HYBRID CENTRAL TRACKING CHAMBER COLLABORATION,
Summary Report - Part I: Progress Report for FY90

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Hybrid Central Tracking Chamber Collaboration

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Abstract

This summary report is submitted to the SSC Laboratory in partial fulfillment of the terms of the Memorandum of Understanding (MOU) between the Hybrid Central Tracking Chamber (HCTC) Collaboration and the SSC Laboratory for FY90. Part I: Progress Report for FY90 provides a comprehensive account of the research and development carried out under the MOU during the current fiscal year; Part II: Proposal for FY91 presents the proposed work scope for the coming fiscal year, identifies task timelines and milestones, discusses the responsibilities of collaboration personnel, and summarizes budgets by task and by institution. The two parts are separately bound for convenience of review, and together form the collaboration's first-year summary report. The HCTC collaboration has added three new members (CEBAF, KEK, and University of Pennsylvania) and now has 12 member institutions. The Executive Summary presents in brief an overview of the HCTC design and the major accomplishments of FY90; each of the four tasks defined in the MOU are discussed in more detail in individual sections. The second-year proposal is similarly divided into an executive summary and task descriptions, but also has an administrative section. During FY90, we have made considerable progress toward our goal of developing a large volume tracking detector for the SSC that borrows desirable features of two promising technologies, straw tubes and plastic scintillating fibers (PSF). Our research confirms our prior position that the hybrid straw-tube/PSF approach offers significant advantages in cost and performance and is a viable candidate for central tracking in a large general-purpose detector for the SSC.
Hybrid Central Tracking Chamber Collaboration

Summary Report — Part I: Progress Report for FY90

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1.0 Executive Summary

1.1 Introduction

This report describes the progress made over the past year by the Hybrid Central Tracking Chamber (HCTC) Collaboration toward the development of a large volume tracking detector for the SSC. In particular, the HCTC R&D effort has been focused on the tracking region outside a radius of about 40 cm and within the central rapidity region $|\eta| < 1.6$. Our design studies have lead us to conclude that the best tracking system in this region will be a combination of straw tube drift chambers and scintillating fibers, hence the name Hybrid CTC. Other Subsystem R&D Groups are designing inner and intermediate tracking systems which would supplement the HCTC in a complete SSC detector. Our R&D work is applicable, in full or in part, to several of the detectors that have recently been proposed via EoI's to the SSC Laboratory. However, as the design of the HCTC becomes more advanced, it has been necessary to make some decisions which are detector specific. When this is required, we focus our design on a tracking system which is compatible with the SDC detector. The SDC detector poses the greatest challenge to our design since it requires the largest tracking volume.

The purpose of this Progress Report is to present a comprehensive review of the R&D results obtained by the twelve institutions which are contributing to the HCTC design. These results are grouped into four major tasks: straw tube drift chambers, scintillating fibers, mechanical engineering and Monte Carlo simulation of the HCTC detector. The detailed presentations can be found in Sections 2 through 5. In the remainder of this Executive Summary we present an overview of the complete HCTC concept and a brief summary of the major R&D results obtained over the past year.

1.2 Overview of the HCTC Design

The HCTC detector is conceptually simple. The detection elements, straw tubes or scintillating fibers, are laid in superlayers on the outer surfaces of concentric support cylinders whose central axes coincide with that of the colliding beam (z axis). A cross section cut along the z axis of a HCTC detector is shown in Fig 1-1. A cross section transverse to the z axis through a straw tube super layer is shown in
Figure 1-1. Cutaway view of one quarter section of a HCTC detector, with eight straw tube superlayers (z wires) and three outer scintillating fiber superlayers (stereo, u-v fibers).
Fig 1-2. This figure shows an eight deep superlayer composed of four mm diameter straw tubes. In our design, all straw tubes are parallel to the z axis and therefore a superlayer is simply supported on the surface of the cylinder. The straw tube drift cells measure points in r and phi (using standard cylindrical coordinates). A superlayer provides a line segment of length 2.8 cm projected into the r,phi plane.

The scintillating fibers are also placed on the outer surface of the support cylinders. Since the fibers are flexible, they can be laid either parallel to the z axis or wound on the cylinders at small angles with respect to the axis. The HCTC design uses scintillating fibers to provide stereo superlayers which measure the z coordinates of the tracks. A stereo superlayer consists of four scintillating fiber layers, two at +5° and two at -5° with respect to the z axis. Fibers used in stereo superlayers will have a diameter of about one mm.

Fig. 1-3 shows a Monte Carlo simulation of the readout from particles passing through adjacent straw tube and scintillating fiber superlayers. The simulation is described in detail in Section 5 and is presented here to simply illustrate the measurement concept. The straw tube electronics provide a drift time measurement which is converted to a distance and represented as a circle around the known wire location. The scintillating fiber hits are simply latched indicating which fiber was struck (squares in Fig. 1-3). The pattern recognition program constructs line segments tangent to the drift time circles and uses the fiber stereo displacement to measure the z coordinate (the complications caused by particle and signal propagation times are discussed in Section 5). The goal of the HCTC design is to provide point measurements in the r,phi plane to an accuracy of better than 200 microns and the z coordinate to about one cm.

A HCTC detector using the concepts described above will provide hermetic, uniform and precise particle detection over large tracking volumes. The stable base support cylinders are at the center of the design concept. Our preliminary studies indicate that a support structure using large carbon composite cylinders (see Section 4) will provide the required alignment precision and long term stability for the straw tubes and scintillating fibers. This can be accomplished with cylinders with radii as large as two meters and lengths over six meters, having walls as thin as 0.3% of a radiation length. This means that the HCTC detector can span the full length of the central tracking region without requiring support structures or end plates at zero.
Figure 1-2. Cross section of a straw tube superlayer.

Figure 1-3. Monte Carlo simulation of straw tube and stereo scintillating fiber superlayers. The circles represent the distances measured from the straw tube drift times. The small squares indicate scintillating fiber hits. The left track is at z=0, the right at z=4 cm (note the stereo displacement of the fiber hits).
rapidity. The thickness of an eight deep straw tube superlayer is 0.9% of a radiation length (straw tube elements plus support structure).

The design of a specific central tracking detector based upon the HCTC concept requires knowledge of the supplementary tracking detectors and the general experiment requirements. As an example of this we focus on the SDC detector. As has been proposed for this detector, we assume an inner silicon strip tracker of the type being designed by the Silicon Tracking Subsystem Collaboration (PC022, Seiden et. al.), and supplementary intermediate tracking as proposed, for example, by the Wire Chamber Subsystem Collaboration (PC024, Hanson et. al.).

Assuming this supplemental tracking and using the geometric constraints imposed by the SDC Solenoid, the HCTC detector would take on the general form shown in Fig. 1-4. Within these constraints, the optimal detector parameters will naturally depend on the assumed SSC operating luminosity. Our approach has been to design the lowest cost detector for SDC operation at turnon (luminosity \(-10^{33}\)) and provide a simple, cost-effective upgrade path to the ultimate SSC luminosity (\(-10^{34}\)). The initial HCTC configuration, illustrated in Figs. 1-1 and 1-4, consists of eight straw tube superlayers, each containing eight straw tubes, for a total of 64 point measurements in the \(r,\phi\) plane. The straw tubes would span the entire length of the detector, but be isolated electrically into two sections which are readout at each end. This requires the development of a mid-length termination scheme as described in the attached proposal. The total number of straw tube readout channels in this detector is 245,000. In addition there are three stereo scintillating fiber layers located on support cylinders just outside the last three straw tube superlayers. Each track would therefore have three \(z\) measurements at the outer extreme of the HCTC detector plus the \(z\) information provided by the inner silicon strip tracker. The total number of scintillating fiber readout channels required is 136,000 assuming one mm fibers in the outer most layer and half mm fibers grouped in triplets in the two inner most layers.

Obviously the details of the HCTC design for the SDC detector are still under study and must be fixed by more detailed Monte Carlo simulations. The purpose of this overview is to show that the general requirements of particle tracking for the SDC detector can be well met by the HCTC. An application of the HCTC concept to the \(L^*\) detector is being independently pursued in a new Subsystem Proposal; A
Figure 1-4. HCTC detector in SDC outer tracking volume. The tracking within a radius of 0.5 m would be done with a silicon strip tracker.
Compact Central Tracker (S. Ahlen, et. al.). The carbon fiber composite cylinders being developed for the HCTC detector are also of interest to the Scintillating Fiber Subsystem Collaboration (PC023, Atac, Elias, Ruchti, et. al.). We have been working particularly closely with this subgroup to avoid unnecessary duplication of mechanical design efforts and to strive for interchangability of the straw tube, and scintillating fiber superlayers.

1.3 Overview of Major R&D Results from FY1990

This section briefly summarizes some of the specific R&D results that have come from our HCTC Subsystem research.

- Wire support in small diameter straw tubes (Section 2.1): The wire support allows gas flow through the tubes and permits wire stringing after the tubes and supports have been assembled.
- Construction of an 8 deep straw tube superlayer (Section 2.2): We have in operation a long (2.7 m) straw tube superlayer composed of 4 mm diameter straw tubes.
- Advancement of straw tube end plate design (Sections 2.3 and 4.2): We have refined the end plate design (electronics, gas manifolds and cooling) and have a first order prototype on the 2.7 m superlayer.
- Radiation hardness studies (Sections 2.4, 2.5, 3.2, and 3.3): Radiation hardness studies of straw tubes, gases and scintillating fibers have been undertaken. The first quantitative measurement of the neutron susceptibility of avalanche photodiodes, operated in the geiger mode at room temperature, was made.
- Finite element analysis of carbon fiber cylinders (Section 4.1): A detailed engineering analysis has shown that the large, rigid, low density cylinders needed for the HCTC design can be constructed.
- Superlayer support and assembly automation (Sections 4.3 and 4.4): Progress has been made on the design of an overall support structure for the HCTC superlayers. Preliminary ideas for straw tube assembly automation have been developed.
- Monte Carlo simulation of complete HCTC detector (Section 5): A detailed simulation of the HCTC detector response to SSC interactions has been made. Preliminary pattern recognition studies have been carried out.
The above results are distributed throughout the four tasks which comprise the HCTC Subsystem Program: Section 2, Straw Tube Drift Chambers (Task 1); Section 3, Scintillating Fibers (Task 2); Section 4, Mechanical Engineering (Task 3); and Section 5, Monte Carlo Simulations (Task 4). The section numbers refer to this Progress Report and the task numbers to those assigned in our Memorandum of Understanding. The total funding for the HCTC Subsystem Program in FY1990 was $330K from the SSC Laboratory. Appreciable additional support of our effort was provided directly by Oak Ridge National Laboratory and the Supercomputer Computations Research Institute.

The second-year funding request appears in the companion document "Hybrid Central Tracking Chamber Collaboration, Summary Report – Part II: Proposal for FY91." Three groups have formally joined the collaboration since the proposal for the first years was submitted; they are CEBAF, KEK, and the University of Pennsylvania. CEBAF joins because of the involvement of Drs. Stan Majewski and Carl Zorn, who were part of the original collaboration when they were at the University of Florida. KEK is a new partner who will assist with straw tube electronics. Penn was involved on an informal, cooperative basis last year and has joined as a collaboration member this year.
2.0 Straw Tube Drift Chambers (Task 1)

This section reviews the progress made toward the development of the straw tube superlayers needed for the HCTC detector. There are four components to this part of our R&D program. Section 2.1 presents a study of the electrostatic stability of 4 mm diameter straw tube drift cells and describes a solution to the wire support problem. Section 2.2 discusses the construction and testing of a 2.7 meter long superlayer composed of 60 4 mm diameter straw tubes. We consider this to be an important step toward the construction of a large-scale straw tube superlayer. Section 2.3 describes some preliminary studies of front end electronics and signal propagation properties. Sections 2.4 and 2.5 present gas selection and measurements of the radiation hardness of gases and other straw tube components.

This R&D program gives us confidence that long straw tube superlayers of the type required for the HCTC detector can be constructed to the required accuracy. Only preliminary studies of the readout electronics and radiation hardness have been done. Considerable work needs to be done on the design of a realistic end plate ring and on the development of mass assembly procedures for straw tube superlayers.

2.1 Electrostatic stability of straw tubes

The straw tube design for the HCTC detector calls for 4 mm diameter detector elements. The sense wire would be operated at ~2 kV to achieve gas gains which give suitable signal pulses. The ideal case in which the sense wire is exactly centered within a perfectly cylindrical cathode is electrostatically stable. Practically, however, the sense wire will not be exactly centered due to positioning error and gravitational sag, and the straw tube cathode will be neither perfectly cylindrical nor perfectly straight. Therefore it is important to determine the conditions under which an operational straw tube detector element will perform satisfactorily.

We have constructed a straw tube model of stainless steel tubing which has an inner diameter of 3.9 mm. The steel tube is placed in a horizontal orientation and a manifold on one end allows gas flow through the tube. We have used CH$_4$, CO$_2$ and CF$_4$ as stable gases. We find that the longest cell that is stable above 2.5 kV with a 25 μm sense wire centered in the tube under 50 grams tension is about one meter.
The tensile strength of 25 μm diameter tungsten wire is 150–200 grams so the applied tension to the wire should be kept below 100 grams. Keeping the wire tension to a minimum will also reduce the mechanical load on the detector assembly.

Using a one meter long tube, we have conducted a series of tests to determine the effect of a position offset of the wire in the tube on the maximum voltage the cell can sustain before breakdown. A sense wire is positioned in the tube so as to be centered vertically. The horizontal position of the sense wire with respect to the center of the tube is adjustable. The distance from the center of the tube to the position of the sense wire is measured by means of a traveling microscope to an accuracy of better than 20 μm. The wire position was adjusted relative to the center of the tube and the potential on the wire was then increased until breakdown occurred in the cell.

Figure 2-1 shows the maximum stable operating voltage that a one meter long cell filled with CH₄ can sustain when the sense wire is displaced from the center of the cathode for two different wire tensions of 50 and 100 grams. These tests show that wire offsets of up to 100 μm will not compromise cell operation.

One can predict the motion of the sense wire under increasing electric potential. This has been studied by drilling a hole in the middle of the steel tube to observe the position of the sense wire with a traveling microscope as the wire potential is raised. The sense wire was positioned off center by a known amount (δ). The sense wire potential was increased and the deflection of the midpoint of the wire (d) from its initial position was measured.

For a one meter long wire, the displacement is given by

\[ d = \frac{\delta \left( \frac{V}{V_0} \right)^2}{\left(1 - \frac{1}{2 \left( \frac{V}{V_0} \right)^2} \right)} \]

where \( V_0 = 2700 \sqrt{\frac{T}{50}} \) with T the wire tension in grams and V the applied potential in volts.
Figure 2-1. Measurement of sense wire electrostatic stability in 3.9 mm diameter drift cell.
Figure 2-2 shows measurements of the wire deflection versus sense wire potential for tensions of 50 and 100 grams. The sense wire was initially positioned 100 µ off center. The solid curves are predictions for the wire deflection. The open circle data points are for initial offset in one direction while the closed circle data points are for initial offset in the opposite direction. The discrepancies between the data are indicative of some nonlinearity of the tube.

With 50 grams wire tension it will be necessary to maintain sense wire centering within 100 µm if the tube is to be operated at 2 kV or greater potential. We anticipate that a suitable drift gas will enable us to hold the sense wire potential below 1.8 kV.

To achieve adequate geometric acceptance for charged tracks the SSC central tracking chamber will have to be six meters long at an outer radius of 1.7 meters. Some designs call for a gap in the middle of the chamber in which case straw tube cells may be about three meters long. In either case it will be necessary to provide centering support for the sense wires in the straw tubes at about one meter intervals to ensure electrostatic stability.

The wire supports must center the wire in the straw tube while at the same time not restrict gas flow through the tube. Our design for the wire support consists of a plastic cylinder with a helical groove which is a cylinder radius deep and makes at least one complete revolution around the cylinder in a length of 1-2 cm. The wire support will provide gravitational support regardless of the orientation of the tube. A schematic drawing of the wire support design with cross section views is shown in Fig. 2-3. Production of a prototype feed through has demonstrated the feasibility of injection molding a piece of the desired shape with suitable precision.

The wire supports will be attached to the straw tube. The wire will then be threaded through the tube. This has the advantage that if a wire should break during installation in a straw tube, as will likely happen, it will be easy to remove the broken wire and restring the tube. We have successfully used air flow through tubes of length 3 meters to draw and guide the sense wire.
Figure 2-2. Deflection of a 1 mil sense wire which is initially positioned 100 μ off center in a 3.9 mm test cell.
2.2 Superlayer construction and operation

2.2.1 Construction of a 60 channel, 2.7 meter superlayer prototype

We have successfully constructed a 2.7 m long prototype chamber with 8 layers of tubes. In this section, we present the construction of the prototype. The geometry of the tubes in the prototype is shown in Fig. 2-4. The 60 tubes are arranged in a pyramid shape with 11 tubes at the bottom and 4 tubes at the top. The radius of each tube is 2 mm. The purpose of the prototype is several fold. First, it is used to demonstrate that long tubes can be placed on a surface with accuracy of better than 100 microns. The final overall resolution of the HCTC detector, including survey error, is expected to be about 150-200 microns. Second, we show that the sense wire can be supported about every meter with proper wire supports inside a tube. Our earlier study (Section 2.1) showed that for 50 gram tension, a wire support is required about every meter. Third, we verify that a sense wire can be threaded through the tube with wire supports in place. Fourth, we demonstrate that a
Figure 2-4(a). Cross section of the straw tube superlayer. The shaded tubes were instrumented with sense wires.

Figure 2-4(b). Photograph of superlayer.
chamber with a large number of straws can be made operational without difficulty. In the past, it was shown that chambers with a few tubes could be operational. And last, the prototype demonstrates the feasibility of assembling a large central tracking chamber for SSC. The technique we have developed to construct this prototype can be easily adapted to construct the full size central tracking chamber.

The construction of the 2.7 m prototype starts with a sturdy base. The base could be something like an optical table or a rail. It is important that the base has a flat surface to support the straw tubes. Our base looks like the bottom third of a disk. It is 3.3 meters long with a 7 cm wide machined face as shown in Fig. 2-5. The surface was scanned with a survey telescope and found to be flat to better than 25 microns over the entire surface.

Four aluminum plates with machined grooves are placed on the top of the base. The grooves on the plates are to guide the straw tube placement. The plates are aligned among themselves using a survey instrument.

Figure 2-5. Overview of straw tube superlayer showing stable base support and completed prototype.
Straw tubes were assembled prior to placing on the aluminum plate. Three sections of length about 90 cm were cut. Before the tubes were connected using thin aluminum cylinders, wire supports were inserted inside tubes as shown in Fig. 2-6. Because we were not able to obtain the wire support shown in Fig. 2-3 in time for use in the prototype, we have used two V shaped disks back to back (Fig. 2-6). Although the disks were machined carefully, measurement using a microscope showed that they are in tolerance to about 75 microns. As we have found out, joining tubes was not the best approach since the tube joints introduced cumulative errors along the vertical direction at the joint. The next prototype will not have joints and the production wire supports (Fig. 2-3) will be inserted from the ends of the straws.

Once enough tubes are assembled for a layer, they are attached to the end plates (Fig. 2-7) and placed in the grooves of the aluminum plate. In order to attach to the end plates, the tubes are bent slightly. To obtain better accuracy, tubes are pressed slightly using finger shaped jigs from the top. After tubes are properly placed, a small amount of fast drying glue (trade name: cyanoacrylate) is used to glue tubes to the plate. The gluing has two purposes. First, the fixed tubes act like the grooves on the aluminum plates, so that the next layer of tubes can be aligned accurately. Second, it straightens the tubes.

Each end plate consists of two walls. Tubes are attached to one plate by a thin wall cylinder and sense wires are tensioned from the other wall (Fig. 2-7). The space between the two walls serve as a plenum to provide gas flow to each tube.

As we place each layer, the vertical and horizontal position of the tubes are measured. Figure 2-8 shows that horizontal position of tubes of a layer at different locations along the tube length. The figure shows that tubes can be positioned to an accuracy of 100 microns or better. Figure 2-9 shows the vertical position of the top layer (8th layer) measured along the tube length. As we mentioned earlier, one of the locations of tube joints is out of place by about 150 microns (at 90 cm).

After all tubes are placed and glued, sense wires are strung. To accomplish this, air with high pressure (we used 20 psi air from a tube with 3 mm diameter) is blow from one end of a tube to string a guide wire with 100 micron diameter. A 25
Connecting cylinder.

Figure 2-6. Tube assembly with tube connector and wire supports in the straw tube.

Figure 2-7. End plates used in prototype straw tube superlayer.
Figure 2-8. Horizontal position of straw tubes in a layer as a function of straw tube length.
microns diameter sense wire is attached to the guide wire and pulled through. The sense wire is tensioned with 50 grams of weight and pinned and soldered.

Each cell is tested for high voltage. Out of 60 tubes, we only instrument 28 tubes (shaded tubes in Fig. 2-4). Out of 28 tubes, we find that only one tube does not hold the operating voltage (1800 volts). For the rest of the tubes, we were able to raise the high voltage to at least 2500 volts. It is not clear why one cell is bad, but we think that the wire support inside the cell may not be positioned properly or moved by high pressure air. We strung another wire with 100 gram tension, and were able to raise the voltage to a maximum of 1900 volts from 1300 volts.

2.2.2 Test of the prototype

Our gas study (Section 2.4) found that a mixture of Ar-Ethane-CF4 (33-33-33) results is not only a fast electron drift velocity but also higher gain compared to the popular mixture of CF4 with other hydrocarbon such as Ethane or Isobutane. For this reason, most of our studies are done with Ar-Ethane-CF4 mixture.

Figure 2-10 shows the averaged signal (1000 triggers) from the chamber at 1800 volts. One is taken with an Fe55 source and the other with a Sr90 source, both into
Figure 2-10. Averaged signals from straw tubes directly into 50 Ω's under different conditions.
50 ohms. The rise time is about 2-3 ns. 30 ns later, the signal is reduced to about 15% of the peak. For comparison, the same is shown for Ar-Ethane (50-50) gas. When the chamber is operating with Ar-Ethane mixture, the high voltage is reduced to 1600 volts to maintain a similar gain.

Figure 2-11 shows plateau curves obtained using Lecroy 2735DC amp-disc with a 3 micro-amp threshold. We used a Sr90 radiation source. One curve is taken with the source very near the readout end and the other 240 cm from the readout end. As expected, the knee of the plateau curve measured with the source at the far end location moves out compared to the other curve.

The shape of the signal from the readout end compared to the far end is very similar although the height is down by about half; i.e., the signal dispersion is small.

The attenuation length is measured using an Fe55 source. The peak of the averaged signal is measured as a function of distance from one end. Because of the variation of gain near the straw tube joints, the peak of the signal is measured from both ends of the chamber. From the ratio of the two peaks as a function of distance from one end, the attenuation length is calculated. Figure 2-12 shows the plotted

![Particle Count vs. High Voltage at 65 cm and 240 cm](image)

Figure 2-11. Straw tube plateau curves measured as described in the text.
Figure 2-12. Measurement of straw tube attenuation lengths for four drift cells.
ratio for several channels. The overlapped curves are fitted using an exponential function. Although there are some variations between tubes, an average attenuation length of 500 cm is obtained.

Figure 2-13(a) shows the measured gain as a function of high voltage. The signal from Fe55 is amplified using an Ortec amplifier and fed into a multichannel analyzer. Figure 2-13(b) shows a typical histogram from the multichannel analyzer. From each histogram, the peaks are plotted as a function of high voltage and shown in Figure 2-13(a). In order to obtain the absolute gain, a known amount of charge is fed to the multichannel analyzer for calibration. Due to the systematics in the process, we estimate that there is about a 15% uncertainty in the gain scale shown in Figure 2-13(a).

Presently, the 28 channels are being instrumented with preamps, discriminators and TDCs for the resolution measurement as a function of distance from the readout end. We are using a Lecroy 2735DC preamp-discriminator for a reference measurement. As frontend electronics becomes available from Penn and KEK (see Section 2.3), the Lecroy 2735DC will be replaced for a performance comparison.

2.3 Electronics for straw tube readout

2.3.1 Overview

The goals for the electronics section of the project during the past year have been as follows.

1. To support the mechanical prototyping effort by providing readout instrumentation for the 2.7 m prototype.

2. To study signal readout from long straw tubes.

3. To evaluate front end IC's developed by other groups.

To date we have designed, fabricated and done initial tests of first generation components of front end readout electronics instrumentation to an array of 4 mm straw tubes. The results obtained to date do demonstrate the feasibility of accurate readout of large straw tube systems with acceptable packing density and power dissipation. These results are summarized below. Our greatest concern remains
Figure 2-13(a). Straw tube gas gain as a function of voltage (4 mm diameter tube, 25 μm wire).

Figure 2-13(b). Typical signal from Fe55 source as measured with multichannel analyzer.
noise resulting from crosstalk and electromagnetic interference. The larger scale prototype planned for fiscal 1991 will pose a more rigorous test of the severity of this problem and provide an opportunity to explore creative solutions.

2.3.2 Prototype Instrumentation

Complete instrumentation of the 2.7 m prototype was desired to provide a means to evaluate the resolution obtainable from a complete mechanical and electrical system. This work involved the design of connector boards for the prototype end plate which provide electrical contact to the central wire of each tube. Although the current design will require modification for use in a truly large scale system, it does demonstrate some useful design concepts. A photograph of the assembled connector boards for the preamp end of the stack is provided in Fig. 2-14. Mounted on the board surface adjacent to the sense wires is an array of spring loaded pins which make electrical contact with the sense wires. The signals feed through to the reverse side of the first board, which contains the AC coupling capacitors and PCB traces that feed to a standard edge connector. The high voltage supply is brought in on the second board and distributed to the first board via an intervening array of current limiting resistors.

In the next generation design, these axial resistors will be replaced with surface mounted chip resistors resulting in a much more compact assembly. The next-generation connector board assembly will be integrated with the PCB on which the front end electronics are mounted. A prototype integrated module will be assembled that will instrument a few hundred channels of super layer. These modules will then be registered and attached to the structural end plate. So, although the structural end plate is monolithic, the electronics will sit on interchangeable modules.

During the month of September, tracking studies will be performed on the 2.7 m straw tube stack using the connector boards with LeCroy preamp/discriminator cards and TDC's for readout. The LeCroy preamplifiers will be modified to provide the proper termination for the straw tubes (around 300 Ohms).
Figure 2-14. Photograph of the connector board assembly for the preamp end of the prototype super layer.
2.3.3 Readout From Long Straw Tubes

A preliminary study of signal transients on long straw tubes has been performed including both direct measurements and transmission line simulations. Of particular concern are reflections caused by incorrect termination and signal attenuation and dispersion. Direct measurements of charge collection transients were obtained using a digitizing oscilloscope set to 50 Ω with a 250 Ω resistor placed in series to provide the correct termination impedance. Figure 2-15 shows recordings taken with a 55Fe source at 0.75 m and 1.85 m from the preamp respectively. The vertical scale is 0.5 mV/Div, the horizontal scale is 10 ns/Div, and each trace represents an average of 1000 transients. Some residual reflection from the far end of the tube can be seen, which arrives closer in time when the source is farther from the preamp. A variety of transmission line simulations have been performed to investigate the effects of various termination schemes and to evaluate attenuation and dispersion in even longer tubes. The results are in general agreement with the direct measurements given above. Specifically we have observed attenuation factors of roughly 17% per m in simulations of the experimental setup described above.

Additional simulations have been performed to evaluate the feasibility of constructing extremely long straw tubes (6 to 8 meters) with recording preamps at both ends and a centrally located break in the wire. This break is intended to allow each half of the tube to operate in isolation for reduced occupancy.

Some results are shown in Fig. 2-16 for an 8-m tube with a central break. Two tracks are present, one occurring 1 m from preamp 1 and one occurring 20 ns later, 3 m from preamp 2. Figure 2-16(a) shows the signals seen at the preamp inputs, and Fig. 2-16(b) shows the simulated outputs using the University of Pennsylvania preamp/shaper chips. The break in the wire is modeled as a 1.0 pF capacitor coupling two isolated sense wires. In practice, the actual coupling capacitance would probably be very much smaller. A very slight feedthrough is essentially negligible, and probably overstates the actual amount of feedthrough by a factor of 10 or more. Both preamp inputs show significant pulse distortion as a result of the open-circuit reflections produced at the break. These reflections do not, however, significantly alter the initial, steep response, and therefore would have little effect on timing measurements made using a low threshold. Most of these details disappear after
Figure 2-15. Oscilloscope photograph of assemblies of track recordings (average of 1000) with the source 0.75 m (a) and 1.85 m (b) from the preamp end of a 2.7-m, 4-mm diameter straw. Vertical scale is 0.5 mV/div., horizontal scale is 10 ns/div.
Figure 2-16. Simulated preamplifier inputs (a) and outputs (b) for a 3-m tube with a central break in the presence of two tracks (see text).
shaping the Penn preamp/shaper circuits. We believe that these simulations demonstrate the feasibility of the use of long straw tubes which span the entire tracking chamber.

2.3.4 Front End Electronics

Combination preamplifier and shaper chips from the University of Pennsylvania and from Japan's National Laboratory for High Energy Physics (KEK) have been used to record transients on the 2.7 m prototype. Both chips seem to perform well based on recordings averaged from 1000 transients. Both of these chips make single-ended rather than differential measurements, which exacerbates the noise coupling problems. The Penn chip redesign which will provide true differential operation has been delayed and will not be received until October. We anticipate that this will provide a significant reduction in noise pick-up.

2.4 Gas selection and aging study

2.4.1 Gas selection

Due to the short bunch crossing time (16 ns) of the SSC machine, it is important to use a gas (or a gas mixture) with fast electron drift velocity. It has been shown that CF4 produces drift velocities larger than 100 micron/ns for the electric field inside tubes. However, CF4 alone does not produce good spatial resolution, so it is commonly mixed with hydrocarbon gases, such as methane, ethane or isobutane to obtain a satisfactory resolution (~100 microns of intrinsic resolution). For these gas mixtures, in order to obtain an adequate gain (~20,000), the operating voltage has to be greater than 2,000 volts. Since the wire instability grows as a function of the voltage squared, it is desirable to lower the operating voltage as much as possible.

We have discovered that we can lower the operating voltage by ~20% without affecting the drift velocity and resolution by adding argon to gas mixtures of CF4 and hydrocarbon gases. In Fig. 2-17(a), the time distribution from a 4 mm diameter straw tube chamber using a mixture of CF4-Ethane (50-50) is plotted. The voltage used for this gas is 2,200 volts. The width of the distribution is about 20 ns, which corresponds to a drift velocity of 100 micron/ns. In Fig. 2-17(b), the same is plotted
CF$_4$-Ethane (50-50), HV = 2200 Volts.

(a) CF$_4$-Ethane (50-50); V = 2200 volts.

Ar-Ethane-CF$_4$ (33-33-33), HV=1850 Volts.

(b) Ar-Ethane-CF$_4$ (33-33-33); V = 1850 volts.

Figure 2-17. Time distributions for 4 mm diameter straw tubes (see text).
for CF₄-Ethane-Ar (33-33-33) mixture. The operating voltage for this gas mixture is 1,850 volts for the same gain. The width is still about 20 ns.

We also measured the resolution by using a 4 straw tube (4 mm diameter) chamber and cosmic rays. In Fig. 2-18, the residual of reconstructed cosmic ray tracks is plotted for the gas mixture containing argon, and we obtain a sigma of about 100 microns, comparable to other gas mixtures tested. The result of Fig. 2-18 is preliminary since no effort was made to correct for the wire position and drift velocity as a function of distance from the sense wire (constant velocity is assumed here). At the present time, we are varying the fraction of argon to obtain the best gas mixture.

2.4.2 Gas aging measurement

For practical reasons wire aging tests are often done at ionization rates greatly exceeding those expected in SSC detectors. We have shown that there is a strong correlation between ionization rate (µA/cm-wire) and measured damage rate (%/C/cm-wire) in Argon/Ethane gas mixtures. Greatly increased damage rates are observed at the lower (30 nA/cm) ionization rates closer to expected SSC rates. Recently completed tests of low rate aging in CF₄/Iso (80:20) @ 40 nA/cm and Ar/Et/CF₄ (48:48:4) @ 50 nA/cm have shown no pulse height degradation. Figure 2-19 shows the results for a CF₄/Iso test chamber which was aged at 40 nA/cm for over a year to a total accumulated charge of 1.4 C/cm. A high rate (300 nA/cm) aging test of the Ar/Et/CF₄ (48:48:4) resulted in a damage rate of 10%/C/cm, roughly what would be expected for an Ar/Et (50:50) test under the same conditions. It appears that the protection provided by the 4% admixture of CF₄ at low ionization rates does not work at higher rates. This may indicate that at high rates the CF₄ close to the wire is being depleted faster than new CF₄ can diffuse into the avalanche region.

Understanding how CF₄ prevents polymer formation in wire chambers may make it easier to customize gas mixtures to provide all of the features required by SSC detectors. Noting a relationship between disassociation energy and polymer formation in other freons, Vavra has suggested that the high disassociation energy of CF₄ may result in a lower density of polymerizing radicals. Another possibility is that the fluorine containing radicals formed in CF₄ avalanche etch rather than polymerize. In order to test this possibility we have taken wire chambers which
Ar-Ethane- $CF_4$ (33-33-33), HV=1850 Volts.

Figure 2-18. Cosmic ray track residuals measured from a 4 straw tube (4 mm diameter) stack.

Figure 2-19. Low rate (40 nA/cm) aging in $CF_4$ Isobutane.
show clear damage (visual observation of deposits on wires, reduced pulse heights, etc.) after aging in Ar/Et (50:50) and then "aged" them in a CF$_4$/Iso. Figures 2-20(a) and 2-20(b) demonstrate the complete recovery in performance seen after exposure in CF$_4$/Iso. Table 2-1 describes the test parameters and results of 5 chambers we have treated this way. In all but one case virtually complete recovery was seen after 0.5 C/cm. The reason for the slow recovery of E34 may be due to the extremely low ionization rate in CF$_4$/Iso or it may be because the damage originally occurred in a high rate Ar/Et/CF$_4$ chamber.

After recovery in CF$_4$/Iso the anode wires were observed visually and with an Electron Microscope (E.M) and with Auger Electron Spectroscopy (AES). In most cases the wires appeared very clean and bright gold colored. Even in the partially recovered E34 the deposits seen were substantially less than those seen before treatment in CF$_4$/Iso. EM photographs revealed no significant deposits on E47 and E48, a very thin fuzzy deposit on E36, and scattered thick deposits on E34. The results of the AES analysis of fresh wire, two totally recovered chambers, a partially recovered chamber and an unrecovered chamber damaged in Ar/ET are shown in Table 2-2. The thickness of the surface layer on the fresh wire, E47 and E36 is calculated from the relative attenuation of the 69 eV and 2025 eV Auger peaks from the underlying gold wire. The calculation assumes the attenuation is due to a smooth homogeneous hydrocarbon layer over the gold. The Auger results indicate that there is very little difference between fresh wire and the wires completely etched in CF$_4$/Iso. Since AES is a surface analysis sensitive to depths of only 50", the reduced Si content in E34 compared to E56 may indicate preferential etching of Si over C.

### 2.4.3 Development of new test facilities at TRIUMF

Recently TRIUMF has started testing chambers which have two straw tubes mounted in a frame similar to chambers of Fig. 2-21. Because of concerns about electrostatic instability of the wire at the voltages necessary to achieve gains of approximately 5 X 10$^4$ in straw tubes, our preliminary tests are using both CF$_4$/Iso and a gas mixture of Ar/Et/CF$_4$ (33:33:33) which has a lower operating voltage. Preliminary measurements have been unreliable due to small random changes in the anode to cathode distance caused by pressure exerted by the gas tubing on the chamber frame. Tests with an improved chamber design are just commencing.
Figure 2-20(a). Recovery of damaged chamber in CF₄/Isobutane.

Figure 2-20(b). Pulse height profile along wire showing successive improvement with increasing accumulated charge (C/cm).
### Table 2-1. Recovery parameters in CF$_4$/ISO 80/20

<table>
<thead>
<tr>
<th>Cell</th>
<th>Type</th>
<th>Aging Gas (µA/cm)</th>
<th>Gas Gain</th>
<th>Current Density</th>
<th>Initial Pts Ht</th>
<th>Recovered (relative pulse height in %)</th>
<th>Total Recovery Charge (c/cm)</th>
<th>Total Recovery Rate (%/c/cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>E34</td>
<td>1</td>
<td>AR/ET/CF4</td>
<td>$5 \times 10^4$</td>
<td>0.04</td>
<td>89</td>
<td>93</td>
<td>0.4</td>
<td>10</td>
</tr>
<tr>
<td>E36</td>
<td>1</td>
<td>AR/ET</td>
<td>$5 \times 10^4$</td>
<td>0.27</td>
<td>72</td>
<td>99</td>
<td>1.9</td>
<td>60</td>
</tr>
<tr>
<td>E47</td>
<td>2</td>
<td>AR/ET</td>
<td>$1 \times 10^5$</td>
<td>1.15</td>
<td>86</td>
<td>98</td>
<td>3.9</td>
<td>35</td>
</tr>
<tr>
<td>E48</td>
<td>2</td>
<td>AR/ET</td>
<td>$5 \times 10^4$</td>
<td>0.63</td>
<td>82</td>
<td>100</td>
<td>2.1</td>
<td>45</td>
</tr>
<tr>
<td>E58</td>
<td>3</td>
<td>AR/ET</td>
<td>$5 \times 10^4$</td>
<td>0.20</td>
<td>74</td>
<td>97</td>
<td>0.3</td>
<td>180</td>
</tr>
</tbody>
</table>

### Table 2-2. Relative elemental abundance in deposits by AES

<table>
<thead>
<tr>
<th>Cell</th>
<th>Description</th>
<th>C (as SiO$_2$)</th>
<th>Si</th>
<th>S</th>
<th>O</th>
<th>Deposit Thickness (Å)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fresh Wire</td>
<td>1</td>
<td>0.19</td>
<td>0.14</td>
<td></td>
<td></td>
<td>11</td>
</tr>
<tr>
<td>E47</td>
<td>AR/ET deposit etched by CF$_4$/Iso</td>
<td>0.08</td>
<td>0.11</td>
<td></td>
<td></td>
<td>6</td>
</tr>
<tr>
<td>E36</td>
<td>AR/ET deposit etched by CF$_4$/Iso</td>
<td>0.06</td>
<td>0.14</td>
<td></td>
<td></td>
<td>33</td>
</tr>
<tr>
<td>E34</td>
<td>AR/ET deposit partially etched</td>
<td>0.39</td>
<td>0.12</td>
<td>0.88</td>
<td></td>
<td>*</td>
</tr>
<tr>
<td>E56</td>
<td>AR/ET deposit unetched</td>
<td>0.63</td>
<td>0.45</td>
<td>1.7</td>
<td></td>
<td>-10,000</td>
</tr>
</tbody>
</table>

* Not measured
Figure 2-21. New radiation damage test cells being developed at TRIUMF.
2.4.4 Development of test facilities at CEBAF

Due to budgetary constraints, CEBAF decided to limit itself to the purchase of several items relevant to pursuing studies of gas aging in drift chambers and straw tubes: (1) an MKS Gas Flow Control system ($6.8K), (2) a Laminar Flow Benchtop ($2.1K), and (3) a NESLAB Refrigerated Bath Circulator ($1.3K). These are all essential devices for the aging studies, drift module preparation, and gas mixing and flow system. A first test drift chamber is expected to be tested in September after completion of this system. We now have an x-ray generator (X-Tech) for generating ionizing radiation within the test module. Thus the major equipment now exists for beginning aging studies complementary to those undertaken by TRIUMF. Future gas aging studies at CEBAF will be performed in cooperation with the work going on at TRIUMF.

2.5 Other radiation hardness studies

The work by Zhou, et al. [1] indicates that straw tubes can be expected to operate at neutron fluences up to at least $1.1 \times 10^{13}$ cm$^{-2}$. Groom [2] estimates that the neutron albedo in the central tracking region of a typical SSC detector will vary from about $4 \times 10^{11}$ to $4 \times 10^{12}$ cm$^{-2}$ per SSC-year over the pseudorapidity range $0 \leq \eta \leq 1.5$ - the approximate range of the proposed HCTC. Over a nominal ten-year operating life and allowing for a possible order-of-magnitude increase in SSC luminosity, HCTC components could thus be expected to see total fluences up to $4 \times 10^{14}$ cm$^{-2}$. To be conservative, we thus began our testing by irradiating several straw tube samples to total fast neutron fluences of about $10^{14}$ to $4 \times 10^{15}$ cm$^{-2}$, to see how much, if any, degradation in mechanical performance could be measured.

In this first year, the major emphasis was on comparing the mechanical integrity of the straw tubes themselves, and of glues used in fixing the straw tubes, before and after irradiations to mixed neutron-photon fields. The mechanical testing was performed at the Duke University physics laboratory and the irradiations were performed at the North Carolina State University PULSTAR research reactor. Before the irradiations could be performed, it was necessary to design and build an irradiation capsule and to perform neutron dosimetry. This effort, which was common to both the straw tube and PSF radiation hardness studies, is summarized in Appendix A. The neutron dosimetry results are summarized in Fig. 2-22.
Four separate irradiations of several 4-mm diameter straw tube samples were conducted on two separate days. The straw tubes were fabricated by Stone Industrial of College Park, MD, from a spirally wrapped ribbon of 50 µm thick mylar film. The overlapping seams of adjacent spiral windings were bonded with a polyester adhesive. The samples were mounted at known positions onto a rod that centers itself within the irradiation capsule. For all tests, the reactor pool temperature was between 105°F and 109°F. The test conditions are summarized in Table 2-3.

A single 49-cm straw tube was irradiated for thirty minutes at full power (one MW). On the basis of the known flux distribution, supplemented by nickel and cobalt wire dosimeters placed at three locations along the centering rod during the irradiation, the straw received a neutron fluence profile (see Fig. 2-23) that varied from about $1.1 \times 10^{15}$ to $3.7 \times 10^{15}$ cm$^{-2}$, fast, and from about $1.0 \times 10^{16}$ to $2.3 \times 10^{16}$ cm$^{-2}$, thermal. The gamma-ray dose was estimated to be on the order of 0.5 Mrad. In order to test the integrity of the seams after the irradiation, the 49-cm long straw was pressurized to determine its burst strength. The straw was able to sustain a gauge pressure of 40 psi, which was the maximum to which it was subjected, and represents many times the expected gas flow pressure in the tubes.

Figure 2-22. Full-power fast and thermal flux profiles at the capsule center in the PULSTAR reactor irradiation port Y.
### Table 2-3. Straw Tube Irradiation Matrix

<table>
<thead>
<tr>
<th>Sample No.</th>
<th>Description</th>
<th>Distance from bottom of central rod (in.)</th>
<th>Irradiation time (min)</th>
<th>Maximum fluence (cm(^{-2}))</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Single mylar straw, 49 cm long</td>
<td>2 to 21(\frac{1}{2})</td>
<td>30</td>
<td>3.7(\times)10(^{15})</td>
<td>2.3(\times)10(^{16})</td>
</tr>
<tr>
<td>2</td>
<td>Nineteen pairs of 1-cm aluminized straws glued together</td>
<td>5(\frac{1}{2}) to 8(\frac{1}{2})</td>
<td>10</td>
<td>1.2(\times)10(^{15})</td>
<td>7.8(\times)10(^{15})</td>
</tr>
<tr>
<td>3</td>
<td>Nineteen pairs of 1-cm aluminized straws glued together</td>
<td>25(\frac{1}{2}) to 29</td>
<td>10</td>
<td>1.5(\times)10(^{14})</td>
<td>2.0(\times)10(^{15})</td>
</tr>
<tr>
<td>4</td>
<td>Trapezoidal array of 25 straws, 40 cm long</td>
<td>2 to 17(\frac{1}{2})</td>
<td>30</td>
<td>3.7(\times)10(^{15})</td>
<td>2.3(\times)10(^{16})</td>
</tr>
</tbody>
</table>

**Figure 2-23.** Fluence profile along single straw (sample no. 1).
We have been assembling straw tube arrays by gluing adjacent tubes at 10 – 20 cm intervals with a cyanoacrylate adhesive (super glue). To test the ability of the adhesive to withstand the radiation environment anticipated at the SSC, pairs of 1 cm straw tube segments were glued together. Forty pairs were stressed to measure the load necessary to cause the glued joint to fail. The average failure load was 520±175 grams. In two separate ten-minute runs at reactor full power, thirty eight 1-cm straw tube section pairs, glued together using the cyanoacrylate glue, were irradiated such that nineteen received neutron fluences of approximately $1.2 \times 10^{15}$ cm$^{-2}$, fast, and $7.8 \times 10^{15}$ cm$^{-2}$, thermal, and the other nineteen received fluences of approximately $1.5 \times 10^{14}$ cm$^{-2}$, fast, and $2.0 \times 10^{15}$ cm$^{-2}$, thermal. In all cases, activation wires were irradiated with the straw sections to verify the fast and thermal fluences. The straw sections received approximate gamma-ray doses of 0.2 Mrad. Failure load measurements on these irradiated samples show the average failure load to be $450 \pm 150$ grams (sample 3, fast neutron fluence $= 1.5 \times 10^{14}$ cm$^{-2}$) and $430 \pm 100$ grams (sample 2, fast neutron fluence $= 1.2 \times 10^{15}$ cm$^{-2}$), indicating an approximately 10% reduction in adhesive strength, presumably due to the irradiation.

Finally a collection of 25 straw tubes, which had been glued together with the cyanoacrylate glue into a trapezoidal array of 5 rows (7 straws in the bottom row, 3 straws in the top row), was irradiated for 30 minutes at full power. The array received the neutron fluence distribution shown in Fig. 2-24 and approximately 0.5 Mrad gamma-ray dose. In order to determine whether the exposure to which the straw tube array was subjected would result in a measurable dimensional change, the array was surveyed before and after irradiation with a traveling microscope that has a measurement precision of better than 20 microns. The width of the 40 cm long array of straws was measured at 5-cm intervals. Comparison of the measurements before and after irradiation show that to within the accuracy of the measurements no variation was observed.

The irradiated samples listed in Table 2-3 were mounted on 1-in. diameter lucite rods to facilitate handling. After the radiation exposures, the lucite rods showed noticeable yellowing and the rods had become brittle. In contrast to this, the mylar tubes showed no visible effects from irradiation.
Similar straw tube samples have also been sent to Florida State University for exposure to a beam of 3 MeV electrons. The results of these and other tests should be available to be presented at the Fort Worth symposium in October.

Figure 2-24. Fluence profile along the straw array (sample no. 4).
3.0 Scintillating Fibers (Task 2)

The plastic scintillating fiber (PSF) research task associated with the HCTC collaboration has concentrated on three study areas. These involve: a continuation of the PSF fiber and ribbon studies which were started with the original SSC Generic Detector R & D program [3]; initial studies of the avalanche photodiode (APD) as a fiber readout device; PSF and APD radiation hardness studies. Our fiber and ribbon manufacture work has concentrated almost totally on the determination of the optical characteristics of individual fibers. Detailed ribbon work will be part of our second year program. All three of the sub-tasks are discussed in more detail in the following three sections.

3.1 Fiber and Ribbon Manufacture

Four industrial concerns are now involved with our PSF research program. These are Bicron (USA), Kurary (Japan), Optectron (France) and NE(GB) [4]. Because of the absence of funding for this particular section of the scintillating fiber task we have been working this last year with free samples from all four companies. To date Bicron, Kurary and Optectron have all provided us with fiber samples to test. From Kurary we have samples in 0.5 mm circular, 1 m long with a white coating; types SCSN-81 (standard blue), 3HF (green/radiation hard) and SCSN-81YR3 (red). From Bicron we have samples in 0.5 mm circular, 1.6 m long with a white coating; types BCF-B, BCF-H and BCF-RH1 (all blue emitters). Optectron has sent a small sample of standard blue emitting 0.5 mm diameter uncoated fiber and plan to send us aluminium coated fibers in the near future. For every fiber we receive we measure its light curve on arrival at NU so that any change to the fiber which affects its optical properties can be recorded and evaluated. Bicron, Kurary and Optectron all claim that they can guarantee a fiber diameter tolerance of under 5% and most likely under 2%. Bicron and Kurary both claim that they can manufacture ribbons wherein the individual fiber straightness standard deviation is 50 microns or less. Optectron are proposing a totally different ribbon making technique and have not yet given us any tolerance estimates. Kurary have previously provided us with ribbons composed of 700 micron by 1000 micron rectangular fibers in which we have confirmed an individual fiber straightness standard deviation of 70 microns. Manufacturing ribbons of rectangular fibers is more difficult than ribbons of circular fibers.
3.2 Avalanche photodiode readout

3.2.1 Introduction

The purpose of the program at General Electric Canada Inc., Electro Optics Operations (formerly RCA Inc., Electro Optics) is severalfold:

1. To select a suitable approach to using APD's (Geiger mode or linear mode) with scintillating fibers.
2. Demonstrate the feasibility of this approach with existing APD's and 0.5 mm scintillating fibers.
3. Evaluate the sensitivity of these devices to neutron damage.
4. Develop a prototype diode array which could be integrated with fiber ribbons.

3.2.2 Detection Technique

Although previous analysis has shown that APD's can be used in either the Geiger mode, or in the linear mode in conjunction with a low-noise amplifier, with single-photon detection efficiencies ranging from 20 to 50% (depending on the diode type and operating conditions), it was decided that the operation in the Geiger mode was more suitable for this application. This decision was made on the basis that:

1. The expected "hit" rate of individual fibers is likely to be considerably less than $10^6$/sec, so that the long recovery time (200–500 ns) in the Geiger mode is not a serious barrier.
2. The cost of low-noise amplifiers necessary for operation in the linear mode is likely to be prohibitive.
3. Diode gain uniformity is much less critical in the Geiger mode than in the linear mode.
4. The signal out of the diode in the Geiger mode ($10^8$–$10^9$ electrons in a few nsec) is sufficient to drive a 50Ω line with no further amplification.
5. The expected chip cost in quantity (a few dollars/chip) is expected to be small compared to the packaging cost (estimated to be $15$–$20$/channel).
3.2.3 Feasibility Demonstration

As a first step to demonstrate feasibility of this mode of operation, a number of standard product APD's (C30921S) were modified for this application. The standard device is designed for use with optical fibers and consists of a 0.5 mm APD and a 250 μm diameter light pipe (N.A. = 0.55) which is accessible on the outside of the package and which conducts the light to within a few thousands of an inch of the diode surface (see Fig. 3-1). The modifications were to replace the 250 μm light pipe with a 500 μm diameter light pipe and to A/R coat the diode for good response in the blue-green range. It should be pointed out that this experiment was for demonstration only, it is not a particularly good design in that losses due to misalignment of the light pipe and detector could be as high as 30-40%. Furthermore, good detection efficiency depends on good coupling from the fiber to the light pipe. Five (5) of these devices were delivered to Northeastern University and tested with scintillating fibers. These devices had relatively low dark count rates (5000-10000 cps at V_B+10 V and 22°C). The detection efficiency was found to be about 90% of that of the PMT used for comparison when biased at V_B+10 V. Better detection efficiencies should be achievable at higher bias voltages, and by using a diode large enough to collect all the light from the fiber.

3.2.4 Radiation Damage Tests

Twenty (20) of the modified C30921S units were delivered to Quantum Research Services for neutron damage studies. Preliminary results confirm previous measurements at CERN that the dark count rate at room temperature increases by about a factor of 3 for a fast neutron fluence of about 5x10^6 cm^-2 (see Section 3.3.3).

3.2.5 Prototype Array Experiment

The purpose of this experiment is to demonstrate that a single package consisting of a number of APD's together with simple low-cost readout electronics could be designed and fabricated. While the eventual number of detectors in such a package might be 32 or more, an array of four detectors was considered adequate to demonstrate the concept. This allowed the use of an existing in-house hybrid package. A simple hybrid circuit for the active quenching and pulse shaping of a linear array of four independently mounted photodiodes, with a spacing of 2.5 mm (0.100 in.), has been designed and tested. The signal obtained is shown in Fig. 3-2. This circuit has allowed counting rate of the order of 1 MHz with a dead time of a few
Figure 3-1. Cross-section of C30921S package. Light pipe core diameter and detector sensitive diameter are both 0.5 mm.

Figure 3-2. Signal obtained with prototype of hybrid circuit.
hundreds of nanoseconds. The ensemble, diodes, pulse shaping and reset circuit, fits in a small package of 3.5 x 13 x 33 mm and is displayed in Fig. 3-3. The free space on the right has been reserved for improvement as may be required in the future - i.e., to increase the counting rate using an integrated internal and individual reset. Manufacturing of these modules is in progress and it is expected than one will be delivered to Northeastern University shortly.

3.3 Radiation hardness studies

Four collaboration members were involved in radiation hardness studies of PSF: CEBAF, Florida State University (FSU), North Carolina State University (NCSU), and Quantum Research Services. Although the various investigations were closely coordinated with each other and with Northeastern University, the geographic distribution of the institutions necessitated that the work be carried out at three separate locals: Virginia, Florida, and North Carolina. The following discussion summarizes each of these efforts.

Figure 3-3. Schematic drawing of the package for a linear 4 element photodiode array showing the photodiodes and the associated electronics.
3.3.1 CEBAF

At present, this is an additional and unfunded project for the CEBAF group within the context of the HCTC collaboration. However, the relevant experience of the group and the importance of this topic have driven us to continue some past experiments at a "low-budget" level. As in the past, the group is continuing to carry out high-dose-rate irradiations of new and interesting scintillating fiber formulations. The results of this group's previous studies have been reported elsewhere [5-8]. We have contacts with all the major scintillating fiber manufacturers: Kuraray (formerly Kyowa), Bicron, Nuclear Enterprises, and Optectron. In consultation with these manufacturers, we are obtaining samples of their most innovative formulations for appraisal. The selection of fiber samples reflects a broad spectrum of current formulational interests: (1) Kuraray 3HF, Bicron 3HF, Bicron RH-1, Bicron PFT-based fibers (both blue- and green-emitting), and (2) a selection of Bicron experimental variations on past fibers, plus the first set of Nuclear Enterprise fibers (PVT-based NE-102 formulation).

We have constructed a fiber scanner designed to measure the attenuation characteristics of fibers up to 4 meters in length. Figure 3-4 is a schematic of this device. It represents a low cost method of obtaining reasonable attenuation characteristics of scintillating fibers. Figure 3-5 displays the attenuation curves of a representative group of fibers obtained with this scanner. Radiation damage affects both the attenuation and light output characteristics of the fibers. Since our current setup does not allow for highly reproducible optical coupling of the fiber to the phototube, a method (simulated in Fig. 3-6) has been devised by which the scintillation losses and attenuation changes can be decoupled. By shielding the first 20 cm of the fiber from irradiation, the light output of the shielded portion can be assumed to be identical before and after irradiation. Hence the post-irradiation data can be renormalized to the pre-irradiation data for the first 20 cm of fiber. In this way, the scintillation losses can be effectively decoupled from the attenuation changes.

We are also conducting low-dose-rate irradiations of a variety of 1 m length, 1 mm diameter scintillating fibers. These formulations cover a range of parameter variations including type of base (polystyrene versus PVT), fluors, and their concentrations. Furthermore, they have been split into two identical groups: one in a flowing air (oxygen-containing) atmosphere, and the other in a flowing argon (oxygen-free) atmosphere. Past studies have indicated that at high dose rates, oxygen
Figure 3-4. Scintillating fiber scanner.

Figure 3-5. Some fiber attenuation data measured on CEBAF scanner.
is an important element in the recovery of the scintillator to some residual level of damage. However there have been indications (in acrylic scintillator) that at a sufficiently low dose rate, oxygen can actually increase the level of damage over what would be observed at a high dose rate (after recovery). It is critically important to evaluate the role of oxygen in situations with a more realistic dose rate. The current (first) experiment uses the facilities of the University of Virginia Reactor Facility. A set of $^{60}$Co gamma rod sources is used to irradiate the fibers (in a water pool) at a rate of 700 rads/hr. The irradiation was started in mid-July (1990) and will be terminated in mid-September (1990) for a total dose of 1 Mrad. In addition to the dose rate checks made by the University of Virginia personnel, numerous samples of radiochromic dye film have been included in the sample holders. These will provide an accurate cross check of the absorbed dose. A full report of this experiment will be made at the upcoming Symposium for Detector Research and Development for the SSC (October 15-18, 1990 at Fort Worth, Texas).

In addition to these projects, we have had, in the past few weeks, the opportunity of running some preliminary tests of the 256 channel Hamamatsu H4140 phototube. By instrumenting 100 central channels, and then grouping these four at a time to form 25 outputs, we have observed for ourselves the significant decrease in crosstalk.
when the PMT is placed in an axial magnetic field (up to 1 kgauss in our case). Some preliminary timing tests at William and Mary (by Charles Perdrisat) indicate a timing resolution of 1.6 ns. Shortly, we will obtain the 64-channel H4139 tube for longer term tests. This latter will probably be more appropriate for a CEBAF-specific tracking application which will use scintillating fibers. An aspect that we wish to test is the center-of-cluster method of obtaining good position accuracy and resolution as this is supposed to provide good position resolution quickly and cheaply (as opposed to the center-of-gravity method).

3.3.2 Florida State University

Plastic scintillating fiber is a serious candidate to be the active tracking medium at the SSC because of its triggerability and speed. Plastic scintillator in plate form with either plate wave shifter or fiber wave shifter is a leading contender to be the active medium for the barrel calorimetry at the SSC, both because of its speed and its ability to achieve compensation without uranium. Both applications critically depend on the ability of the active medium to receive large doses of radiation without degrading instrument performance to an unacceptable degree.

In November 1988, Florida State University and the University of Florida initiated a collaboration to investigate radiation damage to plastic scintillator. During the collaboration, which lasted until December 1989, we developed techniques for controlled irradiation at the FSU 3-MeV electron linac and did comparative studies of the radiation resistance of scintillating fibers as well as composition and temperature effect studies. These results were reported at the Tuscaloosa Workshop on Calorimetry for the SSC, March 1989, at the Berkeley Meeting on the Radiation Survivability of Scintillating Calorimeters, July 1989, Berkeley, California, (SSC-N-650), and in the literature [9].

Radiation damage manifests itself as a decrease in the attenuation length and a decrease in the local light yield. Our fiber investigations have led to partial remedies to both problems. The first fruitful result was the demonstration that the use of a large Stokes' shift fluor results in tremendous advantages, namely, a tenfold increase in radiation hardness and very long attenuation lengths. 3-HF, the first such fluor to be used, was originally investigated by FSU chemists. Its use as a fluor and the expected advantages to be accrued were first suggested by S. Majewski, who recognized that utilizing long wavelengths would by-pass color centers in a damaged plastic base,
thus ameliorating the radiation-induced decrease in attenuation length. A partial remedy to the problem of a decrease in local light yield is to increase the concentration of the secondary fluor by a factor of 10 to 100. With most fluors this will result in very short attenuation lengths due to the reabsorption of emitted light. In the case of a large Stokes' shift fluor such as 3-HF, however, the reabsorption of emitted light is almost nil, and this technique suddenly becomes a viable option. First results showed only 33% light yield loss after an exposure to 100 Mrad. This is an enormous improvement over previous performance. We are now engaged in a thorough and systematic investigation of local light yield, attenuation length and damageability as a function of 3-HF concentration.

A second area of investigation is the damage to the plastic base. Results produced by the FSU/UF collaboration proved that modifications to polystyrene base plastic could 'harden' the base by an order of magnitude. Bicron Corporation, motivated by these results, has recently created an improved base material, designated RH-1, which we are now testing.

Much effort on the past half year has been expended on improving the precision and quality of our data. We can now irradiate even long fibers (>2.5 meter length) to any reasonable dose with extreme uniformity. Dosimetry is nontrivial for low energy electron beams, but we have refined our procedures so that we can measure the absolute dose given to a test object to an error of 7%.

The immediate gas and chemical environment is of fundamental importance in both the severity of damage caused and the recovery therefrom. Scintillating plastic which is embedded inside a calorimeter or epoxied to the mechanical support of a fiber tracker will be affected differently than scintillator which has unrestricted access to air. To investigate these phenomena, FSU initiated a collaboration with the University of Illinois at Urbana-Champaign to build fiber calorimeters with advanced, radiation resistant materials and test them at the UIUC 100 MeV electron Microtron. Modules fabricated from a specially designed PTP/3-HF/PS fiber and from the new experimental radiation hard base material RH-1 have been built and are currently being tested. Results have been presented at the ECFA Study Week on High Luminosity Hadron Colliders, September 1989, Barcelona, Spain, and will be published in the Proceedings of the Workshop on Radiation Hardness of Plastic Scintillator, March 1990, Tallahassee, Florida, and elsewhere.
We summarize in Table 3-1 our results for some of these fibers. In Fig. 3-7, we show recovery effects for a 1-mm RH-1 blue fiber in air. We also compare in Fig. 3-8 preliminary light-output results obtained from eight different fiber types using a particular photocathode (with different efficiencies at different wavelengths) and manual coupling techniques.

In March of this year, FSU and Fermi Lab hosted a workshop in Tallahassee on "Radiation Hardness of Plastic Scintillator." The proceedings will be printed and distributed by the end of the year. The workshop proved to be instrumental in focusing attention on critical problems.

<table>
<thead>
<tr>
<th>Fiber</th>
<th>Dose (Mrad)</th>
<th>Attenuation Length</th>
<th>Light Loss</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Undamaged</td>
<td>No Recovery</td>
</tr>
<tr>
<td>BC408 Blue</td>
<td>10</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3HF Green</td>
<td>10</td>
<td>200 cm</td>
<td>&lt;10 cm</td>
</tr>
<tr>
<td>Opticron Blue</td>
<td>10</td>
<td>200 cm</td>
<td>&lt;5 cm</td>
</tr>
<tr>
<td>Y-7 Green</td>
<td>3</td>
<td>200 cm</td>
<td>&lt;5 cm</td>
</tr>
<tr>
<td>Y-7 Green</td>
<td>1.2</td>
<td>200 cm</td>
<td>&lt;33 cm</td>
</tr>
<tr>
<td>Bicron G Green</td>
<td>3</td>
<td>167 cm</td>
<td>&lt;10 cm</td>
</tr>
<tr>
<td>RH-1 Blue</td>
<td>10</td>
<td>200 cm</td>
<td>&lt;22 cm</td>
</tr>
<tr>
<td>RH-1 Blue</td>
<td>3</td>
<td>200 cm</td>
<td>&lt;40 cm</td>
</tr>
<tr>
<td>RH-1 Blue</td>
<td>1.2</td>
<td>200 cm</td>
<td>&lt;81 cm</td>
</tr>
</tbody>
</table>
Figure 3-7. Light attenuation curves for a 1-mm RH-1 blue fiber exposed to 3 Mrad.

Figure 3-8. Comparison of several fiber types.
Ten GE Electro Optics modified C309215 APD's were irradiated in the NCSU PULSTAR reactor at low power (1 watt), at preset positions within the capsule described in Appendix A, for various times from 10 to 240 sec. The following data were collected before and after irradiation: breakdown voltage, $V_B$; dark count rate, $r_d$, at $V_B+10$ V; and dark current, $I_D$, at $V_B-10$ V. Room temperature at the time of data collection was $72\pm1^\circ$F. An ultra-stable power supply and a high-precision voltmeter were used to record the variation inherent in dark count rate as the bias was varied by ±0.5 volts about the nominal $V_B+10$ V. This variation, and the statistical count-rate variances, were used to estimate the uncertainty in the ratio, $R$, of dark count rate after irradiation to that before.

The APD's were loaded inside the aluminum sample-holder tube (see Appendix A) at two selected levels using spacing rods; flux foils were inserted with the APD's. Since exposure times were typically rather short, the following irradiation procedure was used:

- The sample holding capsule was suspended by a string and lowered into vertical exposure port Y within the reactor pool.
- The capsule was allowed to drop by gravity to the bottom of the port; a preset timer was started as the capsule reached the core, as evidenced by the reactivity change displayed on the reactor instrumentation.
- When the preset time expired, the operator scrammed the reactor, immediately shutting off the neutron supply.
- The capsule was withdrawn to the top of the pool and the samples removed.

The results of the ten exposures are summarized in Table 3-2. We plot in Fig. 3-9 the dark count ratio, $R$, as a function of fast fluence for nine of the ten exposures (excepting no. 7). The results indicate a damage threshold at approximately $4\times10^6$ cm$^{-2}$, as evidenced by a rapid increase in $R$ above the no-damage value of unity, indicative of higher dark count rates due to radiation damage. The dark currents, on the other hand, were unaffected by the neutron exposures. Estimates of gamma-ray dose received during the irradiations are a few rads or less.
Table 3-2. Results of neutron irradiations of avalanche photodiodes

<table>
<thead>
<tr>
<th>Test No.</th>
<th>Fluence (cm(^{-2}))</th>
<th>Dark count rate Before</th>
<th>Dark count rate After</th>
<th>Dark count Ratio, (R)</th>
<th>Dark current Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.1x10(^6)</td>
<td>1.6x10(^7)</td>
<td>4778</td>
<td>5383</td>
<td>1.13</td>
</tr>
<tr>
<td>2</td>
<td>2.2x10(^6)</td>
<td>3.2x10(^7)</td>
<td>6052</td>
<td>5785</td>
<td>0.96</td>
</tr>
<tr>
<td>3</td>
<td>5.5x10(^6)</td>
<td>8.0x10(^7)</td>
<td>6900</td>
<td>8993</td>
<td>1.30</td>
</tr>
<tr>
<td>4</td>
<td>5.5x10(^6)</td>
<td>8.0x10(^7)</td>
<td>5776</td>
<td>21,255</td>
<td>3.68</td>
</tr>
<tr>
<td>5</td>
<td>1.1x10(^7)</td>
<td>1.6x10(^8)</td>
<td>5798</td>
<td>21,055</td>
<td>3.63</td>
</tr>
<tr>
<td>6</td>
<td>1.8x10(^7)</td>
<td>2.6x10(^8)</td>
<td>7693</td>
<td>24,342</td>
<td>3.16</td>
</tr>
<tr>
<td>7</td>
<td>2.6x10(^7)</td>
<td>–</td>
<td>5763</td>
<td>45,724</td>
<td>7.93</td>
</tr>
<tr>
<td>8</td>
<td>2.6x10(^7)</td>
<td>3.8x10(^8)</td>
<td>6836</td>
<td>39,556</td>
<td>5.79</td>
</tr>
<tr>
<td>9</td>
<td>1.6x10(^7)</td>
<td>1.3x10(^8)</td>
<td>5500</td>
<td>60,700</td>
<td>11.04</td>
</tr>
<tr>
<td>10</td>
<td>3.2x10(^7)</td>
<td>2.6x10(^8)</td>
<td>5190</td>
<td>68,062</td>
<td>13.11</td>
</tr>
</tbody>
</table>

Figure 3-9. Variation with fast neutron fluence of the ratio of dark count rate after irradiation to that before irradiation.
In Test no. 7 the APO was covered entirely by cadmium, which filters out thermal neutrons (the cadmium cutoff is near 0.3 eV). The fact that the dark count ratios (7.9±0.9, for test 7, and 5.8±0.7, for test 8) represent comparable damage indicates that the damage is due to fast neutrons, which is consistent with the fact that the silicon elastic scattering cross section exhibits a significant increase at and above 0.15 MeV. We plan in the next month to perform a few more tests in order to confirm the damage threshold at about 4x10^6 cm^-2, fast fluence.

A study of long-term recovery (over months) of the damaged APO's is underway. Quantum personnel are testing the damaged APO's at approximately one-month intervals. Early indications are that damaged APO's do experience modest recovery (10-20% reduction in dark count rate in one month) if they receive no further exposure.

The major conclusion to be drawn is that APO's operated in the geiger mode at room temperature begin to exhibit noticeable radiation damage at fast fluences of approximately 4x10^6 cm^-2. Thus, if used in the HCTC, they would likely have to be shielded, since annual fluences inside the central tracking region will be order of 10^7 cm^-2 or greater, even at zero pseudorapidity. If the APO's can be housed outside the calorimeter, coupled to the PCF's by optical fibers, such shielding could easily be achieved at modest cost.

Irradiation of PSF will be performed in September. In the first test, at least two fibers from each of three types will be irradiated at the same time to total fluences of approximately 5x10^12 cm^-2, fast, and 3x10^13 cm^-2, thermal. A sample holder, as shown in Fig. 3-10, has been constructed that can hold up to eight fibers. In order to obtain an approximately uniform exposure, the 60-in capsule will be withdrawn halfway through the irradiation, rotated by 180°, and reinserted in the irradiation port for the second half of the irradiation. The irradiated fibers will be returned to Northeastern University along with one unirradiated fiber of each type and light attenuation curves will be measured. More extensive testing of PSF is planned for project year 2.
Figure 3-10. The plastic central rod with cut-out disks for holding the PSF samples. (Each fiber has a \( \frac{1}{6} \)-in. diameter by \( \frac{1}{6} \)-in. plastic plug at one end.)
4.0 Mechanical Engineering (Task 3)

Advancement of the Hybrid Central Tracking Chamber (HCTC) from the development stage to a full scale SSC version requires substantial input from the engineering community. The mechanical engineering of the HCTC will, to a great extent, determine the accuracy and reliability of the measurements obtained from this device. In FY1990, a significant effort has been placed on the design of the supporting structures for the components of the HCTC. Our analysis shows that a very low density support structure based upon large carbon composite cylinders appears desirable over alternative approaches.

The mechanical engineering goals for FY1990 were to evaluate the various fabrication and assembly methods and to determine their feasibility and cost effectiveness. Four specific components in this process have been addressed with regard to how they measure up to required criteria. The first item is the overall support for the tracking components of the HCTC. This is called the stable base cylinder. It is basically a full length composite cylinder that is supported only at the ends. The second area of attention is the end plate region. The end plates will be the termination point for the straw tubes and will provide the support for the electronics as well as cooling and gas manifolding. The third mechanical issue is the overall support structure for the superlayers. This determines how the individual superlayers will be related to one another as well as to the overall detector. The final point of discussion is the assembly and construction automation of the entire HCTC. Based on the quantity of components to be handled in the assembly, automation will be required to some extent to reduce the labor costs associated with fabrication. Each of these issues has been addressed this year and the preliminary findings will be carried forward in FY1991 to help generate a formal engineering design of the HCTC.

These studies, described in detail below, were carried out at Oak Ridge National Laboratory (ORNL) in consultation with the Duke high energy physics group. The ORNL effort, representing a mechanical engineering effort of over one man-year, was a contribution to the HCTC Subsystems R&D and received no funding from the SSC Lab.
4.1 Stable base cylinder design

Paramount to the success of the CTC for the SSC is a stable structure onto which mounts the various straws and fibers used for particle tracking. The HCTC design uses a carbon composite cylinder as this stable base. The goal of our group in FY1990 has been to prove the feasibility of this design. The basic premise behind the use of a stable base cylinder is that it can provide a lightweight, low radiation length structure with very small deflections. Additionally, the alignment of each superlayer is simplified by virtue of each element registering from the same common surface. The following figures and calculations will illustrate the overall structural integrity of the stable base cylinder.

The cylinder size chosen for analysis is based on the CTC description in the Solenoid Detection Calibration's Expression of Interest. This translates into an 80 cm radius cylinder that is 6 meters long. This cylinder is representative of the inner superlayer in the outer tracking volume of the CTC. It also represents the smallest cross section cylinder to be used and therefore the most conservative in regards to the results of the analysis. The initial thickness chosen for the cylinder was 2.54 cm, which in the design described below has a radial density of approximately 0.3% of a radiation length.

An initial analysis of the cylinder was performed using traditional engineering calculations for a simply supported beam. These calculations provided a rough order of magnitude estimate for the deflection and stress for the cylinder loaded by the straw tubes, fibers and the cylinder material itself. The deflection was found to be on the order of 10 microns and the material stress negligible. Shear deflection of the cylinder was not evaluated in this simple analysis, but was considered in subsequent models.

In order to more accurately model the cylinder, a series of finite element analyses (FEA) was done using increasingly accurate and refined values for material properties and layup across the 2.54 cm thickness. The first FEA run duplicated the conditions described above and the results agreed within 10%. This verified both the FEA model geometry as well as the hand calculations. Subsequent calculations led to the final analysis, which is based on a superlayer cross section consisting of 10 mil face sheets and a 1.0 in. low density core. This layup is shown in Fig. 4-1. For analysis purposes, the material tensile modulus of the two carbon face sheets
Figure 4-1. A superlayer cross section layout showing the composite graphite face sheets and carbon honeycomb core (note: the carbon honeycomb core is not shown with its optimal orientation).
was set a $0.7 \times 10^6$ kg/cm$^2$. This value was determined using the GENRAD composite material analyzer code. This program allows the user to input varying composite materials and layup orientations. For this analysis, we chose standard strength IM6 composite material with a wind pattern of $[90/45/-45/0]_s$, a symmetric layup giving the properties of a quasi-isotropic material, i.e., the same material properties in both the axial and transverse directions.

The material chosen for inclusion in the analysis for the carbon honeycomb core was based on the properties of the Hexcel Corporation HFT-G-3/16-6.0 Graphite Reinforced Honeycomb core, however, any similar core material may be chosen because the analysis code, MSC/Nastran, ignores the bending properties of core material and only requires input of the shear modulus. The number included in this analysis is sufficiently low that it does not affect the results of the bending analysis and is representative of any number of core materials including foam. Core material properties only affect the shear deflection, which is trivial in this geometric configuration.

The results of this analysis indicate that the maximum deflection for a cylinder with radial density of approximately 0.3% of a radiation length is once again approximately 10 microns. Figure 4-2 displays in more detail the results of the FEA performed on this stable base cylinder. The basic cylinder is sufficiently stable that it can be used with confidence as a support structure for the straw tubes and scintillating fibers. This support structure which shows minimal deflection provides a sufficient base but does not sacrifice the need for low radiation length support. Additional analysis is needed to optimize the material sizing and further reduce the radiation lengths. Radiation lengths for the layup described here are shown in Table 4-1. Other issues to be addressed include handling and local loadings that may be induced upon the cylinder. The production of a prototype cylinder would be helpful in analyzing these concerns as well as establishing fabrication techniques needed to produce the cylinders in larger quantities with the accuracy required by the SSC.

The final cylinder design issue that was evaluated was the compression loading due to the tension in the sense wires. This loading amounts to approximately 2250 kg/superlayer. This portion of the analysis examined the bucking load and the critical compression load for the described cylinder. In each case, the compression
Figure 4-2. Color coded deflection analysis of the stable base cylinder.

See following page
STABLE BASE ANALYSIS - 1.6 M X 6 M
CARBON SANDWICH DEFLECTION

(METERS)
Table 4-1. Thickness of the Support Cylinder and Straw Tube Superlayer Shown in Figure 4-1

<table>
<thead>
<tr>
<th>Component</th>
<th>Thickness</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon face sheets</td>
<td>0.051 cm</td>
</tr>
<tr>
<td>Carbon honeycomb core (typical)</td>
<td>0.018 cm carbon equivalent</td>
</tr>
<tr>
<td>Total support thickness</td>
<td>0.069 cm carbon</td>
</tr>
<tr>
<td></td>
<td>= 0.3% of a radiation length ($X_0$)</td>
</tr>
<tr>
<td>Straw tubes, gas, wires</td>
<td>0.6% $X_0$</td>
</tr>
<tr>
<td>Total superlayer thickness</td>
<td>0.9% $X_0$</td>
</tr>
</tbody>
</table>

strength of the cylinder far exceeded the loads applied by the sense wires. Based on this analysis and the analysis described above, the stable base cylinder provides the structural integrity needed to justify the continuation of the study of its use for the HCTC.

4.2 End plate design

The end plates for the HCTC perform multiple functions. They will serve as the origin and termination points for the straw tubes, provide support for the electronic circuit boards, and manifolding and distribution of the ion gas supplies and the electronics cooling fluids. The end plates will provide stiffening to the ends of the stable base cylinder. The analyses discussed here represent the latest in an ongoing iterative design process of the end plates.

The general end-plate concept is illustrated in Fig. 4-3. This design assumes that the sense wires will be operated at high voltage and the cylindrical cathodes at ground. Other alternatives are being studied, but for a preliminary evaluation of mechanical consideration, we have used the model shown in Fig. 4-3.

The end plates will be bonded to the cylinder and thus become an integral part of its structure. Each end plate will be drilled on a close-pack hexagonal pattern for the cylindrical straw tubes. These drilled holes will be approximately one-half the 4 mm diameter of the straw tubes to allow for the insertion of the end plugs attached to each straw tube. The centerline to centerline spacing of the holes will be fractionally larger than 4 mm to prevent interference from tolerance buildup of the
Figure 4-3. End plate design showing the straw tube connections, gas cooling ports and electrical connectors.
straw tubes. An end plug has been designed to provide an interface to the electronics, and will continue to be evaluated in the following months.

After the straw tubes have been placed on the cylinder and the end plugs aligned with the end plates, a sense wire will be inserted through each straw. As described in Section 2.2 of this progress report, we have shown that air flow can be used to blow the wire through long straw tubes. These wires will be tensioned and connected to a first set of electronic circuit boards. These will be supported on and aligned by the end plates. The alignment of the electronics boards is accomplished by machining or molding of an appropriate cavity in the end plates. The accuracy of the alignment will be adequate to position the sense wires and provide the sealing necessary for the ion gas flow and the electronics cooling fluid.

The end plates provide passages for the various fluids and gases associated with the HCTC. The current end plate models provide individual ports for the fluids to enter from and external manifold. Proposals for future end plates would include this manifolding as an integral part of the end plate. In addition to the structural design work on the fluid passages, an effort has been made to design adequate ion gas and electronics cooling fluid systems to remove the heat generated by the various components during the tracking process.

In the study of straw tube heating, it was assumed that all the heat generated in the straw tubes by the ionization of the gas would be carried away by the ion gas. Additionally, the straw tubes were assumed to be 50% blocked in several locations to simulate the presence of the sense wire supports. The tube length used was 3 meters and the gas was taken as 80% CF4, 20% Isobutane. The heat generated by the tubes was assumed to be a maximum of 2 milliwatts. The graphs in Figs. 4-4 and 4-5 display the temperature rise and pressure drop for various flow rates of the ion gas. The results of these analyses indicate that if the flow rate is maintained in the range of 1 cm/sec, there is no appreciable pressure drop or temperature rise. Additionally, if the environment outside the superlayers is maintained at a temperature lower than the straw tubes themselves, a significant amount of heat will be conducted away through the walls of the straw tubes.

Cooling the electronics of the HCTC has also been addressed. The assumption for these calculations is that each channel of straw tubes, approximately 30,000 per superlayer, generates 15 milliwatts of heat. Two methods of cooling were analyzed:
Figure 4-4. The effect of gas flow rate on the temperature rise in the straw tube gas.
Figure 4-5. The effect of gas flow rate on the straw tube gas pressure drop.
gas cooling with either air or nitrogen, or cooling with water. Each has its own advantages and disadvantages. The tradeoffs will have to be further evaluated to determine the most appropriate choice. The purpose of this analysis was to determine the requirements of the various methods for this application. For the gas cooling methods, a parallel system with an inlet supply pressurized to approximately 100 psi blowing across cooling fins attached to the electronics boards would be required. The fins would be thin aluminum sheets approximately 30 mm by 10 mm, located radially on the outer circuit board. The water cooling method would require much less flow due to the higher thermal transfer coefficient. Water would be piped around the perimeter of the end plates and flow across the components to remove the generated heat. The general concept is illustrated in Fig. 4-6. The use of a water cooling system would necessitate a return system, which may be optional in a gas cooled environment. Additional work will size the water and gas passages, reduce the pressure drop, and minimize the temperature rise.

Finally, the end plates serve as a stiffening ring for the stable base cylinder. This stiffening ring allows the stable base cylinder a minimum cross section thickness, while retaining a high degree of stiffness. It provides a stiffened region for mounting the stable base to the superlayers and to the detector. These issues have been evaluated and included in the design and analysis already performed. The end plate must be optimized for radiation length while retaining all of the features specified herein.

Overall, the end plate design has matured considerably this year. Evaluation must continue to resolve the specifics of the issues outlined. Once again, it is highly desirable that a prototype end plate be fabricated to verify the function and "manufacturability" of this device.

4.3 Superlayer support structure

Supporting the various superlayers in relation to one another and to the detector as a whole is an area of concern in the final alignment and assembly of the HCTC. This structure, or combination of structures, must provide a means of assembling the tracking chamber, and be sufficiently rigid to assure and maintain the overall system alignment. The support structure must provide routing passages for the various electrical and fluid services that are required. The design of this structure is an integral part of the overall detector. It must provide mounting for
Figure 4-6. Schematic view of the gas manifold and water piping around the perimeter of the end plates used to remove the excessive electronic heating.
the inner tracking and the intermediate tracking, and establish mounting locations for the magnet coil. These issues will be addressed more completely by the integration group, but the overall integration task must not be overlooked. An effort has been made to look at initial design concepts to support these tasks.

As an example, the current design for the SDC CTC has the outer superlayer extending to approximately 4.5 meters (half-length). The inner superlayer has a length of 3 meters. This arrangement presents a tapered effect at the end of the superlayers as they progress from the inner to the outer layer. We are currently exploring the use of a cone or series of cones to support the ends of the superlayers which will maintain the progression. This arrangement has several benefits: it reduces the amount of material required for the cylinder support; it has both radial and longitudinal stability, and the conical shape. This method also provides a smooth transition to the support structure for the entire tracking chamber. The focus of this design is on methods to achieve the support requirements without sacrificing accessibility to the end plates.

Figure 4-7 illustrates the connection of the overall CTC to the outer chambers. This connection also provides the interface for electrical and mechanical services. A bulkhead similar to the one shown will likely be used for the majority of these connections, allowing for easier installation of the HCTC. Obviously, these connections to the overall detector will be dependant on the configuration of components outside the CTC.

The interface and support connection for the CTC inner (silicon) tracking and the intermediate (forward) tracking must evolve with the design of these component. The design of the HCTC must be such that it can readily incorporate supports for these modules within its structure. Designers have looked at providing "bolting rings" for attaching the other components. Any method used must provide very accurate registering for these components as their locational accuracy requirements are extremely stringent.

In summary, each of the components of the superlayer structure support have received preliminary mechanical design attention. These initial studies indicate that the general concept we have developed for support of the HCTC detector is sound. We are currently proceeding to more quantitative evaluation and design
Figure 4-7. Schematic illustrating the connection of the overall CTC to the outer muon chamber.
which will be tested with a series of prototypes. This program is described in detail in the HCTC progress report for FY1991.

4.4 Assembly and automation

The final assembly of the Hybrid Central Tracking Chamber will involve hundreds of thousands of components. Manual assembly of this device would be burdensome. Automated assembly techniques are being pursued to simplify the construction. Figure 4-8 represents one method being considered to automate the straw tube layup process. This method would take partially assembled straw tubes and place them on the stable base cylinder in an orderly and accurate manner. The device would require constant attention to verify that the process was in control at all times, however, for a system as critical as the central tracking chamber, full automation is not desirable.

Additional automation techniques are being considered for such tasks as inserting the sense wires in the straw tubes; for tensioning and terminating the sense wires at the end plates; for placing scintillating fibers onto the stable base cylinder; and for other areas where automation is an economical consideration. Additional work will be performed on these areas in the following months.
Figure 4-8. One possible automation procedure for the straw tube layup.
5.0 Monte Carlo Simulation of HCTC (Task 4)

5.1 Detector response simulation

The detector simulation makes use of the SSCSIM [10] application of the GEANT program. All interactions of energetic charged and neutral particles with the material of the detector are simulated. A beam pipe and an inner silicon vertex detector corresponding with 6% of a radiation length are assumed. In addition to a triggering event (most often, a Higgs decaying into four muons), background events are generated at a rate corresponding to the S5C luminosity, both of the triggering beam crossing and for the three preceding and two subsequent beam crossings. The effect of delayed particles from interactions in the preceding microsecond falling within the sensitive time window (corresponding to about 10% of the background hits), is approximately represented by equally delayed particles from the background events explicitly simulated.

Trigger events have been generated using ISAJET to simulate Higgs boson production, mostly decaying via a Z⁰ pair into four muons with PYTHIA used to simulate the background events. Simple single and multiple particle generators are also available.

The detector simulated here consists of eight cylindrical superlayers, each composed of eight axial layers of 4 mm diameter straw tubes in a close-packed configuration. The superlayer radii span the interval from 70 to 180 cm from the beam. There are two identical detector modules upstream and downstream of the nominal interaction point. The straw tube lengths range from 2 meters for the inner superlayer to 3 meters for the three outer superlayers. The three outer superlayers are also equipped with 6 layers of 500 micron of axial, +5 and -5 degree stereo layers. All fibers are 3 meters long. Each superlayer is supported by a carbon fiber mandrel 1 mm thick. The inner superlayers correspond to 0.8% of a radiation length at normal incidence, the three outer ones to 1.5%. The straw material is represented by concentric cylindrical layers of thickness π times the wall thickness of 50 microns, but the exact circular, close-packed geometry is used for the straw digitization.
The detector is contained in a uniform, solenoidal magnetic field of 2 Tesla. The straw tube gas is assumed to have an effective drift velocity in the magnetic field of 6.6 cm/μsec (10 cm/μsec in zero field), corresponding to a maximum drift time of about 30 nsec. The position resolution is assumed Gaussian, with σ increasing linearly from 100 microns at radii beyond 1 mm to 150 microns close to the sense wire. The signal propagation speed along the wire is taken as 25 cm/nsec, as is the light propagation speed along the scintillating fibers. The straw tubes are digitized within a 40 nsec time window, starting 10 nsec after the triggering beam crossing. Only the earliest hit within this time interval is recorded. The scintillating fibers are assumed to be sensitive for an interval of 16 nsec, starting 10 nsec after the triggering beam crossing. Pulse height information is simulated for both straws and fibers, but is not used at present.

The progressive effect of the various contributions to the observed time spectrum for trigger events without pileup is show in Fig. 5-1: drift time (Fig. 5-1(a)), drift time resolution (diffusion, etc.) (Fig. 5-1(b)), signal propagation along the wire (Fig. 5-1(c)), and particle time of flight (Fig. 5-1(d)). There is an anticorrelation between the propagation time along the wire and the time of flight for fast particles.

The expected spectrum of digitized drift times (one hit per wire only), is shown in Fig. 5-2(a). Taking a 40 nsec time window from +10 to +50 nsec accepts approximately 73% of the generated digitizings associated with the trigger. The digitizings missed come primarily from slow particles with long times of flight.

Figure 5-2(b) shows superposed drift time spectra for trigger events only, all events from the triggering bunch crossing, all events, and the digitized time spectrum for all events limited to one hit per straw tube. At a luminosity of $10^{33}$ cm$^{-2}$-sec$^{-1}$, just over half of the hits come from the triggering event, and just under half from the minimum bias background. Figure 5-2(c) shows the relative numbers of hits in the 40 nsec window coming from different bunch crossings. A preliminary, low statistics simulation at a luminosity of $10^{34}$ shows roughly one eighth of all hits coming from the trigger event, as expected (Fig. 5-2(d)).

Graphical displays of simulated events in a single chamber module are presented in Fig. 5-3, corresponding to a luminosity of $10^{33}$. 
Figure 5-1. Time spectra, for trigger events without pileup, showing the effects of different contributors.
Figure 5-2. Drift-time spectra and relative contributions to hits within the 40 nsec window from different bunch crossings (see text for explanation).
Figure 5-3. Simulated events for a single chamber module.
Occupancies of the various detector elements at a luminosity of $10^{33}$ have been determined under the above conditions, and are tabulated below:

<table>
<thead>
<tr>
<th>Straws</th>
<th>( L = 10^{33} )</th>
<th>( L = 10^{34} )</th>
<th>Superlayer Inner Radius</th>
</tr>
</thead>
<tbody>
<tr>
<td>Layer 1</td>
<td>17%</td>
<td>about 28%</td>
<td>70 cm</td>
</tr>
<tr>
<td>Layer 3</td>
<td>11%</td>
<td>about 25%</td>
<td>100 cm</td>
</tr>
<tr>
<td>Layer 5</td>
<td>7%</td>
<td>about 15%</td>
<td>130 cm</td>
</tr>
<tr>
<td>Layer 8</td>
<td>3%</td>
<td>about 8%</td>
<td>175 cm</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Fibers</th>
<th>( L = 10^{34} )</th>
<th>Superlayer Inner Radius</th>
</tr>
</thead>
<tbody>
<tr>
<td>Layer 6</td>
<td>0.4%</td>
<td>about 1%</td>
</tr>
<tr>
<td>Layer 8</td>
<td>0.2%</td>
<td>about 0.5%</td>
</tr>
</tbody>
</table>

The straw tube occupancy varies between 3% and 17%. The inner layers are quite active, but at a level that still permits local track segment finding (Fig. 5-3(a)). The fiber occupancies are an order of magnitude lower than the straw tube occupancies at similar radius, as expected from the smaller cell size and shorter sensitive time.

Preliminary estimates have been made of occupancies at a luminosity of $10^{34}$. These have significant statistical errors, and should be treated with caution. They show the effect of the factor of ten increase in background tracks. At this luminosity, the inner straw tube layers are becoming congested, and it will likely be necessary to concentrate on global methods of finding fast tracks rather than looking for local track segments. The fiber occupancy in the outer layer at $10^{34}$ is consistent with independent estimates made for a fiber-only detector at a similar radius.

5.2 Reconstruction studies

Some track finding and fitting software has been developed for the straw tubes of the HCTC, in order to evaluate the detector performance. Track segments are found in projection locally in each superlayer, using the tube pattern only. Segments are searched for at angles up to about 30 degrees to the radial direction. This limits the whole track finding to transverse momenta above approximately 0.5 GeV/c. A straight line fit is then made to each segment, using the drift times.
is iterated if necessary, and allowance is made for the circular ambiguity of the drift
time measurement. Full tracks are then found by linking track segments together.
The linking makes use of both the position and the direction of each segment.
Finally, a circle fit is made to the whole track to determine the track curvature and
direction.

Figure 5-4 shows a graphical display of an artificial event consisting of about 25
tracks randomly distributed in rapidity, azimuth and momentum. The dotted lines
represent the reconstructed tracks. One full length track is not reconstructed, due to
a decay in flight.

The reconstruction software described above is preliminary, and in particular,
has not been optimized for very high momentum tracks. Nevertheless, we have
taken a first look at the transverse momentum resolution for tracks in range which
could be expected from Higgs decay. We have generated single 200 GeV/c muons,
both alone and superposed on the background expected for an SSC luminosity of
10^{33} \text{ cm}^{-2}\text{-sec}^{-1}. The reconstructed transverse momentum distribution is shown in
Figs. 5-5(a) and 5-5(c), respectively. The observed resolution of 17\% for isolated
muons in in Fig. 5-5(a) is close to that expected from analytic formulae. No vertex
information is used: a precise vertex point could improve the resolution by at least
a factor of two. A similar spectrum for isolated electrons is shown in Fig. 5-5(b),
where the effect of bremsstrahlung is visible. In Fig. 5-5(c), the distribution has
developed tails due to the overlap of background tracks at 10^{33} luminosity. Despite
the very preliminary nature of the algorithms, these first results are encouraging,
and suggest that the detector can work well at a luminosity of 10^{33}.

Studies of the reconstruction of the longitudinal (z) coordinate have
commenced. A very rough estimate of the position along the wire of the straw tube
can be obtained from the signal propagation time, which can be estimated for
individual track segments from the timing differences between alternate straw tube
layers. Figure 5-6 shows the sort of time and z resolution which can be achieved for
tracks having pseudorapidity \( \eta = -1 \). A time resolution of 0.7 ns for the track segment
translates into a z resolution of about 40 cm. The z resolution is best at \( z = 0 \), and
deteriorates at high \( z \) due to the anticorrelation between propagation time along the
wire and the particle time of flight to the straw tube.
Figure 5-4  Reconstruction of several randomly distributed tracks.
Figure 5-5. Reconstructed transverse momentum distributions for 200 GeV/c muons.
Figure 5-6. Time and longitudinal coordinate resolution for tracks at $\eta = -1$. 
The closely grouped layers of stereo scintillating fibers have been used to reconstruct space points in each of the three outer superlayers. Hits in each double layer are grouped into clusters. Each axial cluster is paired with each U cluster in the 500 fiber overlap region. A search is then made for a V cluster, part of which must lie in the interval determined by the outer edges of the X and U clusters plus an additional one fiber tolerance. If alternative combinations are found for the same X cluster, that one is kept whose clusters centers match best.

Figure 5-7 shows a view of the HCTC from above, along with several tracks independently generated close to the X-Z plane. The straw tube digitizings are shown at their true, generated Z coordinates. The jagged, dotted lines connect the independently reconstructed Z coordinates of the track segments. The crosses represent space points reconstructed from the stereo fibers in the three outer superlayers. Reconstructed fiber space points are also shown in full SSC events with background in Fig. 5-3 at a luminosity of $10^{33}$. For near-radial tracks, the reconstruction efficiency is high, even at high luminosity. At $10^{33}$, there are typically 10 U clusters which could match to each X cluster, reduced to 1.5 candidates by matching with V. (This would increase to 5 candidates if the matching tolerance were increased from 1 to 5 fiber widths.) However, most of the ambiguous combinations are related to very slow or spiralling tracks.

5.3 HCTC design parameters

Simulation has demonstrated that 8 layers of straws are sufficient to reconstruct a track segment within a superlayer. The reduction from 12 layers as in the original proposal has reduced both the channel count and the amount of material per superlayer. The successful reconstruction of local space points from stereo fiber layers supports the design decision to keep stereo layers as spatially close as possible, and indicates that two stereo angles are sufficient. The effects of larger fiber diameters and omitting the axial fiber layers remain to be checked. To limit the number of matching ambiguities, the fibers must be laid precisely straight and parallel, to about one fiber width.
Figure 5-7. Top view of the HCTC showing several independently generated tracks.
References


4. Most of our earlier fibers were provided by Kyowa, a company which has recently been absorbed by Kurary. Optectron now has a branch in Massachusetts and this is making it easier to deal efficiently with them. NE used to be known as Nuclear Enterprises. Bicron is now owned by Saint Gobain (France).


Appendix A

Neutron Irradiation Sample Holder and Dosimetry
Appendix A

Neutron Irradiation Sample Holder and Dosimetry

Capsule Description

An irradiation capsule was designed and constructed that allows the simultaneous or sequential irradiation of scintillation fibers, straw tubes and electronic diodes. The capsule was machined from high purity aluminum and contains an active irradiation volume that is cylindrical with a length of approximately five feet and a diameter of two inches. The center of the capsule contains either an aluminum tube or a plastic rod, each with a diameter of 0.5 in., which runs the full length of the capsule.

Circular plates surrounding the center tube serve to position the tube in the center of the capsule and to also accommodate straw tube samples. Approximately six straw tubes of any length up to 58 in. each can be inserted in a series of holes in the positioning plates which are held in place by blank faced end plates and aluminum sleeves that slide over the inner tube. Figure A-1 identifies the dimensions and principal features of the capsule and support structures. A Cd sleeve can be inserted in the space between the guide plates and the capsule wall to allow irradiations in which thermal neutrons have been absorbed. Slots in the circular plates provide for the positioning of gamma ray or neutron dosimeters and dosimeters may also be inserted in the center tube when small components are irradiated in the center section.

Diodes have been irradiated at much lower fluences than scintillation fibers or straw tubes and are positioned inside of the center tube on plates containing dosimeters in the irradiations performed to date. Because the neutron flux decreases sharply along the tube length, it has been possible to place diodes in positions that provide roughly an order of magnitude spread in exposure during a single irradiation. Fibers can be mounted on circular disks that can be positioned at arbitrary positions along the plastic rod, which centers inside the capsule. Eight slits have been cut into the disks to accommodate the fibers, and the ½-in. plastic end plug sits on top of the top disk.
Figure A-1. Schematic of the irradiation capsule showing typical dimensions.
The active reactor core face is two feet high, so thermal and fast neutron fluxes begin to decrease sharply approximately twenty inches above the reactor base plate. The capsule is designed to be inverted when long specimens are inserted so that the fast and thermal flux distributions along the full specimen length is approximated by a skewed Gaussian curve that peaks about four inches from the capsule end and is symmetrical about the tube midpoint, with fluences depressed several orders of magnitude at the tube mid-point. Uniform irradiations of long specimens is therefore not possible but a uniform fast and thermal neutron exposure can be obtained near the capsule end over a length of about four inches.

In the irradiations performed to date, the capsule was inserted into a water filled tube (VEP position Y shown in Fig. A-2) immediately in front of the reactor core face and was rotated in longer irradiations to ensure exposure uniformity across the capsule width.

**Dosimetry**

It will be necessary in different irradiations to obtain accurate measurement of thermal neutron flux, fast neutron flux and gamma ray dose rates as a function of reactor core position. The thermal and fast fluxes should maintain constant ratios in given positions in the absence of strong neutron absorbers but the gamma ray dose rate is a function of past reactor operation and can exhibit variability, particularly in the case of low dose irradiations that immediately follow an irradiation at higher power. The irradiations performed to date have started with "cold core" conditions (reactor shut down for prior twelve hours) to provide some uniformity in gamma ray exposures for exposed specimens.

Thermal and fast neutron fluxes were measured at three inch separations along the capsule tube length using indium and cadmium covered indium foils. Indium absorbs thermal and epithermal neutrons at predictable rates to yield measurable quantities of radioactive In$^{116m}$ in accordance with the reaction:

$$\text{In}^{115}(n,\gamma)\text{In}^{116m} \quad T_{1/2}([\text{In}^{116m}]) = 54.2 \text{ min}.$$ 

The Cd shielded foils remove thermal neutrons and provide a measure of the fast flux with a threshold cutoff of 1.5 eV. Figure A-3 shows the thermal and fast flux distributions as functions of position along the irradiation capsule. The fast neutron fluxes are roughly an order of magnitude below the thermal fluxes near the
Figure A-2. Plan view of the PULSTAR reactor core showing vertical exposure port Y.
core center and decrease somewhat more sharply than thermal fluxes near the extremities. Fast neutron fluences of $\sim 10^{16}$ cm$^{-2}$, which are above the maximum fast neutron exposures anticipated in the HCTC of an SSC detector, should be readily achievable over a ten to twelve inch length of the capsule.

The radioactive In$^{116m}$ was measured with a Li drifted Ge detector set to record only photons in the 1.293 MeV full-energy peak and calibrated against standard sources of Co$^{60}$ and Cs$^{137}$ which bracket the photopeak energy of interest. The dosimeters were located at the periphery of the circular plates and the entire capsule was rotated slowly (one rev/hr) during the irradiation to provide average fluxes for specimens located near the capsule periphery. Since the flux distribution is now known, exposures in future irradiations can be controlled with reasonable accuracy by control of reactor power and exposure time. However, thermal dosimeters will be inserted with each exposed specimen as a cross check against the standard curve.

Longer irradiations will employ Co and Ni as dosimeters which measure thermal and fast fluxes through the reactions:

$$\text{Co}^{59}(n,\gamma)\text{Co}^{60} \quad \text{(thermal)} \quad T_{1/2}(\text{Co}^{60}) = 5.3 \text{ yr}$$

$$\text{Ni}^{59}(n,p)\text{Co}^{58} \quad \text{(fast)} \quad T_{1/2}(\text{Co}^{58}) = 72 \text{ d} .$$

Other dosimetry systems can be employed to establish the neutron spectrum energy distribution as this becomes necessary.

Gamma ray dose rates will be determined using inorganic thermoluminescent dosimeters with particular emphasis on dosimeters containing Li$^7_2$ (SO$_4$) which exhibit low thermal neutron dose sensitivity. Preliminary estimates indicate that the gamma-ray dose rate in exposure port Y is approximately 1 Mrad/hr, at full power. The gamma-ray dose rate measurements and the determination of neutron energy spectrum in the capsule are items to be developed in the program for the coming fiscal year.
Figure A-3. Measured fluxes in exposure prot Y at full power.