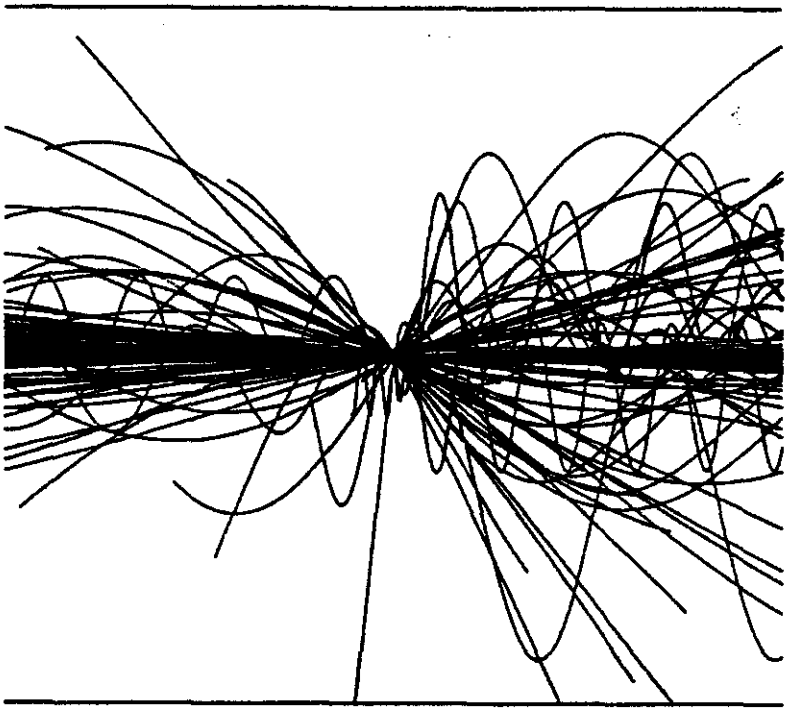
SSC PC-035
112 PAGES

A Proposal for Research and Development of

A Hybrid Central Tracking Chamber for the SSC

Submitted to

Physics Research Division
SSC Laboratory
2550 Beckleymeade Avenue
Dallas, TX 75237



Prepared by

Duke University
Florida State University
North Carolina State University
Northeastern University
Oak Ridge National Laboratory

Quantum Research Services, Inc.
RCA
Supercomputer Computations
Research Institute
University of Florida

September 1989

A Hybrid Central Tracking Chamber for the SSC

Abstract

We propose the construction and testing of a prototype hybrid central tracking chamber (CTC), which will be composed of both straw drift tubes and plastic scintillating fibers. This prototype will be of a size comparable to that needed for part of a CTC in an SSC detector. The main thrust of our investigation will be to establish a construction technique to produce a detector of low density that will be capable of measuring points on the trajectories of charged particles to precisions of σ (transverse) $\leq$ 200 μm and σ (longitudinal) $\leq$ a few mm. Our collaboration has the ability and resolve to carry out the mechanical design and fabrication, the electronics instrumentation, the radiation damage studies, and the complementary Monte Carlo simulations of the prototype detector. If this prototype design is successful, this effort could evolve into the construction of a complete CTC for an SSC detector.

A Hybrid Central Tracking Chamber for the SSC

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I. Executive Summary

A. Introduction

This report describes a proposal for the construction of a cylindrical charged particle tracking module that is large enough to be used as part of the central tracking chamber (CTC) for an SSC detector. The prototype superlayer, 1.4 m in diameter and 2.5 m in length, will use both straw drift tubes (4 mm in diameter) and plastic scintillating fibers (0.5 mm in diameter) as the detection elements. A major aspect of our research will be the determination of a construction technique that minimizes the density of the detector while attaining long term (>5 year) precision placement of the wires and fibers. Our collaboration has the manpower and fabrication facilities needed to construct and fully test the prototype detector. This will include the instrumentation of about 1,000 channels of readout electronics (front-end and digital storage) and an evaluation of the radiation hardness of the detector.

In addition to producing a prototype CTC superlayer, we will identify the fabrication facilities, commercial vendors and mass production techniques needed to construct a CTC containing many such superlayers. This aspect of our proposal will require detailed simulation of the detector's response to SSC events and a cooperative interaction with the design studies of complete SSC detectors.

B. Summary of Project Scope and Goals

Our proposal consists of a rigorous study of one important component of an SSC detector: a cylindrical superlayer for the central portion of a CTC ($|\eta| \leq 1.5$; $0.3 \leq r \leq 2.0$ m). A complete CTC would likely include additional end cap disks and a high resolution inner tracker. We specifically decided to limit the scope of our project, since the R&D needed for a complete evaluation of a cylindrical superlayer module is extensive. Our research program will make maximum use of ongoing generic R&D and will cooperate where possible with other SSC sub-system efforts. In particular, our detector will make use of readout electronics being developed at the University of Pennsylvania (contact person, R. Van Berg) and the design will be guided by extensive SSC detector simulation being carried out at the Supercomputer Computations Research Institute (contact person, M. Corden). We summarize below the major goals of the research we propose to carry out over the next 2 years (January 1990 to January 1992).

1. First Year (1990)

Straw Tubes

- Select tube and cathode material, anode wire, and candidate gases.
- Study electrostatic stability and fix required mechanical tolerances.
- Finalize end plate construction and feed through (engineering models).
- Study sense wire support techniques; finalize with engineering models.
- Construct engineering model with 100 tubes.
- Measure resolution, gas drift speeds.
- Study heat management via gas flow.

Mechanical Design, Fabrication

- Engineering evaluation of possible support structures for superlayer.
- Materials studies, selection for end plates and cylinder support.
- Study technique for fabricating carbon composite/scintillating fiber support structure (engineering model, d = 60 cm).
- Incorporate straw tube/scintillating fiber design results into prototype design.
- Incorporate Monte Carlo detector simulation into prototype design.
- Begin prototype mechanical construction.

Plastic Scintillating Fibers

- Investigate and optimize detector design and construction details. This is especially relevant in deciding between circular or square cross-section fibers and whether the detector planes are assembled from individual fibers or premanufactured fiber ribbon arrays.
- Invent and develop detailed quality control tests of fiber cross-section tolerance, photon yield, attenuation length and alignment precision.
- Demonstrate both the technical and economic feasibility of using avalanche photodiodes as the electro-optical link between the fiber detection and downstream electronics. Single channel tests.
- Investigate neutron and gamma radiation characteristics of fibers.

Electronics

- Design, fabrication and test of front end chip for straw tubes.

- Electrical design of straw tube end plates, PC board assemblies.
- Evaluation of single-element avalanche photo diodes (APD's) with scintillating fibers.

Radiation Damage

- Study ageing characteristics of candidate component materials.
- Conduct straw tube outgassing tests.
- Measure neutron spectrum in reactor beam tube and design irradiation cannister, with appropriate filters.
- Conduct series of neutron irradiations of individual components; components will be performance tested before and after irradiations.
- Conduct Co^{60} irradiation test of front end chips.

Simulation

- Study track-finding performance of proposed and alternative CTC designs. The final prototype superlayer design will be highly influenced by this simulation study.
- Study momentum and angular resolution for the reconstructed tracks.
- Evaluate hadronic background in CTC due to calorimeter albedo.
- Investigate the effects of structural materials and the materials in the straws and fibers themselves.
- Develop a simple CAD package to enter and check data and to create input files for the simulation codes.

2. Second Year (1991)

Straw Tube

- Instrument 10's of channels of the engineering model with front end analog electronics.
- Measure detector resolution.
- Measure effects of magnetic fields on performance.
- Compare and exchange results with Monte Carlo simulation.
- Install and test digital electronics when available.
- Install and string 1,000 straw tubes on full scale prototype.
- Beam tests of prototype superlayer (resolution, pileup, cross talk).

Mechanical Design, Fabrication

- Complete prototype mechanical construction.
- Measurements of mechanical precision and stability (including full sense wire load simulation).
- Design of multi-superlayer construction; use Monte Carlo simulation to optimize design; introduce constraints imposed by other subsystems of an SSC detector.
- Identify commercial vendors, design a mass production program and estimate the cost and time table for the construction of a complete cylindrical CTC detector.

Plastic Scintillating Fibers

- Continue APD feasibility tests for multi-channel arrays, both linear and two-dimensional.
- Investigate readout system packaging and interface with fiber arrays in the prototype detector.
- Begin beam tests of entire prototype detector system. Investigate stability and precision.

Electronics

- Design, fabrication and test of straw tube readout chip.
- Assembly and test of electronics for CTC prototype.
- Design and construction of instrumentation for beam testing.
- Design, fabrication and test of APD arrays.
- Construction and test of APD-based fiber readout prototype.

Radiation Damage

- Complete ageing studies of individual materials.
- Conduct integrated X-ray and electron effects studies on radiation testing model.
- Complete neutron irradiations of individual components; both flux (rate) and fluence (total) effects will be investigated.
- Irradiate radiation testing model to $\sim 10^{13}$ neutrons/cm^2.
- Conduct neutron and Co^{60} irradiations of final electronics chips.

Simulation

- Study vertex resolution and multiple beam crossing effects.
- Integrate calorimeter albedo effects into GEANT simulation code, and evaluate effects on tracking sensitivity and resolution.
- Incorporate simple CAD data input and checking package.
- Use various performance measures to evaluate final design; determine and monitor calibration constants.

C. Organization of Proposal

This Executive Summary and Section II (conceptual design of the prototype module) provide a concise overview of our proposal's scope and goals. Section III presents a review of some previous R&D relevant to the construction of our prototype module. Rather than reproducing a complete survey of the literature, we concentrate on R&D work done by members of our collaboration.

The more technical details of the hybrid CTC's construction and evaluation are presented in Sections IV through VII. These are divided so that a reader interested in a particular subject can read one section in a fairly self-contained manner. The mechanical design and fabrication studies are intimately connected with the straw drift tube and scintillating fiber installation. These are all described in Section IV. The electronics design and fabrication is described in Section V. Radiation hardness measurements are discussed in Section VI. The Monte Carlo simulations that are needed to guide the prototype design are summarized in Section VII. Finally, we briefly describe anticipated test beam needs in Section VIII.

D. Overview of Collaboration

Our collaboration was formed with the intent of making use of ongoing generic R&D and where desirable, forming cooperative liaison with other groups that will be submitting subsystem proposals. This allows us to make maximum use of the manpower that will be committed to this proposal. In the summary given below, cooperative liaisons are contained within brackets [ ]. Only senior collaboration members are listed here. For more details see Appendix A.

Research Area	Collaboration Members
Straw tubes	Duke; A. Goshaw, S. Oh, W. Robertson [SLAC; J. Va'vra]
Scintillating Fibers	NU; S. Reucroft, G. Alverson, B. Faissler, D. Garelick, M. Glaubman, I. Leedom
Electronics	NCSU; J. Paulos ORNL; H. Brashear, M. Bauer RCA; R. McIntyre [U. of Penn; R. Van Berg]
Mechanical Design and Fabrication	ORNL; M. Rennich Duke; A. Goshaw, S. Oh, W. Robertson
Radiation Hardness	UF; S. Majewski, C. Zorn QRS; B. Dunn, F. O'Foghludha FSU; V. Hagopian [LBL; J. Kadyk]
Monte Carlo Simulation	SCRI; M. Corden QRS; B. Dunn, A.M. Yacout ORNL; T. Gabriel, C.Y. Fu

The project will be coordinated by Drs. Goshaw (Director) and Reucroft (Deputy Director) through an Executive Committee that has representation from each institution. All of the participating organizations are committed to the proposed research and will actively participate in performing the R&D. Each organization brings unique capabilities to the project, and the collaboration was carefully structured not only to incorporate all relevant technical areas but also to assure efficient and constructive coordination of effort.

II. Conceptual Design of a Hybrid Central Tracking Chamber

In this section we present an overview of our proposed tracking chamber module and discuss its application to a complete central tracking chamber (CTC) for an SSC experiment. Key elements in this design include attempts to optimize the advantages offered by straw tube drift cells and plastic scintillating fibers with the ultimate goal of constructing a complete CTC that is both reliable and affordable. To set the stage for this discussion, we summarize in Table II-1 some general requirements of a CTC that would be part of a large, general-purpose SSC experiment. Details will depend on the particular detector, but it is clearly necessary to establish overall design parameters even at the stage of constructing a prototype.

A complete description of the mechanical fabrication, electronic instrumentation, radiation damage measurements and Monte Carlo tracking/pattern-recognition studies are given in Sections IV to VIII. An overview of previous relevant R&D work performed by members of this collaboration is given in Section III. The discussion below gives a brief description of the proposed prototype module, describes the rationale for combining straw drift tubes and scintillating fibers and comments on the potential of this module for meeting the CTC design goals described in Table II-1.

A. Overview of Proposed Hybrid CTC Module

We propose the construction of one cylindrical straw drift tube/plastic scintillating fiber superlayer of a suitable size for use as a component for the CTC of an SSC experiment. Figure II-1 shows the dimensions and basic components of the superlayer module. The inner cylinder has a diameter of 1.4 meters and the module's active length will be at least 2.5 meters. Our design integrates scintillating fiber layers into the cylindrical structure needed to support the end plates for the straw tubes. This construction uses an inner carbon-fiber cylinder to support six layers of scintillating fibers (0.5 mm diameter). These layers would provide both structural strength and u-v-z planes for high resolution point measurements as described below. A second carbon-fiber cylinder will be wound on top of the scintillating fibers.

Table II-1.

Overview of Design Goals for an SSC Central Tracking Detector

• Spatial region to be covered	$0 \leq \varphi < 2\pi$
	$r_\perp$ from ~0.3 m to ~2 m
	$\lvert\eta\rvert$ 0 to ~ 1.5 (cylindrical shells)
	1.5 to ~ 3.0 (end caps)
• Point measurement resolution	$\sigma_x, \sigma_y \leq 200\ \mu m$
	$\sigma_z \leq$ few mm
• Sensitive to all beam crossings	(16 ns hit resolution)
• Good pattern recognition capability	($\leq$ 10% cell occupancy)
• Radiation hard	(up to a few Mrad for $r_\perp \geq 30$ cm)
• Low density construction	(minimize secondary interactions, photon conversions, and multiple scattering)
• Simplicity of mechanical and electrical construction	
• Fail-safe operation	
• Affordable cost	($\leq$10% of full SSC detector cost)
• See Section IIC for a discussion of momentum measurement capabilities	

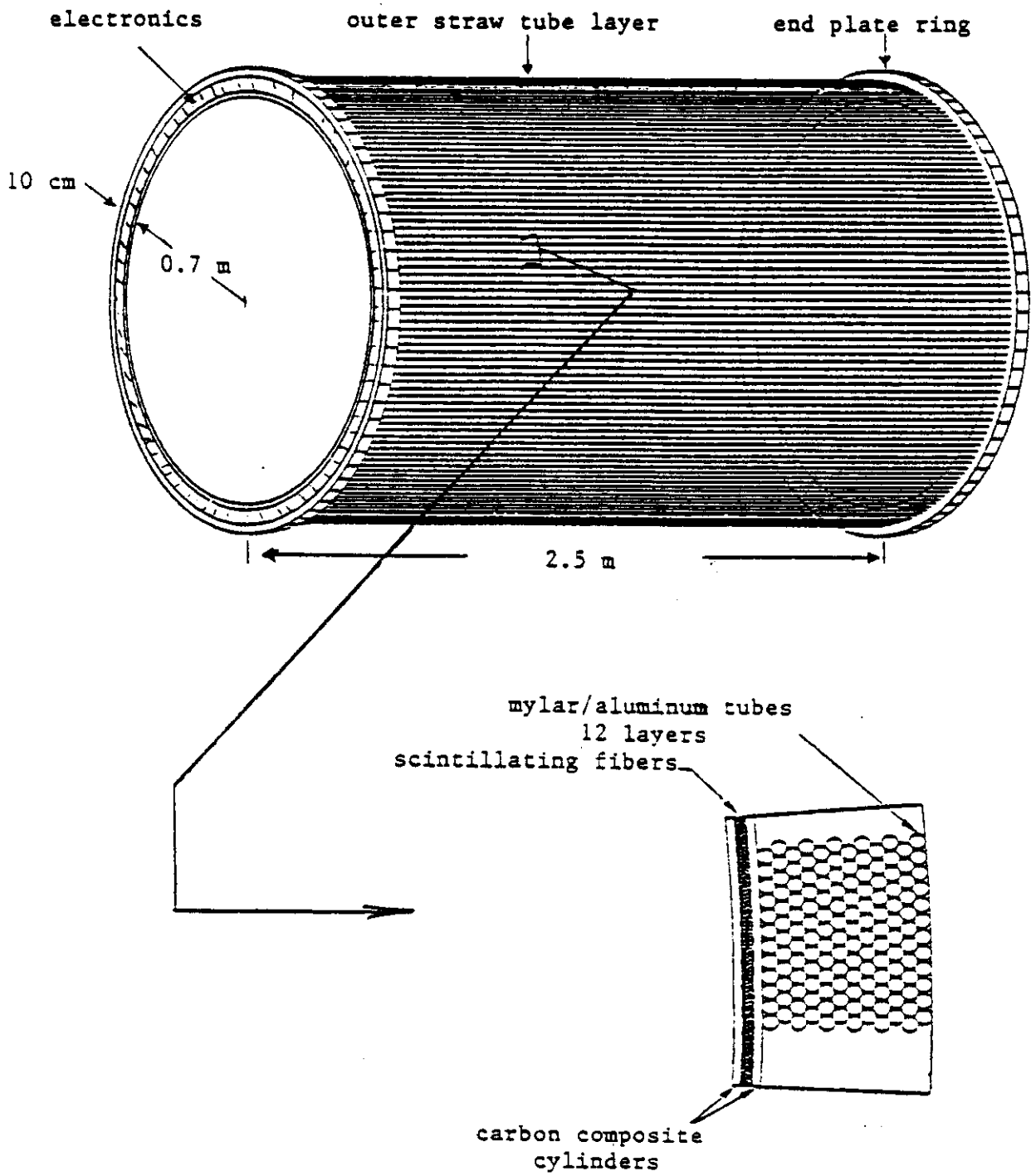


Figure II-1. Overview of Prototype Superlayer Showing Cross-Section Construction

The straw tubes, 4 mm in diameter, will be stacked into twelve interlocking cylindrical layers which use the carbon-fiber cylinder as a base. This layer would provide the ability to measure charged particle track segments accurately in the r, φ plane as required for momentum measurements using an axial magnetic field. The line segments would be 4 cm long and allow extrapolation to adjacent superlayers as an aid in global track pattern recognition. The inherent accuracy of the straw tube point measurements is better than 100 μm. A major thrust of our proposal is to determine if this precision can be maintained in the fabrication of a large module.

Figure II-1 also shows a cross section of the detector superlayer detailing the straw drift tube and scintillating fiber structure. The details of our design will be optimized by Monte Carlo simulation and may change from those described here.

The complete superlayer would contain 13,700 straw tubes and 53,000 scintillating fibers. The scintillating fibers may be grouped in triplets making the number of electronic readout channels comparable for straw tubes and scintillating fibers. In our prototype, we propose to install and fully instrument (electronics and gas) 1,000 straw tube cells clustered in two groups positioned 180° apart. The effects of the missing sense wire load will be simulated by an array of tension cables. All 53,000 scintillating fibers will be installed in the support cylinder, although only about 1,000 channels will be instrumented for electronic readout.

In order to obtain high precision wire location, our module uses single end plate rings which will contain holes for the sense wire feed throughs. The plate is slotted to allow access to the scintillating fibers. The gas manifold and readout electronics will be integrated into the end plate support structure (see Figure II-2). We mention here that the problem of sense wire sag and other misalignments causing electrostatic instability within straw tubes requires careful study. We will use generic R&D results from work being done at Duke, by Va'vra at SLAC and by Ogren at Indiana University to guide our prototype design (see Section III for more details). One option is to include thin, precision drilled mid-plates to fix each wire location to the same accuracy as that provided by the end plates. This solution has the potential for attaining higher accuracy in sense wire location than one which relies upon the straw tubes for support. As described in Section III, we plan to use a small model to study support techniques and will select the solution which is the best compromise between wire location accuracy and detector mass.

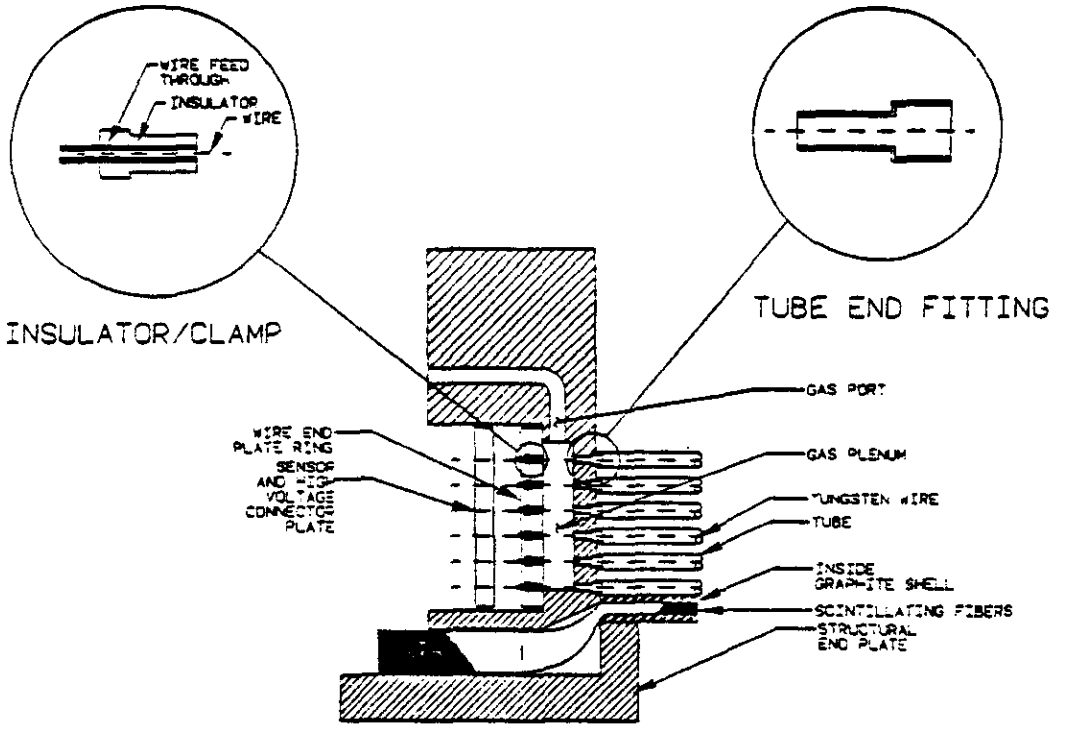


Figure II-2. Superlayer End-Plate Structure

We have considered several methods for z measurement of track trajectories. The first, charge division along the sense wire, will not be used in our prototype. Having made this decision, we can use non-resistive sense wires – gold plated tungsten (Au-W) – and place all the readout electronics on one end of the detector. This has three advantages: Au-W wire has good strength and wire aging properties; the TDC readout electronics are simple and relatively inexpensive; and a module with readout on only one end offers the possibility of assembling a long CTC (~6 m) by placing two adjacent cylindrical modules back to back.

Another option for z measurement is to use small angle stereo straw tubes tangent to the outer surface of the superlayer midway along its length. In this geometry, the straw tubes no longer have a simple packing geometry, since the stereo tubes fan out to the end of the module. Although this method of z measurement has some attractive features (low density, simplicity of readout electronics), we have decided to propose for our prototype module a scintillating fiber u-v-z layer.

The scintillating fibers would be 0.5 mm in diameter and layered within the cylindrical support structure as described above. The u-v layers (each two deep) will be wound in helices with close packing of the fibers. The z resolution is controlled by the pitch of the helix. For example, a ±6° pitch would result in a z measurement to $\sigma \sim 1.5$ mm. This method of z determination is geometrically compact and hermetic, and has the potential for relatively high z-measurement precision. We propose to add a third z layer (two deep) of fibers to help with calibration of the superlayer.

B. Advantages of a Hybrid Straw Drift Tube-Scintillating Fiber Detector

The construction of a CTC superlayer from both straw drift tubes and plastic scintillating fibers provides the opportunity to emphasize the strengths and minimize the weaknesses of each detection method. A disadvantage of long, small diameter straw tubes is the tedious mechanical construction required to insure accurate wire location. A practical disadvantage of using scintillating fibers for a large volume detector is the requirement of a prohibitively large number of readout channels. Our hybrid detector uses straw tubes in the simplest geometry (axial straws) to minimize construction difficulties and maximize their potential for precise r-φ measurements. The 12 deep layers we propose will define 4 cm line segments. This is not possible, with acceptable cost, using scintillating fibers. On the other hand, scintillating fibers are ideal for providing stereo u-v measurements since they can be helically wound onto a cylinder. In addition, scintillating fibers can be positioned in the detector to high absolute precision (<1 mil). We propose to use a layer of axial fibers to provide a calibration for the straw tube sense wires.

The common advantages of straw drift tubes and scintillating fibers are preserved in our hybrid detector. The inherent point measurement accuracy of the 4 mm diameter straw tubes and 0.5 mm diameter scintillating fibers is fairly well matched (100 to 150 μm). Both detectors have good single-cell hit isolation. Although the scintillating fibers require a photon-electron transducer, we propose to use the same subsequent readout electronics (see Section V). This will simplify the detector electronics and lower the per channel cost.

C. Application of the Hybrid Tracking Module to an SSC Experiment

The CTC of an SSC detector could be constructed from a set of hybrid modules similar to our prototype. A set of 10 superlayers covering a radial distance from 0.5 to 2.0 meters would be capable of measuring momentum to an accuracy σ_p/p of about 0.30 p (TeV). This uses a 2 Tesla axial magnetic field and assumes that we can achieve a point setting

precision of ~150 μm. It does not use vertex constraints or the benefits of a high resolution inner tracking chamber. Two modules, each of length 2.5 meters, in series, would cover a rapidity range $\eta < 1.05$ (outer ring), 2.3 (inner ring). Tracking at higher rapidities would require the use of end cap disks.

It may not be necessary to instrument all 10 superlayers with 12 layers of straw tubes and 6 layers of plastic scintillating fibers as will be done for our prototype. Lower density modules could be constructed by replacing the scintillating fibers with syntactic foam or an aluminum honeycomb between the carbon-fiber cylindrical shells. This would reduce the thickness of a superlayer from 2.4% to about 1.9% of a radiation length. The radiation length quoted above is an upper limit of our design (i.e., conservative). The radiation length will likely get smaller once we understand the mechanical strength of straw tubes, which can provide some structural support (see Section II.A). Any further reduction in the density of a superlayer would require external support for the end cap plates rather than the self supporting structure incorporated in our design.

As a part of this proposal we will simulate SSC events and determine the optimum configuration of superlayers to be used in a CTC. This will include a study of the compromise between a low mass density detector and one which provides a high point measurement density for good pattern recognition (see Section VII for more details). In the second year of this R&D work we would anticipate an interaction with specific SSC detector proposals in order to optimize the CTC design for a particular experiment.

III. Review of Previous R&D

Straw drift tubes have been used for charged-particle tracking for many years. Scintillating fiber technology is more recent, but has recently been implemented in major detector systems. Although the unique characteristics of the SSC environment call for significant advances in central-tracking technology, there is no *a priori* reason to believe that these advances cannot be accommodated through the use of straw tubes and scintillating fibers. In the following, we review recent work in straw chambers, scintillating fibers, read-out electronics, and radiation damage testing; for the sake of brevity, we concentrate on work in which the applicants have been involved.

A. Straw Drift Chambers

The high energy physics group at Duke has been working with chambers made of straw tubes since 1984. The project started in order to construct drift chambers for the spectrometer arm of experiment E735, one of the collider experiments at Fermilab. The chambers were constructed from 5-cm diameter straw tubes whose wall thicknesses were 0.2 mm. The chambers were successfully constructed, tested, and installed at the experimental area. We took data for two different running periods in 1987 and in 1988-89 without any problems. In this section, we will discuss ongoing research on straw drift chambers using both large-diameter tubes and the small-diameter (4 mm) tubes that will be used for the proposed chamber [III-1,III-2].

1. Study of Tube Material

The selection tube material is very important. The thicknesses of both the tube wall and its inner conducting layer have to be minimized because a track is expected to traverse at least 100 straw tubes. In order to keep the total radiation length of the straw tubes in a complete CTC below 10%, the wall thickness should be less than a few mils, if mylar or a similar material is used. Presently, two materials, mylar and polycarbon plastic, are being considered. Tubes made from each material will be subjected to various tests, such as pressure, compression load, and radiation hardness, before the final decision on tube material is made.

As an inner conductor material, we are testing aluminum and copper of different thicknesses. In the Fermilab detector, we have used aluminum with 15 μm thickness.

Although we did not encounter any problems, we would like to try optimized thinner coatings, down to a few thousand angstroms of copper or aluminum. The effect of ion bombardment on such a thin coating was found to be important in past studies, in some cases leading to disappearance of the conductive layer. Extensive tests of this effect will be performed in different working gases.

2. Wire Support

Since it is expected that the full size detector will be several meters in length, the sense wires have to be supported for mechanical and electrical stability. Calculation shows that 1.5 meter long, 25 μm diameter tungsten wire sags about 100 μm at the center. The wire sag causes two problems: first, position measurement error increases (although it can be corrected by off-line software), and second, electrical instability can move the sense wire toward the cathode and cause arcing.

Although the final wire displacement can be calculated for a given initial displacement, tension and electric field, we decided to verify the calculation by setting up an experiment. We measured the final sense wire position as a function of high voltage applied to the sense wire for a given initial displacement and wire tension. The initial displacement could be due to wire sagging from gravity or due to misplacement of the tube with respect to the sense wire.

In order to measure the displacement, we set up three long parallel wires, which approximate the electrostatic problem of a wire inside a tube. In this setup, the wire in the center is the sense wire, and the outside wires simulate the image charge in the tube. We measured the final wire position for a different initial wire displacement from the center as a function of the tension in the sense wire and the applied voltage. The data were obtained using wires with 1.2 m length and a simulated tube diameter of 5 mm; the tension in the wire was 50 gm. We plot in Figure III-1 the displacement as a function of the potential difference between the sense wire and the image wires for a preliminary test.

Another test is being performed using two aluminum tubes. One has a length of 1.25 m and the other of 2.1 m; the diameter of the tubes is 4 mm. The straightness of the tubes and their uniformity of diameter are better than 100 μm. 50 μm sense wires are centered inside the tubes. For a given tension in the sense wire, we measure the maximum voltage on the sense wire when the tube is in a vertical position and a

horizontal position. This test and the test with three parallel wires should tell us the effect of sagging and how often wire support is necessary.

3. Mechanical Strength of Tubes

One of the advantages of using straw tubes is that the tubes can provide some structural support. The larger diameter straw tubes used in the E735 detector can support about 10 kg of load at the end, even with a wall thickness less than 0.2 mm. Presently, we are systematically testing the effect of bunching many straws together to find out, for example, the increased end-loads that can be supported by gluing 10 or 100 tubes together, as a function of tube diameter, wall thickness and length. We shall also study the bending of small-radius tubes as a function of their length and wall thickness, and of the number of tubes glued together. The findings from this study will be incorporated in the mechanical design of the chamber. For this test, we have purchased 180 cm long tubes with 4 mm diameter, made of 50 μm thick mylar.

4. Drift Velocity and Dispersion Measurement

Due to the short bunch length in SSC, the gas used in the chamber should produce a fast electron drift velocity, something over 100 μm per nsec. We have made a simple setup (Figure III-2) to measure the drift velocity of any gas. It consists of two slits (1 mm wide and 1 cm long) and a straw tube drift chamber sandwiched between the two slits. A Sr^{90} beta source is used for the beam. We measure the relationship between the drift distance and the drift time, and from it, we calculate the electron drift velocity as a function of electric field. Some of the results are shown in Figure III-3. Mixtures of CF_4 with CH_4 produce a desirable drift velocity. Studies by other groups have shown that mixtures of CF_4 with isobutane and DME combine excellent diffusion and quenching properties necessary in small-diameter tubes with a high electron drift velocity.

Using this setup, not only the drift velocity, but also the relative dispersion (due to the slit size and the multiple scattering of electrons), can be measured for different gases. In Figure III-4, the dispersion is plotted as a function of drift distance for different gas mixtures. The slit size is 1 mm, so the expected dispersion is about 0.5 mm. Figure III-4 shows that the dispersion of pure CF_4 is poor. Mixing with CH_4 improves the dispersion. It may be necessary to mix more than 50% of methane to obtain an adequate resolution.

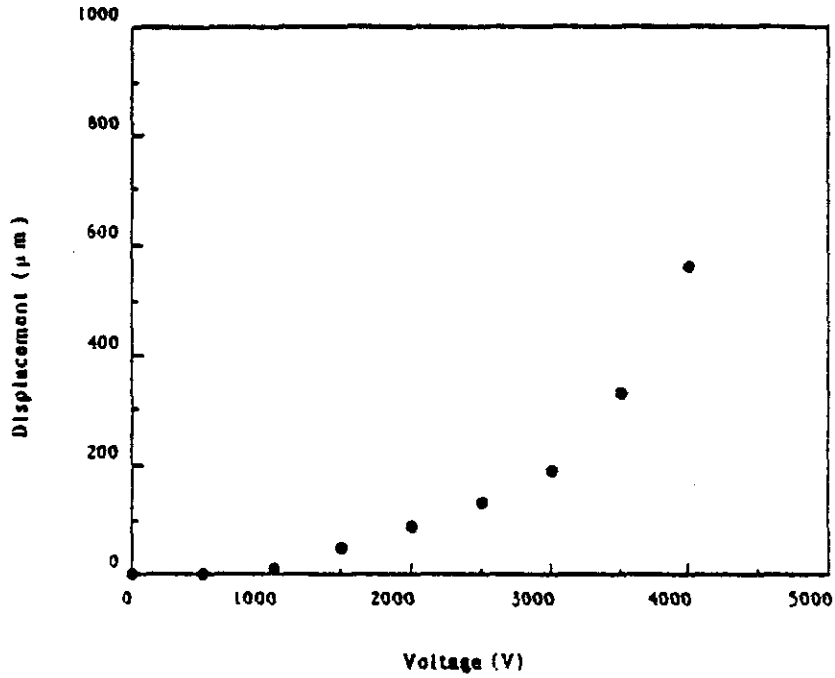


Figure III-1. Displacement of Central Wire Under 50-gm Tension as a Function of Applied Voltage In a 3-Wire Setup

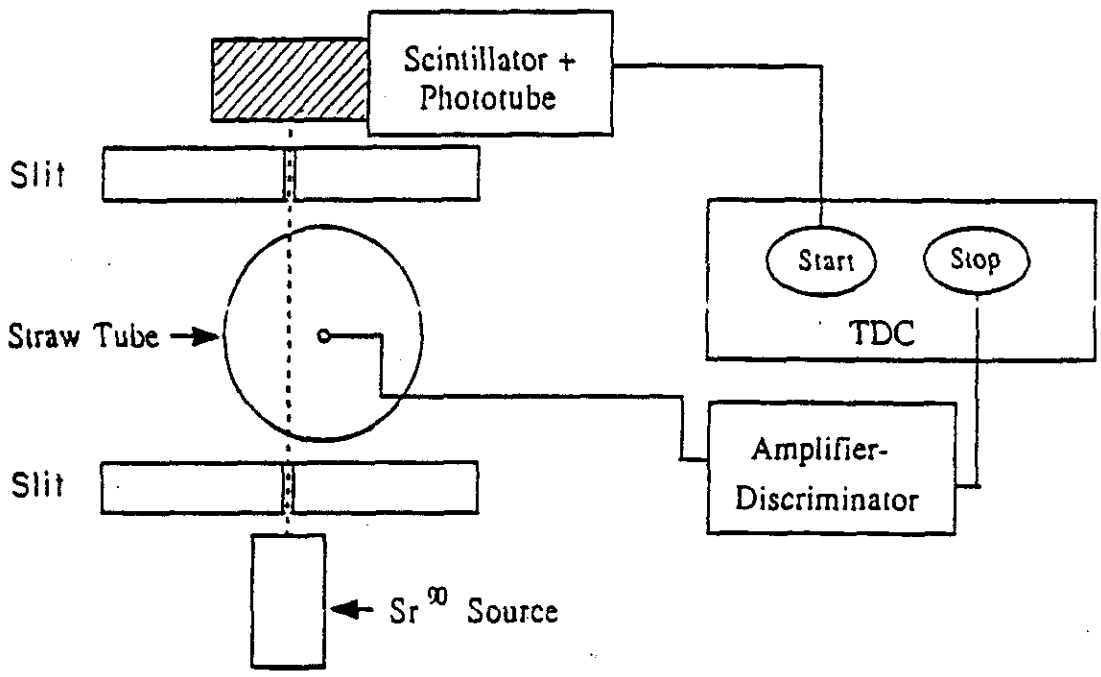


Figure III-2. Gas Drift Velocity Measurement System

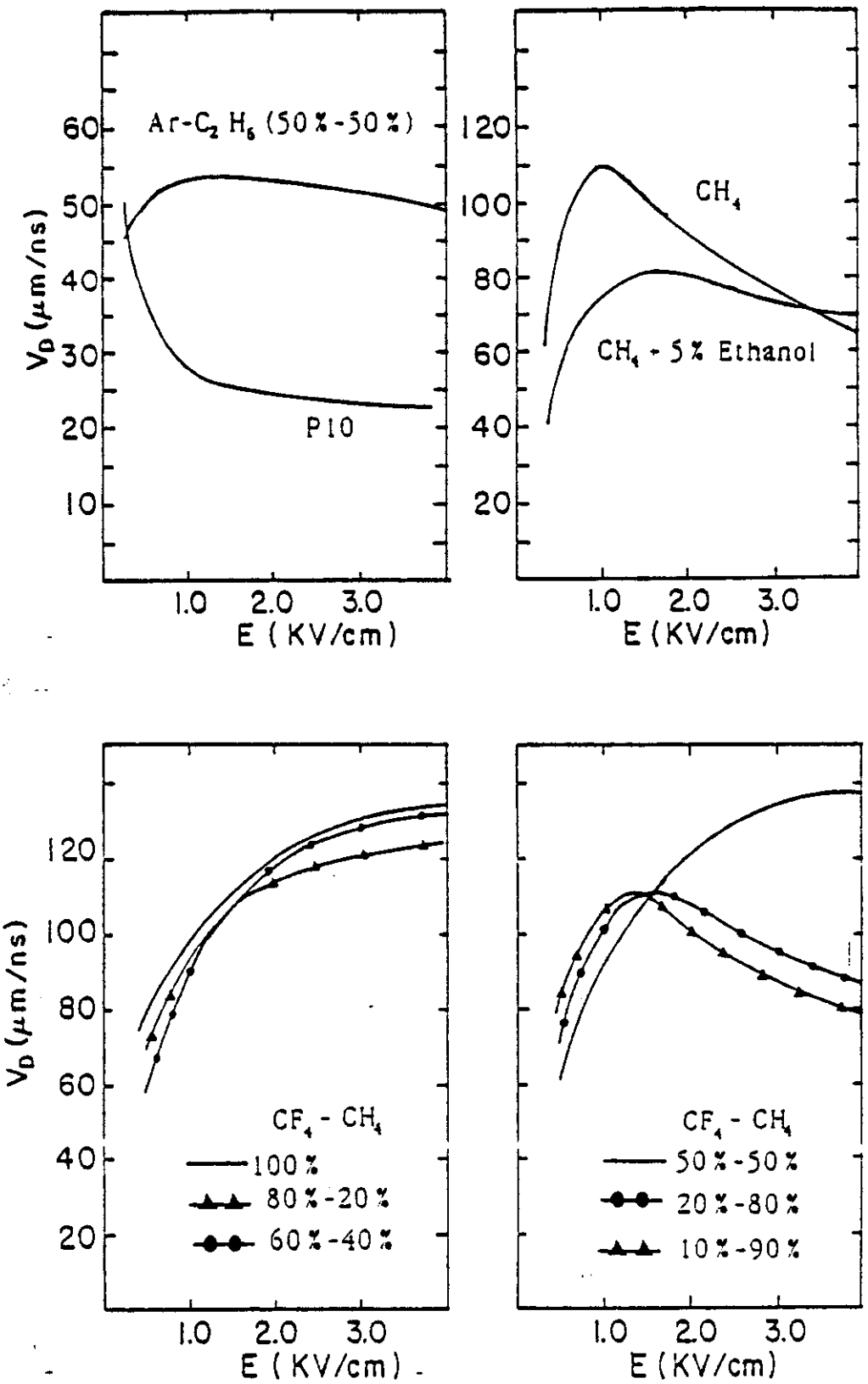


Figure III-3. Drift Velocity Variation with Electric Field Strength for Various Gases

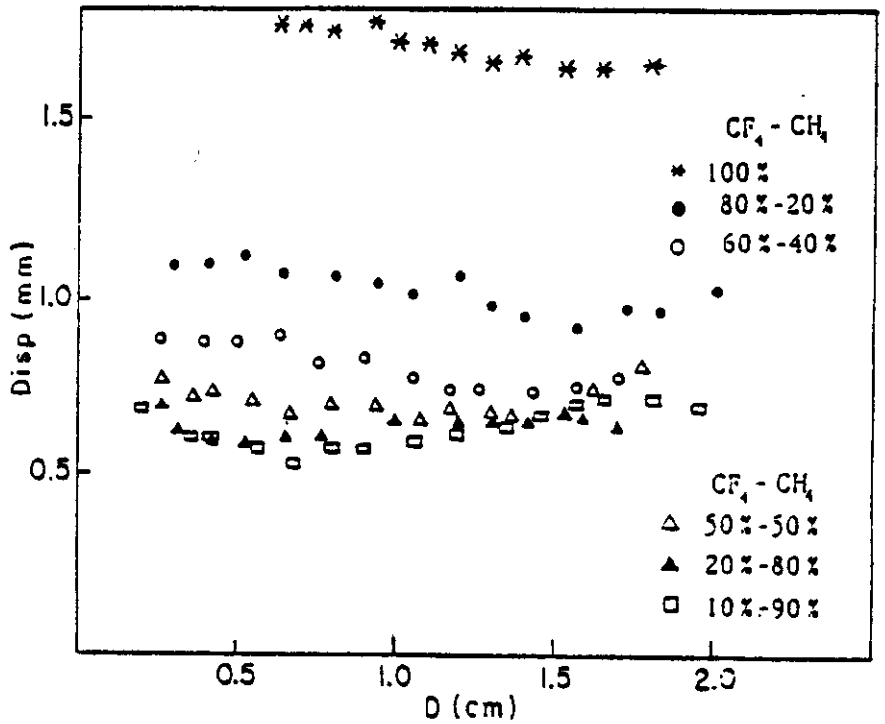


Figure III-4. Dispersion Curves for Various Mixtures of CF_4 and CH_4

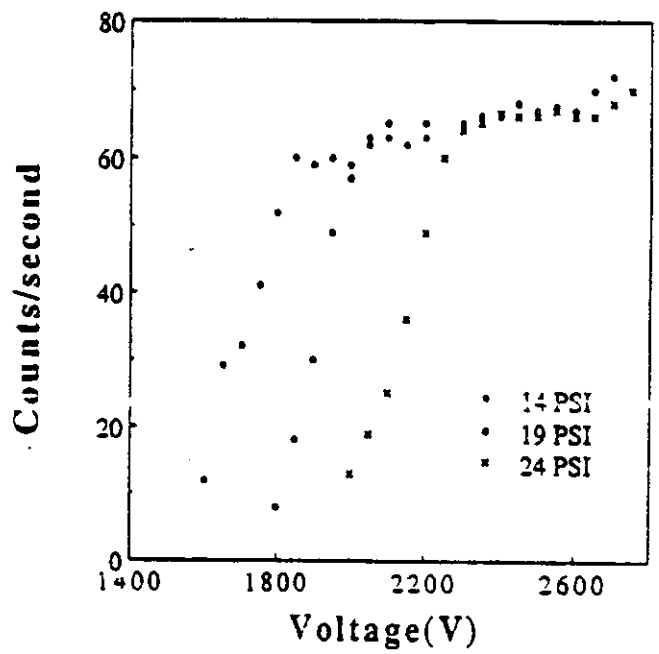


Figure III-5. Count Rate Versus Voltage Curves for CH_4 at Different Pressures

We shall continue to study different mixtures of gases to discover the greatest electron drift velocity with least dispersion.

Another area we are investigating is the effect of an external magnetic field on drift velocity, which is important because the final chamber will be operating inside a solenoid. This measurement will be performed with the setup shown in Figure III-2; a powerful pulsed laser will be used instead of an electron source to simulate tracks. A small chamber with a 6 mm diameter tube is being constructed. This chamber will be placed in a high magnetic field up to 2 Tesla along the perpendicular to the field. We will measure the electron drift velocity as a function of magnetic and electric fields.

5. Resolution Study

We also constructed a one-tube chamber using a 4 mm diameter tube with a 25 μm sense wire. We obtained plateaus at several different pressures using pure methane. The result is shown in Figure III-5. The signal amplitude is about 25 mV on 50 ohm at the center of the plateau, with a rise time of about 4 ns.

In order to study the intrinsic resolution of the chamber, we have just constructed a small chamber which consists of 8 tubes each 4 mm in diameter and 10 cm long. Due to its small size, this chamber can be constructed with high precision. The chamber is being instrumented with the same electronics used for the E735 chambers. Using Lecroy TDC with 50 psec resolution, we plan to measure the intrinsic resolution using cosmic rays. The chamber will be tested using different gas mixtures, including the fast gas whose drift velocity we measured. Earlier studies (using large diameter tubes) show that there is a degradation of the resolution very near the sense wire (within 300 microns) for some gas mixtures.

B. Plastic Scintillating Fibers

Most of the work reported in this section has been supported by DoE Grant DE-FG02-85ER40233. In particular, these DoE monies were provided via the Generic Detector Development Program – a forerunner of the present SSC Sub-System Support Program. Our research started with some theoretical investigations into the principles behind scintillating fiber techniques, continued through scintillator manufacturing details and into the optical properties of plastic scintillating fibers. In order to determine the detector characteristics of scintillating fiber arrays, we have installed a radioactive source/cosmic

ray testing station in our laboratory at Northeastern University. This facility has been used in initial quality control studies of individual fibers and of fiber arrays. These studies have included not only optical properties but also geometrical precision and alignment characteristics. In addition, we have just begun to investigate fiber readout options. All these points are briefly discussed in the following.

1. Theoretical Aspects

Before embarking upon a research program involving the use of small diameter plastic scintillating fibers (PSF), we wanted to fully understand the principles behind the technique in order to see the natural limitations and identify potential development areas. Our study is summarized in a Northeastern University preprint [III-3]; many hundreds of copies of this paper have been circulated to research colleagues around the world and it has had a significant influence on the chosen research directions. It, of course, underlined the importance of optimizing the scintillating material to maximize the Stokes shift (the wavelength separation between characteristic emission and absorption spectra), to minimize self-absorption and to maximize the attenuation length. It also pointed out the importance of a low-index cladding material with good interface to maximize the attenuation length. An interesting prediction that came out of this work was that the attenuation length should increase as the ambient fiber temperature decreases. This we confirmed experimentally and it is being summarized in a forthcoming publication [III-4,III-5].

2. Fiber Manufacture and Cladding Investigations

Our early work was concerned with the actual manufacture of PSF. We learned how to add the appropriate amounts of fluorescent dye, wavelength shifter, etc., to the styrene and we learned how to polymerize the styrene and make a 'boule' of doped polystyrene. We learned how to add an acrylic 'sleeve' which would eventually become the fiber cladding material. All of this work was done in collaboration with, and under the expert guidance of, W.R. Binns and his collaborators at Washington University in St. Louis. We took our boules to H. Watts and his company, FODS, in Santa Barbara and learned the techniques to pull fibers out of the boule. We learned how to control the fiber size via the oven temperature and fiber wheel speed. We researched alternative cladding techniques in order to use plastics with lower refraction indices than acrylic. One very hopeful material that we researched is a DuPont proprietary plastic referred to as HM1.

This material has a refractive index of 1.35 (the index is 1.59 for polystyrene and 1.49 for typical acrylic clad). Unfortunately it has thermal and mechanical properties very different to those of polystyrene and so cannot be added to the boule as a sleeve. HM1 is soluble in Freon and so we tried dipping unclad fibers in an HM1 solution. Even though we finally gave up this technique, the things we learned could have an important bearing on future fiber manufacture. By the time we had learned everything we could about fiber manufacture, several companies, such as Kyowa (Japan), Bicron (U.S.) and Optectron (France), had started marketing top quality PSF and so we moved on to the rigorous testing of fiber characteristics and the design of particle detectors.

3. Installation of a Fiber Photon Counting Facility

In order to be able to test the optical characteristics of fibers, we have installed a testing station in our research laboratories at Northeastern University. As a first step, we equipped a long coffin-shaped dark-box with photomultiplier and all the necessary electronics, built a triple scintillator coincidence trigger and measured the light output of selected fibers. After learning how to work with the very low light yields intrinsic to the PSF business, we found the 'coffin' approach to be somewhat clumsy and so we built a dark-room. The dark room has the advantages that it allows us to test full-size prototype PSF detectors under reasonably normal conditions, allows a good separation of the optical detectors and their associated signals from the readout electronics, and it provides an environment free of optical and electrical noise. The system is now on-line to a Zenith 286 PC with interfaces to both CAMAC (DSP controller) and FASTBUS (LeCroy controller). Our DAQ software is available for both data-taking and/or display purposes with both interactive and hard copy features. Our photon counting standard is an RCA 8850 Quantacon with a fully calibrated bi-alkali photo cathode. We use either a Sr^{90} source or hardened cosmic rays. Our system is still fully humanized and a full person-day is needed to accumulate a sensible light curve to determine a given fiber attenuation length. Some of the results we have obtained with this system are reported in [III-6,III-7]. Our entire system is reasonably user friendly and, for example, was recently used by the Rockefeller University group to check some mysterious results [III-8].

4. Fiber Quality Control Studies

In order to build a precision, fully calibrated detector, one needs geometrically precise, optically reliable fibers. Our early fibers were of questionable quality and we

therefore put a significant amount of effort into fiber quality control. Optical quality is relatively straightforward to monitor; a bad fiber can always be identified by an anomalously low attenuation length. For example, the Kyowa 500 micro fibers that we have worked with recently have a typical attenuation length of between 150 and 200 cm. An attenuation length below 150 cm usually, and below 100 cm always, signals a bad fiber. Geometrical precision is more difficult to monitor. We have researched both optical and mechanical methods of measuring fiber size at various points along their length. Neither give totally satisfactory results.

5. Geometrical Precision and Alignment

Our approach to date has been to align individual fibers into ribbons which can then be assembled into an entire detector. We have tried two different techniques for this. The first was to buy the fiber in a continuous reel and assemble the ribbon in our laboratory. This has the advantage that, if we can select lengths of fiber with dimensions well within our specifications, then we can use only in-spec fibers to make ribbons. (As noted above, however, making the fiber selection is not trivial). Gluing the fibers in a precise manner onto a rigid structure that defines the ribbon is difficult. The second, better way was to buy a fully assembled ribbon from the PSF company (Kyowa, in this case). This has the disadvantage that the individual fibers are not necessarily in-spec and therefore the entire ribbon itself has precision and alignment problems. We have just recently purchased a precision motor-driven 2-dimensional stage (with 150 cm throw in the long direction) as a prototype device to determine the individual fiber alignment precision within a ribbon. Current plans involve the use of a 2 mCi Ru^{106} source to scan across a ribbon and investigate the PSF sensitive regions as a function of position. We use a pair of fibers (at right angles to the ribbon axis) as trigger to define the edges and effective area of each fiber. The source and trigger precision movement is PC controlled thus obviating the need for any operator action.

6. Readout

As noted above, we use an RCA 8850 Quantacon as photon counting standard for single fiber readout. We also have Hamamatsu R647-04 finger tubes, which can be used for single fiber readout. Both these devices are 'standard' photomultiplier tubes in that the output singles are about 10-100 mV high. The RCA gain is more stable that that of the finger tube and so it is more reliable for single photon counting. Just recently we

purchased a Philips XP4072 8x8 multianode phototube. This also puts out typical photomultiplier signals for each of the 64 output channels. ITT have loaned us an ITT F4149 MCP 10x10 multi-anode tube. The gain of this device is about 10-100 times less than the photomultiplier gain and so the signal is typically a few mV. The MCP amplification gives a narrower output pulse. All these devices are fine for R&D and laboratory work, or for applications involving no more than a few thousand channels, but at typically $100 per channel, some other readout method has to be found for detectors involving 100,000 or more channels as in the present case.

C. Electronics

The proposed hybrid CTC presents several significant challenges in the design of electronic subsystems for signal acquisition and readout. Given hundreds of thousands of channels of drift tubes and scintillating fibers, considerations of size, power, and cost force the aggressive use of custom integrated circuits and solid-state photo-conversion devices. Moreover, as some components of the electronic subsystems must be placed within the CTC itself, the integrated circuit technologies to be used must be carefully selected for radiation hardness. This program will exploit substantial prior work in electronic design for drift tube and scintillation detectors, in radiation hardened integrated circuit technology, and in solid-state devices for photo-conversion. Several critical areas of prior work are highlighted below.

The use of custom integrated circuits for drift tubes, silicon strip detectors, and scintillating fiber systems is currently being explored under several Generic Detector Research and Development grants. The electronics used in each case are quite similar and generally include front-end circuits for signal acquisition and signal conditioning and readout circuits that typically involve some type of analog memory. The analog memory is provided to store output signals until a trigger is produced, and to facilitate multiplexing of the post-trigger readout. Using custom integrated circuits it is possible to pack several channels of electronics on a single chip with power dissipation of only a few milliwatts per channel. This program will directly exploit circuits developed for DOE at the University of Pennsylvania (Penn). The Penn group has designed and demonstrated a two-chip system for drift tube readouts which could be modified to process data from scintillating fibers [III-9]. The two-chip approach consists of a bipolar front-end chip and a CMOS analog store and readout chip. These circuits will be used as a starting point for the development of a second generation chip set that packs several channels on each chip. Drs. Van Berg and

Newcomer from the University of Pennsylvania will participate in the development of these integrated circuits for the hybrid CTC.

The custom integrated circuits used for straw tube signal acquisition and readout must be placed in close proximity to the ends of the tubes, and therefore, will experience a severe radiation environment. It is estimated [III-10] that these chips must be able to withstand a lifetime (5-10 years) ionizing dose of 0.5-5 Mrad(Si) and a lifetime neutron fluence of 10^{13}-10^{14} cm^{-2} at the inner radius of the proposed CTC. Radiation tolerance of integrated circuits is primarily a matter of process technology, although design practice does play an important role. Significant advances have been made in the development of radiation-hardened IC technologies over the past several years, and many of these technologies are capable of meeting the estimated radiation requirements [III-11,III-12]. These specialized processes are intended primarily for strategic defense applications, but are also frequently used in commercial satellites and in controls for nuclear reactors. Radiation-hardened bipolar and CMOS processes are available from several companies including Harris, Texas Instruments, United Technologies, AT&T, and Orbit. Further work is needed to determine the actual radiation requirements and to select manufacturers who can meet these requirements.

At the present time, the only readily available photo-conversion devices suitable for use with long, small diameter scintillating fibers are photo-multiplier tubes, microchannel plates, and avalanche photo diodes. Although these devices are available in a variety of types and configurations (number of elements), they share the common characteristic that they are extremely expensive, on the order of hundreds of dollars per channel. Recently, two solid state photo-conversion devices have been developed which ultimately may be low enough in cost to realize systems with tens of thousands of channels [III-13,III-14]. The RCA device is particularly interesting in that it may be able to operate at or near room temperatures [V-2]. Although one of these devices may ultimately find application in an SSC detector, these technologies are not ready for use in a near term demonstration project. Therefore, the scintillating fibers in the hybrid detector prototype will be instrumented using conventional multi-anode photo-multiplier tubes. However, as a parallel effort, RCA will participate in the development of a scintillating fiber readout based on their latest avalanche photo diode (APD) technology. This will include device design and characterization for use with plastic-scintillating fibers, as well as packaging and preamplification for either linear or mosaic arrays.

D. Radiation Damage Studies

1. Straw Tube

Previous ageing studies [III-15,III-16] indicate that wire chamber "lifetimes" in excess of one C/cm-length-of-wire are feasible, provided that certain conditions are met. The first and the most important is choice of appropriate gas, with controlled levels of impurities. Impurities are well known to cause deterioration in gas detectors, and are responsible for many contradictory results of different ageing studies, sometimes even if performed in the same laboratory. Appropriate purification systems should be installed, when necessary, to convert commercially available gases to sufficiently pure materials. Of course, the selected type of gas must also fulfill other requirements, such as stable proportional gas amplification (no sparking at high rates), speed of operation (which is especially important at the expected high SSC particle fluxes), safety, availability, and reasonable cost. There is a rather long list of possible choices [III-13,III-14], with some candidates having superior properties, but further research to identify the optimum gas for SSC application is warranted.

The next important step is the right choice of chamber construction materials. A selection must be made on the basis of chemical compatibility of these materials with the selected gas(es). Also, information on outgassing properties should be available (and/or special tests should be performed) to minimize risks of gas contamination. Glues, frame materials, cleaning solvents, solder flux, feedthroughs, tubing, etc., should all be carefully selected. There have been many unfortunate experiences with damage to wire chambers due to improper choice of constructional materials; these have ranged from pollution/poisoning to outright mechanical destruction, such as in the case of ageing-controlling gas additives (alcohols, methylal, etc.) dissolving glues used in chamber production. A long battery of appropriate tests therefore seems to be unavoidable.

Finally, in order to achieve straw tubes with lifetimes in excess of one C/cm, previous research indicates that careful ageing tests will have to be performed in order to study the effects of many parameters on longevity. These parameters include fresh gas flow rate, counting rate (average current flowing in the chamber per cm-length-of-wire per sec), gas composition or mixture ratio, kind and amount of additives preventing ageing, gas amplification factor, gas temperature and pressure, etc. The collaborating group at the University of Florida has performed preliminary tests of specially selected very pure

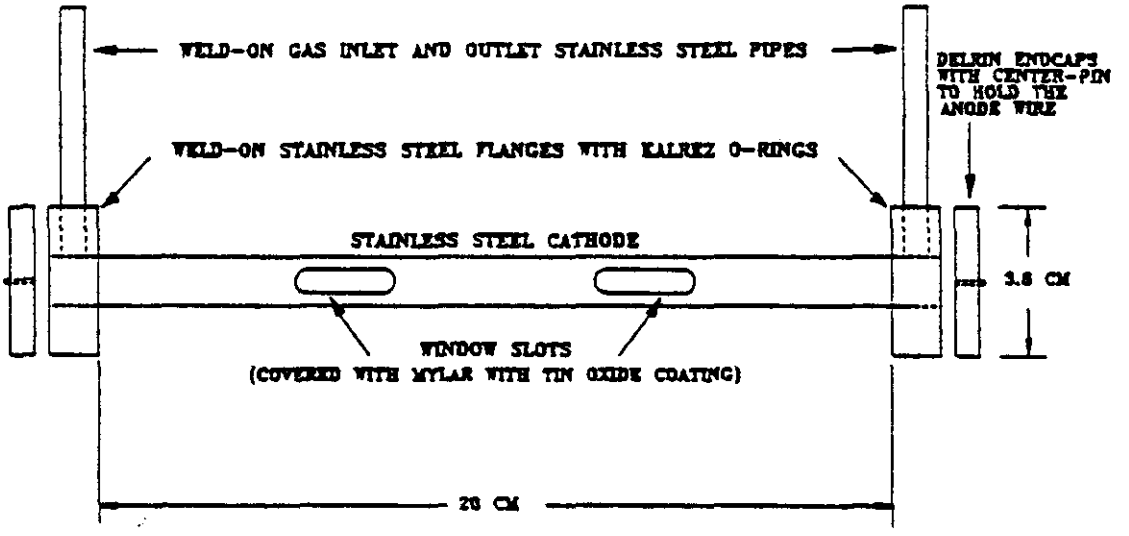


Figure III-6. Experimental Apparatus Used to Study Stainless Steel Tubes

construction materials, in order to separate effects of gas from effects of practical materials preselected for use in the real detector; these materials include glues, composite frames, potentially chemically reactive (oxidizing) electrodes, such as resistive wires, etc. For example, Jibaly, et al. [III-17] studied stainless steel cylindrical tubes with carefully selected epoxy and O-rings (see Figure III-6). Several other groups have gained experience in ageing studies and collaborative efforts with them will be arranged. For example, the group of Dr. John Kadyk from LBL is specializing in a generic R&D study of wire chamber gas ageing, and systematic tests with different gases of interest for the SSC and different wire materials are being performed with a unique experimental setup and analytical equipment. Also, the TRIUMF Group [III-18] is studying ageing with very fast (important for SSC) CF_4-based gases in small-cell multiwire chambers.

The collaborating groups at NCSU and Quantum Research Services also have experience in relevant irradiation studies, although not on materials or components specifically designed for the SSC. Dr. Paulos (NCSU) has performed gamma-ray radiation

testing of electronics in a Co^{60} irradiation facility at NCSU, whose use is proposed for this study (see Section VI.B), and Dr. Dunn (Quantum) has extensive experience with neutron irradiations for radioisotope production, neutron activation analysis, prompt gamma-ray analysis, and neutron gauging applications. The one MW PULSTAR reactor at NCSU, whose research applications Dr. Dunn oversaw for over two years, offers an ideal facility for the requisite neutron studies (see Section VI.B).

2. Plastic Scintillating Fibers

The University of Florida (UF) group has been involved in a generic SSC R&D study to develop radiation resistant organic scintillators suitable for use in the SSC environment. This work has been reported in a number of publications. A good representation of the work is found in Refs. III-19 and III-20. A key result has been the development of a radiation hard plastic scintillator based on a polystyrene base and doped with PTP and 3HF, the latter a large Stokes shift fluor resulting in an emission spectrum in the yellow-green region (500-500 nm). With the current interest in plastic scintillating fibers, the UF group has measured the performance of several commercially available scintillating fibers in order to gauge their performance in terms of radiation resistance.

Figure III-7 displays the measurement setup. A continuous, collimated X-ray source (8 keV) is used to excite the fiber, with the resultant DC current read out from the phototube by an electrometer. The result is an attenuation curve for the fiber (Figure III-8). The key problem is the loss of transmission in the blue end of the spectrum by the plastic base after irradiation. Many of the commonly used fluors (such as p-terphenyl) are essentially radiation hard. Hence, greatly enhanced radiation resistance is achieved by shifting the emission spectrum of the scintillator to longer wavelengths (i.e., >500 nm). This is illustrated most succinctly by Figures III-8(a) and III-8(b). Figure III-8(a) shows the complete recovery (in attenuation) of a 3HF-doped (i.e., green-emitting) fiber after a 10 Mrad irradiation at the 3 MeV electron beam facility of FSU. In contrast, Figure III-8(b) displays the performance of a standard blue-emitting fiber, SCSF-38. (All the curves are normalized to the current reading one inch from the PMT.) The intrinsic light loss was measured to be 10% for SCSF-38 and 15% for the 3HF fiber. One concludes that the attenuation characteristics of the two fibers will dominate their performance under severe irradiation. (Both fibers are 1 mm in diameter, and use a PMMA cladding on a PS base.) Some of the current results have been published [III-20], and the rest have been reported at

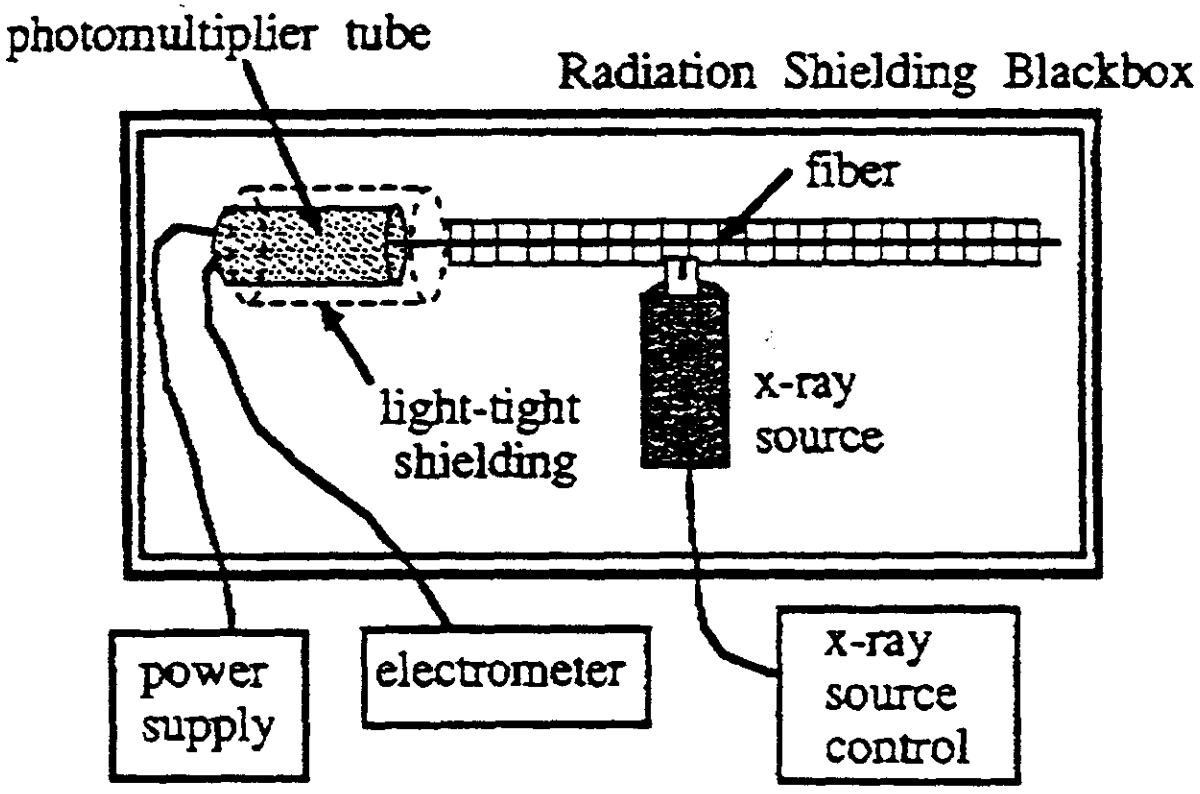
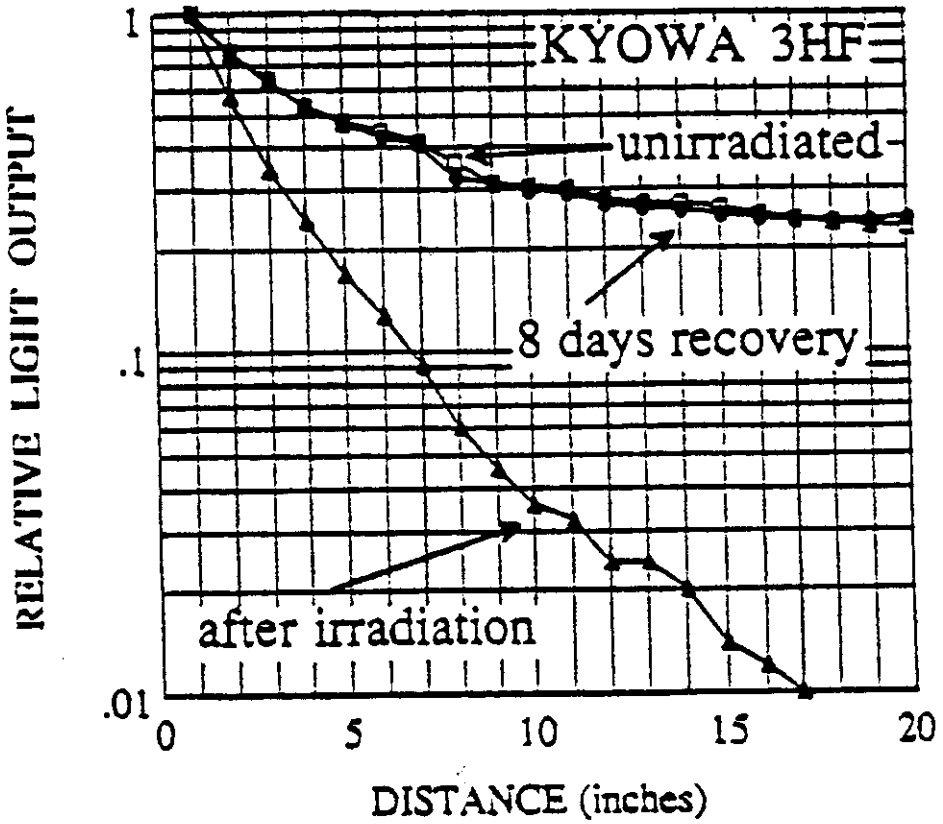


Figure III-7. Fiber Testing Setup



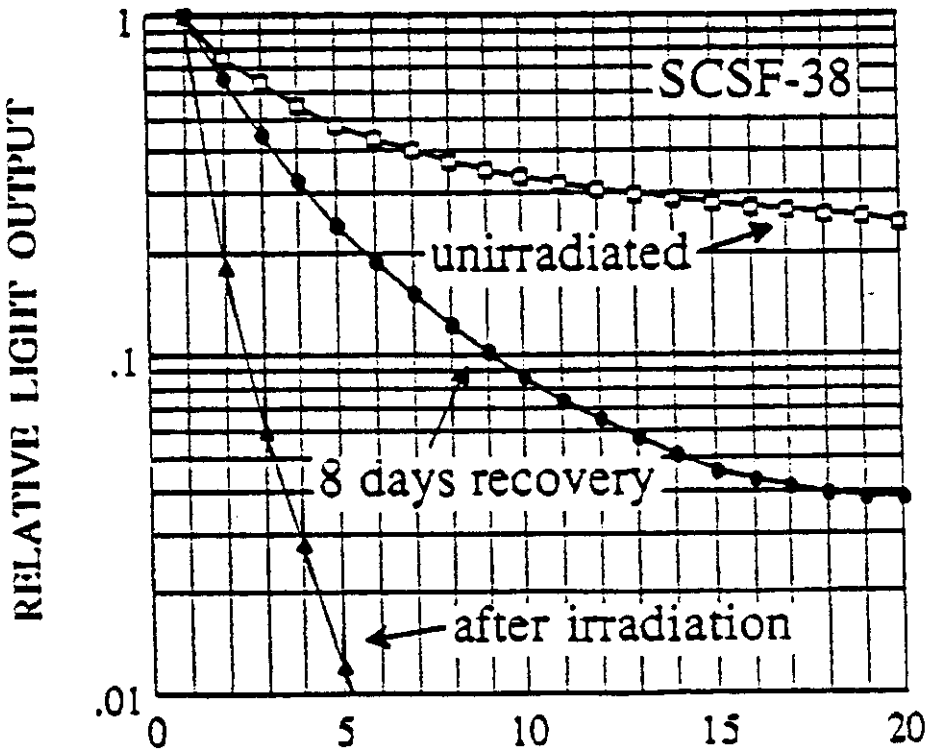


Figure III-8. Results of Radiation Damage Studies to Plastic Scintillating Fibers

the recent EFCA Study Week on Instrumentation for High Luminosity Hadron Colliders (Barcelona, Spain, September 14-21, 1989).

The UF group will carry out research appropriate to optimizing radiation resistance of plastic scintillating fibers. This includes the following:

- Using appropriate radiation resistant, large Stokes shift fluors (eventually shifting to above 650 nm),
- Utilizing more radiation hard bases (e.g., PVT and polvinylxylene are known to be more radiation resistant than polystyrene),
- Investigating the effect of different claddings (PMMA is the standard – however an Optectron fiber with a fluorinated acrylic cladding was found by the UF group to have an enhanced radiation resistivity over those clad with PMMA).

Of course, the optimization in radiation resistivity will also be done with light output and speed taken into consideration. The irradiations can be done with the electron and neutron sources outlined elsewhere in the proposal.

IV. Mechanical Fabrication of the Prototype Detector

A. Proposed Construction Techniques

The objective of the mechanical fabrication development program is to demonstrate, through construction of a series of increasingly elaborate engineering models, that the final hybrid detector design is feasible and can be efficiently and economically constructed. The ultimate model in the development series will be a full-scale (1.4 m diameter by 2.5 m length) prototypical superlayer section. An overview of the superlayer's construction was given in Section II and the basic structure is shown in Figure II-1.

In order to provide a sound basis for the proposed engineering development program, we have evaluated the mechanical design, fabrication, and assembly of a hybrid CTC for the SSC. The mechanical design for this detector is based on existing technology, materials and assembly techniques; there are however, several areas in which we intend to extend known technology in order to achieve the best dimensional and structural stability. In addition, design details such as the wire clamps and tube fittings will be refined to simplify installation and insure reliability. The cost effectiveness of the design will be improved through the use of commercial vendors to the maximum extent possible. This will be particularly important during the fabrication of a full scale CTC due to the large number of components in that assembly.

1. Mechanical Engineering Requirements

The analysis of the design for an SSC hybrid detector resulted in a compilation of significant development issues that will be addressed in the proposed program. Specific design issues will first be resolved in single-component studies, such as the tube tests currently underway at Duke. These tests will be followed by a series of engineering models that will analyze subsystem designs, such as the methods used to install tubes, wires, and electrical connectors. It is our goal for the subsystem test program to resolve most of the known engineering issues in preparation for the construction of the prototype. The full-scale superlayer prototype is expected to serve three purposes. First, it will confirm the component assembly design developed earlier in the program. Second, it will provide a model which can be used to evaluate dimensional and structural stability. And, lastly, it can be used in beam tests to measure the particle detection capabilities of the superlayer.

The major development issues to be addressed in the proposed program are discussed below.

a. Tolerancing Requirements

Knowledge of the precise location of individual straw tube wires and scintillating fibers within the assembly is critical to the performance of the detector. Consequently, the most significant engineering problem anticipated during the fabrication and assembly of the components will be the determination and maintenance of the best achievable tolerances. Two approaches will be used to solve the problem. First, the structure of the assembly will be constructed as precisely and rigidly as possible, and second, locating features will be included in the assembly to permit the determination of the final positions of the wires and scintillating fibers. The development team may at this point rely on the large precision inspection machines at the Martin Marietta Energy Systems (MMES) weapons production plant (Y-12). That operation has over 40 years experience working with the inspection of machined assemblies at the sub-mil tolerance level. Additional steps may be taken to determine the alignment of the detector using cosmic rays and test beams.

b. Structural Stability

Preservation of the initial detector alignment for the ≥5 year design life of the detector will have to be weighed against the requirements for minimizing the radiation length of the detector. Material type, creep rate, radiation resistance, and age deterioration will all be evaluated to accumulate sufficient data to insure the detector will remain effective throughout its working life.

Three approaches are being taken to enhance the structural stability of the SSC detector. First, the superlayers will be directly connected. This linking will provide load sharing and stress distribution. Second, composite assemblies using foam, honeycomb or scintillating fiber cores will also be evaluated as methods of increasing the rigidity of the individual superlayers. Third, we will evaluate the added structural strength provided by the straw tubes in the superlayer. As a world leader in the design and fabrication of carbon composite cylinders ORNL is expected to bring a unique expertise and fabrication capability to the development program. ORNL is currently involved in several similar development programs with the Departments of Energy and Defense which should provide further support and experience.

The prototype assembly will be the primary vehicle for evaluating structural stability. The model will be calibrated with indicator marks and tooling balls to permit dimensional inspections to be performed after assembly is complete at intervals over an extended period.

c. Materials Evaluation

Materials will be evaluated in both the engineering development models and the full-scale prototype. Of particular interest are the carbon composite cylinders, core materials such as syntactic foam and honeycomb, and the aluminum or carbon end plates. Radiation effects on these and the other structural materials are considered in Section VI.

d. Vendor Development

Commercial vendors will be developed for many of the components used in the engineering models and the full-scale prototype. The straw tubes, wires, tube end fixtures, and scintillating fiber ribbons will all be procured items. Commercial vendors will be used to the maximum extent possible for component assembly. ORNL engineering has a tradition of establishing contact with commercial enterprises to exchange technology and reduce the cost of fabrication. Virtually all significant development projects having the involvement of ORNL mandate the transfer of technology to commercial vendors. This will insure that the SSC hybrid detector is built by the most efficient means at the lowest cost.

e. Wire and Tube End Connection Development

Due to the large number (350,000+) of wire and tube end connections, a significant portion of the development program will be dedicated to reducing the complexity and cost of these elements (Figure IV-1). Mass production techniques will be developed through commercial vendors while simplified installation procedures will be tested on the engineering models. Past experience on wire type detectors has shown that wire breakage during assembly is a particularly complex problem which places a premium on the inclusion of features in the assembly to simplify the threading of the wires. Note, that either in-tube wire supports or a fixed center plate complicate this task significantly.

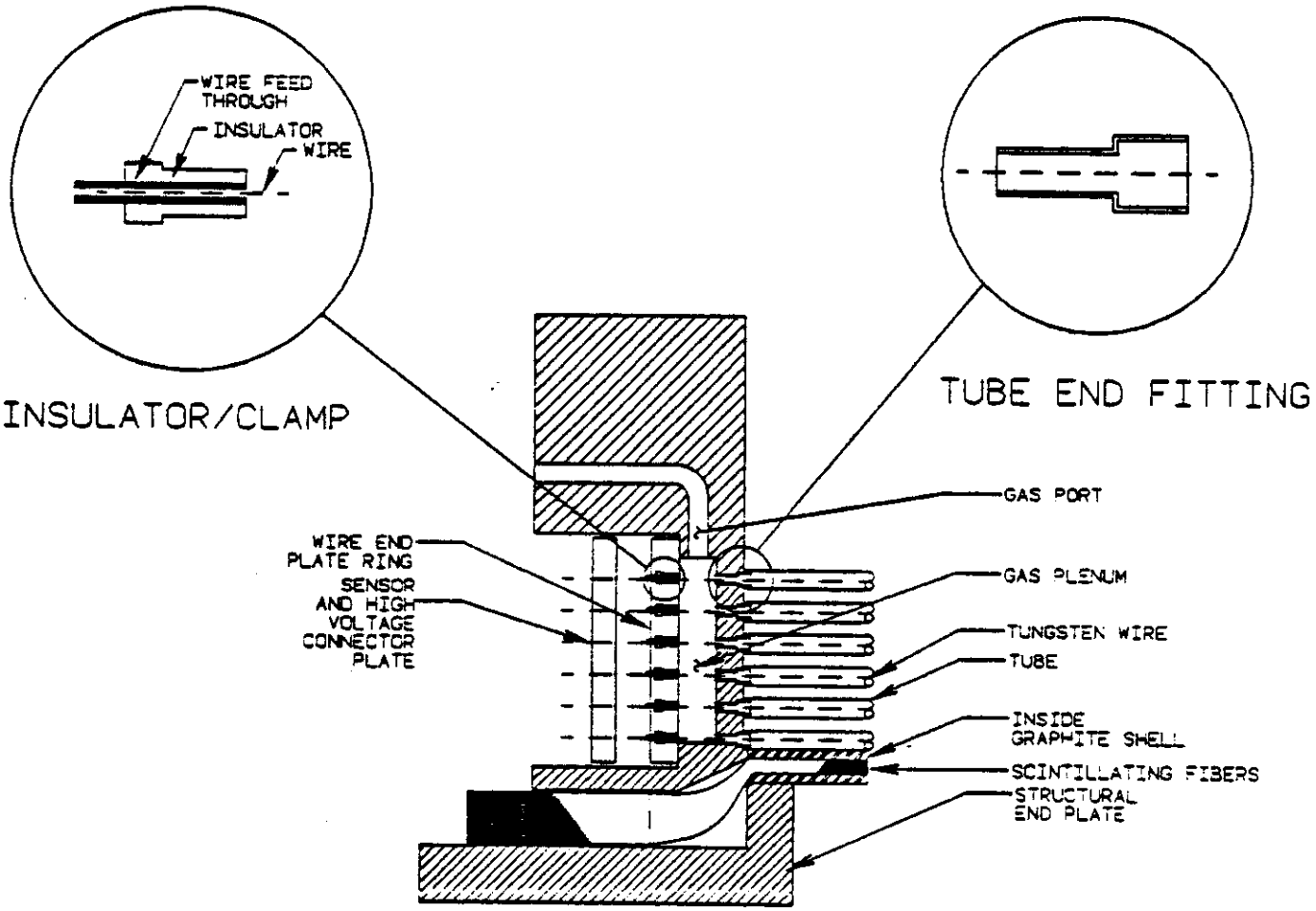


Figure IV-1. Typical Straw Tube End Connection

f. Scintillating Fiber Installation

There are several issues associated with the installation of the scintillating fibers. First, practical techniques for the alignment of the fibers will be developed; second, containment of the fibers between layers of carbon-graphite cylinders will be tested; and lastly, an efficient method of connecting the fibers to readouts will be accomplished. Through the Y-12 production plant, ORNL has direct access to state-of-the-art bonding and adhesives technology. This source will be particularly useful in the design of the scintillating fiber assembly.

2. Engineering Studies

A three-stage program of engineering studies will be used to achieve the objective of developing a valid design for an SSC hybrid detector. Starting with the single tube tests now underway, the proposed program moves through a series of subsystem engineering models and concludes with the full-scale prototype. The engineering models will be built in a progressive series of assemblies, in order to efficiently incorporate the lessons learned at each stage in the program.

a. Single Tube Models

As discussed in III.A, we have constructed various models to study mechanical and electrical stability. We will continue to work on this project and the results will be compared to the studies being conducted by J. Va'vra at SLAC and H. Ogren at Indiana University.

The necessity to provide internal support to 2.5 m long sense wires to maintain stability is one of the principal difficulties to be overcome in assembling a full scale detector. We will investigate the possibility of using support inserts which center the wire in the straw tube as has been suggested in previous detector design studies as part of our single tube model test.

We will also test the feasibility of using low mass intermediate support planes to align the sense wires and maintain electrostatic stability in the cells. Both methods would result in a small fraction of each cell being insensitive to tracking.

b. Small-Scale Engineering Models

Four small-scale test models will be built to evaluate known subsystem design issues of the hybrid detector. Most of the details of the component designs are expected to be finalized at this stage of the proposed program. The engineering models may also be used to train prototype assembly personnel at the completion of the testing program.

- Radiation Testing Model: The radiation test apparatus will include prototypical materials in an assembly that can be handled in the available radiation testing facilities. Scintillating fiber tests will be performed both independently and concurrently with this apparatus in a prototypical configuration.

- End Connection Test Assembly: The end connection test apparatus, shown in Figure IV-2, will be constructed. It will provide a prototypical model of end rings. The connection rings will be designed for interchangability to permit a wide range of tests to be performed with relative ease. Although the model will have a capacity of up to 100 tubes, a majority of tests will require only a few. Verification tests prior to the design and procurement of the full scale prototype will use the larger number of tubes.

- Tube Test Assembly: The tube test apparatus, shown in Figure IV-3, will be designed for the installation of various lengths of straw tubes and wires. It will be used to evaluate a wide range of detailed design issues associated with tubes, such as tolerancing, gas flow, wire sag, tube installation methods and wire insertion techniques. The apparatus will be extendable from 100 to 300 cm and will hold up to 100 tubes.

- Scintillating Fiber Installation Test Assembly (Figure IV-4): The scintillating fiber installation test assembly will be used to evaluate practical techniques for the precise installation of fibers in the hybrid detector. To reduce cost, it will be fabricated using an existing ORNL mandrel (60 cm diameter) and will not incorporate end connections or tube assemblies. Of particular concern will be the evaluation of alignment techniques, bonding agents, and carbon composite winding pressures.

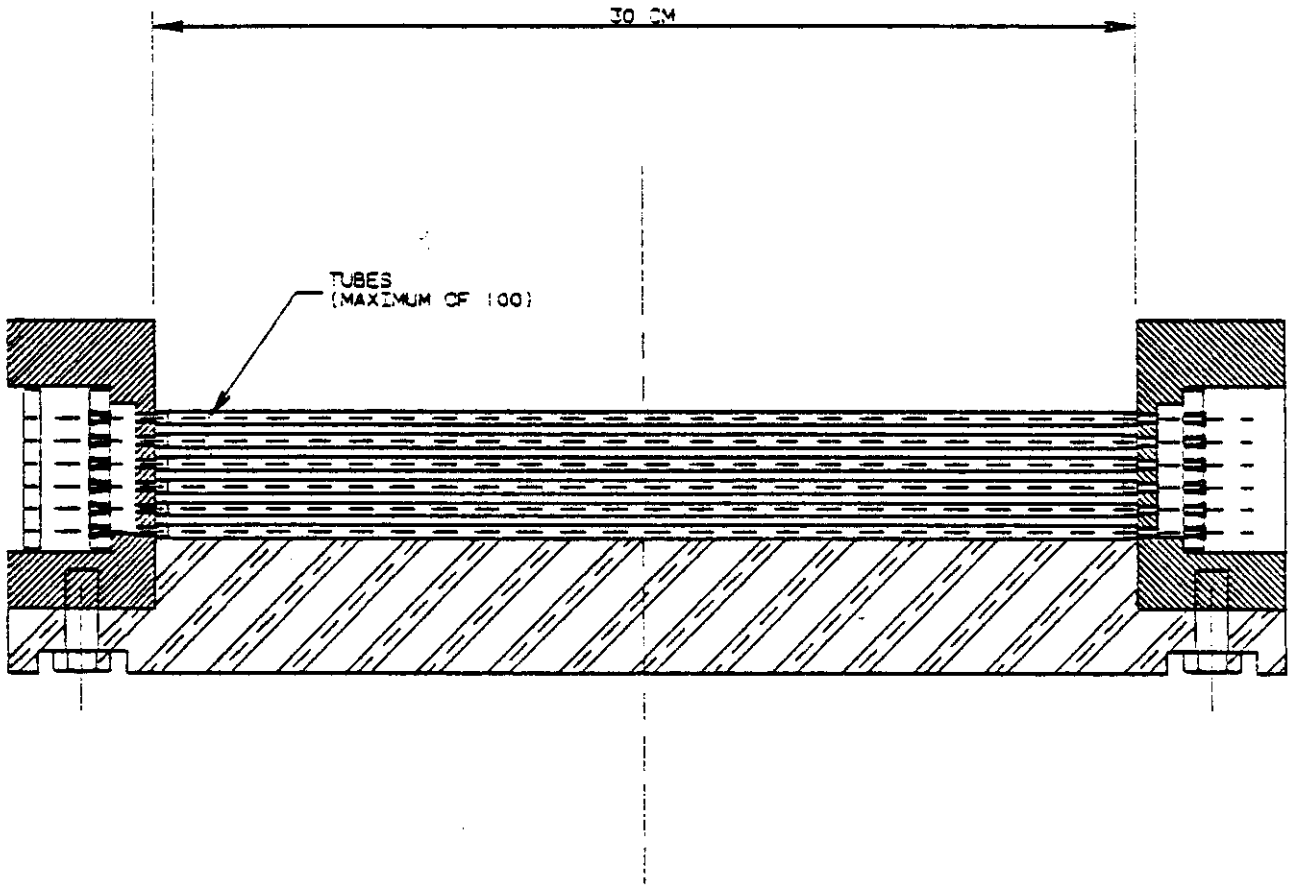


Figure IV-2. Schematic of End Connection Test Assembly

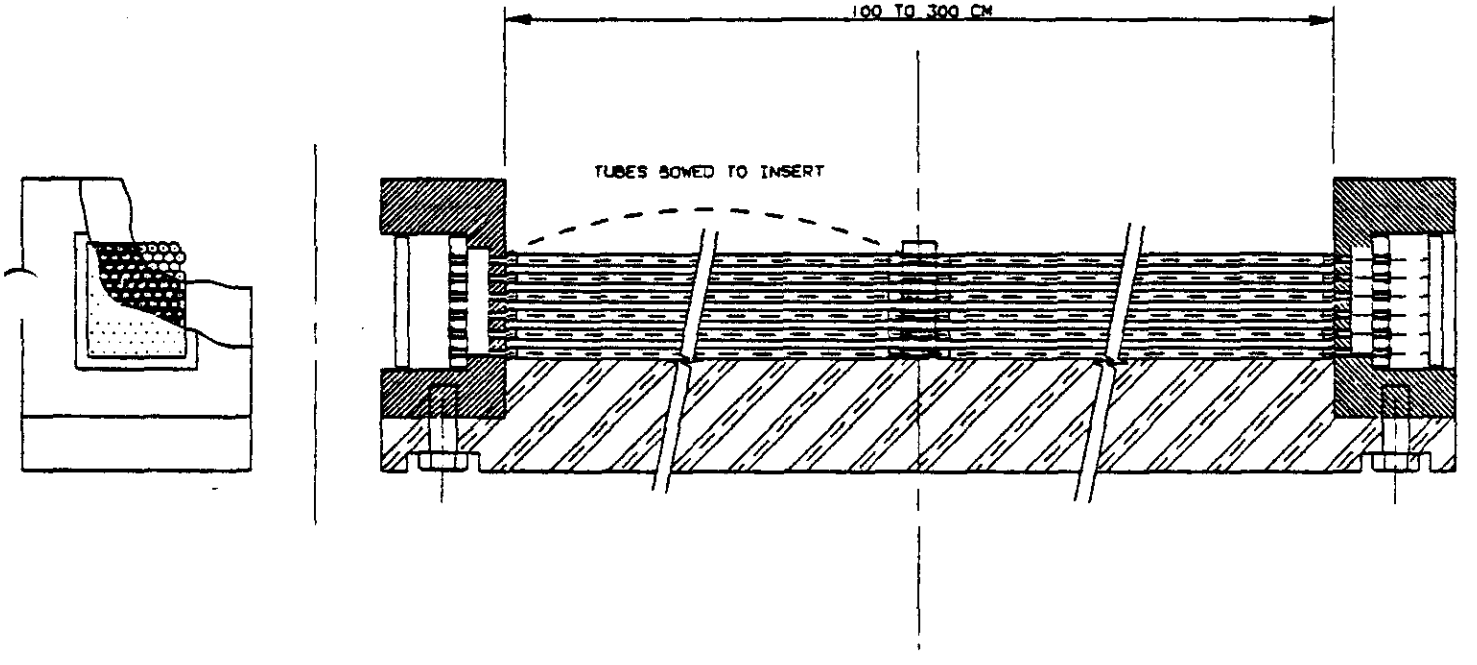


Figure IV-3. Tube Test Engineering Model with Centerplate

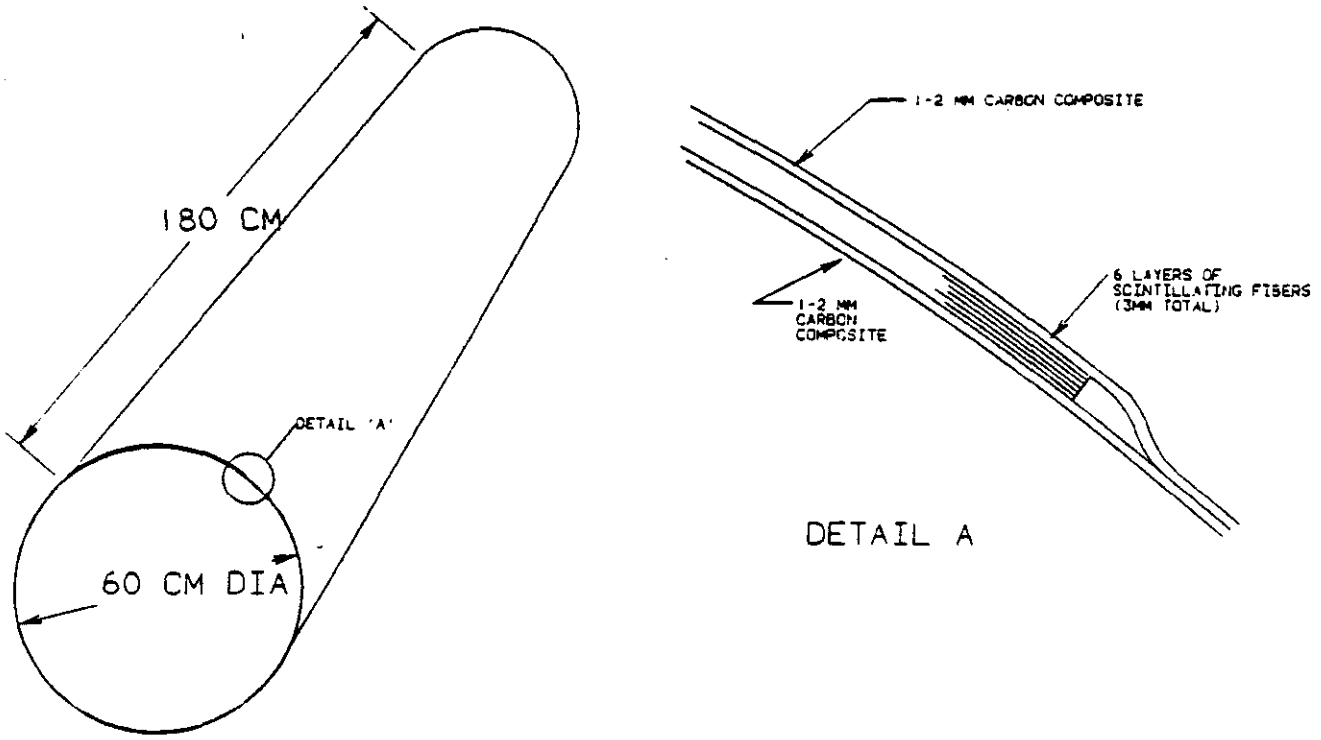


Figure IV-4. Scintillating Fiber Installation Test Model

3. Full-Scale Prototype

The construction of the full-scale prototype, shown in Figures II-1 and IV-5, will provide the final validation of the engineering design concept for the SSC hybrid central tracking detector. The prototype assembly will also be used in physics tests (see Section VIII). The prototype assembly represents one full-scale superlayer with respect to materials, dimensions, fabrication techniques and instrumentation. Non-prototypical features of the assembly will be the reduced number of instrumented scintillating fibers, due to the relatively high cost of photo-sensing devices and electronics, and the reduced number of straw tubes (1,000 instead of 13,700), due to the cost of installation. Spring-loaded tie-rods will be used in place of the missing straw tubes to provide a simulated load on the cylindrical structure. Since the scintillating fibers are to be an integral part of the structure, all six layers will be installed. Thus, the prototype will provide an accurate representation of the structure of the full-scale unit.

It is the intention of the development team to address any known design problems on the engineering models, where changes can be made efficiently, and not on the full-scale prototype. The final design of the prototype will be completed after the results of the engineering models tests are complete. The prototype will be used to validate the final design and will also be used in subsequent physics tests.

B. Plastic Scintillating Fiber Construction

We plan to use 500 μm square polystyrene fibers assembled under laboratory conditions into 50 mm wide ribbons, each of which contains 100 individual fibers. After each ribbon has been constructed we shall calibrate it using our two-dimensional precision table and Ru^{106} source. The calibration will determine the location of the scintillating portion of each fiber at 10 locations along the length of the ribbon. We shall demand individual fiber tolerance of no worse than ±20 μm over the ribbon length. Out-of-spec ribbons will not be used in the prototype detector assembly.

Ribbons which pass the stringent quality control tests will be incorporated into the carbon fiber precision support tubes. After a 2,000 μm layer of carbon fiber/epoxy has been laid on the mandrel, the six z-u-v PSF layers will be glued precisely, one by one, on the outer surface of the cylinder. A final carbon fiber/epoxy layer will complete the support tube. Each of the ribbons will have its 100 individual fibers bunched into a readout bundle

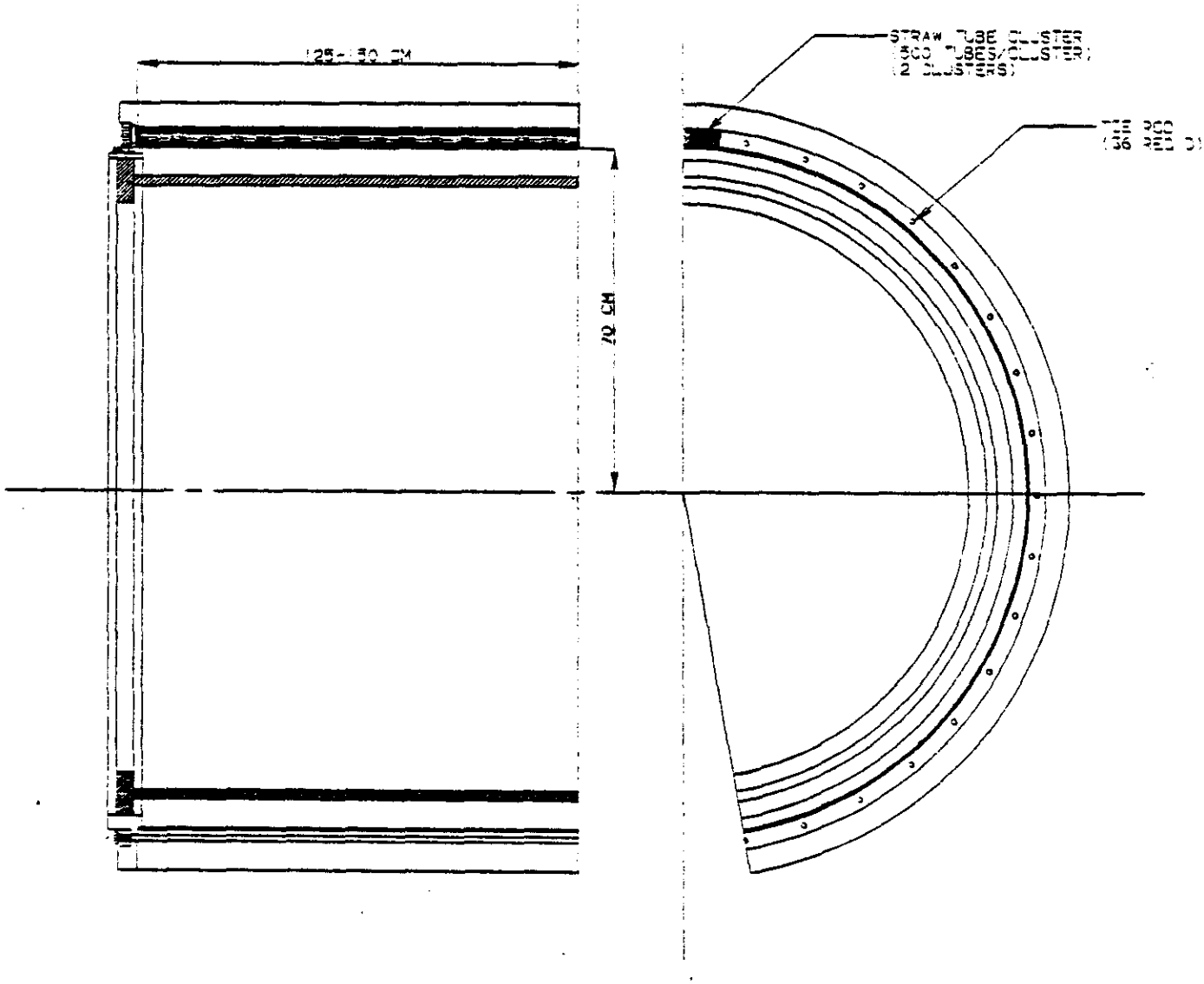


Figure IV-5. Full Scale Prototype Assembly

wherein each fiber is located precisely in a 10x10 matrix. This matrix will be coupled to the readout system after the entire prototype tube has been assembled.

C. Straw Tube Assembly

After the structural cylinder of the full scale prototype is constructed (including two end plates and a carbon fiber cylinder with scintillating fiber embedded), the straw tube insertion will begin. The structural components remain on the mandrel used to form the carbon composite cylinder throughout the straw tube installation process to retain the dimensional accuracy of the completed assembly. To assist with the installation procedure the mandrel will be mounted on a structural frame which will permit the cylinder to be both rotated and tipped on end. The assembly process will begin with the installation of the tube end fittings (Figure IV-1) which are inserted and glued to a tube using conducting glue. Each assembly is tested for electrical conductivity and gas leakage. The tubes with end fittings are then inserted into holes in the end plates. The tubes have to be bent slightly for insertion. The tube end fittings are glued to end plates for gas seal after the insertion. As each tube is inserted, it is glued to the carbon fiber cylinder every ~20 cm along the tube. A minimum amount of glue will be used for this purpose. To reduce the effort of installation, the whole chamber will be rotated as tubes are inserted such that tubes are installed from above.

Each layer of tubes will be completed before the next layer of tubes is installed. Each tube is glued to two tubes in the layer just below. As tubes are inserted, the position of tubes are monitored for tolerance.

Once all tubes are inserted in a superlayer, the chamber will be tested for gas leakage before stringing. The gas is provided to each tube through the tube end fitting, which is inserted onto the end plate as shown in Figure IV-1.

Stringing will be a comparatively easy task (although tedious). We do not anticipate any difficulty with stringing since the diameter of tube end fitting is fairly large. For stringing, the detector will be positioned vertically. After a sense wire is passed through a tube, the wire is then fed with a feed-through (insulator/clamp in Figure IV-1), which defines the wire position accurately. The wire is then tensioned and clamped.

V. Electronic Design

A. Overview

Complete electronic subsystems for straw tubes and plastic scintillating fibers will be designed, constructed, and tested. The purpose of this work is two fold. First, it is our intention to demonstrate that electronics for these systems can be realized within the constraints of physical space, power consumption, cost, and radiation hardness. Second, we require fully functional electronic assemblies in order to perform beam tests on the prototype detector. As discussed in Section III.C, the design requirements will necessitate the use of radiation-hardened custom integrated circuits for signal acquisition and readout. It is our belief that these components are within the reach of existing integrated circuit technology. As discussed below, solid-state photo-conversion devices will ultimately be necessary to realize a full scale system within a reasonable budget. This technology is still immature, and while substantial development work is included in this program, the scintillating fiber readouts constructed for beam testing will be based on conventional multi-anode photo-multiplier tubes.

In the discussions below, the overall approaches to be taken for each subsystem will be summarized, and the critical design issues will be highlighted. Some specific design concepts will be presented that address these critical issues. Although these design concepts are subject to change, they serve to demonstrate the feasibility of the project goals. Also, specific tasks and schedules will be presented below for the electronics portion of the program.

B. Electronics for Straw Tubes

1. System Approach

The electronic assembly for straw tube detection and readout will be based on an architecture developed at the University of Pennsylvania. This architecture, shown in Figure V-1, can be realized in two custom integrated circuits; a bipolar chip which includes the charge-sensitive preamplifier, shaper, and discriminator, and a CMOS chip which includes the time-to-voltage converter, analog memory, and post-trigger readout [V-1]. An initial version of the front-end bipolar chip has been fabricated and tested. The chip achieves a noise level of 1500 electrons using less than 10 milliwatts per channel. An

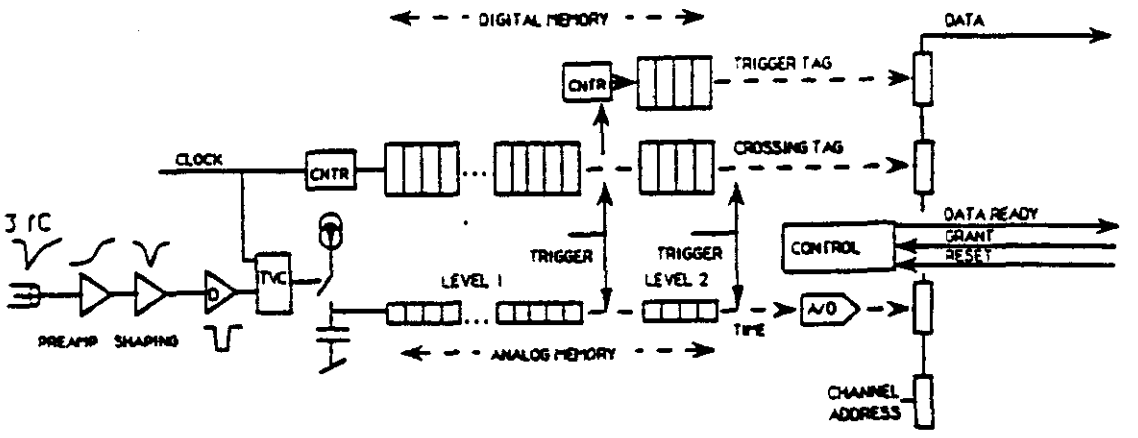


Figure V-1. Block Diagram of High Rate Tracking Electronics

initial design of the CMOS readout chip has also been completed. This chip has been fabricated and is currently being tested. The time-to-voltage conversion is achieved by charging a storage capacitor with a constant current during the time interval of interest. Once captured, the analog voltage is held on the same capacitor until it is read out. A digital addressing scheme is used to label each sample with a bunch crossing identifier. The limited occupancy of the straw tubes is exploited by reusing storage capacitors for which there was no charge event. This makes it possible to retain a moving window of time samples, equal in length to the Level 1 trigger delay, using a comparatively small number of capacitors. The readout chip also facilitates a second level of triggering by continuing to store time samples selected at the Level 1 trigger. These prototypes will be evaluated and modified with the goal of placing at least eight channels of circuitry on each chip.

Although these integrated circuits will perform essentially all of the required signal acquisition and readout tasks, there are several other aspects of the overall electronic subsystem design which must be considered. These include the supply of high voltage to the sense wire, the electrical coupling of the sense wire to the preamplifier, the mechanical

design of the end plate electrical feedthroughs, and the IC packaging and PC board design. The mechanical design of the electronic assembly is particularly challenging given the space limitations at the end plates. Using 4 mm outer diameter straw tubes, roughly 7 channels of electronics must be packed into each square centimeter of end plate. Clearly, placing a large number of electronic channels on each chip simplifies the mechanical design problem, as the PC boards can be mounted parallel to the end plate rather than at right angles to it. A rough sketch of the proposed end plate assembly is shown in Figure V-2. The electronic components are mounted on a PC board attached to a plastic carrier with injection molded "feet" which slide over conducting crimps. A conductive lining on the inner surface of the foot makes connection to the sense wire, while a conductive lining on the outer surface of the foot maintains an electrical shield. This design will need to be refined as the overall end plate design evolves.

2. Critical Issues and Design Tradeoffs

This section will discuss the design issues that are perceived to be the most critical. The first of these is the performance and general suitability of the integrated circuit techniques developed at Penn. Samples of the first generation chips will be

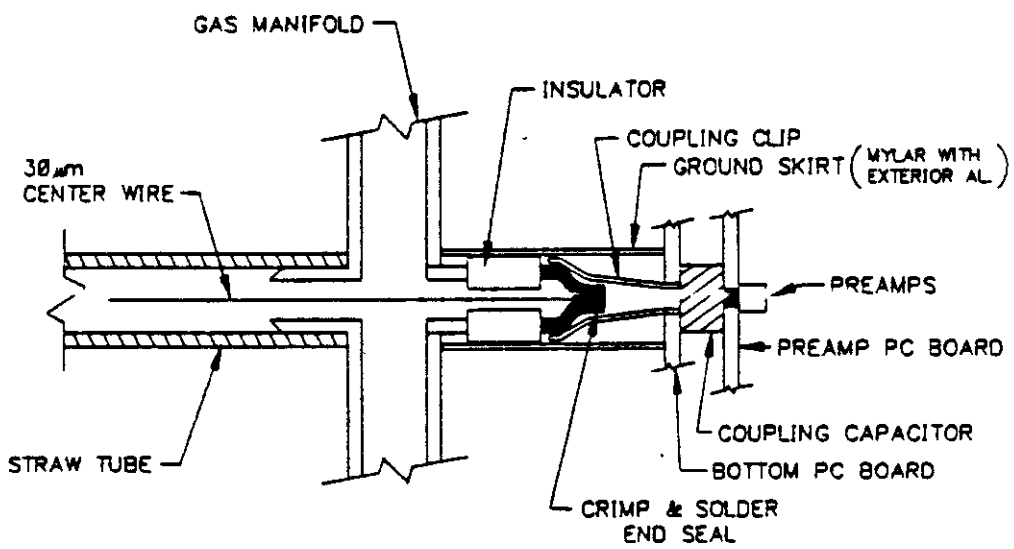


Figure V-2. Clip-On Coupling of Preamps to Straw Tube Anode in Positive High Voltage Operation

evaluated in tests with individual straw tubes. Penn, ORNL, and NCSU will then collaborate in the design of multi-channel IC's optimized for the specific straw tube characteristics and possibly incorporating new features as discussed below. The initial runs of these chips may be fabricated in commercial (radiation-soft) technologies as a cost savings measure. However, the final production IC's for the prototype assembly will be fabricated in radiation-hardened technologies and will be thoroughly tested for radiation tolerance. As the chip designs are specific to a particular vendor, it may be necessary to do some minor redesign in order to use a different vendor to obtain the required radiation hardness.

A second critical issue is the susceptibility of the straw tube system to electromagnetic interference (EMI). A sense wire of a few meters in length will act like an antenna for signals in the vicinity of 50 to 150 MHz. The wire is surrounded by the cylindrical shielding of the aluminized tube; however, this shielding is too thin to be very effective. Although the surrounding calorimeter will shield the sense wire from external RF sources, the straw tube system may be extremely sensitive to electromagnetic signals at the bunch crossing frequency. Moreover, the detection scheme conventionally used is a single-ended (ground referenced) measurement, which is extremely sensitive to electromagnetic interference and noise in the ground lines. The feasibility of a fully differential approach will be considered where common-mode signals, such as ground noise and EMI, can be rejected.

One possible approach to differential measurement is shown in Figure V-3(a). Here fully differential charge sensitive preamplifiers are connected to pairs of adjacent wires, and the outputs are shaped and fed to dual discriminators. A signal which exceeds the positive threshold of the left hand discriminator indicates a charge event in the tube on the left, while a signal which exceeds the negative threshold of the right hand discriminator indicates a charge event in the tube at the right. Such a configuration is blind to simultaneous events on both wires arising from dual tracks passing through adjacent tubes. These adjacent tracks can be recovered by interleaving the differencing connections on alternate layers within the super layer, as shown in Figure V-3(b), or by interleaving twice as many differencing connections within a single layer, as shown in Figure V-3(c).

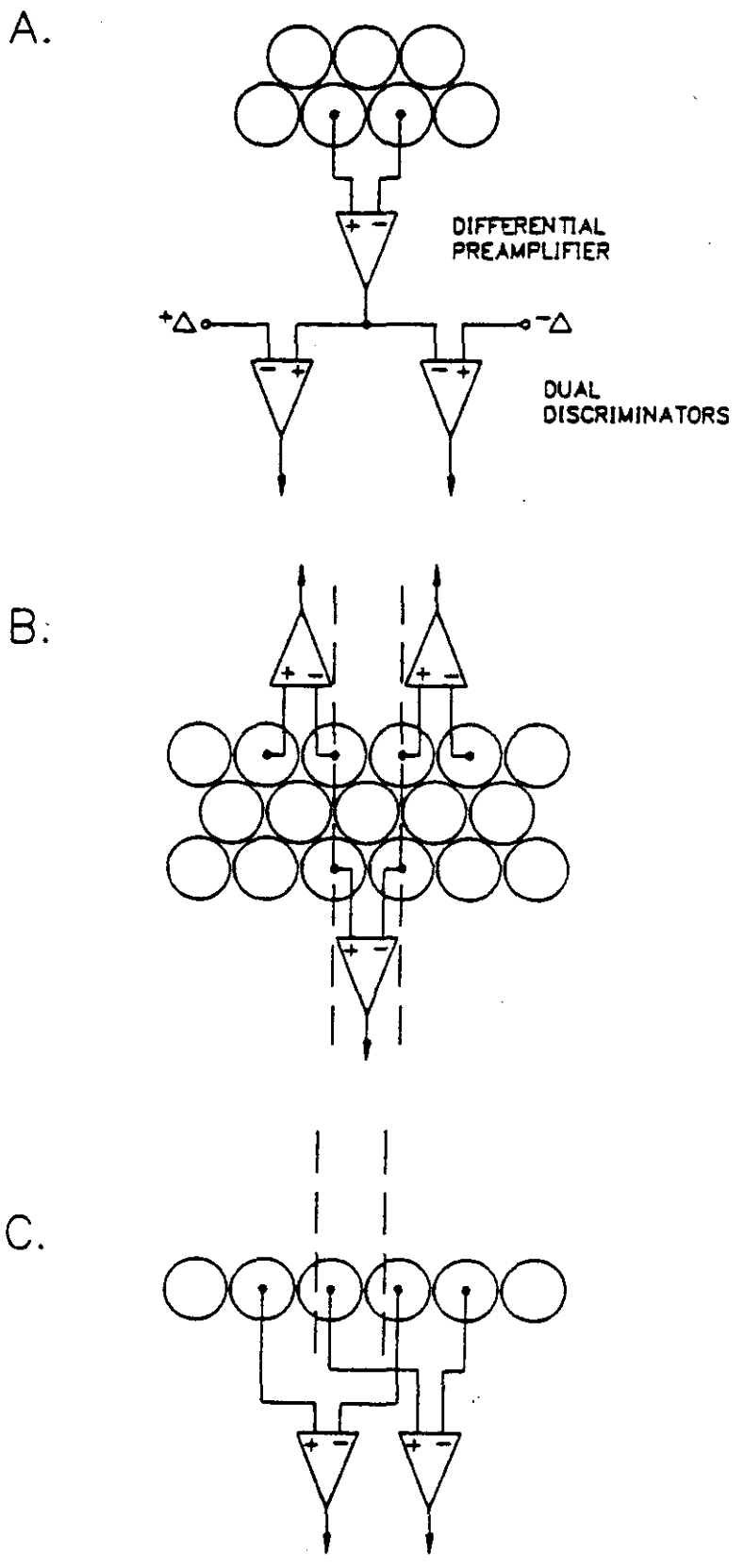


Figure V-3. Differential Preamplifier Connections

A third critical design tradeoff concerns the method used for supplying the high voltage bias between the sense wire and the tube wall. Traditionally, high voltage is applied to the sense wire through a limiting resistor while the tube wall is held at ground. The resistor protects the supply in the event of a broken wire and prevents sustained arcing. (Arcing can be triggered by high density tracks that pass through the center of the tube.) The disadvantage of this scheme is that a physically large, high-voltage capacitor is required to couple the sense wire to the preamplifier. This capacitor will aggravate the mechanical design and may also be a source of inter-channel crosstalk. In contrast, if the high-voltage bias is applied to the tube walls, the sense wires can be dc coupled to the charge sensitive preamplifiers. Limiting resistors could be introduced by using an anodized contact surface where the end plate contacts the aluminized surface of the tube. However, this approach may aggravate electromagnetic interference as the shield is resistively decoupled from the supply. These and other related design concepts will be analyzed further.

3. Tasks and Schedules

Tasks and schedules for the development of electronics for straw tube detection and readout are summarized below.

Task 1 – Evaluation of Prototype Front End and Readout IC's, Months 1-6

Task 2 – Front End Chip Redesign, Fabrication and Test, Months 3-12

Task 3 – Electrical End Plate and PC Board Design, Months 9-15

Task 4 – Readout Chip Redesign, Fabrication and Test, Months 6-18

Task 5 – Prototype Assembly and Test Instrumentation, Months 15-24

C. Electronics for Plastic Scintillating Fibers

1. System Approach

The electronics required for detection and readout of scintillating fibers is essentially the same as that described above for straw tubes, except that the optical signals from the fibers are first converted into low-level electrical signals by a photo-conversion device. Given these low-level signals, front-end circuity (again consisting of a preamplifier, pulse shaper, and discriminator) is used to obtain logic-level signals which indicate the detection of a scintillation event. Traditionally, the readout circuity stores

these signals as a digital record of scintillation for a given bunch crossing. For the hybrid detector, a readout circuit is desired that can record the arrival time of the scintillation photons. This information will provide a coarse measure of the position of the particle track, which will be used as an aid in track reconstruction. Therefore, the integrated circuits required for the scintillating fibers are functionally equivalent to those required for straw tubes. It is anticipated that the same readout chip can be used for both systems. However, it is likely that a redesign of the bipolar preamplifier will be required as the target photo-conversion devices produce smaller signals and do not need a matched input impedance.

At the present time, the only readily available photo-conversion devices suitable for use with long, small diameter scintillating fibers are photo-multiplier tubes (PMT's), microchannel plates (MCP's), and avalanche photo diodes (APD's). Although these devices are available in a variety of types and configurations (number of elements), they share the common characteristic that they are extremely expensive, on the order of hundreds of dollars per channel. Recently, two solid-state photo-conversion devices have been developed which ultimately may be low enough in cost to realize systems with tens of thousands of channels [V-2,V-3]. However, neither device will be available in a multiple element configuration in time for use in the hybrid detector prototype. Therefore, this project will employ conventional, multi-anode PMT's or MCP's to instrument the hybrid CTC prototype, and will include a parallel effort to develop a scintillating fiber readout based on the RCA "Slik" (super-low k) APD [V-2].

2. Critical Issues and Design Tradeoffs

Measurement of the scintillation light in long, small diameter fibers may approach the detection of single photons for minimum ionizing events. The actual amount of light available for detection depends upon the type of fiber, diameter of the fiber, amount of energy absorbed in the fiber, the wavelength of the scintillation light (or that of a wavelength shifter), and the distance from the energy absorbing event to the light sensor [V-4]. Since the number of photons will be very low in number and each event should be detected, the quantum efficiency of any photo-conversion device becomes one of the critical issues in the success of the system. Both PMT's and MCP's have semitransparent photocathodes which have relatively low quantum efficiencies, in the range of 15% to 25%. Given these efficiencies, the smallest reliably detectable event must present at least 5 or 6 photons to the photo-conversion device. Avalanche photo diodes on

the other hand, can have quantum efficiencies of more than 90% [V-2], and the Rockwell solid-state photomultiplier (SSPM) has a development goal in this range.

In addition to quantum efficiency, the new solid-state devices under development at RCA and at Rockwell provide the potential for a significant cost advantage over PMT's and MCP's as single-chip, multi-element arrays can be fabricated at a greatly reduced per-channel cost. Per-channel costs of $10-20 seem realistic in the quantities required for an SSC detector. However, both of these solid-state devices must be operated at crogenic temperatures in order to reduce internally generated noise to acceptable levels. The RCA APD's have a significant advantage here in that acceptable noise performance may be obtained at room temperature or with thermoelectric cooling to -25–0°C [V-2]. In contrast, the projected operating temperature for the SSPM is 7°K.

Given that requirements for cryogenic operation will be common at the SSC, the availability of liquid helium and liquid nitrogen may not be a problem. However, the need for cryogenic operation may require extending the scintillating fibers with nonscintillating light guides in order to reach the readouts if the readouts must be accessible for operating maintenance. The main difficulty in the extension of scintillating fibers with nonscintillating light guides is splicing the two types of fibers with minimum light loss. Also, while timing accuracy should not be affected, several tens of nanoseconds of latency will result, which may add to the trigger delay. If it is determined that adequate cooling of a solid-state device can be achieved within the chamber, the radiation tolerance of these devices will be called into question. If a radiation hardened device is possible, it would obviate the need for extension of the fibers by splicing.

It should be noted that a similar constraint is present with conventional tube-based readouts, which are highly sensitive to magnetic fields. Although this problem can be solved with careful orientation of the PMT's or MCP's, the field sensitivity of these devices would nevertheless place a constraint on the physical location of the scintillating fiber readouts. In contrast, the solid-state photo-conversion devices are almost immune to the magnetic field strengths expected during operation of the tracking system.

As a result of their potential cost advantages, solid-state photo-conversion devices appear to be the best prospect for use in the final SSC detector. However, a substantial effort will be required to develop devices specifically tailored for use with small-diameter plastic scintillating fibers. Although Rockwell has already demonstrated the use of SSPM's

with scintillating fibers, the RCA APD is an attractive alternative due to its higher operating temperature. RCA will collaborate in this program on the development of a demonstration readout based on APD arrays. This effort will include device design and characterization, concepts for packaging and optical coupling to ribbons or bundles of fibers, and preamplifier design and packaging. RCA has demonstrated a technology for linear APD arrays for fiber optic communication systems, however, these devices are not suitable for direct use with scintillating fibers [V-5]. APD arrays for scintillating fibers will be developed based on the "Slik" (super-low k) device. These devices, when operating in "normal" mode near breakdown, should provide a 40% detection probability for single photons, improving to more than 90% for multiple photon events (5-10) [V-2] (see Figure V-4). This level of performance requires careful control of bias to achieve high gains and the use of very low noise preamplifiers to achieve a low false detection rate. Device design must therefore be closely coupled to the development of bias and preamplification circuits. An initial concept for packaging of linear arrays with ribbons of fibers is shown in Figure V-5. Alternative packaging concepts will be investigated for coupling bundles of fibers to mosaic arrays.

3. Tasks and Schedules

Tasks and schedules for the development of instrumentation for beam testing of scintillating fibers and for the development of an APD based readout are summarized below.

Task 1 – Evaluation of Current Generation APD's, Months 1-6

Task 2 – System Tradeoffs for APD Versus SSPM Devices, Months 3-9

Task 3 – Evaluate Straw Tube IC's for Use with Scintillating Fibers, Months 6-9

Task 4 – Design Fabrication and Test of APD Arrays, Months 6-15

Task 5 – Design, Fabrication and Test of Preamplifier IC's for APD Arrays, Months 9-18

Task 6 – Design of Packaging for APD Arrays, Months 12-18

Task 7 – Design and Assemble PMT or MCP Based Instrumentation for Beam Testing, Months 15-24

Task 8 – Assemble and Test APD Based Readout, Months 18-24

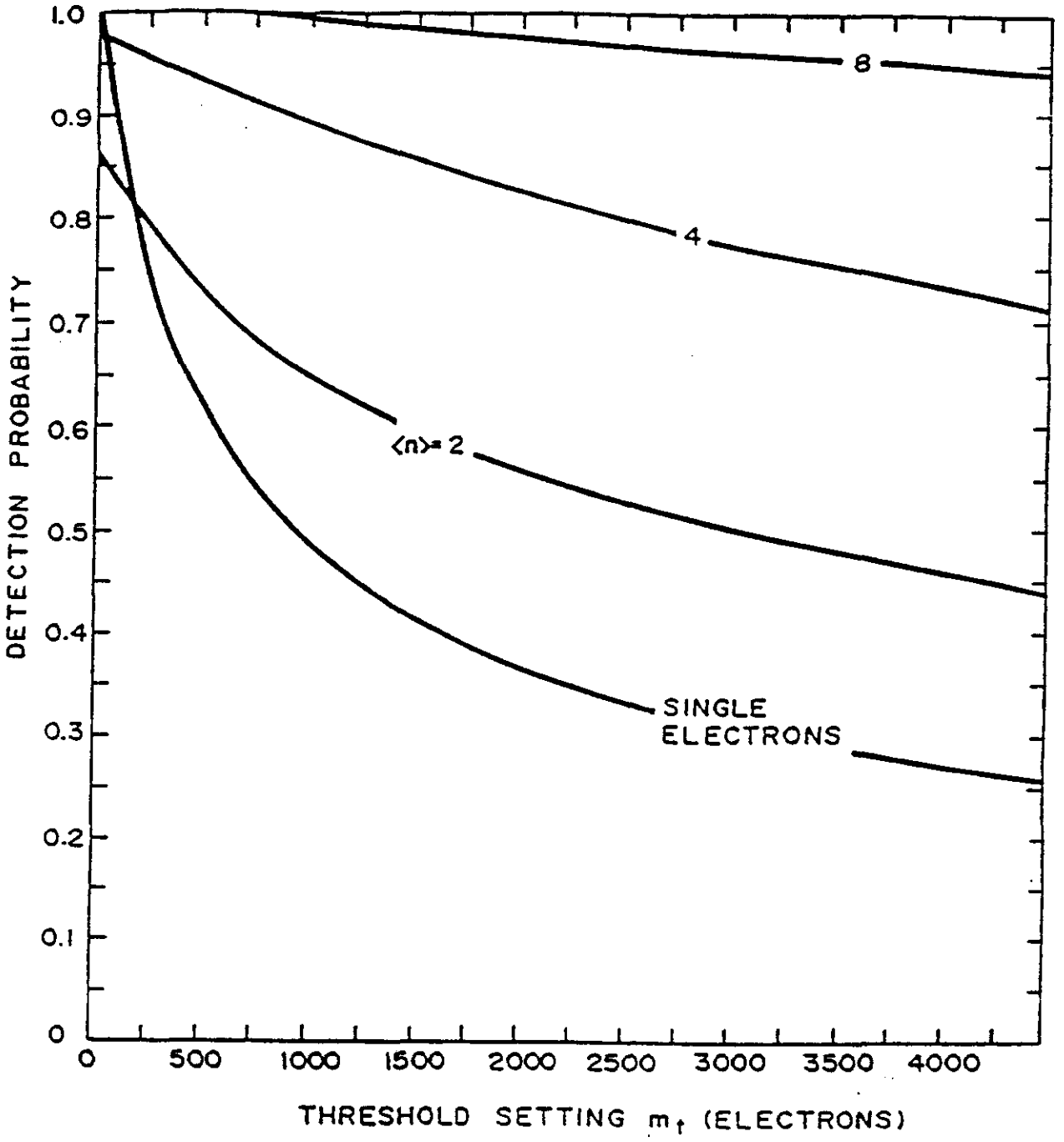


Figure V-4. Detection Probability for Both Single and Multiple Photoelectron Pulses as a Function of Threshold Setting Assuming the Diode Voltage is very Close to its Breakdown Voltage

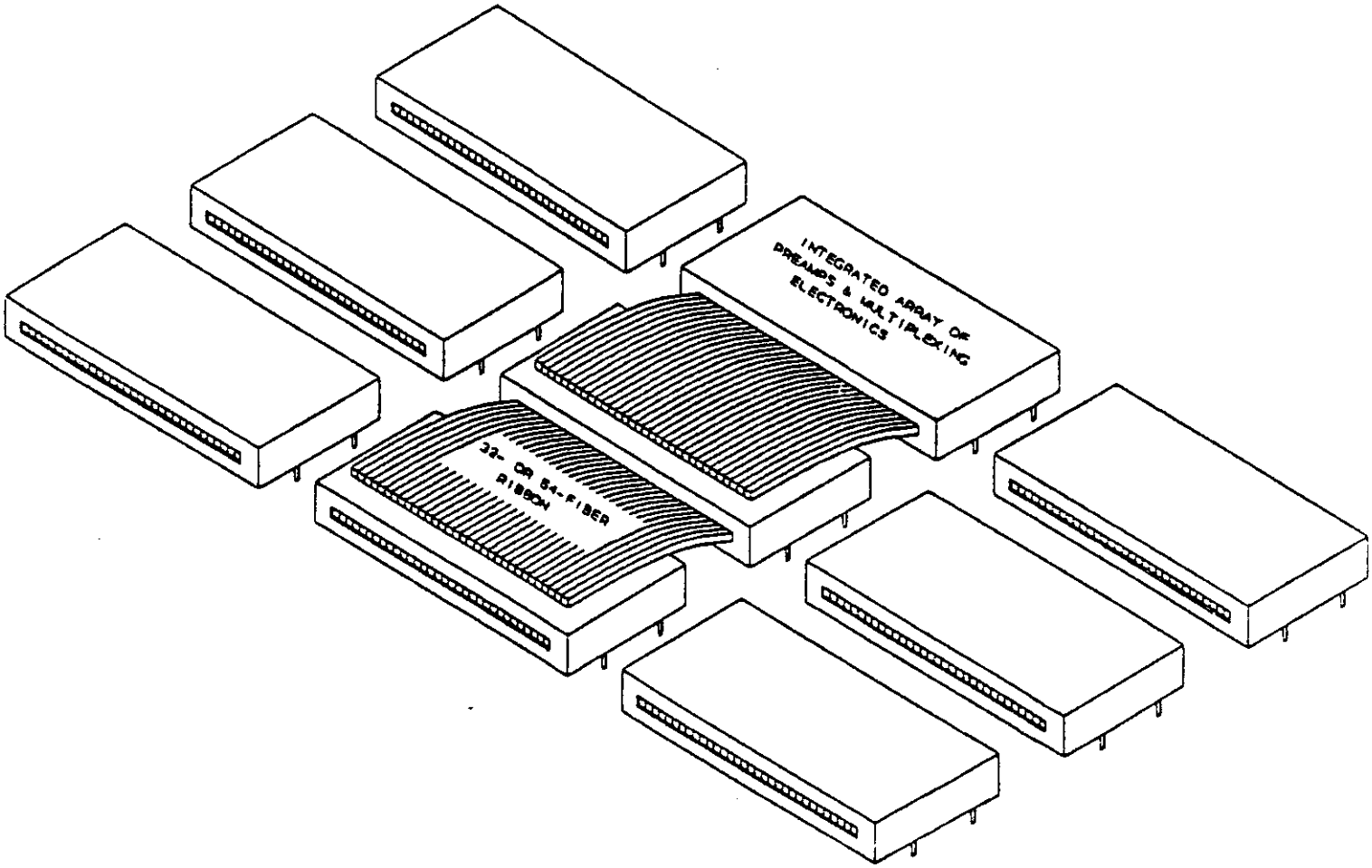


Figure V-5. Proposed Packaging Concept for Use with Fiber Ribbons and Integrated Amplifier Arrays

VI. Radiation Damage Measurements

The radiation environment near the beam axis at the SSC will be quite hostile. For instance, at 10 cm radius, the radiation dose is estimated (see Ref. VI-1 and Figure VI-1) to be about 0.4 Mrad/yr and the occupancy would be 20% per event (see Figure VI-2). Primarily on this basis, the minimum radius of our hybrid CTC is expected to be on the order of 30 cm; at this distance, fluxes in excess of 10^5 particles/(cm^2-sec) and radiation doses of the order of 0.04 Mrad/year are expected to prevail; these conditions would lead to an average cell occupancy of about 6% per SSC event. All components (e.g., straw tubes, central wires, scintillating fibers, electronics, structural components, glues, etc.) must be able to withstand these harsh conditions without significant loss of integrity. Based on an operating lifetime of five to ten years, our design goal for the hybrid CTC is thus set at about 2-4 Mrad. In order to assure the proposed detector would be sufficiently radiation resistant, we plan to conduct the following series of radiation damage studies and tests: straw-tube ageing studies (at UF), neutron irradiation studies (Quantum), Co^{60} irradiation tests (Quantum and NCSU), and electron studies (FSU).

A. Straw Tube Ageing Studies

Apart from the obvious operational problems of a potential detector due to high rates (physical limits in the detection processes and limits in electronic readout/data accumulation), charged-particle and neutron-albedo radiation will cause damage to construction materials of the detector and will produce ageing in the active, gaseous detector volume as a result of the radiation-induced ion and molecular chemistry [VI-2, VI-3]. Assuming that the minimum practical cell size will be about 3 mm in diameter and that an average avalanche carries a charge of about $3*10^6$ electrons, the total collected charge per unit length of wire will be about 0.02 C/(cm-yr) at 50 cm radius (this increases to about 0.5 C/(cm-yr) at 10 cm radius). In order to achieve operation over many years, straw tube lifetimes approaching or exceeding 2 C/cm will thus be necessary. We propose a multi-stage ageing study, described below, which is designed to test whether such lifetimes can be achieved within the SSC radiation environment.

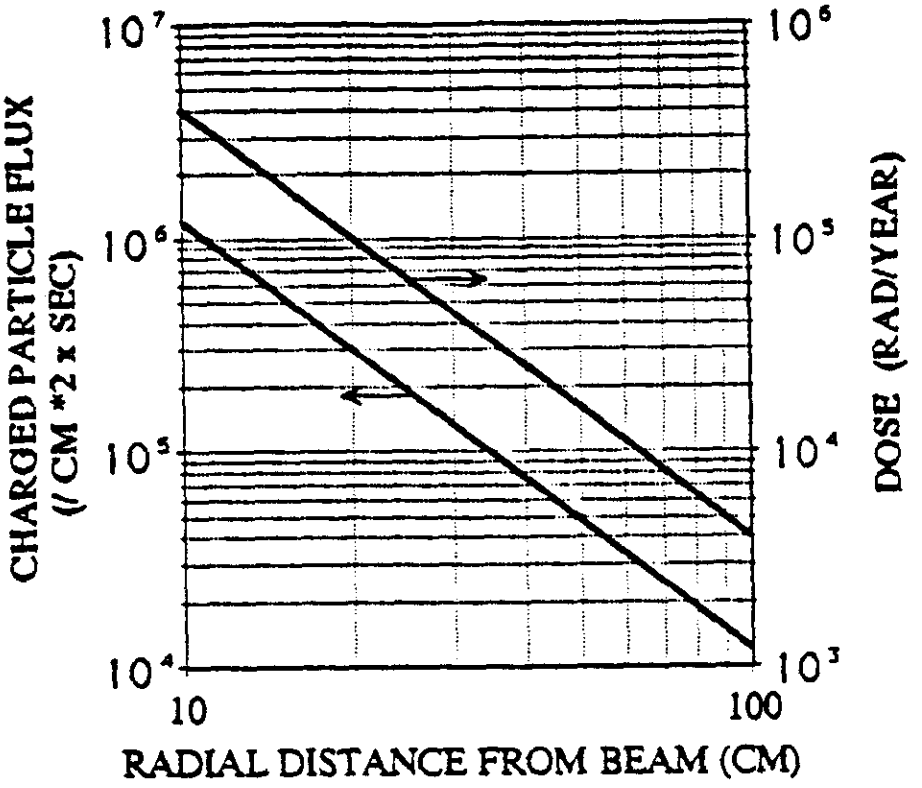


Figure VI-1. SSC Charged Particle Flux/Annual Dose

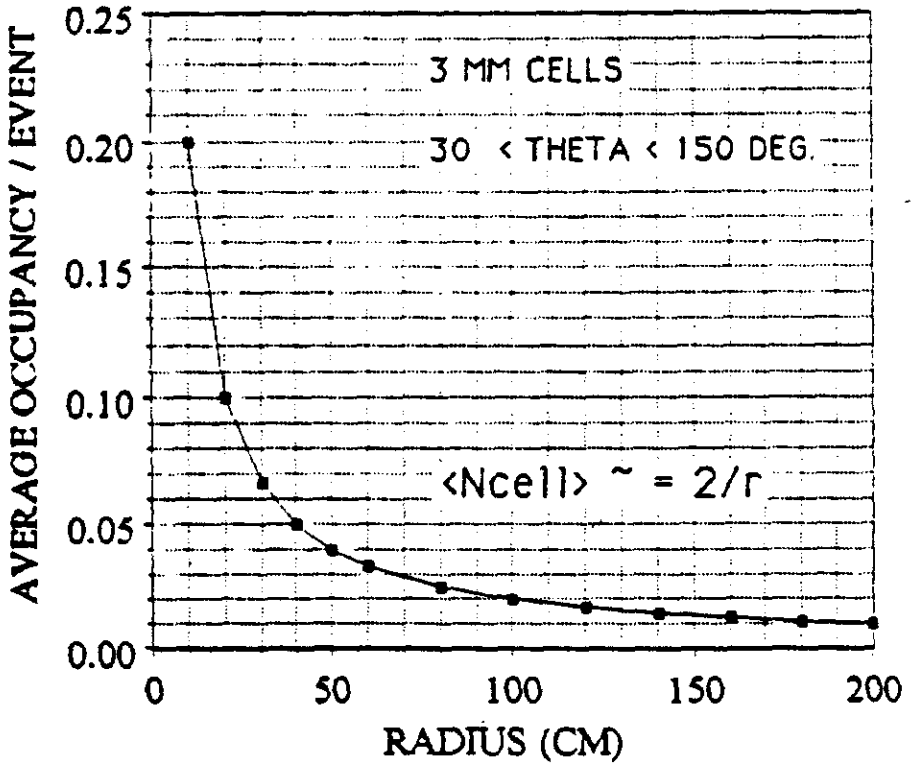


Figure VI-2. SSC Central Tracker Cell Occupancy

1. Preliminary Testing

First, individual tests of specially selected very pure construction materials will be conducted, in order to separate effects of gas from effects of practical materials preselected for use in the real detector. Such a preliminary study should eliminate some gas candidates as unacceptable for use. As a part of this study, tests will be performed with different cathode/anode materials. In the case of cathode material, inner straw coatings other than aluminum will be considered because of the etching and oxidation of aluminum layers reported in many ageing studies. Materials such as graphite, gold, etc., will also be tried, depending on the availability of different coated straws, which may also be made from plastics other than mylar. At least two types of anode wires of different diameters will be tested: standard gold-plated tungsten or molybdenum and stainless-steel wires, which combine chemical resistance and very good surface quality (relevant to the ageing problem).

2. Studies Under Realistic Conditions

The second series of tests will be performed in conditions as close as possible to the realistic final conditions planned for the detector. As discussed in Section IV.A.2.b, a small-scale engineering model, using exactly the same materials (epoxies, glues, etc.) and the same construction methods as selected for production, will be developed specifically for radiation testing. Several iterations of these hopefully "converging" tests can be envisioned with the final ones performed at dose rate, gas purity, gas exchange rate, and gas amplification factor values expected in the real experimental environment. There is, of course, a limit to what is practically feasible in these accelerated ageing tests.

Selections made as a result of this two-stage ageing study should give us confidence that the hybrid CTC as finally constructed will remain functional through many years of SSC operation.

3. Straw Outgassing Test

A separate study will address the problem of radiation damage to straws. The common part of these two tests, however, is the radiation-induced outgassing from the straw materials and gas tubing which could potentially lead to gas poisoning and consequent ageing. A possible procedure will include irradiation of straws filled with selected working gases in the 3 MeV Florida State University electron beam followed by

chemical analyses of gas samples. Also, laboratory ageing tests performed with powerful electron sources will simulate charged-particle radiation damage to straws, with accompanying outgassing. etc.

4. Ageing Limit

It is reasonable to assume that a longevity safety factor of about 10 should be set as a goal of these laboratory studies. Referring to the numbers presented in the introductory section, this translates (at a radius of 10 cm from the beam axis) to a charge limit of at least 2 C/cm-length-of-wire per "accelerator year" of 10^7 seconds. This scales according to $1/r^2$ and so is about 0.2 C/cm at 30 cm radius and less than 0.1 C/cm at 50 cm radius. Assuming that 10 years is an acceptable lifetime for the detector, the innermost part should survive total collected charges on the order of 2 C/cm. If a radius of less than 30 cm is desired, the mechanical structure should probably allow for replacement of the inner part of the detector.

Despite all precautions, one cannot rule out long-time ageing effects, which are practically impossible to study in a laboratory, as well as accidental events such as poisoning of gas by malfunction of the purification system.

To be consistent, all the construction materials, including glues, straw material (aluminized Mylar bonded with polyethylene or any other straw versions), feedthroughs, etc., should be selected from materials which do not substantially change their mechanical properties up to at least a total radiation dose of 2 Mrad (charged particles only). Also, tests with fast (1 MeV or so) neutron beams should be performed up to fluences of 10^{13} neutrons per cm^2 (see Section IV.B below).

5. Experimental Procedure

a. Sources

Most irradiations of single wire modules and straws will be performed with intense 6-8 keV X-ray beams from X-ray generators (Figures VI-3 and VI-4). Our devices (two types, produced by X-Tech Corp., each having different target materials) deliver a wide, diverging, and very intense continuous X-ray beam, which can be collimated

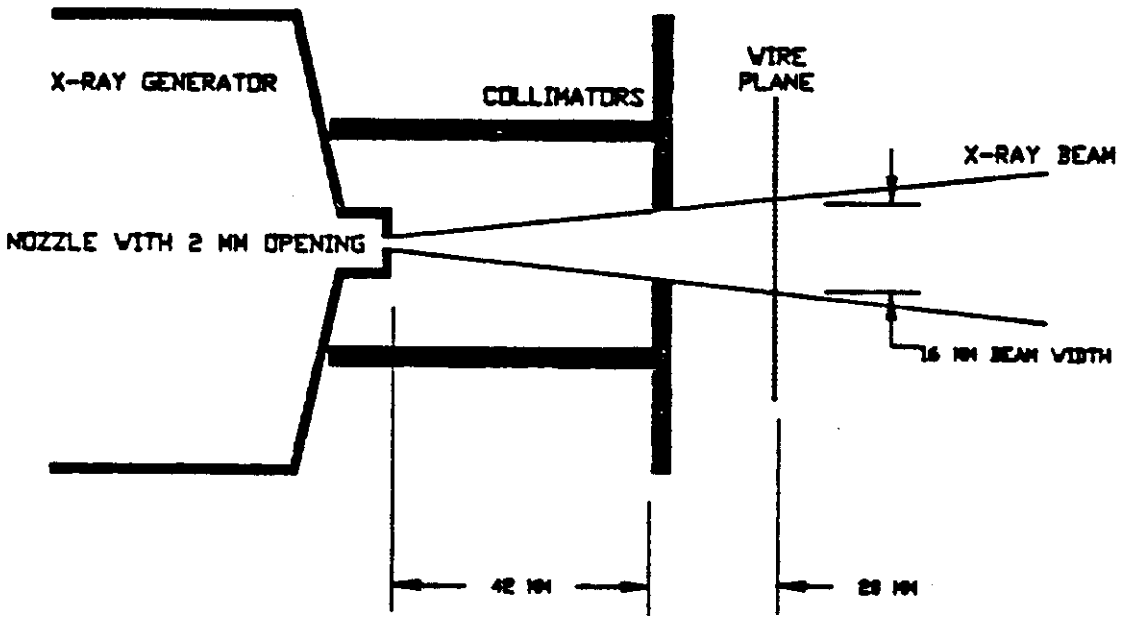


Figure VI-3. Irradiation Geometry for the High-Density Chamber

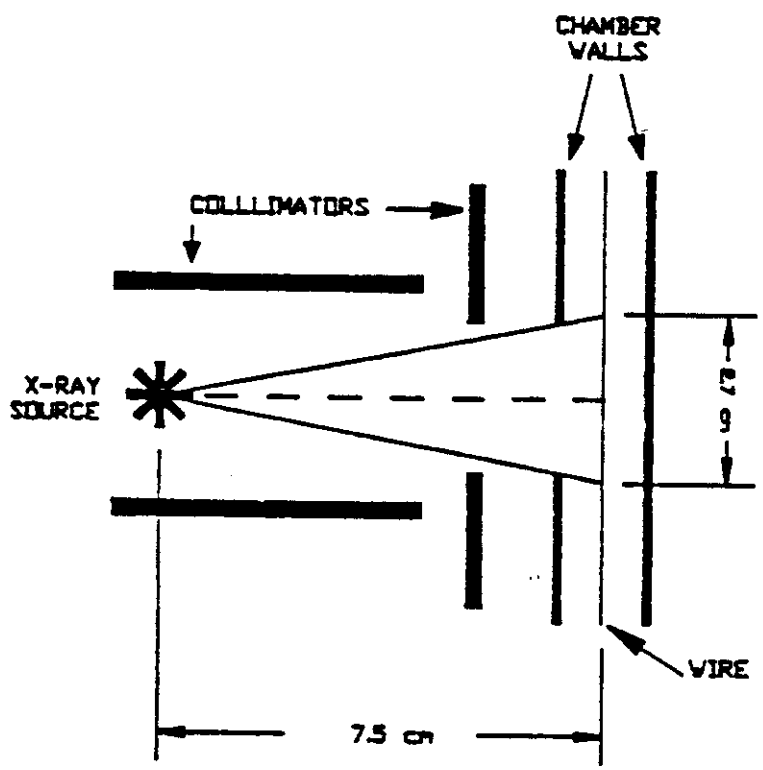


Figure VI-4. Irradiation Geometry for the Single Wire Chamber

down to the necessary area. Several modules will be irradiated at the same time. The generator temperature is stabilized with circulating cooling water, and its operation is very stable for periods of up to many weeks continuously. To make sure that any changes in the beam intensity are accounted for, a reference sealed proportional X-ray detector will be placed behind the irradiated component and a partial beam absorber, operating with a mixture of Xenon and CO_2 will be used to check beam intensity at regular time intervals. Some irradiations will be performed with a powerful Sr^{90} electron source, to include effects of construction material outgassing, discussed previously.

b. Control Parameters

In the proposed test-bed, a continuous electric current flowing in the detector under test, caused by ionization from X-ray conversions in the gas volume and amplified by a given gas multiplication factor, will be monitored at equal time intervals by a computer. Also, many other relevant variables, such as operational voltage, temperature, pressure, and gas flow will be read at the same time (Figure VI-5) and the effects of varying pressure/temperature on the output will be corrected for (Figure VI-6 shows an example of a typical I/p/T daily variation). Amplification curves, such as the one presented in Figure VI-7, will be measured in the actual ageing test conditions in these highly accelerated damage tests as compared to the real life experimental situation in the SSC environment. At high current levels (~1 μamp), space charge effects are typically observed, depending on the exact cell structure, size, sense wire diameter, gas type, amplification factor, etc.; thus, care will have to be taken to achieve the desired collected charge of 2 C/cm in realistic irradiation time periods (months or less).

c. Signs of Ageing

Examples of current versus time curves obtained during long irradiation studies performed at UF with DME gas are shown in Figure VI-8(a). The curves on the left represent a detector showing signs of deterioration, and those on the right, one that remains stable. Though decreasing current is an indication of damage, the relative change in current does not reflect (usually it greatly underestimates) the actual damage due to typical saturation conditions. Therefore, at approximately equal time intervals the assessment of damage will be made by measuring pulse-height spectra with a 6-keV Fe-55 X-ray source (Figure VI-8(b)). Also, signs of increased dark currents, for example, due to Malter effect on cathodes, sparking, or other sources of noise will be examined.

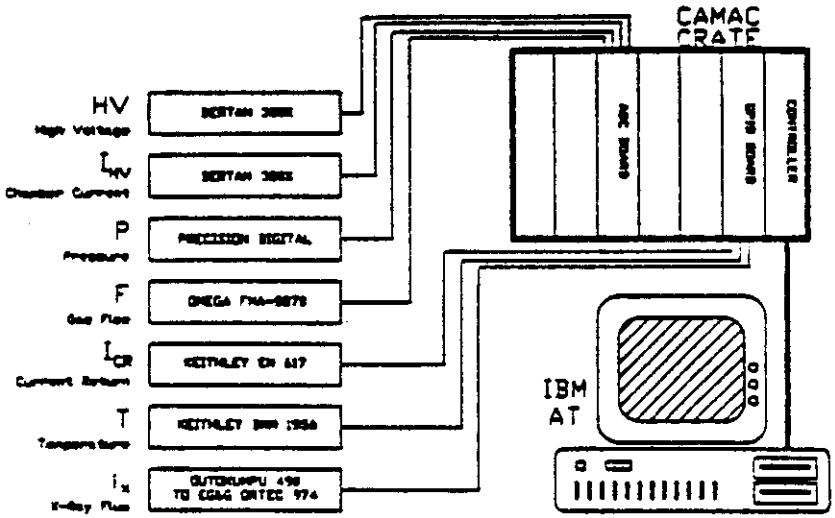
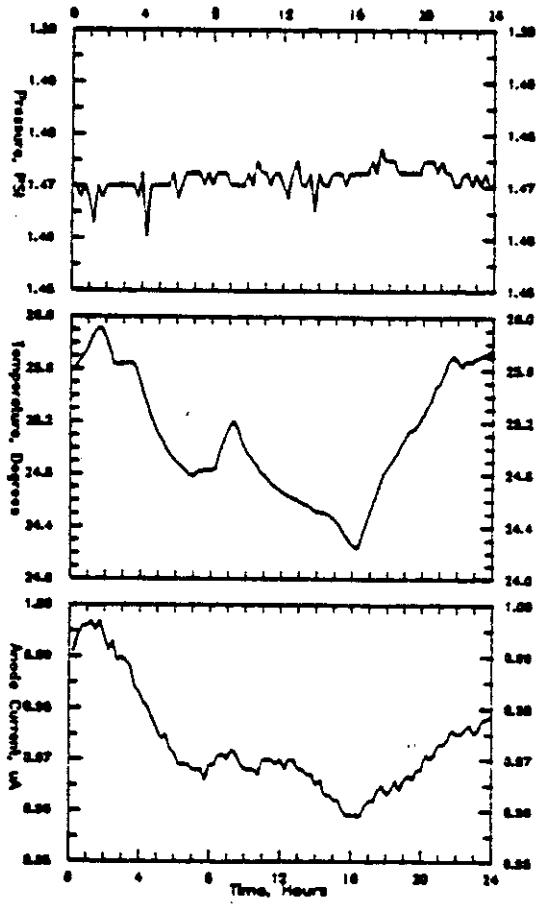
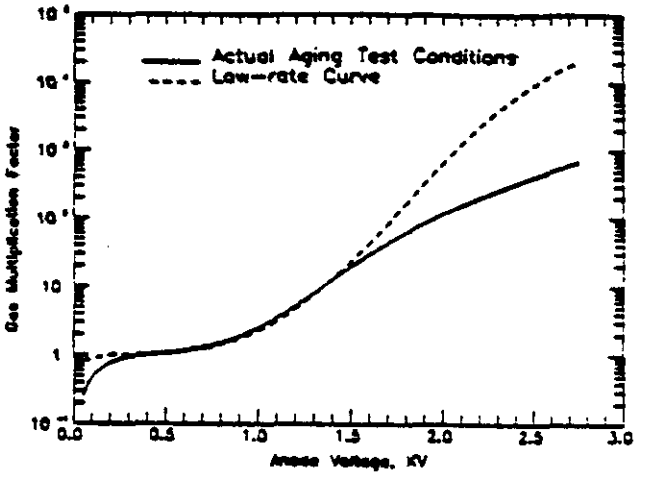


Figure VI-5. Computer-Controlled Monitoring System



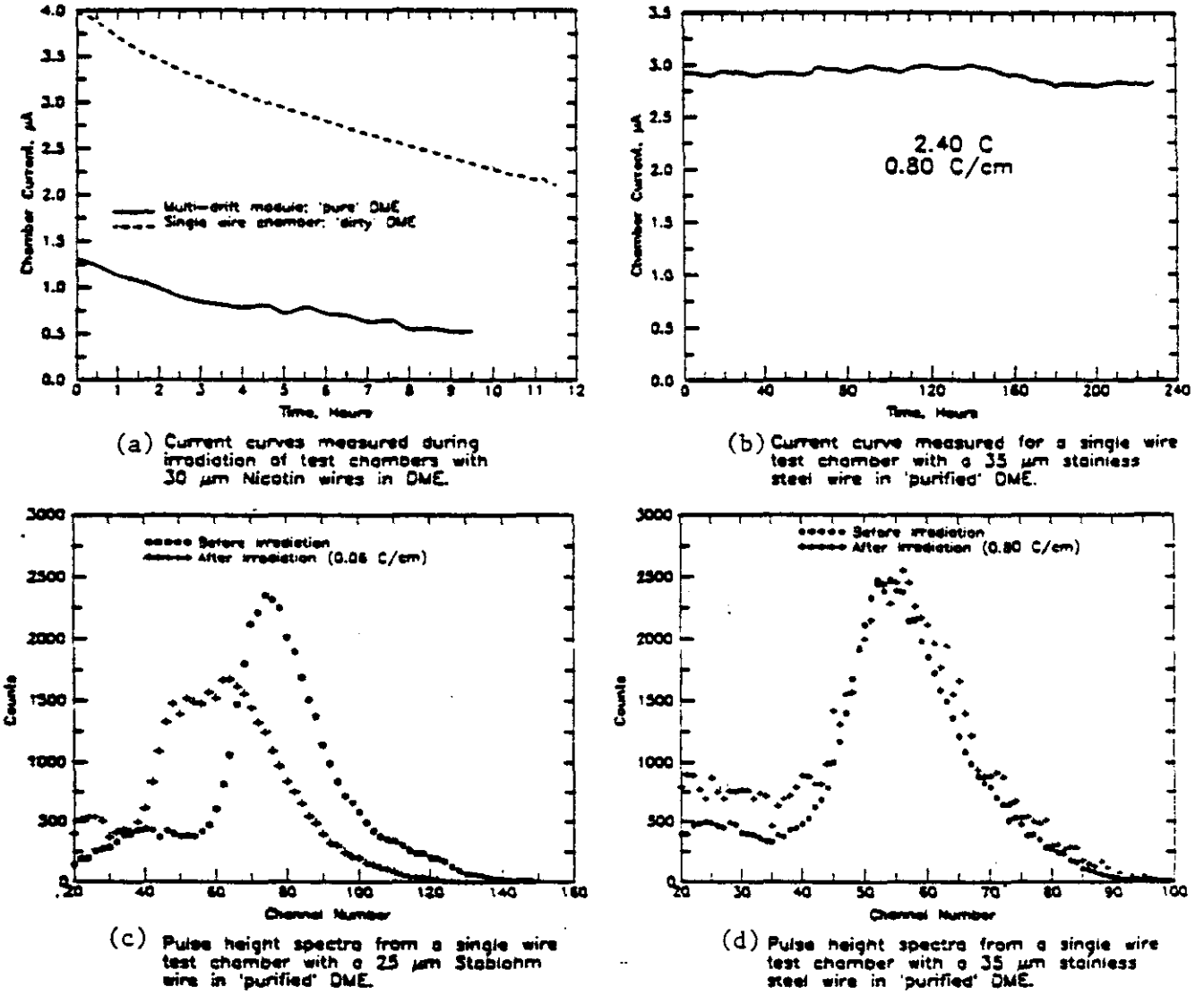
Chamber: Single wire test chamber with 50 microns stainless steel wire.
Gas mixture: Purified 'dirty' DME.

Figure VI-6. Typical Daily Pressure, Temperature, Current Variation



Absolute amplification curves for a single wire test chamber with a 35 μm stainless steel wire in 'purified' DME.

Figure VI-7. Amplification Curves for 35 μm Stainless Steel Wire in "Purified" DME



(a) Current curves measured during irradiation of test chambers with 30 μm Nicotin wires in DME.

(b) Current curve measured for a single wire test chamber with a 35 μm stainless steel wire in 'purified' DME.

(c) Pulse height spectra from a single wire test chamber with a 25 μm Stablohm wire in 'purified' DME.

(d) Pulse height spectra from a single wire test chamber with a 35 μm stainless steel wire in 'purified' DME.

Figure VI-8. Current Curves and Pulse Height Spectra for Typical Ageing Studies

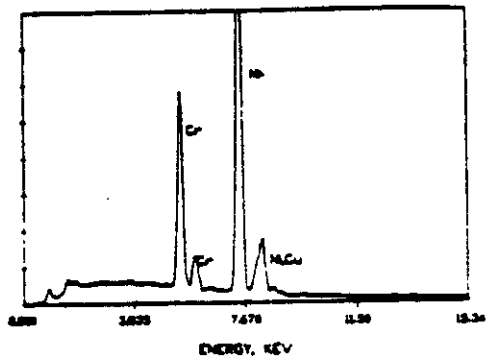
d. Analysis of Deposits

After detecting damage, and before making the final decision to accept or abandon a given gas or construction we shall try to understand the source of damage. This is usually quite difficult, but the great body of available experimental data on gases, and on the role of impurities in causing damage [VI-2,VI-3] should help to provide the necessary understanding.

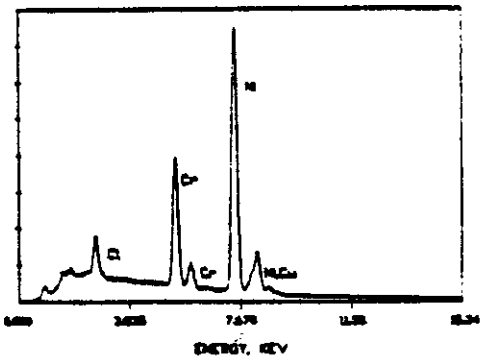
As an example, Figures VI-9 and VI-10 show some examples of surface analyses of sense wires performed at UF as a part of damage studies with DME gas. A chlorine signal is evident in Figure VI-9 which shows the results of the Energy Dispersive X-ray Spectroscopy (EDX) analysis of the surface of a damaged Stablohm wire. The peak was attributed (and was later confirmed) to the contamination of DME gas by chlorinated freons, mostly Freon 11. The spectra in Figure VI-10 were obtained by the Auger Electron Spectroscopy (AES) technique, and again show chlorine on the same Stablohm wire (Figure VI-10(a)) as well as silicon deposits on a gold plated molybdenum wire (Figure VI-10(b)), which had been damaged in a test with a silicon oil bubbler. Such measurements, combined with scanning electron micrographs of damaged wires, should help in elucidating the cause of damage and in selecting improved operational conditions.

e. Gas Analysis

In the case of highly reactive chlorinated freons, a simple method of gas chromatography can be used to detect their presence in gas. The gas chromatograph at UF will be used to analyze gases for these impurities, as well as other (not only electronegative) admixtures. Figure VI-11 shows an example of earlier analysis of two DME batches (regular, pure, or dirty (Figure VI-11(a)) and purified (Figure VI-11(b)) showing different levels of freon contamination. Table VI-1 lists all the impurities identified at UF in the tested samples of DME. These results were very helpful in defining maximum freon levels to avoid ageing in the laboratory conditions. In the particular case of freon impurities in DME, the final definition of a freon mostly responsible for damage can be done by contaminating the very pure DME in a controlled way and performing a series of ageing tests. In the tests represented by Figure VI-12, for example, it was exstablished that ageing with regular purity (contaminated) DME was mainly attributable to Freon 11.

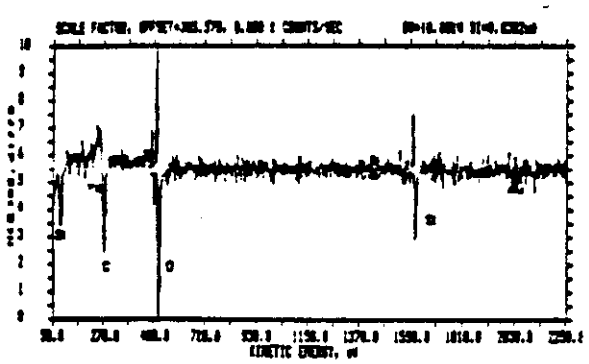


Clean Stablohm wire



Irradiated Stablohm wire. Note presence of chlorine peak, attributed to freons.

Figure VI-9. Example X-ray Spectroscopy Analysis of Sense Wire



AES spectrum for an irradiated 50 μm gold-plated molybdenum wire showing silicon, carbon and oxygen peaks.

Figure VI-10. Example Auger Electron Spectroscopy Analysis of Sense Wires

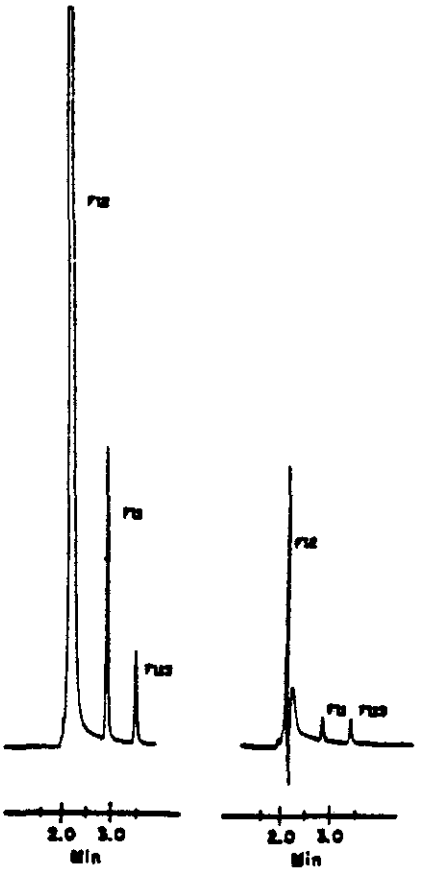


Figure VI-11. Gas Chromatograms of "Dirty" (left) and "Pure" (right) DME Samples from Matheson

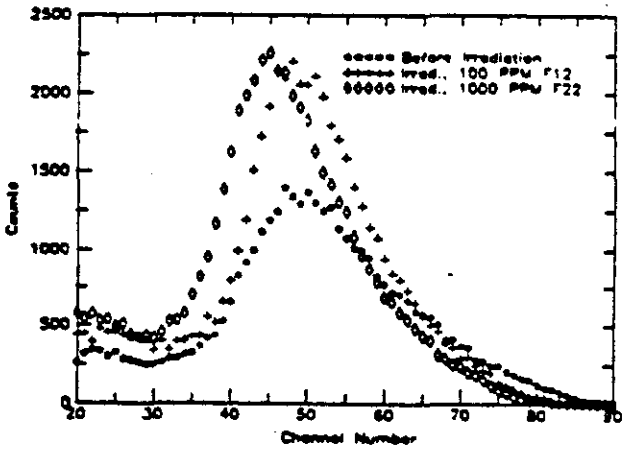


Figure VI-12. Pulse Height Spectra from a Single Wire Test Chamber with a 35 μm Stainless Steel Wire in Pure DME with Controlled Freon Contaminations

Table VI-1.

Impurity Levels of Different Contaminants in Dimethyl Ether as Determined with Gas Chromatography Utilizing Electron Capture and Flame Ionization Detectors

	DME Grades			
Contaminant	"Dirty"	"Pure"	"Purified"	"CERN"
Freon-11	0.2 ppm	10 ppb	≤ 1 ppb	150 ppb
Freon-12	45 ppm	1 ppm	Trace*	160 ppb
Freon-22	870 ppm	< 15 ppm	< 15 ppm	Not Checked
Freon-113	Trace*	Trace*	No Trace**	Trace*
Methane	30 ppm	100 ppm	40 ppm	Not Checked
Ethylene	15 ppm	80 ppm	Trace*	Not Checked
Propylene	120 ppm	20 ppm	40 ppm	Not Checked
Isobutane	290 ppm	10 ppm	245 ppm	Not Checked

* Trace = Chromatographic peak was too small to be integrated.
** No Trace = No peak was visible.

Since various mixtures of various gases, such as CF_4, isobutane, CO_2, CH_4, DME, etc., will be tested in straws, it is difficult to be more specific at this time on the kind of tests which should be performed; this will be decided when the time comes. We are confident that drawing from the previous experience, we will be able to find a correlation between ageing and the types and levels of age-producing impurities. A standard test procedure will include pre-irradiation tests in a gas chromatograph to avoid time-consuming irradiation when obvious poisoning agents such as Freon 11 are present. Samples of gas exiting detector cells will be tested for possible traces of outgassing impurities from construction materials, tubing, etc., or other potentially age-causing species produced in the gas before and during the irradiations with X-rays and electrons. In this part of the study we will consult other groups working on similar problems, and especially the group of Dr. John Kadyk from LBL.

6. Time Schedule

It is estimated that the first year will be spent entirely on systematic ageing studies of different potential gas candidates with different sense wires (three variables: wire material, diameter, and surface quality) in close collaboration with the group of Dr. John Kadyk and with Dr. Openshaw from TRIUMF. As soon as satisfactory results are obtained, measurements with straw candidates will begin. To accelerate the study, many single-wire modules will be irradiated in parallel, making use of the wide and intense X-ray beams. However, as already pointed out, there is a limit to how much the tests can be accelerated. The limit is imposed by the necessarily prolonged final ageing tests performed at low intensity conditions, close to the expected real experimental conditions. For example, the group at TRIUMF has been continuously irradiating some of their modules for about a year now, to confirm the results obtained at high rates.

B. Neutron and Co^{60} Studies

Previous studies [VI-1] have predicted annual neutron fluences on the order of 10^{12} to 10^{13} neutrons/cm^2 at a radius of 2 m and pseudorapidity less than 1.5; the energy spectrum of these neutrons appears to be approximately Gaussian in the logarithm of neutron energy, with a maximum at about 1.3 MeV. Some studies suggest that a comparable thermal neutron flux may also be present, but this has received less consideration because these neutrons are below the 0.15 MeV threshold for neutron damage in silicon devices. We propose as part of this investigation to perform detailed neutron irradiation studies of

various components (scintillating fibers, straw tubes, electronics, and a small subassembly that incorporates these items with structural materials). Over a nominal ten-year performance period, total neutron fluences would be expected to vary from about $4x10^{12}$, at zero rapidity, to about $4x10^{13}$, at $\eta=1.5$.

1. The Neutron Irradiation Facility

We will perform our neutron irradiations at the North Carolina State University (NCSU) PULSTAR reactor, which is operated by the Nuclear Reactor Program within the Nuclear Engineering Department at NCSU in Raleigh. The reactor is a one MW research reactor, with typical in-core neutron flux levels at full power of 10^{13} neutrons/(cm^2-sec), thermal, and 10^{12} neutrons/(cm^2-sec), fast. In addition to various small near-core irradiation tubes, the reactor has six beam tubes, one tangential and five radial, and a bulk irradiation facility at the end of a graphite thermal column. Figure VI-13 presents a plan view of the PULSTAR facility showing these irradiation facilities. Two of the beam tubes are in use (one for neutron radiography and one for thermal neutron prompt gamma-ray analysis), but the remaining beam tubes and the thermal column are available. One of the proposed investigators from Quantum Research Services was formerly in charge of reactor applications on the PULSTAR and installed the prompt gamma-ray facility there, and so is intimately familiar with the operation of the reactor for research purposes.

We intend to use beam tube #1, #3, or #6 (the choice will be made on the basis of specific size requirements), and the bulk irradiation facility (BIF). The BIF is approximately 4-ft by 4-ft by 2-ft, which allows irradiation of larger objects. Because the BIF is on the far side of a large graphite pile, the flux in the BIF is completely thermal; its magnitude is approximately 10^7 neutrons/(cm^2-sec). Beam tube #1 is a 6-inch diameter tube that is directly adjacent to the core, while beam tubes #3 and #6 are larger (8-inch diameter and 12-inch square, respectively), but are slightly offset from and view the core at an angle of about 45 degrees to the normal from the respective face of the core; all three are shown in Figure VI-14. At the core edge of the beam tubes, the full-power flux is estimated to be approximately $5*10^{12}$ neutrons/(cm^2-sec), thermal, and $5*10^{11}$ neutrons/(cm^2-sec), fast. The energy spectra are somewhat thermalized fission spectra, since the reactor is water cooled and moderated, but are not known exactly and so will have to be measured. We will conduct a series of measurements, using activation foil packets and threshold detectors, to estimate the flux spectrum in the beam tube we decide to use.

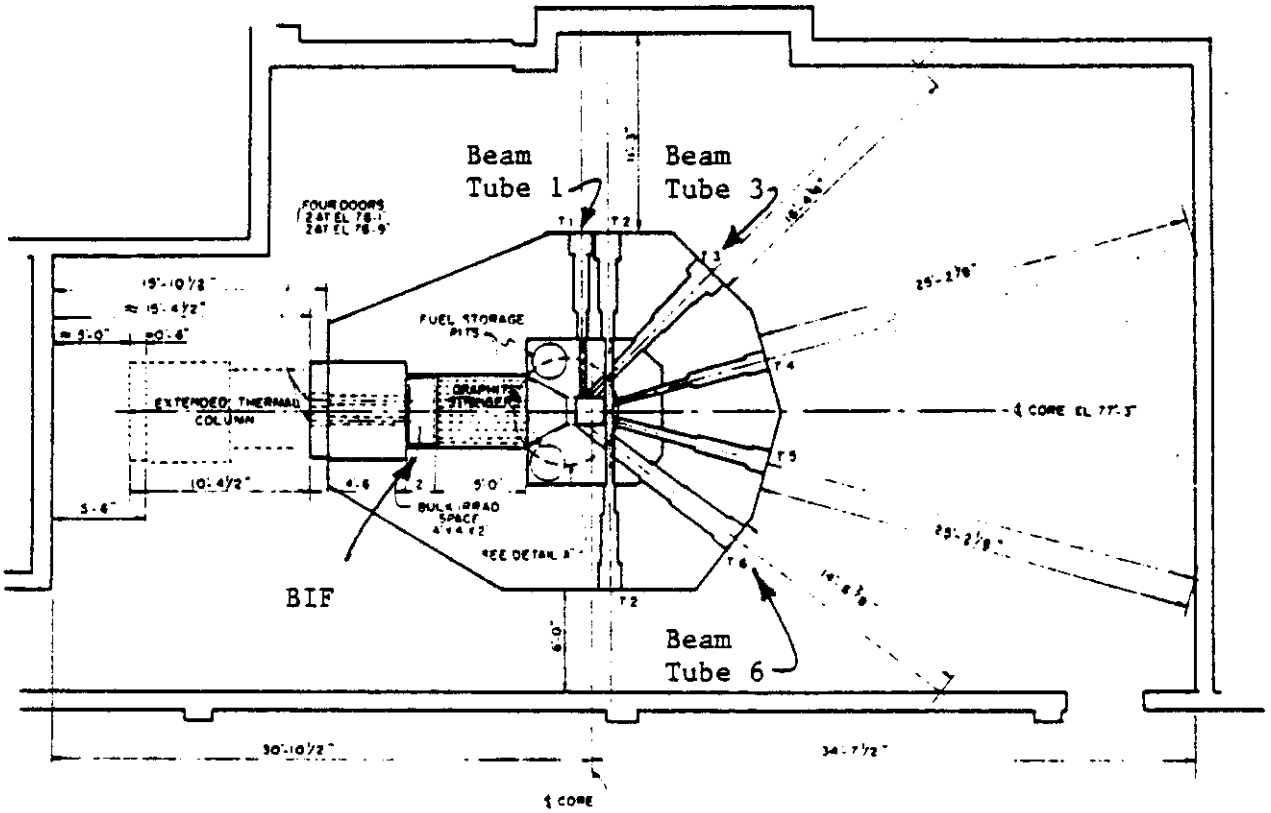


Figure VI-13. Plan View of the PULSTAR reactor

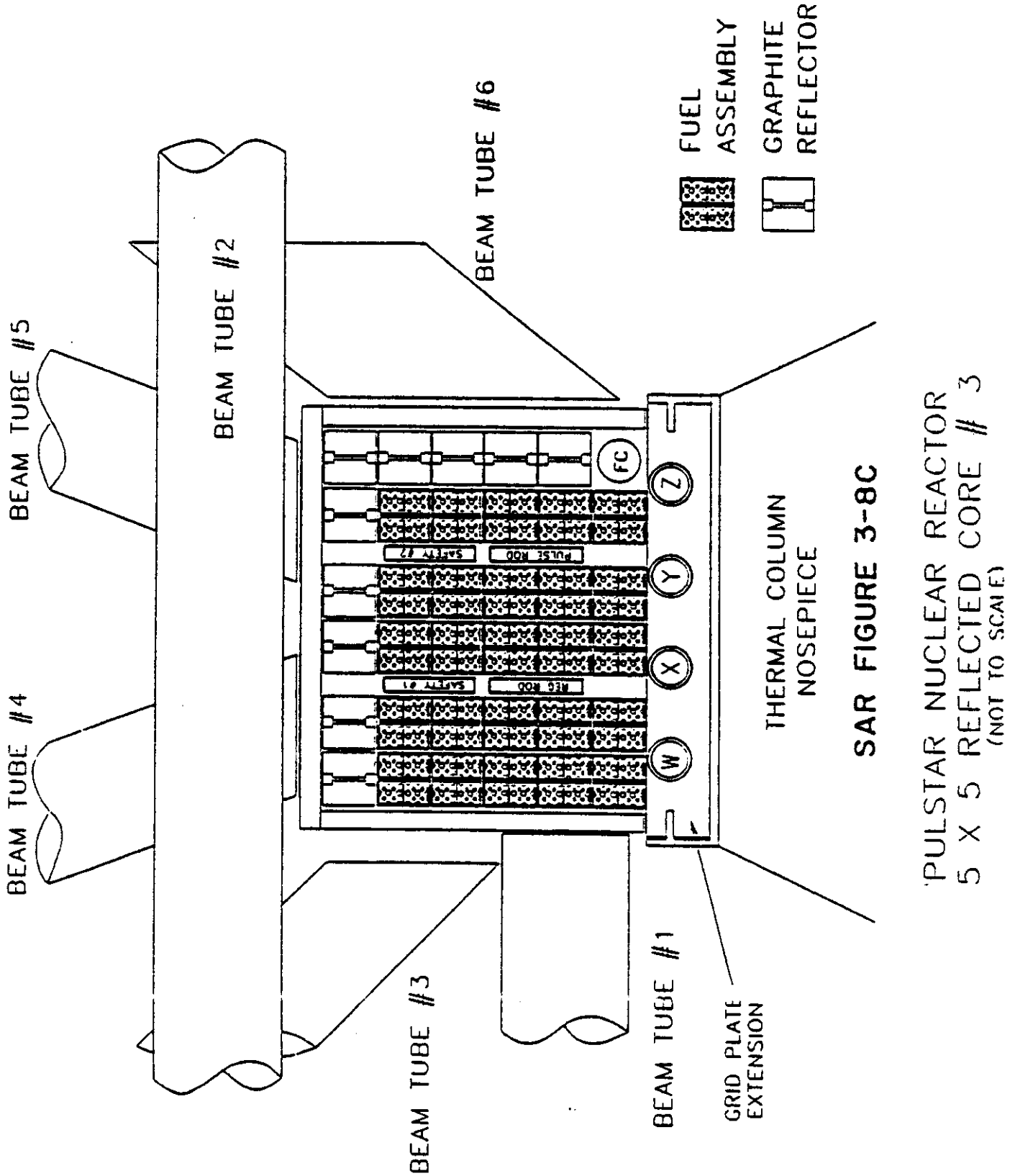


Figure VI-14. PULSTAR Core and Beam Tube Arrangement [VI-4]

In order to obtain a fast flux, we will attempt to use cadmium between the core and the sample to absorb the thermal neutrons (the reactivity effect on the core will have to be determined by reactor staff). If the epicadmium flux is adequate, it will be used as is; otherwise some further beam conditioning will be performed to obtain an adequate flux spectrum near one MeV. These tests and measurements will be performed in the first few months of project year one, and initial neutron irradiations of CTC components will be carried out by the end of year one. Mixed thermal/fast irradiations can be performed in the beam tube without the cadmium absorber, and strictly thermal irradiations will be carried out, beginning early in project year one, in the BIF. Irradiations in the beam tube will require encapsulation of the samples, since it is preferable to flood the beam tube with water before the reactor is brought up to power. Design and testing of a water-tight sample holder will be performed before component irradiations begin.

2. Irradiation of CTC Components

In order to study the effect of neutron irradiation on straw tubes and scintillating fibers, irradiations will be performed at different fluxes (which can be achieved by varying reactor power) and different exposure times to obtain different total fluences. We feel it is important to test not only the effect of total neutron fluence but also the effect of exposure rate. The general approach will be to take multiple (two or three) samples (straws or fibers) that have been previously tested for performance characteristics and irradiate to a known fluence at a known flux rate. The samples will then be returned to the laboratory for follow-up performance testing.

Since the samples may be activated during irradiation, safety procedures must be employed and the samples can only be returned to laboratories that are licensed to receive them. All samples will be thoroughly surveyed for residual activation and will only be returned to the submitting laboratory once it has been determined that it is safe to do so. The straw tubes and scintillating fibers are composed primarily of low atomic number elements, so we do not expect significant activation during the neutron exposure. Also, when exposing primarily to fast neutrons, activation will be minimized.

As an example, we propose the following general procedure for testing scintillating fibers.

- Obtain about 20 individual scintillating fibers, each ~2 m long, from NU. A light curve will have been generated by NU for each of these fibers using a Quantacon (RCA 8850).
- Coil or wind two into a shape that will allow their insertion in one of the irradiation beam tubes.
- These two will then be returned to NU so that they can test to see if the shipment and coiling operations affect fiber performance.
- Next, irradiate two fibers in a strictly thermal flux of about 10^7 neutrons/(cm^2-sec) to ~10^{11} neutrons/cm^2. Test these for activation and return to NU.
- Irradiate in batches of two fibers in the beam tube to different total fluences (up to 10^{13} neutrons/cm^2) and at different flux rates.
- NU will generate light curves at various times after irradiation, in order to investigate relaxation recovery.

Similar procedures will be employed for straw tubes. The radiation test model will be irradiated one time to a large total fluence (~10^{13} neutrons/cm^2).

We note that since the reactor beam tubes view the core, there will be a substantial gamma-ray dose to items irradiated in the beam tube. This gamma-ray background will be measured, so that gamma-ray absorbed dose can be estimated for each neutron irradiation.

Electronic components that have been designed to be radiation-hardened will be tested for both neutron and ionizing radiation. The electronic chips will be irradiated to about 10^{13} cm^{-2} total fluence in the reactor, and then tested. In addition, separate chips will be irradiated in one of the Co^{60} irradiation facilities (1.3 Ci or 2.8 Ci) at the Chemical Engineering Department at NCSU. This will be a simple test to confirm that adequate performance is achieved following exposure to 2-4 Mrad of ionizing radiation.

C. Electron Irradiation Studies

At Florida State University (FSU) we have a 3 MeV electron accelerator that has a beam of approximately 2 cm diameter. This accelerator is available for radiation damage studies. The beam intensity can be varied between 1 nanoamp and 1 milliamp. For materials that are not too thick, i.e., no more than 1.5 gm/cm^2, this accelerator can give a radiation dose of 1 Megarad in irradiation times of less than a minute to several hours. Beams can also be moved in a scan mode allowing material up to 30 cm long to be irradiated. If combined with a computer-controlled sample beam scanner, long samples up

to 2 m long (and possibly even longer) can be uniformly irradiated. Measurements performed during the past year have shown that for plastics and scintillators, radiation damage effects from electrons and gamma rays (from Co^{60}) are, as expected, essentially identical for the same absorbed dose. The advantage of the electron accelerator is that material can be exposed to radiation over a short time period.

VII. Monte Carlo Simulation

A systematic simulation of the response of the proposed detector subsystem is an essential ingredient for making timely and informed design decisions. Such a simulation will be carried out in collaboration with the experimental high energy physics group at SCRI, with supporting simulation activities performed at Oak Ridge National Laboratory and Quantum Research Services, Inc. The major computing resources needed for this simulation will be supplied by SCRI, although some of the tasks will be performed on machines at ORNL and Quantum. The SCRI group have made an independent proposal to augment the personnel available for SSC simulation projects [VII-1].

The simulation effort is divided among the three collaborating institutions. SCRI will conduct the most general study, simulating all major aspects of the CTC performance, using a series of codes built around GEANT/ZEBRA. ORNL will use its CALOR89 code to study hadronic background effects. The results of the CALOR89 analysis will be fed back into the GEANT simulations as a background noise. Quantum will perform geometric investigations to develop a simple CAD geometry interface. The three simulation efforts are briefly described below.

A. Performance Simulation

The overall simulation will investigate the following topics:

- track finding performance;
- momentum and angular resolution for reconstructed tracks, and their dependence on the detailed straw and fiber configuration;
- vertex resolution and the unscrambling of multiple events in the same or consecutive beam crossings;
- the effect of material in the straws and fibers themselves and especially in the end plates and supporting structures;
- alternative readout schemes, such as differential read out from adjacent pairs of straws (see Section V.B.2);

- the determination and monitoring of calibration constants from cosmic rays and tracks from collisions. Some parameters, such as the time-distance relation and position resolution for straws, will depend on input from test measurements;
- investigation of calorimeter albedo effects.

We consider studies of the reconstruction of the z (longitudinal) coordinate to be especially vital. It needs to be demonstrated that a stereo layer approach (whether utilizing fibers or straws) will work in a high multiplicity, high background environment. We will look at the alternatives of independent track reconstruction in the different stereo views, followed by matching the different projections; and the direct reconstruction of individual space points from multiple stereo views, followed by track finding in three dimensions. This will help to choose the number and angles of the stereo layers.

At the SSC, the signal propagation time along the length of a straw or fiber is of comparable duration to the drift time and the time between beam crossings, and so the complete time evolution of several events must be simulated. The first z matching must be performed before correction of drift times for wire propagation times, and so this correction will be iterative. After this correction, the staggered straw configuration should in principle allow ready recognition of out of time tracks. We hope to demonstrate that the contributions of drift time, particle and signal propagation, and out of time events can be satisfactorily unscrambled from a single time measurement. However, we will also examine the possibility of reading out both ends of the straws, and/or making a time measurement from the scintillating fibers, to allow identification of multiple hits or out of time tracks, and to provide a rough z measurement to help the stereo matching.

We have started initial studies with simple central tracking detector geometries using GEANT [VII-2] and the SSC SIM applications package written at SCRI. FigureVII-1 shows an eight superlayer straw chamber that has been modeled. Figure VII-2 is an enlargement of one superlayer of this configuration. At this point only simple digitization is done by computing the distance of closest approach to the straw centerline. Figure VII-3 shows circles which represent drift times. We believe that enough software tools are now in hand to start careful design evaluations.

If funded, we would immediately proceed to develop a more detailed simulation of the time evolution of electronic signals, which would include the effect of pile-up and signal propagation delays, using a generalization of the Aleph TPC simulation [VII-3]. In

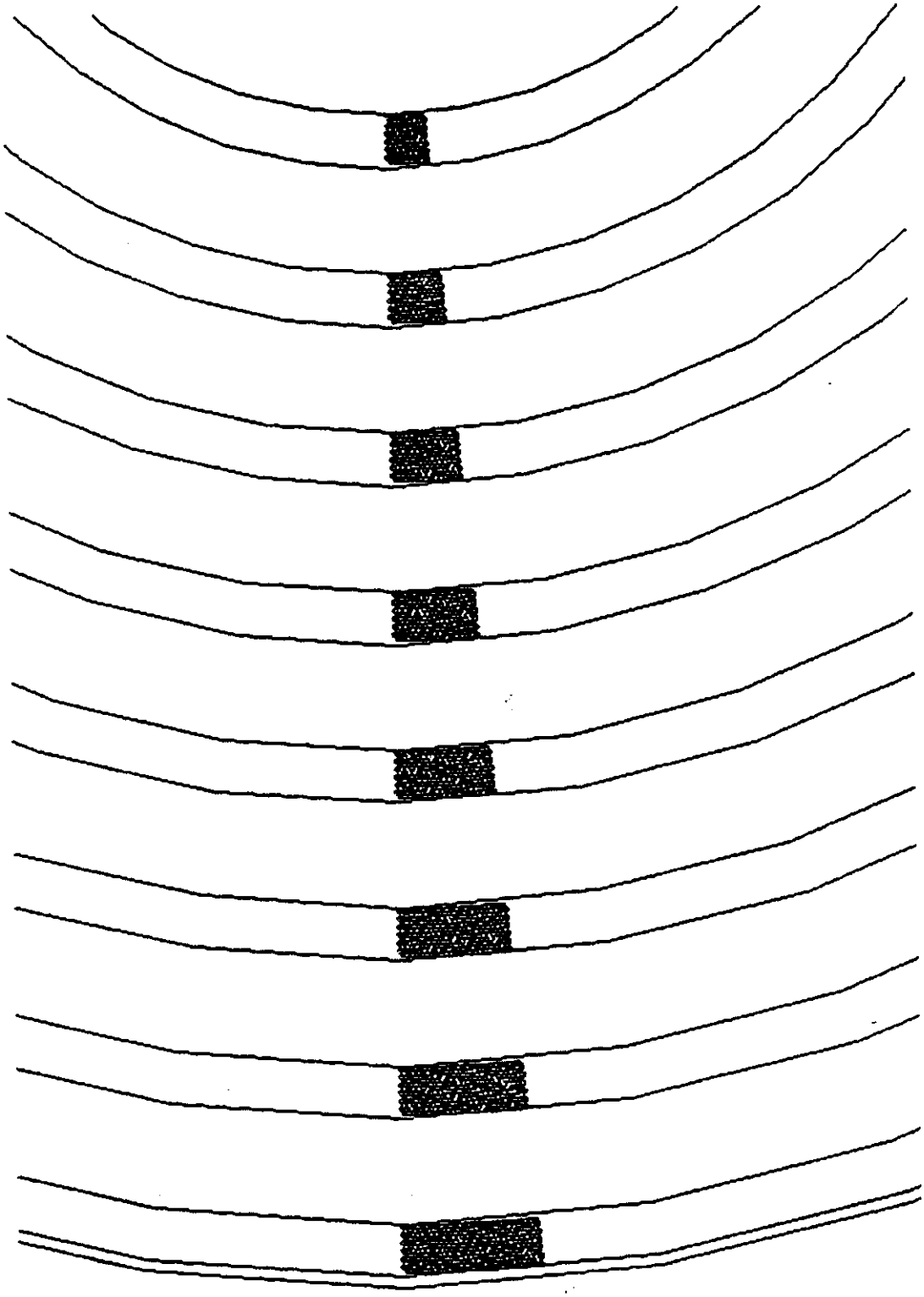


Figure VII-1. Straw Chamber with 8 Superlayers;
Each Superlayer has 12 Layers of Straws

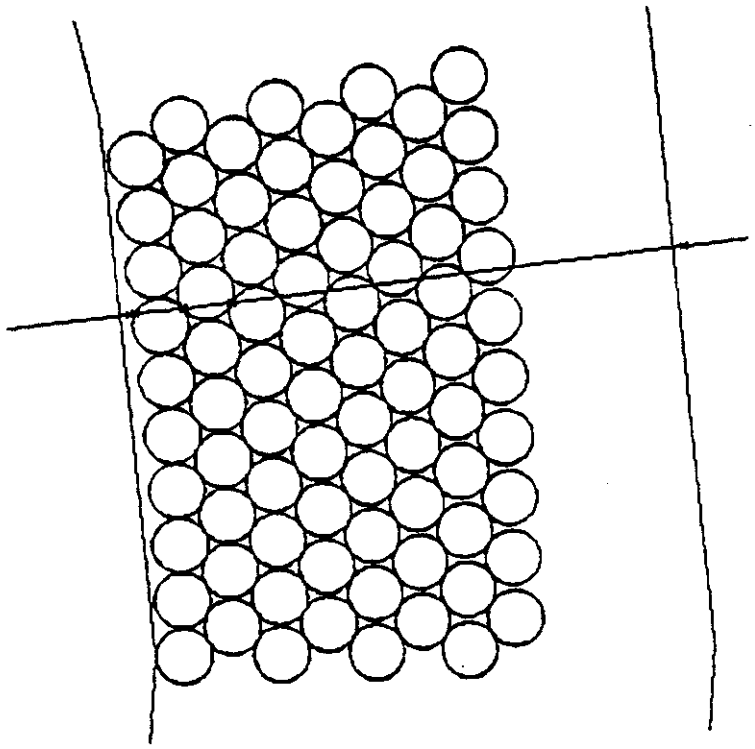


Figure VII-2. Straw Chamber Superlayer Showing Equal Diameter Straws in a Close-Packed Configuration

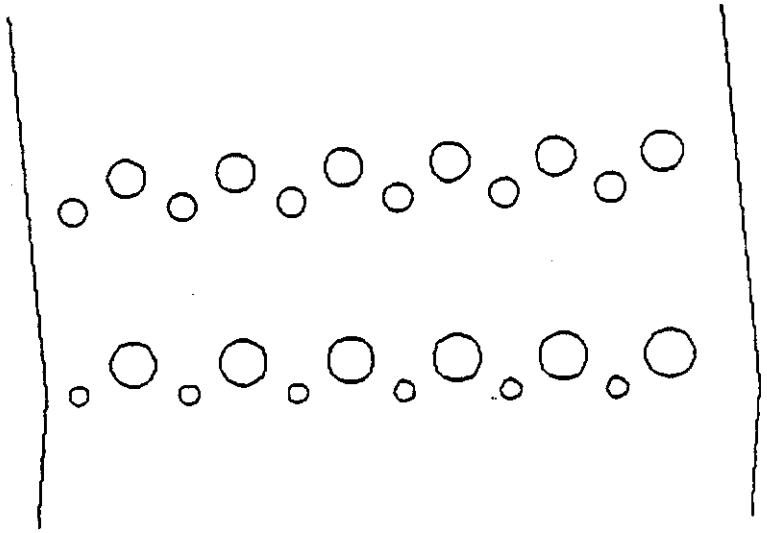


Figure VII-3. Straw Chamber Superlayer Showing Drift Time Circles

parallel with this effort, we will construct a track finding and fitting program which is generic enough to evaluate a wide range of layer/superlayer configurations. This program would make use of code and experience gained on Aleph and FNAL E711. Various designs will be evaluated based on developed figures of merit, such as track-finding performance, momentum and angular resolution, multiple-interaction vertex resolution, material effects, readout schemes, and calibration and monitoring.

B. Effects of the Hadronic Background Tracking Sensitivity and Resolution

1. Introduction

In many instances, the ability to separate detector signals from many incident particles separated by very short time and spatial intervals determines the success or failure of an experiment. The CALOR89 code system will be modified to include time dependence so that the spatial dependence of the energy deposition in the hybrid central tracking chamber can be monitored in time. By utilizing this time dependence through pulse shaping and proper segmentation, the background generally associated with a large number of soft particles (neutrons, protons, pions and electrons) can potentially be identified on a single or at most a multiple particle basis. The geometry of the tracking detector will be fashioned after those defined in this proposal. The CALOR89 system, which has a large energy range of applicability (20 TeV to 10^{-3} eV) has been shown to be substantially superior to the other simulation codes in terms of the treatment of the low energy particles, especially albedo particles, and should be able to realistically generate the response of the tracking system to these low energy particles.

At present, timing is included only in the MORSE [VII-4] and MICAP [VII-5] codes in CALOR89. Neither EGS4 [VII-6] nor HETC88 [VII-7], which are also included in CALOR89, has a timing scheme incorporated. It has been assumed for past calculations that no time passes for this phase of the particle cascade (roughly correct) and that all neutrons produced below 20 MeV are produced at t=0. For the proposed calculation, this is not sufficiently accurate.

The geometry of the calorimeter, which through hadronic collisions yields the particle albedo, will be fashioned after generic SSC detectors. The calorimeter materials considered in the first series of calculations will be lead and plastic. The current geometry routines in hadronic tracking codes are not able to handle many thousands of bodies as encountered in tracking chambers. To maintain reasonable computational speed methods

have to be developed by which those geometries that have large numbers of repeating patterns or symmetries can be handled with ease and with substantial increases in computational speed. This type of geometry improvement will also be investigated in this research.

2. Background and Methods of Calculations

In order to have a strong experimental calorimeter development program, a substantial effort must be involved in calculational analysis of the detector system. This calculational capability must be fundamentally sound and based on previous interchange between theoretical calculations and experimental test programs. The CALOR89 code system for analyzing calorimeters offers a solid approach for investigating all facets of detector systems and will be used in this work. Some of the code improvements proposed have been put forth in two other proposals: "A Calculational Approach to Calorimeter Response to High Densities of Soft Particles (≤1 GeV)," by C.Y. Fu, et al. (a RHIC Generic proposal), and "Simulation Studies for Lead and Scintillating Fiber Calorimeter," by D.W. Hood, et al. (SSC Generic proposal). The work proposed in this report can be performed with the manpower requested whether or not the above proposals are funded. However, if they are funded, the ORNL budget for this proposal can be reduced by $55K.

Due to financial constraints, only a few prototype detectors can actually be built and tested. However, once the calculated results have been shown to agree with the test program data, much wider design variations can be investigated using simulation codes. This will be the approach followed in this proposal so as to maximize effort and minimize cost. A close connection will be maintained with the experimental design part of this proposal.

The calculations to be carried out will be performed with the new CALOR89 computer system. The major changes in CALOR are in an improved high energy collision model following the FLUKA87 model and the inclusion of a better low energy neutron transport code, MICAP. A flow diagram of the codes in CALOR is given in Figure VII-4.

3. Analysis to be Performed

During the initial phases of this work the timing schemes will be added to the CALOR89 code system. For neutrally charged particles, the timing can be calculated simply, i.e.,

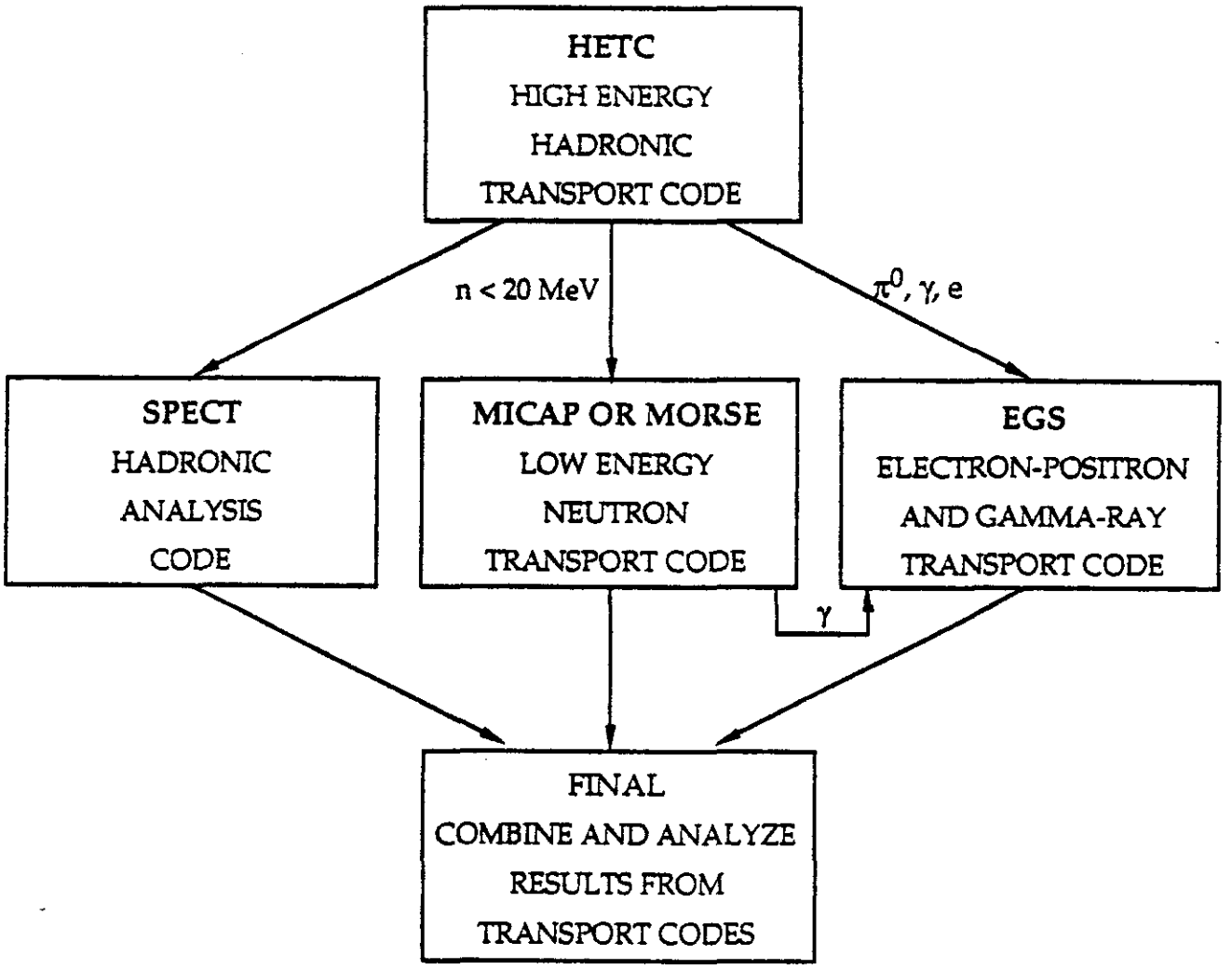


Figure VII-4. Diagram of the CALOR Computer System

$$t = t_0 + \frac{|\vec{r} - \vec{r}_0|}{\vec{v}} ,$$

where t_0 and $\vec{r}_0$ are the previous time and spatial coordinates of the particle, t and $\vec{r}$ are the current time and spatial coordinates of the particle $\vec{v}$ is the velocity of the particle.

For charged particles, since the velocity is constantly changing, the timing is not as straightforward, but can be obtained from the following:

$$t = t_0 + \int_{r_0}^{r} \frac{dx}{\vec{v}} = t_0 + \frac{1}{c}\int_{E_0}^{E} \frac{\left(\frac{dx}{dE}\right) dE}{\left(\frac{p}{\varepsilon}\right)} = t_0 + \frac{1}{c}\int_{E_0}^{E} \frac{\varepsilon dE}{\left(\frac{dE}{dx}\right)\left(\sqrt{\varepsilon^2 - m^2}\right)} ,$$

where the variables have the same meaning as before and ε is the particle total energy, E is the particle kinetic energy, and dE/dx is the ionization energy loss per unit path length, x.

At the same time that timing is being incorporated into CALOR89, the geometry modifications will start to develop methods to handle many thousands of bodies in an efficient manner. This can be accomplished because of the large amount of repeating patterns or symmetries found in these tracking chambers.

To implement the changes will require the concepts of "macro" and "micro" geometry regions. The macro part of the geometry will be used to describe the gross characteristic of the tracking chamber, for example, the superlayers, scintillating fiber layers, and support structure. When a particle enters a superlayer or scintillating fiber layer, the geometry will switch to the micro geometry which will be composed of a minimum number of bodies and the tracking will take place. A proper spatial rotation and translation will be carried out to return the particle to its correct spatial point and direction.

Once the above improvements have been debugged, calculations will be carried out to determine the time tagged "hits" in the tracking chambers due to albedo particles produced in the calorimeter. These hits will be incorporated with initial tracking chamber analysis of the particles produced in 20 TeV p-p colliding beams to determine the overall effect of albedo particles. Due to the large number of secondaries produced, only a small number of p-p collisions will be considered.

C. Geometric Modeling

We intend to investigate the use of a simple CAD package (we have experience with AUTOCAD and others), to construct an efficient way to enter the design data for a detector, to display and check it, and then to create the input for the simulation codes (either GEANT or CALOR). Because of the complexity of possible CTC designs, a complete CAD interface is a substantial task that is beyond the scope of what we are proposing here. A separate proposal for CAD interface development is being submitted by other parties at FSU. If both groups are funded, we will certainly cooperate with the FSU group so as to avoid duplicative efforts and maximize achievements. However, whether or not other CAD efforts are funded, a significant assist in preparing/checking data input can be achieved with a modest (~3 person-month/yr) effort.

VIII. Anticipated Test Beam Needs

We will need particle test beams to evaluate two aspects of the performance of the superlayer module. The first is a measurement of the tracking precision of the two straw tube/scintillating fiber clusters located 140 cm apart on opposite sides of the detector. In addition, we will want to study the high rate performance of the detector elements and associated readout electronics (including cross talk levels between channels).

The complete prototype module will not be available until late 1991 and we would project our major test beam needs to occur in December 1991 to January 1992. However, we will have available an engineering model containing 100 long straws by late 1990. We would request a limited amount of beam time then. This would be used to study detector performance on the few element levels and measure effects of magnetic fields on the detector's resolution.

For most tests, either charged hadron or electron beams would be acceptable. A reasonably high energy hadron beam (100 GeV) would be useful for some measurements to limit multiple scattering and allow precision measurements on the 100 μm level over the full detector diameter. For the rate dependent studies, it would be useful to have particle breams with ~16 ns pulse rates. A detector test lab will be proposed at Duke University which may have this capability. It would use a 1 GeV electron linac with cathode emission controlled by laser-induced photoelectron emission. If funded, this facility could be available in early 1992.

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Appendix A

Collaboration Organization and Management Structure

Appendix A

Collaboration Organization and Management Structure

The project organization consists of nine formal collaborating institutions and two cooperative liasons. The collaboration was organized through Duke University, under the direction of Dr. Alfred Goshaw; Northeastern University serves as the deputy directing institution, under Dr. Stephen Reucroft. Each formal collaborating institution has a Principal Investigator (PI) and other senior project staff, who are committed to contribute to this project, if funded. The collaborating institutions, PI's, and senior staff are:

Institution	Principal Investigator	Senior Staff
Duke University (Duke)	Alfred T. Goshaw Professor of Physics	Seog Oh Bill Robertson
Florida State University (FSU)	Vaskan Hagopian Professor of Physics	
North Carolina State University (NCSU)	John Paulos Professor, Electrical and Computer Engineering	
Northeastern University (NU)	Steve Reucroft Professor of Physics, Department Head	George Alverson Bill Faissler David Garelick Mike Glaubman Ian Leedom
Oak Ridge National Laboratory (ORNL)	Tony Gabriel Engineering, Physics, and Mathematics Division	Hugh Brashear C. Y. Fu Martin Bauer Mark Rennich
Quantum Research Services, Inc. (QRS)	William L. Dunn President	F. O'Foghludha A.M. Yacout
RCA	Robert J. McIntyre	
Supercomputer Computations Research Institute (SCRI)	Martyn Corden	
University of Florida (UF)	Stan Majewski Research Scientist	Carl Zorn

Other technical and support staff from these institutions will be involved in the project; the listed individuals are the senior staff who will direct various aspects of the R&D effort.

Two cooperative liasons have been established, one with the University of Pennsylvania (Newcomer and Van Berg), and one with SLAC (Va'vra)/LBL (Kadyk). These groups have agreed to directly cooperate with us, by providing timely results of their own ongoing research and by contributing to discussions and reviews of our results. In the case of the Pennsylvania group, they will provide us with chips, at cost, that result from their generic design studies.

The overall project will be run by an Executive Committee, which will meet two times per year. The committee membership will be made up of the PI, or a PI-appointed representative, from each collaborating institution. The Director and Deputy Director of the Executive Committee will be Drs. Al Goshaw and Steve Reucroft, respectively. These two individuals will remain as the primary contacts with the SSC Laboratory, for purposes of project continuity.

Below, we give very brief descriptions of the relevant experience and general intended involvement of the PI's and most of the senior staff from each collaborating institution.

Duke University

The Duke high energy physicists involved with this proposal are Alfred Goshaw, Seog Oh, and William Robertson. In addition, Duke is searching for a research associate, who would have a major commitment to this project. This group will devote 50% of their research time to SSC detector development if this proposal is approved. Their salaries will be paid by Duke University and the DOE high energy physics contract with Duke. Goshaw, Oh, and Robertson have been most recently doing research at the Fermilab Tevatron collider. The experiment, E735, was designed to look for quark-gluon plasma formation in $p\bar{p}$ collisions at $\sqrt{s} = 1.8$ TeV. This group, together with three Ph. D. students, will be analyzing these data over the next few years. Duke plans to involve some graduate students with SSC detector development in parallel with ongoing research work at Fermilab.

North Carolina State University

John J. Paulos received the B.S., M.S., and Ph.D. degrees from the Massachusetts Institute of Technology in 1980, 1980, and 1984, respectively. He joined the faculty of North Carolina State University in 1984, where he is currently an Assistant Professor in the Department of Electrical and Computer Engineering. His research interests are in the areas of analog integrated circuits, MOS device modeling, and radiation effects in microelectronics. Dr. Paulos will be responsible for the design of radiation-hardened integrated circuits in collaboration with researchers at ORNL, Penn, and RCA. Dr. Paulos will supervise one full-time and one part-time graduate student. Salary support for Dr. Paulos is based on 12% of the academic year and one month of summer. This effort is compatible with outstanding teaching and research commitments.

Northeastern University

The Northeastern University group consists of six faculty (Alverson, Faissler, Garelick, Glaubman, Leedom and Reucroft), three research associates and a technical research assistant. Alverson, Faissler and Garelick are all spending the majority of their time on Fermilab's experiment E706; Glaubman, Leedom and Reucroft are concentrating their efforts on CERN/LEP experiment L3. On average, each of these is planning to spend approximately 30% of his time on the SSC development program described in this proposal. One of the research associates and the technical research assistant will both have a 50% commitment to the SSC program. Funds derived from this proposal will be used to hire a visiting scientist who will work full-time on this work. In addition, we plan to take advantage of the unique features of the NU undergraduate coop program and involve two NU undergraduates in this SSC work.

Oak Ridge National Laboratory

Dr. T.A. Gabriel has been involved with the analysis of high energy physics detector systems for the last 20 years. The CALOR89 code system, METG88, SPECT89, EG34, MORSE, MICAP, and LIGHT, which was developed as part of this research is one of two major codes recommended for SSC detector research. Major understandings of the physics of calorimetry has resulted from the utilization of CALOR89. He is currently a senior research staff member in the Engineering, Physics and Mathematics Division of Oak Ridge National Laboratory. His involvement in this research will be as the coordinator of the Oak Ridge National Laboratory effort.

Mark Rennich has designed research and development hardware for 12 years with an additional 4 years of industrial experience in the plastics industry. He has been the lead engineer on a wide range of experimental equipment design projects including extensive commercial vendor involvement, special materials and precision machining. Professional experiences with applicability to SSC detector engineering include the design of calorimeter structures for the WA-80 project (CERN) and the calorimeter/absorber No. 4 (Fermilab); design of vacuum target vessel for the ORNL linear accelerator; precision design of components for the David Taylor Research Center; design of test bed assemblies for the advanced laser isotope separation process for Lawrence Livermore Laboratory; and the design of a refrigeration test loop in conjunction with the National Institute of Standards and Technology.

Hugh R. Brashear has been Head of the Research Instruments Section (RIS) for the past eight years at the Oak Ridge National Laboratory (ORNL). This section has a staff of approximately seventy (70) professionals engaged in applied research, development, design, and fabrication of nuclear instrumentation for the experimental community, applied health physics and related scientific fields. Mr. Brashear (B.S., Electrical Engineering, minor in Nuclear Physics, Oklahoma State University) was group leader of the detector and electronics systems development in RIS for five years, and development staff member in the Instrumentation and Controls Division for fourteen years. Projects in which he has been involved include: process nuclear instrumentation development for the Molten Salt Reactor Experiment; detector development for the Apollo shielding project; multiwire proportional chamber and 2-Mx2-M drift chamber development for particle tracking down stream from the Fermilab 30-inch bubble chamber; project manager for the detector, electronics and system development, design, fabrication, and field experimental direction fo the Radioisotopic sand tracer studies conducted on the east and west coasts, New York bight, and English channel areas; and director of the highly successful ORNL/Navy RADIAC developemtn program for all of the Navy's health physics programs.

Martin L. Bauer is a member of the Instrumentation and Controls Division at ORNL. He received his B.S. in Physics and M.S. in Measurement and Control (Instrumentation), both at Carnegie-Mellon University, Pittsburgh. Presently, he is a group leader of the Senson Systems Development Group doing work in the area of radiation detection and environmental monitoring instrumentation. He has expertise in electron beam, optical sensing, and signal processing technologies; extensive experience in analog and digital

design, and process measurement systems; and expertise in the area of fiber optic systems and radiation effects on materials. Mr. Bauer is a member of the American Vacuum Society and the Society of Photo-optical Instrumentation Engineers.

C.Y. Fu received his Ph. D. in Nuclear Engineering from the University of Tennessee. His professional experience includes the following: Monte Carlo calculation for the response function of a Compton Diode Detector; Monte Carlo analysis for the NE213 response function; 1985 RSIC MORSE workshop; development of multigroup cross-section libraries and response functions; and evaluation for ENDF/B-III, -IV, -V, and -VI. In addition, he served as a theorist on development of a consistent Hauser-Feshbach/pre-equilibrium model and exciton level density.

Quantum Research Services, Inc.

Dr. William L. Dunn has M.S. and Ph.D. degrees in Nuclear Engineering from N.C. State University. He has over fifteen years work experience in radiation applications, shielding, and transport analysis. From 1977 through 1979 he was on the staff and faculty at NCSU and was in charge of research utilization of the PULSTAR reactor and related facilities. Since late 1979, Dr. Dunn has been involved strictly in contract research, and has been PI on more than twenty contracts. His general research areas have included neutron irradiations for activation analysis (EPA), neutron capture prompt gamma-ray analysis (NSF), measurement of lubricant thickness on needles by proton bombardment (commercial client), multidimensional radiation transport methods development (NSF, SDIO), shielding (DNA, DOE), and Monte Carlo methods (NSF, NIH). For almost two years Dr. Dunn managed, on contract to the state, North Carolina's bid to serve as the site of the SSC. In mid-1988, he assumed the presidency of Quantum Research Services, Inc. Dr. Dunn will devote about 30% of his time to the project, and will oversee the neutron and Co^{60} irradiations and assist with the simulation effort.

Dr. Fearghus O'Foghludha has been with Quantum since he retired from Duke University in 1988; he headed the radiation physics group (Radiology Department) there for nearly twenty years, and retains an adjunct appointment in the Duke Physics Deptartment. During his forty-year career as an experimenter he has worked with large cosmic ray counter arrays, and on the fabrication and evaluation of many other types of radiation detector. He has been responsible for commissioning and for precision photon, electron, proton and neutron dosimetry of various generators, e.g., Marx impulse

machines, van de Graaff's, linear accelerators, reactors, radioactive sources, etc. and for the design and fabrication of a great variety of support equipment. He will expend 5-10% of his effort in Quantum's support of the test irradiations.

RCA

Dr. Robert McIntyre is the Manager of Research and Development at RCA Electro Optics in Vaudreuil, Canada. He has 20 years of experience in the development of high efficiency avalanche photo diodes (APD's). RCA produces both single element and linear array APD's suitable for use in single photon detection. Dr. McIntyre will collaborate with Dr. Reucroft of Northeastern University to produce new device structures optimized for use with 0.5 mm diameter plastic scintillating fibers.

Supercomputer Research Institute

The Supercomputer Computations Research Institute (SCRI) at Florida State University is funded by the Department of Energy Applied Mathematics Division under Contract No. DE-FC05-85ER250000. SCRI is a multidisciplinary institute with an experimental high energy physics group of five members (Cordon, Georgiopoulos, Linn, Mermikides, and Youssef). The group has commitments to the D0 and Aleph experiments at the level of 50% of each members' time. We have no teaching responsibilities; however, we are involved with a number of SSC related R&D proposals. Our intentions is to participate as a group on all of these projects drawing on our different areas of expertise when necessary. We have submitted a separate proposal to hire additional manpower for SSC projects. The actual number of FTE's that will work on this proposal depends on the success of our proposal as well as others that we are now associated with. For the Hybrid Central Tracking proposal, Martyn Corden will act as designated contact person.

University of Florida

Dr. Stan Majewski heads the High Energy Physics Instrumentation Development Group at the University of Florida, Gainesville. He is a principal investigator on the DoE funded R&D study of the radiation-resistant plastic and liquid scintillators, and fast, non-ageing gas chambers. The group, whose member is also Dr. Carl Zorn, was very successful in developing new plastic scintillators with highly increased immunity to nuclear radiation. Also, under Dr. Majewski's direction, extended studies of wire chamber ageing with dimethyl ether gas were performed during the past two years. As a result, the

necessary conditions to avoid radiation damage were defined in multidrift tubes being developed at CERN for tracking detectors at SSC/LHY. Dr. Majewski's past professional experience includes almost 10 years (1974-1984) of collaborative work with Dr. Charpak's group at CERN on different types of gaseous detectors. Before coming to Florida in 1985, Dr. Majewski was working at Fermilab (1984-1985) on low-pressure gaseous photodetectors for Cherenkov ring imaging, and on the readout and radiation resistance of barium fluoride crystal scintillator. Dr. Majewski will be responsible for the straw ageing studies, and he will spend between 20 and 30% of his time on this research, helped by a post doctoral research associate, dr. Carl Zorn. Also, they will use their expertise in radiation damage to plastic scintillating materials and fibers to help with selection of scintillating fibers and evaluation of irradiation results.

After obtaining his Ph.D. at the University of Toronto, Toronto, Canada, in 1987, Carl Zorn accepted a post doctoral position at the University of Florida as a member of the High Energy Detector Development Group under the supervision of Dr. Stan Majewski. Dr. Zorn has conducted research to develop radiation resistant organic scintillators for use in the SSC. This work has resulted in the development of radiation hard plastic scintillators utilizing the fluor 3HF as the dopant in one case, and a radiation hard polysiloxane base in the other. The research concentrates on the radiation resistance of plastic scintillating fibers and the development of radiation hard liquid scintillators.

Appendix B

Project Timeline Milestones

Appendix B

Project Timeline Milestones

	Jan '90	Jul '90	Jan '91	Jul '91	Jan '92
Mechanical Fabrication ORNL, Duke	Begin construction of engineering models	Begin full prototype construction		Ship prototype to Duke for straw tube and wire installation	Evaluate construction technique and vender identification for CTC construction
Scintillating Fiber NU	Scintillating fiber ribbon construction	Installation on support cylinder		Continuing study of readout electronics	
Straw Tubes Duke	Single straw tube tests (gas and resolution study)	Test of straw tube engineering models		Assembly of 100 tube model	Begin straw tube and wire installation on full prototype
Radiation Tests FS, UF, QRS	Radiation of scintillating fiber and straw tubes, construction materials	Gas studies, wire chamber ageing electrons		Radiation of mechanical model electronics	Ageing studies of final straws/ selected gas(es)
Electronics NCSU, ORNL, RCA, Penn	Evaluation of front end electronics Evaluation of APD's for scintillating fiber fiber readout	Design of integrated circuits (front end) Design of APD arrays		Test integrated circuits, design	Assembly and instrumentation Assembly of prototype APD array
Detector M.C. Simulation SCRI, QRS, ORNL	Monte Carlo simulation relevant to superlayer construction	Tracking and pattern recognition studies		Monte Carlo simulation relevant to CTC detector in an SSC experiment	

Detailed Project Goals

First Year (1990)

Straw Tubes

- Select tube and cathode material, anode wire, and candidate gases.
- Study electrostatic stability and fix required mechanical tolerances.
- Finalize end plate construction and feed through (engineering models).
- Study sense wire support techniques; finalize with engineering models.
- Construct engineering model with 100 tubes.
- Measure resolution, gas drift speeds.
- Study heat management via gas flow.

Mechanical Design, Fabrication

- Engineering evaluation of possible support structures for superlayer.
- Materials studies, selection for end plates and cylinder support.
- Study technique for fabricating carbon composite/scintillating fiber support structure (engineering model, d = 60 cm).
- Incorporate straw tube/scintillating fiber design results into prototype design.
- Incorporate Monte Carlo detector simulation into prototype design.
- Begin prototype mechanical construction.

Plastic Scintillating Fibers

- Investigate and optimize detector design and construction details. This is especially relevant in deciding between circular or square cross-section fibers and whether the detector planes are assembled from individual fibers or premanufactured fiber ribbon arrays.
- Invent and develop detailed quality control tests of fiber cross-section tolerance, photon yield, attenuation length and alignment precision.
- Demonstrate both the technical and economic feasibility of using avalanche photodiodes as the electro-optical link between the fiber detection and downstream electronics. Single channel tests.
- Investigate neutron and gamma radiation characteristics of fibers.

Electronics

- Design, fabrication and test of front end chip for straw tubes.
- Electrical design of straw tube end plates, PC board assemblies.
- Evaluation of single-element avalanche photo diodes (APD's) with scintillating fibers.

Radiation Damage

- Study ageing characteristics of candidate component materials.
- Conduct straw tube outgassing tests.
- Measure neutron spectrum in reactor beam tube and design irradiation cannister, with appropriate filters.
- Conduct series of neutron irradiations of individual components; components will be performance tested before and after irradiations.
- Conduct Co^{60} irradiation test of front end chips.

Simulation

- Study track-finding performance of proposed and alternative CTC designs. The final prototype superlayer design will be highly influenced by this simulation study.
- Study momentum and angular resolution for the reconstructed tracks.
- Evaluate hadronic background in CTC due to calorimeter albedo.
- Investigate the effects of structural materials and the materials in the straws and fibers themselves.
- Develop a simple CAD package to enter and check data and to create input files for the simulation codes.

Second Year (1991)

Straw Tube

- Instrument 10's of channels of the engineering model with front end analog electronics.
- Measure detector resolution.
- Measure effects of magnetic fields on performance.
- Compare and exchange results with Monte Carlo simulation.
- Install and test digital electronics when available.
- Install and string 1,000 straw tubes on full scale prototype.
- Beam tests of prototype superlayer (resolution, pileup, cross talk).

Mechanical Design, Fabrication

- Complete prototype mechanical construction.
- Measurements of mechanical precision and stability (including full sense wire load simulation).
- Design of multi-superlayer construction; use Monte Carlo simulation to optimize design; introduce constraints imposed by other subsystems of an SSC detector.
- Identify commercial vendors, design a mass production program and estimate the cost and time table for the construction of a complete cylindrical CTC detector.

Plastic Scintillating Fibers

- Continue APD feasibility tests for multi-channel arrays, both linear and two-dimensional.
- Investigate readout system packaging and interface with fiber arrays in the prototype detector.
- Begin beam tests of entire prototype detector system. Investigate stability and precision.

Electronics

- Design, fabrication and test of straw tube readout chip.
- Assembly and test of electronics for CTC prototype.
- Design and construction of instrumentation for beam testing.

- Design, fabrication and test of APD arrays.
- Construction and test of APD-based fiber readout prototype.

Radiation Damage

- Complete ageing studies of individual materials.
- Conduct integrated X-ray and electron effects studies on radiation testing model.
- Complete neutron irradiations of individual components; both flux (rate) and fluence (total) effects will be investigated.
- Irradiate radiation testing model to ~10^{13} neutrons/cm^2.
- Conduct neutron and Co^{60} irradiations of final electronics chips.

Simulation

- Study vertex resolution and multiple beam crossing effects.
- Integrate calorimeter albedo effects into GEANT simulation code, and evaluate effects on tracking sensitivity and resolution.
- Incorporate simple CAD data input and checking package.
- Use various performance measures to evaluate final design; determine and monitor calibration constants.

Appendix C

Budget

Appendix C

Budget

The proposed budget is summarized by year and by institution in Table C-1; first-year budget details are given for each collaborating institution on pages C-2 through C-6.

Table C-1.

Two-Year Budget Summary

Institution	Year 1	Year 2
Duke University	$ 256,290	$ 300,000
Florida State University	58,080	60,000
North Carolina State University	132,166	138,499
Northeastern University	296,601	310,000
Oak Ridge National Laboratory	700,000	1,270,000+
Quantum Research Services	164,235	172,446
RCA	247,927	250,000
SCRI	0*	0*
University of Florida	53,650	55,000
Annual Totals	$1,908,949	$2,575,945

+ Second-year costs are significantly larger because the fabrication of the full-scale prototype occurs in year 2.

* The budget for the group at SCRI is covered through existing and ongoing support, which may be supplemented by support through other proposals submitted separately.

1. Detailed First Year Budgets

Duke University

Salaries and Wages	
Technician (12 months)	$ 30,000
18.8% fringe benefits	5,640
Graduate studies (6 months)	8,500
Hourly student help (800 hours)	6,400
Subtotal Salaries and Wages	$ 50,540
Travel, Shipping, Communication	
Travel	$ 10,000
Telephone, mailings	1,000
Shipping (ORNL-Duke-ORNL)	7,000
Subtotal Travel, Shipping, Communication	$ 18,000
Laboratory Setup, Shop Work	
Clean room setup	$ 12,000
Shop work	10,000
Subtotal Laboratory Setup, Shop Work	$ 22,000
50% Overhead A+B+C	$ 45,270
Capital Equipment	
Straw tubes, wire, feed throughs, gas flow system	$ 35,000
High voltage power supplies	2,800
Data acquisition system	
VAX 3200	15,000
Interface with DMA	2,000
CAMC crate controller	2,180
VMS CAMAC driver	2,500
CAMAC TDC's, ADC's	12,000
NIM logic modules	4,000
Survey equipment	8,000
Laser interferometry monitoring	6,000
Pulsed laser	8,000
Subtotal Capital Equipment	$ 97,480
Contingency (10%)	$ 23,000
DUKE TOTAL	$256,290

Florida State University

The electron accelerator is now available for such studies. To be able to radiate various samples, measure radiation damage as well as recovery will require technical manpower. We estimate one full time technical person is required to perform the radiation tests and measure for damage.

Technical person (including fringe benefits)	$ 28,000
Electron accelerator maintenance	5,000
Miscellaneous expenses (including shipping)	10,000
Travel	5,000
Subtotal	$ 48,000
Overhead @ 21% (assumes funds are through our DOE grant)	$ 10,080
FSU TOTAL	$ 58,080

North Carolina State University

1.	Salary	
	A. Principal Investigator	$ 11,000
	B. Secretary	1,500
	C. Graduate Student	18,000
2.	Fringe Benefits (1.A and 1.B)	$ 2,625
3.	Supplies and Materials	$ 1,500
4.	Current Services	
	A. Travel	$ 6,000
	B. Computer Time	1,800
	C. Other Expenses (phone, postage, etc.)	500
5.	Subcontracts	
	A. Travel for U. Penn Personnel	$ 4,000
	B. IC Fabrication and Packaging	40,000
	C. Electronics Assemblies	5,000
6.	Overhead (46% of 1-4, 25.5% of 5)	$ 32,241
7.	Equipment	$ 8,000
NCSU TOTAL		$132,166

Northeastern University

Equipment	
Plastic scintillating fibers	$ 50,000
Readout devices plus associated electronics	70,000
Alignment equipment	10,000
Total Equipment	$130,000
Salaries	
Machining work, etc.	$ 10,000
Visiting Scientist	50,000
Coop Student	12,000
Fringe Benefits (22% of salaries)	15,840
Total Salaries	$ 87,840
Travel	
Domestic Travel (Duke U., FSU, ORNL, FNAL; 10 trips)	$ 10,000
Foreign Travel (Kyowa, Tokyo; 1 trip)	5,000
Total Gravel	$ 15,000
Overhead	
62% of Salaries and Travel	$ 63,761
NU TOTAL	$296,601

Oak Ridge National Laboratory

1. Labor (includes all overhead)

Category	Person-Years	Amount	
Mechanical Engineer	1.0	150,000	
Carbon Composite Engineer	0.2	30,000	
Programmer (includes computing)	1.0	150,000	
I&C Engineer	0.5	80,000	
Subtotal Labor			$410,000
2. Fabrication of Models			
Three bench-scale test models		100,000	
Small-scale composite model		125,000	
Subtotal Fabrication Costs			$225,000
3. Electronics Equipment			$ 10,000
4. Other Direct Costs			
Travel, publication costs, etc.			$ 15,000
5. Contingency			
20% of Item 1			$ 40,000
ORNL TOTAL			$700,000

Quantum Research Services, Inc.

Direct Material	
Cadmium, flux mapping foils, etc.	$ 5,000
Material Overhead (15%)	750
Subtotal Direct Material and Material Overhead	$ 5,750
Direct Labor	
Senior Staff (W.L. Dunn, F. O'Foghludha)	$ 24,060
Technical Staff (A. Yacout, J. Simpkins)	20,900
Aide, Clerical Staff	4,016
Subtotal Direct Labor	$ 48,976
Testing	
Reactor use charges (120 hrs @ $100/hr)	$ 12,000
Equipment	
Transputers, NaI(Tl) detector	$ 6,000
Travel	
RDU to ORNL, FSU, etc.	$ 3,800
Other Direct Costs	
Computer	$ 3,000
Telephone, shipping, photocopying	1,000
Subtotal Other Direct Charges	$ 4,000
Indirect	
106.19% of Direct Labor	$ 52,008
Subtotal	$132,534
G&A	
14.75% of subtotal	$ 19,535
Fee	
(7% of Subtotal + G&A)	$ 12,166
QRS TOTAL	$164,235

RCA

1.	Material				$ 18,700
2.	Material Handling Charge @ 13% of 1.				$ 2,431
3.	Labor – Engineering				
	Category	Hours	Rate	$	
	Sr. Engineer/Leader	750	37.14	27,854	
	Jr. Engineer	675	27.04	18,250	
	Sr. Technician		25.62		
	Jr. Technician	450	17.44	7,848	$ 45,860
4.	Overhead @ 204% of (3)				$ 93,553
5.	Travel				$ 8,500
6.	Subtotal (Sum of 1–6)				$169,044
7.	Cost of Money 3.5%				$ 5,917
8.	General & Administrative @ 32.3% of 7				$ 54,601
9.	Total Estimated Cost				$229,562
10.	Fee 8% of Item 10				$ 18,365
	RCA TOTAL				$247,927

University of Florida

Personnel	
Post Doctoral Research Associate (1 yr @ 50% including benefits)	$ 17,000
Graduate Student (1 yr @ 100%)	14,000
Materials	
Gases (plus cost of additional ex-house purification)	$ 2,500
Purifier cartridges (oxygen, freons, etc., for in-house use)	3,500
Subtotal	$ 37,000
Overhead	
45% of subtotal	$ 16,650
UF TOTAL	$ 53,650

Collaboration Members

Duke University

Dr. Alfred T. Goshaw

Dr. Seog Oh
Dr. William Robertson

Florida State University

Dr. Vaskan Hagopian

North Carolina State University

Dr. John Paulos

Northeastern University

Dr. Stephen Reucroft

Dr. George Alverson
Dr. Bill Faissler
Dr. David Garelick
Dr. Mike Glaubman
Dr. Ian Leedom

Oak Ridge National Laboratory

Dr. Tony Gabriel

Mark Rennich
Martin Bauer
C.Y. Fu
Hugh Brashear

Quantum Research Services, Inc.

Dr. William L. Dunn

Dr. Fearghus O'Foghludha
Dr. A.M. Yacout

RCA

Dr. Robert McIntyre

Supercomputer Computation Research Institute

Dr. Martyn Corden

University of Florida

Dr. Stan Majewski

Dr. Carl Zorn

Primary Contact Persons are:

Dr. Alfred T. Goshaw
Physics Department
Duke University
Durham, NC 27706
(919) 684-8134
GOSHAW @ FNAL

Dr. Stephen Reucroft
Physics Department
Northeastern University
Boston, MA
(617) 437-2901
REUCROFT @ NUHUB