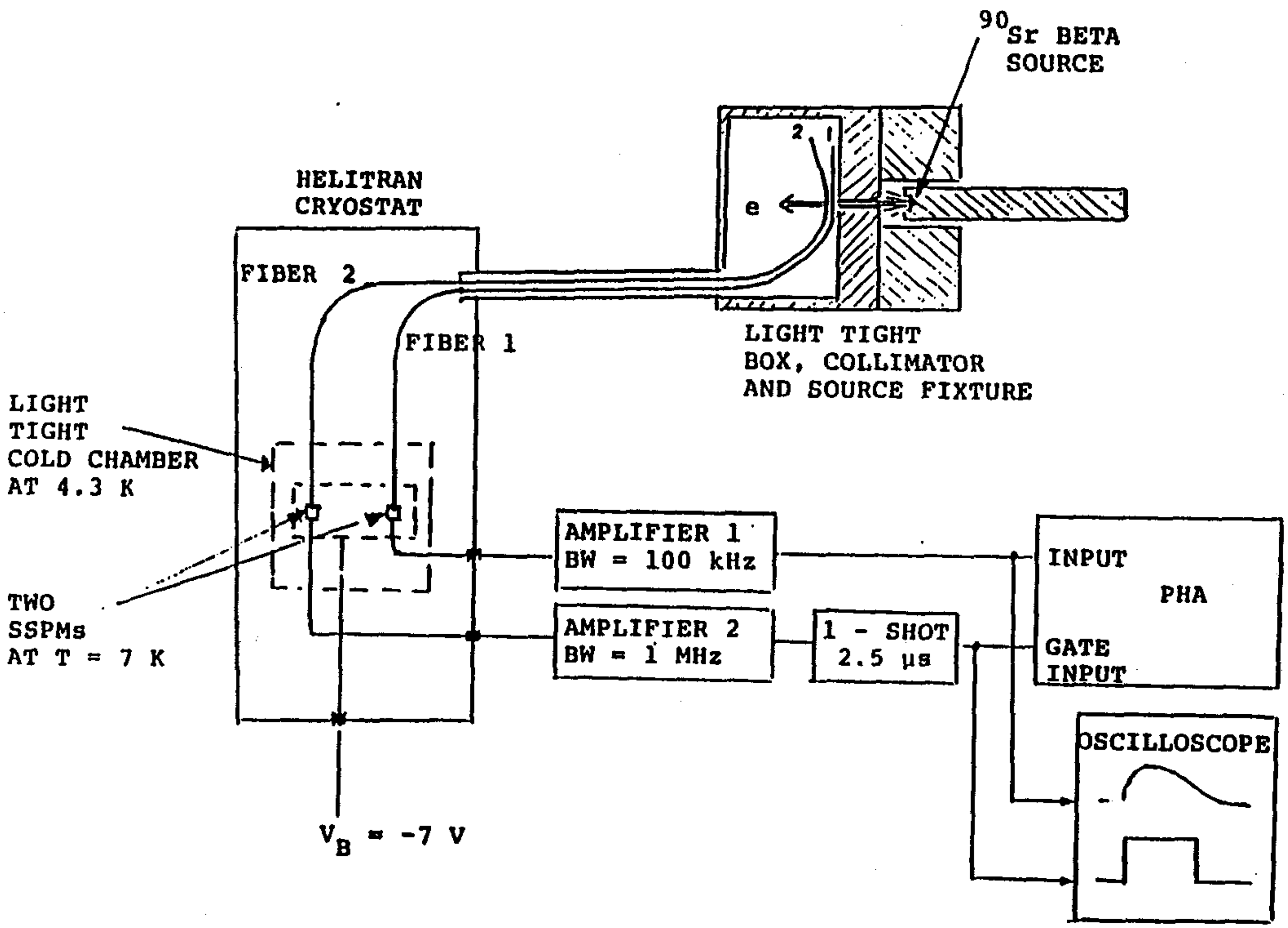


Figure 5 Experimental Arrangement for Detection Of Fiber Scintillations

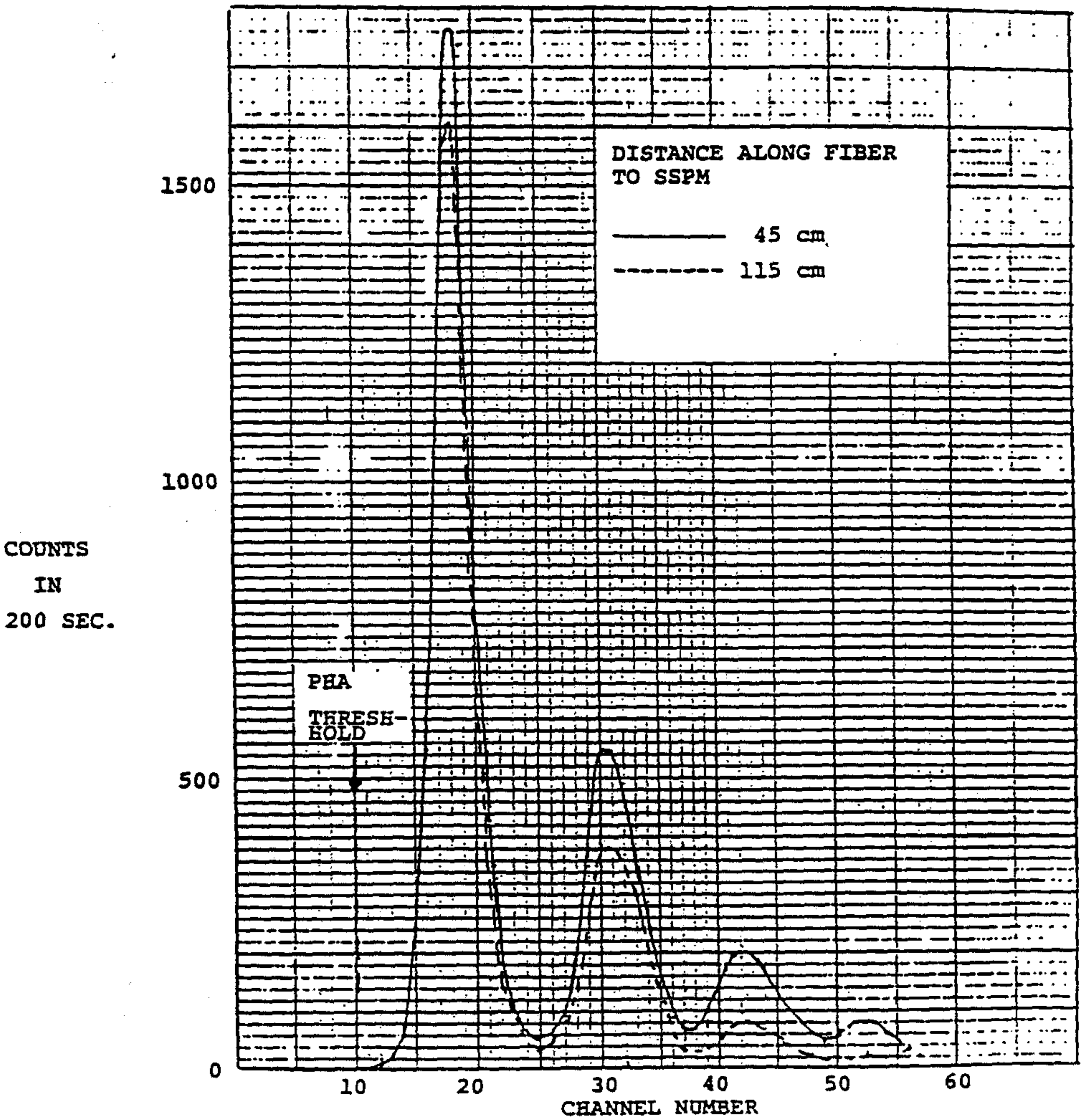


Figure 6 SSPM Pulse Height Distributions for Fiber Scintillations at two Positions of Beta Beam

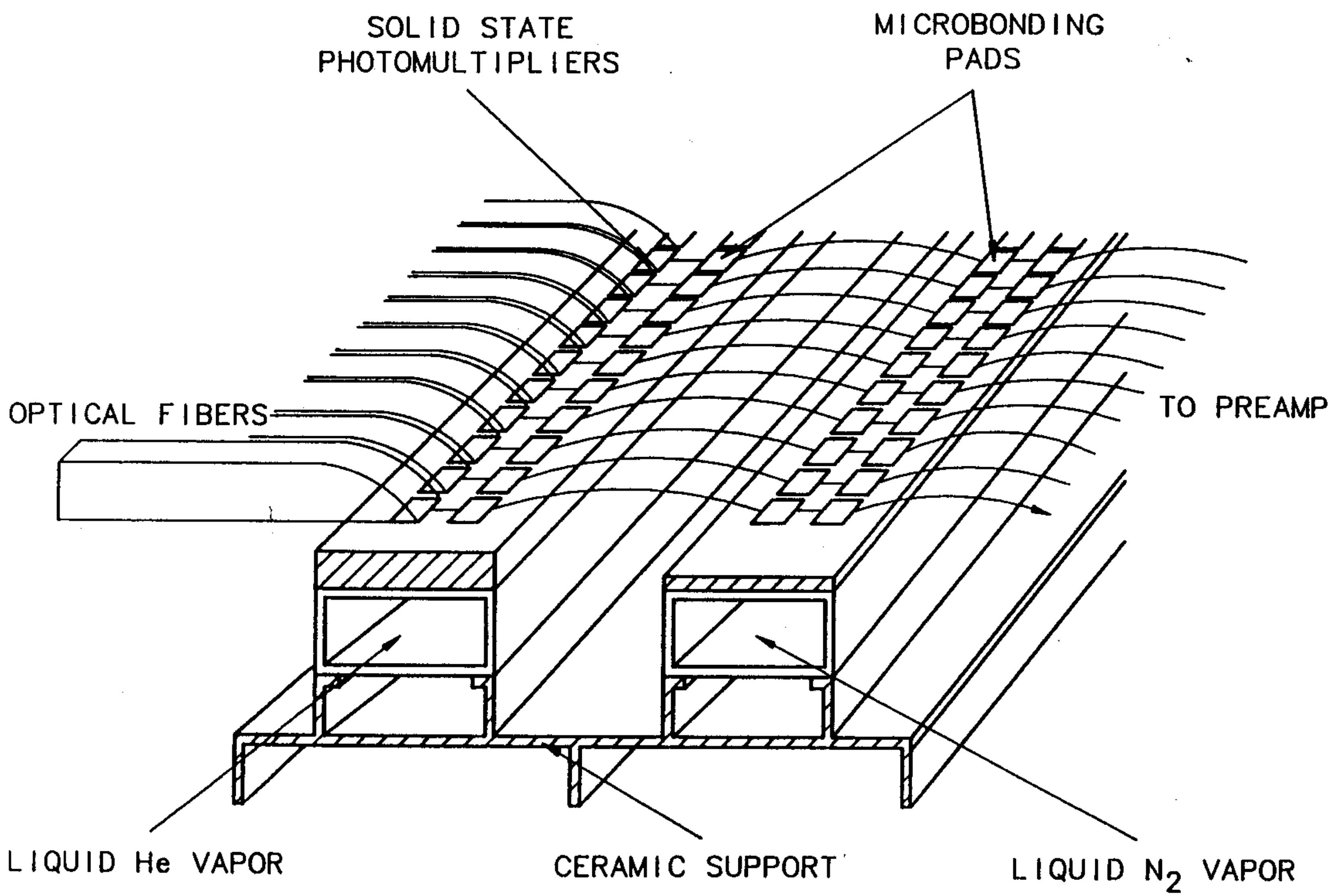


Fig. 7 Test appartus for beam tests.

Fermi National Accelerator Laboratory

FERMILAB-Conf-89/30

High Energy Particle Tracking Using Scintillating Fibers and Solid State Photomultipliers*

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Anaheim, California 92803

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January 1989

*Presented by M. Atac at the Workshop on Scintillating Fiber Detector Development for the SSC, Fermilab, Batavia, Illinois, November 14-16, 1988.

Operated by Universities Research Association, Inc., under contract with the United States Department of Energy

High Energy Particle Tracking Using Scintillating Fibers and Solid State Photomultipliers

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Abstract

The Solid State Photomultiplier (SSPM)[1] recently developed at the Rockwell International Science Center, coupled with fast scintillating fibers can have a rate capacity of 10^8 tracks per second per cm^2 of fiber cross section in systems for tracking of high energy ionizing particles. Relative to other approaches the SSPM can provide substantial improvements in spatial and temporal tracking accuracy. Results of preliminary experiments with 0.225 x 0.225 mm^2 cross section step-index-of-refraction fibers exposed to electrons from a beta source are presented. The experiments involved pulse height analysis of SSPM photon detection pulses induced by coincident scintillations in two adjacent fibers traversed by the same electron. The data for two different scintillating fibers tested indicate that meter long fibers of this type, optimally coupled to SSPMs, will be effective in detecting minimum ionizing particles.

Scintillating fibers provide fast timing with impressive spatial resolution for the tracking of particles produced in collision regions of high-luminosity colliders. A key component of such tracking systems is the means for detection of the small number of photons guided to the end of each fiber penetrated by a particle. The Solid State Photomultiplier[1] (SSPM) developed at Rockwell International is well suited for this purpose. For example, a tracking

[1]This work was supported by the Department of Energy Contract No. DE-AM03-76SF00010, Project Agreement No. DE-AT03-88ER40384

system using scintillation fibers and SSPMs implemented around the Fermi National Accelerator CDF collision region could provide spatial accuracies better than 0.08 mm. The system would also be suitable for Superconducting Supercollider vertex tracking due to the SSPM's capability of high detection rates and very good time resolution. Such performance is based on the nanosecond pulse risetime of SSPMs and achievable 90% SSPM quantum efficiency at scintillation light wavelengths near 500 nm, allowing use of fibers having a cross section less than 0.25 x 0.25 mm^2. Fig. 1 shows a possible vertex tracking scheme using one group of straight and two groups of stereo layers of scintillating fibers at $\pm 30°$. The amount of materials in the way of the tracks normal to a total of 12 layers of fibers would be about 0.8% of the radiation length of the particle. Four layers of fibers in each group would provide a high probability of detecting several photons per particle track.

Other devices, such as avalanche photodiodes (APDs)[2], considered as scintillating fiber photon detectors have given disappointing results in experimental tests. The use of scintillation fibers as an active target coupled to an image intensifier with CCD readout has been successful[3]. However, the slow readout speed of the CCD precludes the use of such an arrangement at high rates. Furthermore, the relatively low quantum efficiency of image intensifiers (less than 25%) limits this approach to fibers about 1 mm in diameter with a corresponding spatial accuracy of only 0.35 mm.

A preliminary test of the SSPM's effectiveness as a light detector for scintillating fibers was performed using step-index-of-refraction square 0.225 x 0.225 mm^2 fibers with a 0.18 x 0.18 mm^2 core[4]. Two fibers having different emission wavelengths, $\lambda = 440$ and 530 nm, were investigated. The experiment, illustrated schematically in Fig. 2, involved exposure of two adjacent fibers to a partially collimated beam of electrons, with a 2.25 MeV maximum energy, from a strontium-90 beta source. Coincident photon detection pulses were pulse height analyzed to obtain distributions such as those plotted in Fig. 3 for one of the fibers. The distributions are for two fiber lengths between the point irradiated and the SSPM. Because the amplitude of SSPM pulses is proportional to the number of simultaneously-detected photons with very little amplitude dispersion, such distributions allow determination of the average number of photons detected per electron that passes through the fiber. The first n peaks correspond to 1.2...n detected photons per electron through the fiber, and their areas A(n) are expected to approximately follow the Poisson distribution, $p(n, < n >) = < n >^n \exp(- < n >)/n!$. The average number of electrons detected per electron passing through the fiber, $< n >$, is therefore equal to the ratio (n+1)A(n+1)/A(n). It is noted that the distribution for photon numbers greater than three may contain enough events from electrons scattered through large angles, resulting in long paths in the fiber and therefore may deviate from Poisson statistics.

The first five columns of Table 1 give the parameters for two fibers of different wavelength coupled to an SSPM with no special provisions to reduce reflection losses. λ is the peak wavelength of the fiber emission band. The $\lambda = 440$ nm fiber cores are polystyrene containing Butyl PBD and POPOP and the $\lambda = 530$ nm fibers use 3HF (3-hydroxy flavone) in polystyrene. The parameter n_1 is the core index of refraction, n_2 that of the cladding, and f is the percentage of isotropically-emitted photons that are within the angle for total internal reflection in one direction along a fiber. The actual values of f may be smaller if the fibers have small radius bends of deviate otherwise from the perfect geometry assumed in the estimates.

The last three columns of Table 1 give the average number of detected photons and photon attenuation length from the pulse height data and the expected number of detectable photons assuming that for minimum ionizing particles (MIPs), in plastic scintillators, on the average, about 400 eV of particle energy is consumed in creating one photon. Some of the scattered electrons and the low energy (< 0.5 MeV) part of the beta electron distribution may produce somewhat larger scintillations than those of MIPs created in a collider. The calculated photon yield may therefore exceed the average number of photons that would be detected if heavy MIPs were used in the same experiment. Nevertheless, the photon yields in Table 1 are probably quite close to the yield per collider MIP in a system where the fibers would be aluminized, terminated with a reflecting surface, and optically matched to an SSPM. It should be noted that none of these provisions were employed in the experiments reported here, and several 1.5 cm radius 60° bends in the fibers could not be avoided inside the dewar. Further experiments using MIPs in a set-up with improved SSPM-fiber coupling and with no fiber bends of radius less than 2.5 cm are indicated.

Acknowledgments

The authors would like to express their appreciation to Drs. C. Buchanan, D. Cline, and J. Kolonko for their support of the project.

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4. Fibers were provided by A. Bross, Fermilab. They were produced for scintillating fiber calorimetry.

Table 1

λ nm	SSPM Q.E. at λ	n_1	n_2	f %	Average Photons/e from data	Measured Attenuation Length (m)	Calculated Detectable Photons/MIP
440	0.4	1.60	1.48	3.5	0.9	1.8	1.08
530	0.6	1.56	1.48	2.6	0.95	1.06	0.90

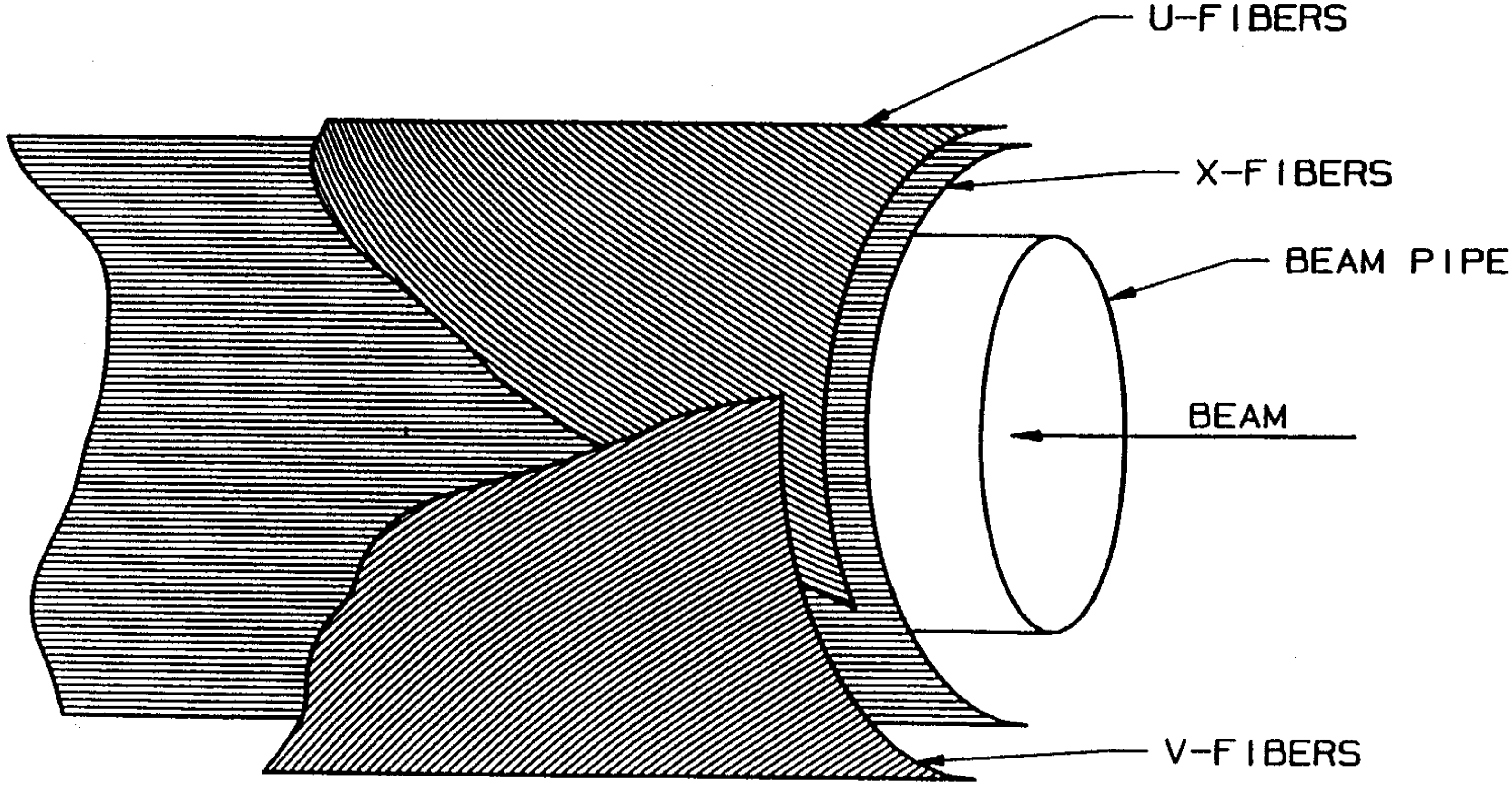

Fig. 1

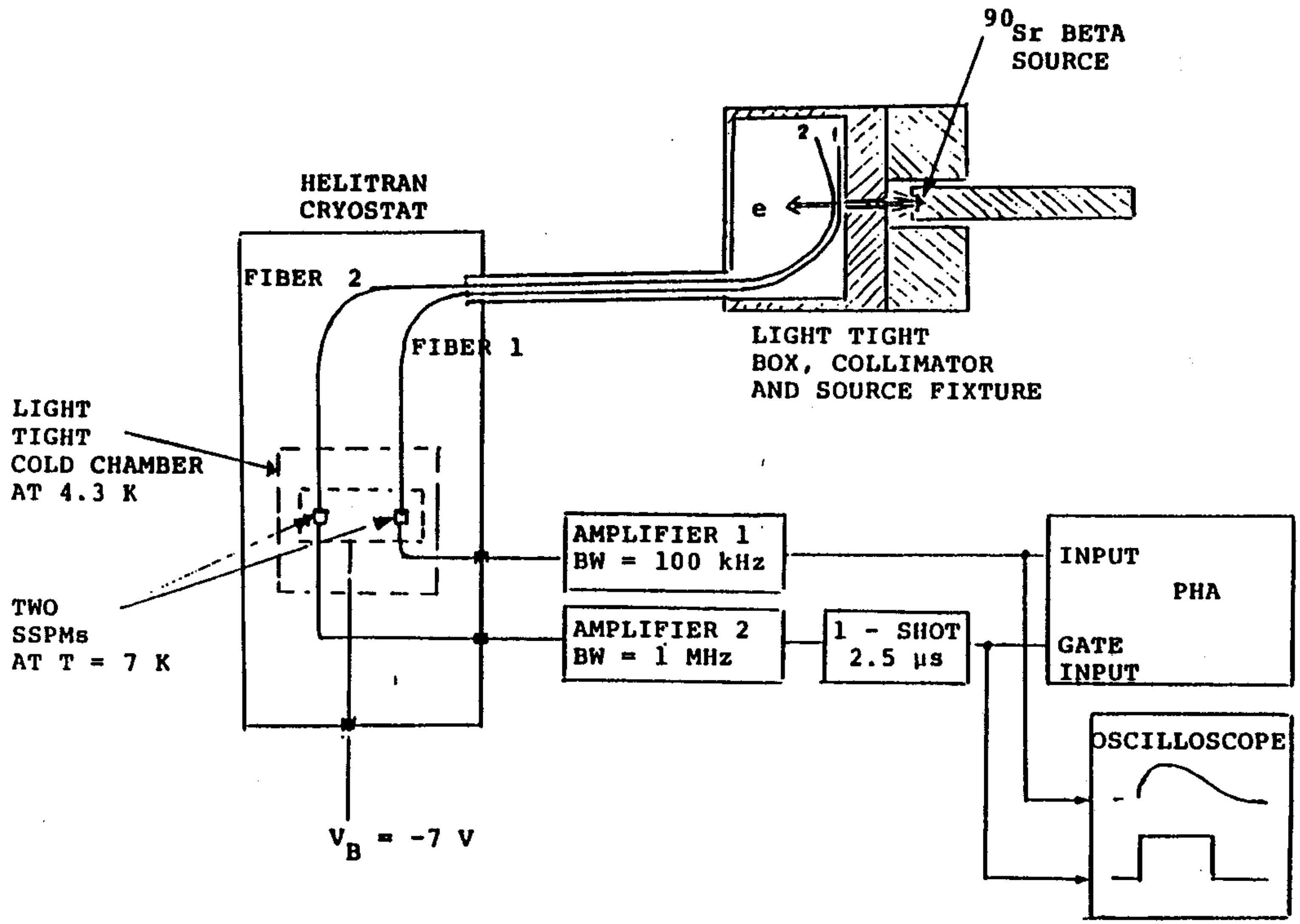

Fig. 2 Experimental Arrangement for Detection Of Fiber Scintillations

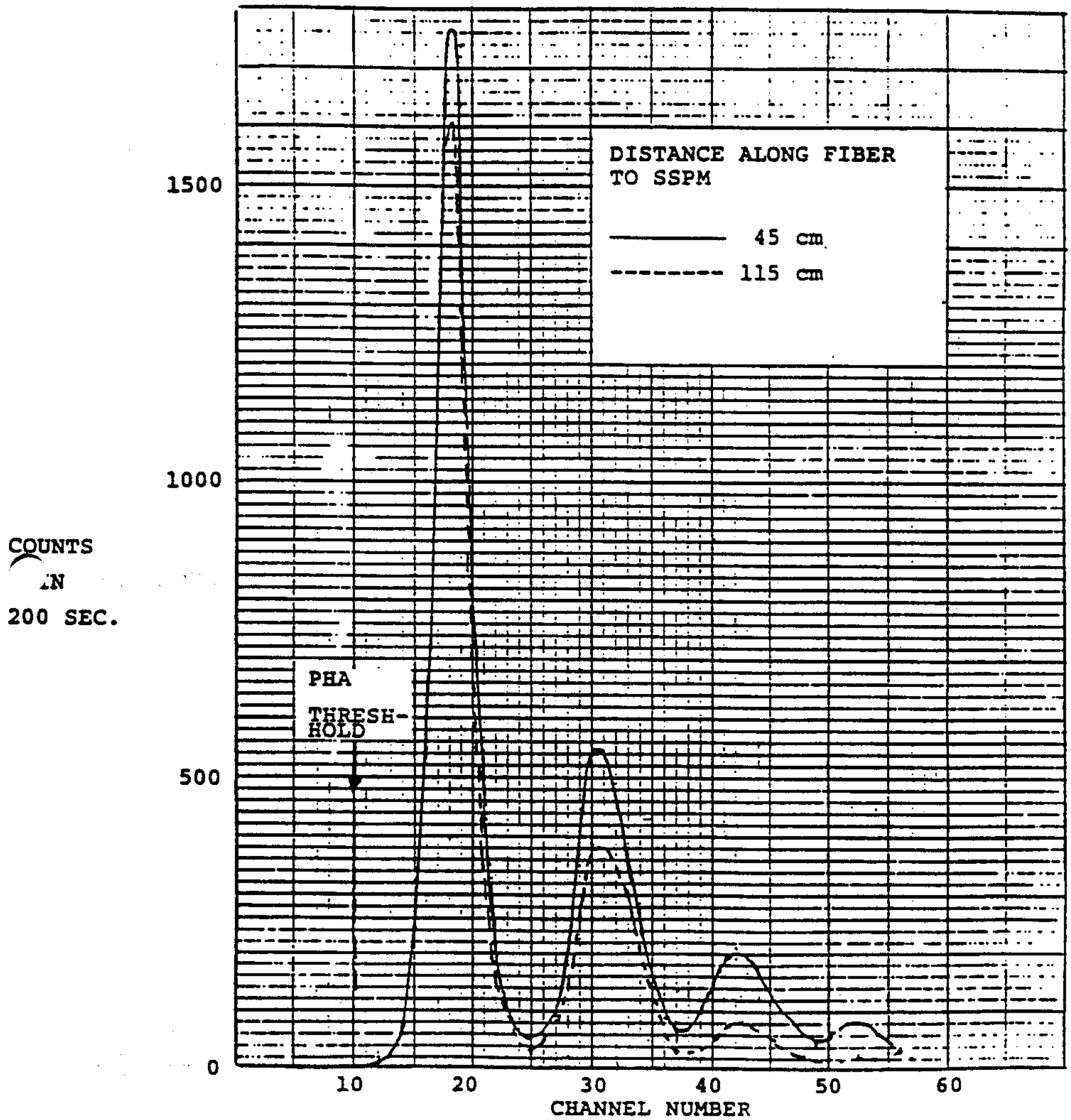

Fig. 3 SSPM Pulse Height Distributions for Fiber Scintillations at two Positions of Beta Beam

ORNL Involvement in Tracking Detector Subsystem for the SSC Using Scintillating Fibers

ELECTRONICS

Front End Preamp - Collaborate with UT Dallas on designing a preamp for the SSPM that operates at cryogenic temperatures. This collaboration will consist of design optimization with emphasis on low noise high speed systems drawing on ORNL's experience in nuclear instrumentation and in particularly recent work in VLSI CMOS analog high speed preamplifiers. Subsequent work is expected to include chip fabrication of prototype quantities utilizing MOSIS or other appropriate silicon foundries.

DAQ and Pattern Analysis - Data system design input structure will be predicated on the cooled preamplifier characteristics. This part of the system, however, is not planned to be in a cryostat but will operate at ambient temperatures. The architecture will be predicated on the ability to serve a "quick look" pattern system and a data storage system that can be extended until the third level trigger completion is accomplished for the entire detector system. While there is no plans for this prototype to experience a wait time equivalent to the third level trigger, the archecture should be able to eventually accept such a time wait with data integrity. A slaved sub-clock system will be synchronized with the system clock to provide the ability to separate distances along the fibers to approximately one meter or less to provide additional information to the "quick look" system. System clock for bunch crossing identification will be integrated in to this portion of the data system and will be provided into data storage in addition to each fiber's unique identification. Issues such as data sparsification and trigger generation will be addressed during this first phase of the project. The highest degree of integration practicable will be pursued for the data system for the purposes of speed, reliability and cost. Radiation hardening of the electronics maybe an issue in the final tracking system but will not be implemented in this test version. However, this issue of radiation hardening will be part of the overall philosophy such that future iterations in rad. hard processes will not cause major rethinking of the design philosophy.

Development of algorithms and circuit architectures for "in the neighborhood" or "in the vicinity of" track recognition to compact multiple fiber scintillations into localized track vectors within each superlayer will be accomplished for the "quick look" system. Strategies will be aimed at least course pattern recognition within the beam crossing times of 16 ns. Once established, these track vectors can be combined to provide a first-level trigger based on coincident local vectors created along a high momentum trajectory. The "neighborhood" chip architecture will be such that it operates on any location along the detector circumference combining a fixed matrix of processed fiber signals. These algorithms will be developed and implemented using MOSIS CMOS technology. The final design topology may be implemented using a faster technology such as 1 micron or less in CMOS.

RADIATION DAMAGE STUDIES

Photomultipliers and Electronics - ORNL has several facilities that could be used for neutron damage studies. Probably the most suitable for achieving very high flux and MeV energies would be the HFIR facility. There are also a number of neutron sources in the Laboratory with a suitable energy spectrum, although they would have a lower dose rate.

MECHANICAL DESIGN

ORNL participation in the mechanical aspects of this tracking system may embrace two or more logical parts. As you saw, the dimensional metrology via machine vision is a logical aspect. A second logical part is the composite materials development that has had 100s of Millions of DOE dollars poured in to already and is available. This material technology was developed for the ultra-centrifuge program for uranium separation. Very large structures that are extremely rigid and light weight (low Mass) certainly looks like an ideal candidate for the structural portion of this tracking system. We have looked at the dimensional tolerance and creep factors and it appears that a suitable support could be manufactured for this system. If this appeals to you, we would have to up the budget or put some of the other thing off perhaps for a year. The third aspect of this section would be the actual construction of one or more superlayers here at Oak Ridge.

Dimensional Metrology via Machine Vision Inspection

Our machine vision expertise is focused on image acquisition, processing, and system calibration techniques in demanding applications. A relevant application area has been systems for automated inspection during security document production. In these systems, image features must be spatially located to better than 20 microns. This requirement has been met through a careful application of optical and electro-optical components as well as innovative image processing algorithms. The real-time (production) nature of the inspection also requires the use of state-of-the-art pipelined image processing hardware. We propose to build on this technology to determine the positions within detector assemblies of small diameter (250 um) fibers. This will require an extension of the measurement from 2D to 3D. An understanding of the manufacturing process is also necessary to determine an appropriate design: in-process inspection, in-process acquisition of images with off-line processing, or off-line inspection.

CAPITAL EQUIPMENT - Most of the needed equipment such as CAD/CAE workstations are already in place, so no money is needed for major purchases.

PERSONNEL - Assignment of engineers to these tasks are expected to be ..
3 Electrical Engineers at 50% time
1 Mechanical Engineer 50% time.

ORNL staff member would be:
Hugh Brashear, EE
Hans Cohn, Physics
Mike Emery, EE
Mark Rennich, ME
Dick Todd, EE
Bill Zebrisie, Metrology

APPENDIX C

Data Acquisition Electronics for SciFi Tracking

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This proposal outlines an R&D program for converting signals from SciFi tracking detectors into digital information in a format needed in a multi-level trigger scheme.

I. Outline of SSC Detector

Figure 1 is the FAST SSC detector, showing the central tracker (SciFi), calorimeter, and muon chambers. Forming a first level trigger from the above elements will require about 1000 nsec [1]. Each of the elements involves > 100,000 channels of information. Issues concerning the tracker which require further R&D include:

a) power dissipation and space requirements of front and amplifiers and digitizing devices;

b) storage of information for 1000 nsec, while remaining sensitive to new information every 16 nsec; and

c) cost.

II. Central Tracker

Possible detectors for the central tracker include straw tubes [2], silicon strips [3] and scintillating fibers [4]. This proposal focuses on a scintillating fiber system, including up to 10 million fibers, each viewed by a SSPM [5] and yielding 10 million yes/no bits of information. We propose to develop the discriminator system which determines the presence and time of signals from the detector.

III. Signal Delay and Storage

Several possible schemes for delaying the data from the tracker have been discussed:

a), lumped delay lines on a chip;

b) a 67 MHz shift register [3];

c) gas/vacuum image delay tube using cold emission tunnel diodes to inject electrons into the gas/vacuum tube [5]; and

d) Plessy SAW (surface acoustic wave) delay.

Options which we consider viable for further R&D include:

a) design of 96-pin chip layouts of delay lines, shift registers, etc. with subsequent procurement in industry;

b) same as item 1), except collaborating with industry on initial layout work; and

c) construction of an image delay tube.

For purposes of the proposed R&D program, a variation of the shift register concept is used. In this application, a RAM memory is used as a FIFO, by indexing an address register, rather than shifting data from register to register. This scheme places the burden of high speed (16 nsec) on the address register only, rather than the individual data registers. This RAM/FIFO is a candidate for the item labelled "Level 1 Storage" in Figure 2.

The proposed setup for testing data delay electronics is shown in Figure 3. Signals from several phototubes are used to generate pulses with realistic time fluctuations. The data are stored in the VME card labelled "RAM" in the figure. The MVME147 microcomputer tests the accuracy of the storage system, by comparing with the time sequence of hits in the phototubes. The VME equipment prototype boards and components required for instrumenting the VME crate are requested in the attached budget.

Figure 4 shows the concept of the RAM storage. An address register, clocked every 16 nsec by a beam crossing signal, indicates the RAM address for the next set of data. A trigger is formed by delaying the signals from one of the phototubes for 16*60 = 960 nsec. The address for the event containing the trigger should be found by subtracting 60 from the address register.

Figure 5 shows part of a VME card layout for 12 of the 96 data channels. The ECL signals are converted to TTL, and buffered to a data buss. Four RAM's share a common data buss so that each RAM samples data at only 1/4 of the 60

MHz rate. A digital scope and multichannel logic analyzer scope are required to solve problems expected due to propagation delays in both the data buss and address lines. These devices are listed in the attached budget request.

Figure 6 shows an alternative FIFO system, based on the LeCroy MLL400. Data on the input lines are sampled at a rate of once every 4 nsec. The 4 meter length of a fiber corresponds to a time spread of 24 nsec, so a 4 nsec time sample corresponds to 1/6 of the length of a fiber. This redundant information is useful in matching the x, u and v segments of a track.

IV. Data Storage Hardware

The key element in the electronics is the storage device. Only low-power TTL devices have been considered since heat dissipation will be a problem with 10 million channels of data.

The most attractive device is the LeCroy MLL400, largely because of its track record in the TDC pipeline system. The redundancy afforded by its 250 MHz capability would be useful in the data compaction. These chips are difficult to manufacture, as the SOS (silicon on sapphire) technology is labor intensive. The Fairchild 74F213 RAM, depicted in Figure 5, no longer appears in catalogs. For testing purposes, the 74F219 with 4 inputs will be used as a substitute to sample the Schottky fast TTL electronics.

For initial tests we plan to use existing technology with standard connectors, VME crates and relay racks. A complete system for 10 million fibers would require 1000 relay racks to house the 100,000 VME cards required.

V. Data Compaction

At the time a level 1 trigger is formed, the data from the SciFi detector are in the form of N*10 million bits, where N is the number (2 or 6) of samples per event used in the FIFO memories. Since the data are sparse (<< 1% occupancy), a system based on the multiplicity of zeroes is used for data compaction [6]. Figure 7 shows a schematic of the wiring pattern, which is most efficient for the data compaction scheme. The 257,280 axial fibers in the fourth superlayer lie between the two circles. The large annular segments each contain the ~ 9600 fibers which can be stored in one relay rack containing 5 VME crates. The arrow indicated the size of a segment which corresponds to one VME crate. For an average event with 50 tracks crossing the downstream half of superlayer 4, the occupation density is 50/134 - 0.4 tracks per VME crate. Most VME cards will contain zero hits.

Figure 8 shows the hit pattern for the axial wire hits of a track segment. The 96 circles represent the 96 fibers on one VME card. The 8 crosses represent hits from the track segment. The hits do not appear perfectly aligned, since the fibers are laid out in a staggered pattern. In this example, the track has been deflected through 30 degrees, so that its hits are shared among 4 columns of fibers.

The information which must be passed on to the VME crate controller/microprocessor are indicated in Figure 8. The data can be compressed as follows:

a) a byte containing the flag information, 011110, which indicate the pattern of zero multiplicity words and data words;
b) two half bytes, containing the numbers "2" and "6", indicating the multiplicities of zero bytes; and
c) four bytes of data.

For the system employing the ML1400, an additional 2 bits are needed to indicate on which phase of the cycle the hits occurred.

The microprocessor needs to scan all 20 VME cards in its crate. The information which the microprocessor has to send to a central processor is compressed as follows:

a) the four data bytes;
b) four bytes, containing the subaddress (5 bits each) and time phase (2 bits) for each of the data bytes.

For a system of 5000 VME crates, with an average of 0.4 track segments/crate, the number of bytes which must be transmitted to a central processor is as follows:

# VME crates in SciFi system		5000
# track segments/VME crate		0.4
# bytes/track segment		8
	product:	16000 bytes,

or 128,000 bits.

For comparison, the FIFO memories contained 6*10,000,000 bits of information from each event. The compaction scheme reduces the number of bits by a factor of 60,000,000/128,000 - 469, so that only 16 kilobytes have to be transmitted from the local VME crates to a central processor.

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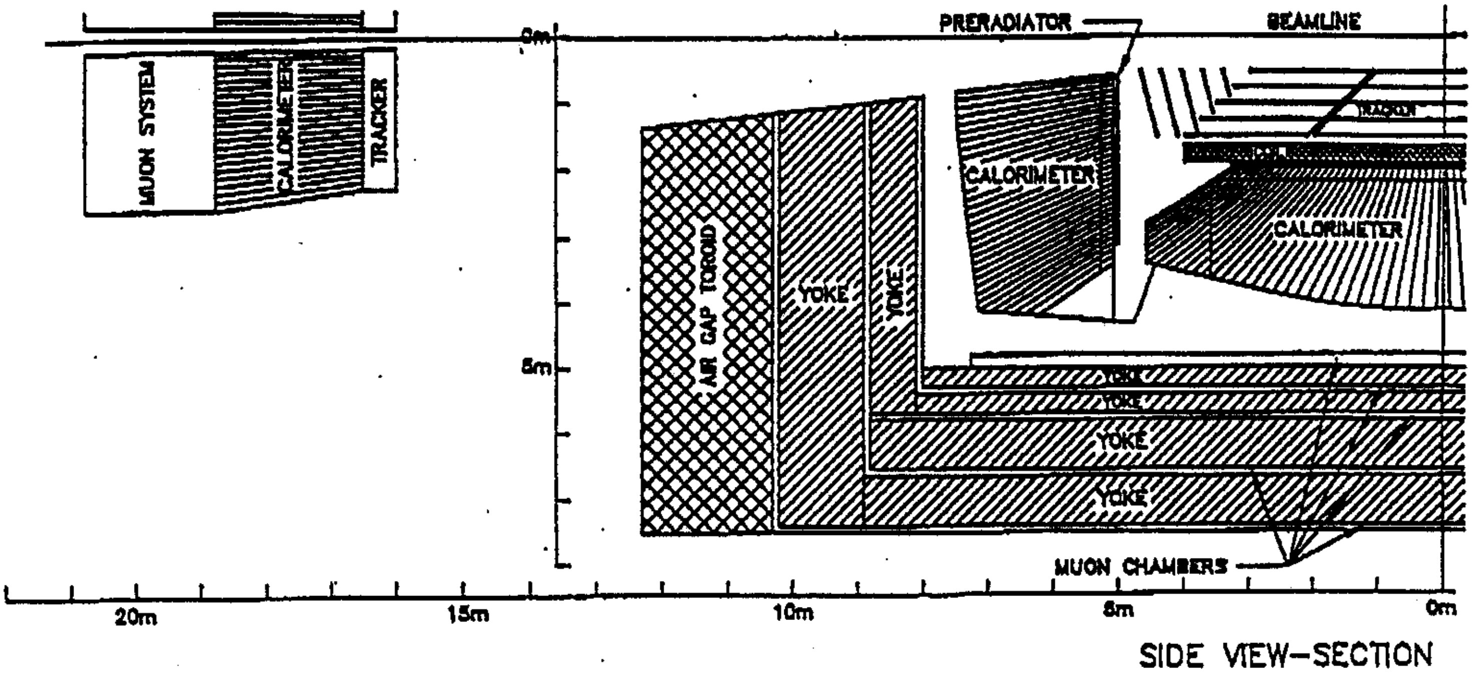

Figure 1

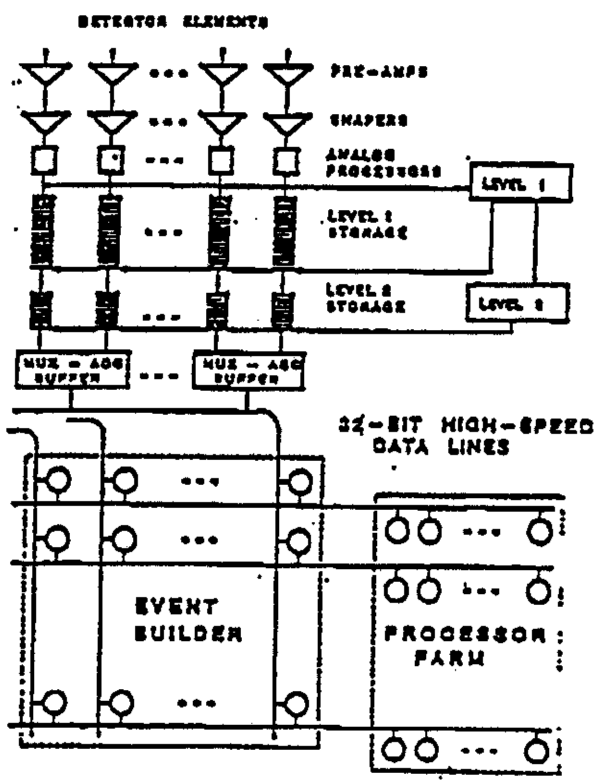

Figure 21
Schematic diagram showing the front end electronics, level 1 - level 2 buffers (primarily analog) multiplexer - ADC - digital buffer, event builder, and processor farm.

Figure 2

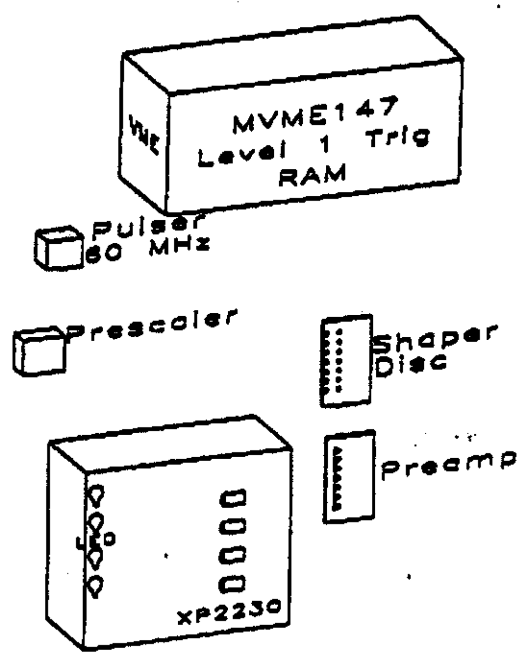

Figure 3

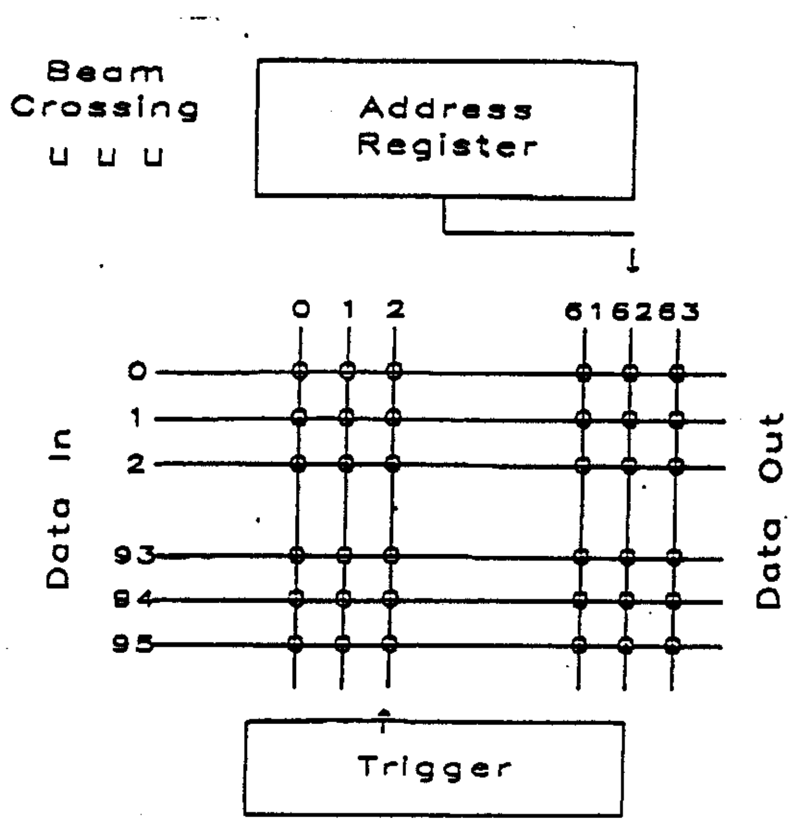

Figure 4

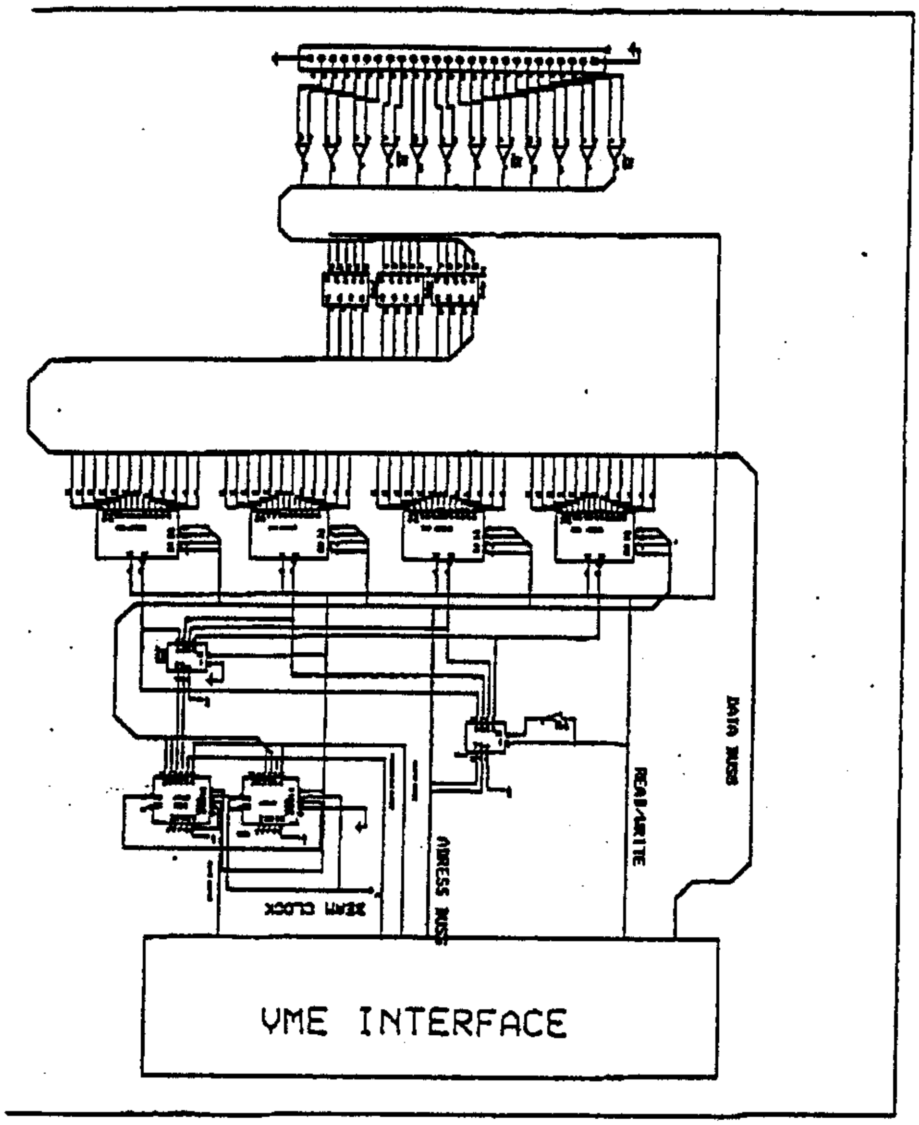

Figure 5

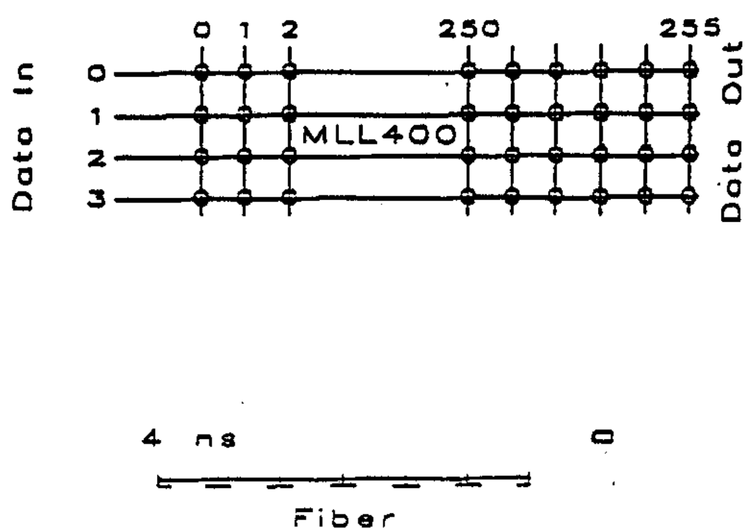

Figure 6

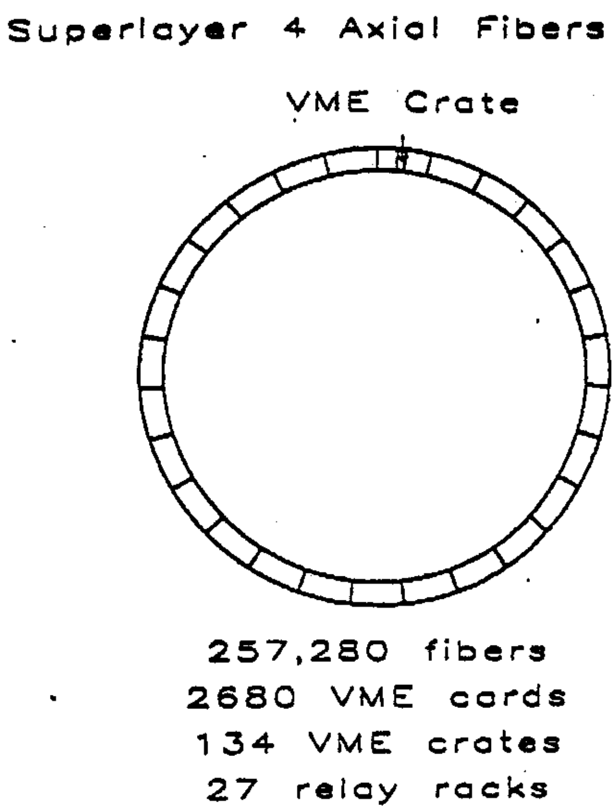

Figure 7

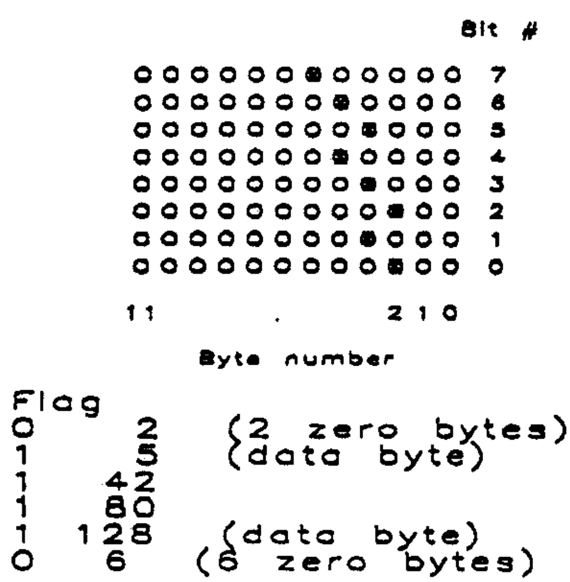

Figure 8