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Proposal to the SSC Laboratory for Research and Development of a Straw-Tube Tracking Subsystem

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Abstract

We propose an R&D program to develop a straw-tube tracking system for use at the SSC. It emphasizes precision resolution and could be located in the volume 10-100 cm from the beam pipe. These features are compatible with running at an intermediate luminosity, $\mathcal{L} \approx \infty/^{\ni\in}$ cm^{-2}sec^{-1}, appriopriate for an experiment such at the Bottom Collider Detector that requires detailed particle analysis at transverse momenta less than 10 GeV/c. The present proposal covers only one year of an ongoing program to produce a 1000-tube prototype system in 1990, followed by a 10,000-tube system in 1990. There are three parts to the proposal:

1. Prototype construction and testing at Princeton and IIT, **$???**;
2. A Manufacturing feasibility study by Westinghouse, **$???**;
3. VLSI chip development with the Westinghouse SIMOX process, **$???**.

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The dollar amounts shown in **boldface** associated with certain sections indicate the funding request of the present proposal.

I. Executive Summary

We propose an R&D program to develop a straw-tube tracking system for use at the SSC. It emphasizes precision resolution and could be located in the volume 10-100 cm from the beam pipe. These features are compatible with running at an intermediate luminosity, $\mathcal{L} \approx \infty\prime^{\ni\in}$ cm^{-2}sec^{-1}, appriopriate for an experiment such at the Bottom Collider Detector that requires detailed particle analysis at transverse momenta less than 10 GeV/c.

The present proposal covers only one year of an ongoing program:

1990 (The period of the present proposal.)
  - Produce a 1000-tube prototype system and test this in the M-Test line at Fermilab;
  - Produce front-end preamp/shaper/disrci chips for the 1000 tubes, requiring an optimzed run of the Bipolar design of U. Penn;
  - Initiate a manufacturing feasibility study with the goal of industrial production of chambers in 1991;
  - Investigate the applicability of the SIMOX VLSI process to fast-pulse analog + digital front-end electronics

1991
  - Produce a 10,000-tube system to be tested in the C0 intersect at Fermilab. It is expected that this will be done by industry;
  - Produce VLSI electronics for this system that includes both the preamp/shaper/discri and the TDC functions, either in a Bi-CMOS hybrid or in the SIMOX technology;.

1992-1993
  - Produce a 50,000-tube system for testing at the C0 intersect at Fermilab in 1993.

The work in 1990 divides into three tasks:

1. Prototype construction and testing at Princeton and IIT, **$???**. This includes production of the Bipolar front-end chips;
2. A Manufacturing feasibility study by Westinghouse, **$???**;
3. VLSI chip development with the Westinghouse SIMOX process, **$???**.

II. The Opportunity for B Physics at a Hadron Collider

We are embarking on a long-range program with the goal of detailed investigation of CP violation in the B-$\bar{B}$ system.[1] Of all known phenomena, we believe that CP violation is the clearest indication that new physics is to be found at energy scales above 1 TeV. The greatest opportunity to explore this subject at present energies is at a hadron collider such as the SSC: the cross-section for B-meson production is about 10^6 times larger at the SSC than at the $\Upsilon(4S)$ resonance at an e^+e^- collider.

Because the B lifetime is 1 picosecond, a B meson travels far enough before its decay that the decay products may be isolated from the primary pp interaction. A silicon vertex detector can then provide a signal for the B of quality similar to that in the nominally cleaner environment of an e^+e^- collider. The vertex detector will be surrounded by tracking chambers and particle identification in a spectrometer based on a large 1-Tesla dipole magnet, sketched in Fig. 1.

Fig. 1. View of a B-physics experiment at the SSC.

The study of CP violation in the B-$\bar{B}$ system can be accomplished by measurement of an asymmetry in the decay of B mesons to all-charged final states:

$$A = \frac{\Gamma(B \to f) - \Gamma(\bar{B} \to \bar{f})}{\Gamma(B \to f) + \Gamma(\bar{B} \to \bar{f})}.$$

While the asymmetry A may be as large as 10%, this likely occurs in modes with branching fractions $\Gamma \sim 10^{-5}$. This requires at least 10^8 reconstructible decays for a significant signal to be discerned. Further, the cleanest signals are for modes with $f = \bar{f}$, so the particle-antiparticle character of the parent B must be 'tagged' by observation of the second B in the interaction. Of course, a detailed study should include measurement of asymmetries in several different decay modes.

The production of B mesons at a hadron collider is a low-transverse-momentum process, so that coverage of angles from 10° to 60° to the beams is much more important than in detectors for W's, Z's, and e^+e^- interactions. This suggests the use of dipole analysis magnets, with fields oriented transverse to the beam. Rather than building two spectrometers, each covering one of the forward regions, it is more effective to construct a single dipole magnet around the interaction region. This maintains large solid-angle coverage as well as optimal momentum analysis for small-angle tracks.

The detector must operate in the high-multiplicity environment of a hadron collider. Efficient pattern recognition will be achieved if each particle track is sampled many times, and if the occupancy of each channel is low. Roughly, 100 tracks per interaction will be sampled 100 times each, while maintaining 10^{-3} occupancy. This requires of the order of 10^7 detector channels.

The detector should operate at luminosities of up to 10^{32} cm^{-2}s^{-1}. At the SSC, this corresponds to 10^7 interactions per second, each with about 10^4 words of information, or about 10^{12} bytes per second, assuming 10 bytes per word. The data-acqusition system to process this information rate is ambitious!

Such considerations leads to a detector architecture containing 7 subsytems:

1. The **Silicon Vertex Detector**, with silicon as close as 1.5 cm to the beams.
2. The **Tracking System**. It is too costly to perform all tracking in silicon detectors, so these must be supplemented with tracking chambers, composed of straw-tube detectors in the current design.
3. **Ring-Imaging Čerenkov Counters** and **Time-of-Flight Counters** to provide identification of charged pions, kaons, and protons.
4. **Transistion-Radiation Detectors** to provide partial identification of electrons from pions, in conjuntion with item 5.
5. An **Electromagnetic Calorimeter**, to complete the electron identification and to provide a trigger and tag on the decays $B \to eX$.
5. A **Fast Trigger** to reduce to event rate by a factor of 50 before the event information is moved off the detector.
6. A **Barrel-Switch Event Builder** capable of organizing the data streams from 10^5 events per second into individual events.
7. An online **Processor Farm** of about 10^6 MIPS (= 1 TIP) capability to provide the higher-level triggering needed to reduce to event rate to 1000 per second for archival storage.

The restriction of the experiment to luminosities $\lesssim 10^{32}$ cm^{-2}sec^{-1} derives from consideration of the radiation level on the silicon vertex detector and of the overall data rate. In addition, at this luminosity a straw-tube tracking system is much more effective than would be the case at 10 times the luminosity:

- The lower radiation level permits the straw tube to be located as close as 10 cm from the beams, so that the tracking system extends out to only 1 m from the beams, thus reducing the overall detector cost. vertex detector can be done in a single system;
- The reduced interaction rate of one event per 100 nsec permits use of a 'slow' gas so that spatial resolutions of 40 μm may be achieved in each straw tube using electronics of only 1-nsec time resolution. Thus excellent momentum resolution in a compact tracking system.

III. Overview of the Straw-Tube Chamber System

The silicon vertex detector in a B physics experiment provides precision measurement of particles' tracks near the primary vertex, so that secondary vertices may be isolated. It does not provide tracking over sufficient distances to yield accurate momentum measurements, not does it provide enough hits along a track to ensure good track finding in a high-multiplicity environment. The silicon vertex detector could be extended in principle to include many layers, but at great financial cost.

Thus we intend to surround the vertex detector by a tracking system that occupies a large volume for good momentum resolution and good pattern recognition. Gas-filled wire chambers appear adequate for this task, although one readily arrives at the number of sense wires as 250,000: 64 layers of wires, each layer arrayed along a perimeter of 6 meters on average, with 300 wires per meter (3-mm pitch). (Devices such as a 'jet chamber' with long drift times are not suitable for a hadron collider.)

The straw-tube technology is rather appealing for such a large tracking system, due to its relatively low mass, high accuracy, and mechanical isolation of each sense wire. A review by DeSalvo[2] has been influential in thinking about large tracking systems for colliders, while the work of Kagan *et al.*[3] is an excellent starting point for construction of actual detectors.

A straw-tube chamber is a direct descendant of the Geiger-Müller proportional tube counter, in which the tension of the axial sense wire is born by the strength of the walls. In a straw chamber the walls can be reduced to 1 mil thickness, being a spiral-wound tube of a layer of aluminized polycarbonate film surrounded by a layer of mylar (this particular construction is due to Kagan *et al.*[3]). By operating the straw tube as a drift chamber with dimethyl-ether gas, resolutions of 35 μm can be achieved at atmospheric pressure. If pressurized, the resolution improves as $1/\sqrt{P}$, supposing mechanical tolerances can be maintained.

Straw tubes can be made in 2-meter lengths, the maximum needed in the dipole-magnet spectrometer, but a single tube is not stable against buckling. A suitably rigid structure is obtained by glueing tubes together into 'superlayers' of perhaps 8 layers. A superlayer module is then the mechanical building block of a straw-tube system. The superlayers can be planar or sections of a cylinder. Figures 2 and 3 sketch a possible configuration of the superlayers.

The mechanical necessity of superlayers leads to an advantageous organization of the task of track pattern recognition. Particles with momentum more than 500 MeV/c have negligible sagitta across a single superlayer in a magnetic field (along the tube axis) of 1 Tesla. Hence one may search for track segments in each superlayer separately, using straight-line algorithms. A segment is then characterized by a vector. The second phase of pattern recognition combines vectors into the helical, momentum-dependent tracks. Such a procedure will be implemented in the near future in our computer simulations of the detector performance. Efforts are underway in collaboration with Fermilab and U. Penn to assess the suitability of this pattern-recognition architecture for hardware implementation in a fast trigger.

IV. The R&D Program

Overview

The present proposal is related to an R&D program[4] that offers opportunities for testing the straw-tube tracking system at Fermilab. The development program will proceed in three phases:

1. Construction of an 800-tube system to be tested in the M-Test line at Fermilab in 1990; the front/end preamp/shaper/discri will be that designed at U. Penn and implemented in the AT&T bipolar process; the TDC's will be conventional LeCroy.
2. Construction of approximately 10,000 tubes for a system test at the Fermilab C0 intersect in 1991; for this the TDC's will be a custom VLSI design.
3. Construction of approximately 50,000 tubes for a second test run in C0 with a modest physics capabiity–reconstruction of D and possibly some B decays. The construction of such a large system would test the industrial-scale production techniques that would be needed for a full-scale SSC detector.

The present proposal covers Phase I (1990) of the above program. The issues we plan address are discussed in greater detail in the following sections.

Fig. 2. First view of straw superlayers.

Fig. 3. Second view of straw superlayers.

1. Construction of the Straw Tubes

Our considerations of mechanical issues in straw-tube construction have been greatly influenced by the excellent work of H. Kagan *et al.*[3]

Recently it has proven practical to manufacture straws that are two-ply laminates of an inner polycarbonate film about 14 μm thick surrounded by a layer of 12.5-μm (48 guage) Mylar. The Mylar provides sufficient strength that a 5-mm diamter tube can support more than 5-atmospheres pressure. The polycarbonate film is metallized on its inner surface. The film itself is a reasonably good conductor–about 600 ohms/□. This is useful in that small scratches in the metallization need not result in an open circuit on the cathode. The film is also opaque, which elimates photoejection of electrons from the cathode due to ambient light.

The polycarbonate film, Makrofol KL3-1009, can now be ordered directly from its U.S. distributor, Mobay Co. of Pittsburg, PA; contact George Schexnaydar (412-777-2833). The film is manufactured in Germany by Bayer. We have purchased enough film to make several thousand straws.

a. Cathode Metallization

All straws tubes manufactured to date have used a thin layer of aluminum as the conductor on the cathode surface. The layer is typically deposited on the cathode foil by evaporation.

However, the inevitable oxide layer that forms on the cathode surface has a high resistivity that can make for poor electrical connections at the tube ends. A copper cathode would be superior in this regard as copper oxide is a relatively good conductor. Namely, CuO has a conductivity about 10^{12} times larger than Al_2o_3 (although 10^{-8} times that of pure copper.[5] Further, the work function of copper (≈ 4.65 eV) is slightly higher than that of aluminum (≈ 4.28 eV) so that a copper cathode is somewhat less sensitive to photoejection of electrons.

We are having a roll of polycarbonate film copperized to a thickness of 3000 Å by A.D. Tech (Glenn Walters, 508-823-0707). This thickness is greater than that used in previous metallizations, due to our desire to reduce the electrical resistance of the cathode to 0.1 ohms/□. The process of evaporation of the cathode metal places a considerable heat load on the polycarbonate foil, causing blisters if too much metal is deposited at a time. This has limited the aluminization to about 1000 Å (0.6 ohms/□) in the past, according to Sheldahl Co. (Mark Swanson, 507-663-8258).

We anticipate making two more metallization runs in the next year and request funds of \$3000 for each run, for a total of **\$6k**.

b. Straw-Tube Impedance

A long straw-tube chamber is a transmission line with impedance

$$Z[\text{ohms}] = 60 \ln(D/d),$$

where D is the tube diameter and d is the anode-wire diameter. For example, if $D = 5$ mm and $d = 20$ μm, then $Z = 331$ ohms.

The resistance of a gold-plated-tungsten anode wire is 200 ohms/m for $d = 20$ μm, and the resistance of the cathode foil is 40 ohms/m for 1000 Å of Al and a 5-mm tube diameter. Recall that tube lengths of up to 2 m to be used in our program.

It seems desirable that the anode and cathode resistances be small compared to the tranmission-line impedance. This suggests that a thicker anode wire be used, and also that the cathode metallization be thicker.

If a copperization of 0.1 ohms/□ can be achieved, the cathode resistance would be about 6.5 ohms/m for a 5-mm diameter tube.

The implications of thicker anode wires and cathode metallization on the number of radiation lengths per straw are summarized in Appendix A.

c. Winding the Tubes

Until recently, straw tubes for particle detectors have been exclusively wound by Precision Paper Tube Co. (Rick Hatton, 312-537-4250). However, their price is now rather high: \$10-\$50 per tube.

The technology of spiral winding was invented in 1888 and has produced billions of paper drinking straws given away free. Nowadays the ‘free’ straws are made by a plastic extrusion process, and spiral winding of tubes is done for toilet paper cores, battery cases, *etc.*We have had sample straws wound by two new vendors: Electrolock Inc. (Steve Castleberry, 216-543-6626), and Stone Industrial (Joseph DiSilvio, 301-474-3100). Both vendors produced tubes, 3 mm in diameter, that appeared quite satisfactory and held 10 atmospheres pressure. Stone Industrial (who invented the spiral winder) added a Nomex ‘slip sheet’ on the interior of the tube that may be removed just prior to use, protecting the interior metallized surface until then.

We propose to have Stone Industrial wind tubes for us when we use a commercial vendor. This will include the winding of some 1500 2-m long tubes from the foil now being metallized by A.D. Tech. We do not have a quotation yet from Stone Industrial for this job.

As we contemplate large-scale production of tubes, even a cost of \$1-\$2 per tube is significant. Further, any kinks in the tubes during transport may render them unusable. So we are investigating winding the tubes ourselves. We have purchased a small spiral winder (\$9400) from Dodge Resources (Robert Dodge, 216-492-4483).

Once the spiral winder is delivered, we must master the art of winding tubes, which is somewhat arcane, but which we have witnessed. The Princeton High Energy Physics Group has very recently hired a new machinist whose primary responsibility will be work on the straw-tube development. We anticipate the need for building guiding fixtures for the three plys (Mylar, Makrofol, and the Nomex slip sheet), and for building special glue applicators. Some experimentation will be needed to determine the best glue. Also, the various foils must be slit to the needed widths prior to winding. This will be done by a commercial vendor, although we will investigate the suitability of purchases a slitting machine.

We include a request for **$10k** in the next year for foils, slitting, and construction of fixtures. The goal is to produce the 10,000 tubes for the 1991 test in C0 with this funding.

d. Establishment of a Cleanroom Facility

The assembly of straw-tube chambers should be performed in a dust-free environment of Class-100 quality. It is essentially impossible to clean the tubes; they must be built cleanly in the first place.

We wish to build a 16′ by 20′ Class-100 clean room with ceilings 10-12′ high. This would be located inside an existing room in the High Energy Physics Assembly Building at Princeton. We are now building an 8′ by 12′ Class-1000 room (without temperature and humidity control) as a temporary assembly facility; this would be reconfigured as the gowning anteroom when the large room is constructed.

The cleanroom would house the spiral winder and assembly facilities for 2-m long tubes. We would like to have high ceilings so that 2-m-long chamber modules could be hung vertically in certain steps of assembly. For this a simple crane would be located inside the room.

We have contacted about 15 vendors of cleanrooms, asking for a preliminary estimate for such a room, including temperature control to ±5°F and ±10% relative humidity. The estimates vary from $70k to $150k.

We have approached the Provost of Princeton University for matching funds, and he has agreed to provide up to $30k. We therefore request **$60k** towards the cleanroom, crane, and furnishings.

e. Improvement of Shop Facilities

The ability to perform an R&D program at Princeton is dependent on excellent shop facilities. Because of Princeton's long involvement in high energy physics, rather good capabilities have been created over the years, but continued investment in these is needed to maintain a high standard in the next decade. Here we request two items:

1. Toolroom lathe, **$25k**. We have five lathes, manufactured between 1943 and 1974, but none was of high quality even when new. We cannot now reliably turn parts to 1 mil tolerances due to wear of the lathes. The fine tuning of the design of the straw-tube end plugs will require frequent, precision lathe work beyond the capability of the present machines.

   This contrasts with our milling capability: one CNC mill and two mills with retrofitted digital readouts. In discussion with our machinists it emerged that a high-quality 'toolroom' lathe with digitial readout, such as from Hardinge, would be more useful than a specialized CNC lathe, and costs only 40% as much.
2. AutoCad system, **$10k**. To minimize costs, our mechanical shop does not emply a draftsman, this work being done by our design engineer. This man is retiring next year (but will continue part-time consulting on the straw-tube project). We anticipate promoting a young engineer, William Sands,

to be head of the shop. He is of the generation that prefers computer-aided drafting, and is experienced with AutoCad, although we have no such system here at present.

We propose to purchase a system from discount houses consisting of an IBM PC-clone with a 25-MHz 80386 processor, 80387 coprocessor, 2- Mbytes memory, 60-Mb hard disk, 1024 × 768 VGA monitor, H-P D-size plotter, digitizer pad, and Autocad 3.10 software for a cost of $10k.

2. Anode Wire

a. Wire Instability

Using an image-charge approximation, one can derive a relation for the maximum voltage on a straw tube before the transverse wire instability sets in:

$$V[\mathrm{kV}] < 20\frac{D}{L}\ln\left(\frac{D}{d}\right)\sqrt{T[\mathrm{gm}]}.$$

For example, with
tube diameter $D = 4$ mm;
wire diameter $d = 20$ μm;
tube length $L = 2$ m;
wire tension $T = 50$ gm;
the limiting voltage is calculated to be $V = 1.5$ kV, very close to the expected operating voltage of such a straw. The wire tension has been chosen close to the breaking strength of the gold-plated-tungsten wire.

We would like to avoid use of a wire support in the middle of the tube, for tube lengths up to 2 m. This suggests consideration of use of a thicker anode wire.

H. Ogren of Indiana U. reported[6] a test with a 4-mm-diamter, 2-m-long straw chamber in which he reached only 1/4 of the calculated voltage before the instability set in.

C. Lu of Princeton tested a 7-mm-diameter, 42-cm-long straw chamber for which the critical voltage is calculated to be 10 kV. He reached 5 kV before sparking set in. So we did not confirm Ogren's result for our fatter straw....

b. Gas Gain vs. Wire Diameter

With a larger diameter anode wire, the straw tube must be run at a higher voltage to achieve the same gas gain. This may be disadvantageous due to the greater chance of electrical breakdown, and may be the reason that people tend to use small wires.

A model for the gas gain can be made, based on knowledge of the first Townsend gain coefficient, $\alpha(E)$, where $dN/dx = \alpha(E)$ describes the number of electrons in an avalanche as a function of distance. The simple assumption (sometimes associated with Diethorn[7]) that

$$\alpha = kE$$

apparently is in good agreement with such measurements as exist, and leads to the result

$$\ln(\mathrm{Gain}) = \frac{V \ln 2}{I \ln(D/d)} \ln \left(\frac{2V}{d E_{\mathrm{crit}} \ln(D/d)} \right),$$

where I is an effective ionization potential (about 25 eV) and E_{crit} is the minimum electric field at which multiplication occurs (about 5×10^4 V/cm).

[Charpak uses the model $\alpha = b\sqrt{E}$, but this seems to fit the data less well than the Diethorn model.]

Then if $D = 4$ mm we calculate that the voltage required for gain $= 5 \times 10^4$ with 80-μm wire is only 1.5 times that for a 20-μm-diameter wire. Namely, $V = 1.07$ kV for $d = 20$ μm, and $V = 1.55$ kV for $d = 80$ μm. Thus the voltage penalty for use of a larger diameter wire is not too severe.

c. Anode-Wire Resistance

As noted in section 1-b above, the resistance of a 20-μm-diameter gold-plated-tungsten wire is about 200 ohms/m, which is larger compared to the transmission-line impedance of a straw tube ($\approx$ 300 ohms). This also suggests use of a larger anode wire.

d. Tests of Various Wire Diameters

We have ordered several diameters of wire from 20 to 80 μm (Luma Fine Wire, c/o SAES Getters, 719-576-3200), and will study the benefits of a larger wire, if any. To obtain greater wire stability a greater tension must be used. But eventually the tension of the wire will collapse the tube.

Each batch of wire will be scanned for mechanical imperfections with an electron microscope.

We request **$2k** in 1990 for purchases of additional samples of anode wire.

e. Test of Wire Tension

Whatever wire is chosen, it will be important to string the wire with uniform tension from straw to straw. Once the wire is installed in a tube it is no longer accessible, so we need a test facility to check the wire tension without the need for direct contact. We will build a setup in which an AC current is applied to the anode wire which then vibrates when placed in a magnetic field.[8] More details...

We include **$3k** in the budget for construction of the wire-tension test setup.

3. End Plugs and End Plates

a. Ohio-State Design of End Plugs

Among the several styles of end plugs developed for straw tubes in recent years we have been most impressed by that of the Ohio-State group.[3] Their present version is sketched in fig. 4.

The heart of the scheme is the plastic feedthrough (≈ \$1.3 each, McCourtney Plastics, Dell Kincaid, 612-929-3312) that positions the wire to 1/2 mil accuracy in a V-groove. The feedthroughs include two transverse holes that allow the chamber gas to enter the tube. There is a \$10k setup charge for any change in the design of the feedthroughs that requires a new mold.

The wire is secured by insertion of a slightly tapered brass pin (≈ \$0.2 each, Fairfield Screw Products, Bob Davis, 614-653-7627) that pinches the wire against the wall of the feedthrough; the wire is not soldered or crimped. For production runs the pin is secured to the feedthrough by a drop of epoxy, but for tests a friction fit suffices and the pin may be readily extracted and a new wire strung.

The plastic feedthroughs are centered inside the straw tube by the gold-plated aluminum inserts (≈ \$2 each, Pallidin Precision Products, Tony Pallidino, 203-574-0246). Although the inserts transfer the cathode voltage to the outer edge of the plastic feedthrough this is no problem of breakdown due to the length of the feedthrough. The step in the insert allows precise positioning of the straw-tube in the end plate.

Because of the cost and time delay in making new tooling for the plastic feedthroughs, we propose to use the present Ohio-State design for the fixed-target test of 1000 tubes in 1990. We have already ordered 3000 feedthroughs and taper pins. A consequence is that the tube diameter must be larger than about 5.5 mm, which is larger than our eventual goal.

During 1990 we plan to design a new, smaller-diameter feedthrough to be used in the 1991 tubes. We request **\$15k** for new tooling, and **\$40k** for the production of feedthroughs, pins and inserts for 10,000 tubes. This money should be available in 1990 if the 10,000 tube system is to be ready for beam tests in 1991.

b. Assembly Procedure

An individual straw-tube is not mechanically stable against bending, so several tubes must be glued together into a module before the wires can be strung. In the procedure developed at Ohio State, each tube has a stainless-steel rod inserted into it to aid in alignment and clamping during the gluing of one tube to another. Earlier, the Ohio-State group used various epoxies to glue the tubes to each other, but recently they have had success using a ‘super glue. After removal of the rods (at some risk of scratching the cathode) the aluminum inserts are glued in with conducting epoxy and the tube bundle attached to the precision end plates. Finally the feedthroughs are inserted and the wires are strung.

We must explore whether this procedure is suitable for large-scale production. It suggests that the chambers be built out of modules of no more than a few hundred straws each. For a system of 500,000 straws this might imply 1000 modules of 500 straws each.

We request **$5k** in 1990 for materials to construct the assembly fixtures.

c. Macor End-Plate/Gas Manifolds

As mentioned above, the aluminum inserts must be placed into a precision end plate to provide the alignment of the straw tubes. In the Ohio-State design, the end plates were $\frac{1}{2}$-inch-thick stainless steel, permissible because the forward angles beyond the straw chamber were not to be instrumented at the e^+e^- collider.

We desire to measure particles that pass through the end plates, and wish to use a lower-mass structure. The end plates primarily serves to provide precision centering of the anode wires, and does not play a structural role in supporting the wire tension. Hence we have the option to use a machinable ceramic such as Macor (Corning) for which there is well-established industrial support for drilling holes with 0.1 mil tolerances. A $\frac{1}{16}$-inch-thick plate of Macor appears rigid enough to serve as our end plate.

The end plate must also surve as one surface of the gas manifold for the straw tubes. The volume enclosed in the gas manifold also contains the high-voltage distribution and the front-end electronics. We propose to make the entire gas manifold out of Macor.

The structure of the manifolds differs on the two ends of the straws. On the 'signal' end the front-end electronics should eventually be mounted inside the gas manifold and be cooled by the chamber gas. This will require a three-layer structure. For the 1990 fixed-target test we will, however, mount the front-end electronics outside the gas manifolds, while designing the three-layer structure for 1991. On the other end of the tubes the gas manifold will contain the high-voltage distribution and the anode-wire termination. Layout of the electrical components is described in the next section.

We request **$10k** in 1990 for machining and assembly of the end plate/manifolds for the 1000-tube system, and prototyping for the 10,000-tube system.

d. Electrical Layout

The electrical and mechanical functions of the end plates lead to some conflicts in a very compact design.

On the 'signal' end, the anode signal and the signal return from the cathode must be transmitted to the front-end electronics. Ideally this would be done in a coaxial arrangement to minimize crosstalk between the tubes. A coaxial sleeve connected to the cathode is somewhat incompatible with good gas flow. In any case, the cathode is at high voltage and must be isolated from the electronics by a blocking capacitor.

In our initial design we give up the coaxial geometry, and mount a small rectangular high-voltage capacitor (xxxx) on a small, flat G-10 board that attaches to a short sleeve in contact with the cathode, as shown in fig. ??. Both the cathode and anode leads are in the form of pins that mate into sockets mounted on the second end-plate layer, outside of which the front-end chips will be mounted.

On the other end, the inner surface of the second end plate layer will serve as the high voltage bus, and each straw-tube cathode connected to this via a 100 MΩ resistor. If a wire breaks, we wish to be able to run even with the current draw due to a short. Assuming a 2-kV operating voltage, this would imply a 20 μamp current in a shorted tube. In Appendix B we estimate that the steady current in a straw-tube that comes within 10 cm of the beams at 10^{32} luminosity will be $\frac{1}{6}$ μamp. This would imply a 17 volt drop across the 100 MΩ distribution resistor; in turn this would imply about a 9% reduction in the gain of the tube, which appears acceptable.

Also at the other end of the tube, the anode wire should be terminated in the characteristic transmission-line impedance of the tube, about 300 Ω. This requires a blocking capacitor as well. The two resistors and the capacitor needed at this end will be mounted on a small G-10 board as sketched in fig. ???

We will be testing the proposed layout of the passive tube-end components in Fall 1989. If crosstalk proves to be a problem we will explore the use of a coaxial geometry, which would require custom resistors and capacitors made inthe form of hollow cylinders. We request **\$5k** in 1990 for the tube-end components and their assembly for both the 1,000- and 10,000-tube sytems.

4. Choice of Chamber Gas

A review of measured parameters of the most relevant chamber gases, dimethylether (DME), Ar/CO_2, or CF_4/isobutane, is given in Appendix C.

a. Resolution

As mentioned at the end of sec. II, the operation of the detector at ‘only’ 10^{32} luminosity permits one to be ambitious about the resolution of the straw-tube chambers. At this luminosity the average time between interactions is 100 nsec, which sets the scale for the acceptable drift time without undo complications from multiple events. That is, if we have the freedom to choose the drift time in the straw-tube gas, it should be about 100 nsec (16 nsec for 10^{33} luminosity). Then if the time digitization is accurate to 1 nsec and the drift distance (tube radius) is 2.5 mm, each time bin corresponds to 25 μm in space. To achieve such a resolution, the diffusion in the gas must be comparably small.

Results are presented in Appendix C for diffusion and drift velocity in various gases as a function of electric field strength expressed in terms of kV/cm, and in V/(cm-Torr). We suppose the straw tubes will operate at one atmosphere pressure = 760 Torr. The electric field strength can be written

$$E = \frac{V}{r \ln(D/d)}.$$

To set the scale, suppose we operate at $V = 1.5$ kV for a tube with $D = 4$ mm and $d = 20$ μm. Then the minimum electric field, which occurs at $r = D/2$, is $E_{\rm min} = 1.42$ kV/cm = 1.86 V/(cm-Torr).

From the figures in Appendix C we find that for field strength up to a few times $E_{\rm min}$ the drift velocity is apprximately

v[cm/μsec] = 0.35E[kV/cm] in DME;
v[cm/μsec] = 0.70E[kV/cm] in CO_2;
v[cm/μsec] = 10 in CF_4/isobutane (80/20).

For the case that drift velocity varies linearly with electric field strength, the drift time in from the outer edge of a tube is

$$t[\mu\text{sec}] = \frac{\ln(D/d) D^2}{8kV[\text{kV}]},$$

where k is the coefficient 0.35 for DME and 0.7 for CO_2. Then, for example, with $D = 4$ mm, $d = 20$ μm, we find

$t = 168$ nsec for DME, using $I = 30.5$ eV, $E_{\rm crit} \approx 8.3 \times 10^4$ V/cm, inferred from Jibaly *et al.*,[xx] $\Rightarrow V = 1800$;
$t = 141$ nsec for CO_2; using $I = 25$ eV, $E_{\rm crit} \approx 5 \times 10^4$ V/cm, which numbers are really for P-10 gas, $\Rightarrow V = 1070$;
$t = 20$ nsec for CF_4/isobutane (80/20).

But if we use a thicker anode wire with $d = 80$ μm and raise the voltage to maintain the same gain, then

$t = 85$ nsec for DME, at $V = 2640$;
$t = 60$ nsec for CO_2, at $V = 1550$;
$t = 20$ nsec for CF_4/isobutane (80/20), as v is saturated.

Thus there are tube parameters that are well matched to the drift velocity of both DME and CO_2 for running at 10^{32} luminosity. The CF_4/isobutane mixture could be quite appropriate to running at 10^{33} luminosity, but the electronics must be extremely fast if good position information is to be extracted.

The data on the diffusion coefficients presented in Appendix C indicate that CO_2 and Ar/CF_4 have similar diffusion (an impressive result for the 'fast' gas CF_4), and that both are only about 30% worse than DME. We estimate that diffusion in CF_4/isobutane is not worse than in Ar/CF_4, although there appears to be no direct measurement to support this. Over a 2-mm drift distance the longitudinal diffusion in DME is in principle only about 20 μm, and about 27 μm for CO_2 and for CF_4/isobutane. A longitudinal diffusion in DME of 30 μm over 2-mm drift is inferred from actual measurements in straw tubes.

Thus DME seems the best candidate gas in terms of spatial resolution, especially if a thicker anode wire is used. Pure CO_2 is also quite attractive, and considerably more benign than DME.

b. Ageing

As noted in Appendix C, all of the gases under consideration have demonstrated fairly good ageing – more than 1 C/cm charged can be collected before the gain deteriorates due to deposits on the anode wire. In Appendix B we estimate that a 1 C/cm lifetime translates into 6 years of operation at the SSC at 10^{32} for straw-tubes that come within 10 cm of the beams. We consider this to be acceptable, and do not propose to make any ageing studies in the immediate future.

c. Chemical Aggressivity

Dimethlyether is reported by some to cause damage to the straw materials. See Appendix C. The story here is not very consistent. On the West Coast lots of trouble occurred, but H. Kagan of O.S.U. reports good success in using DME in CLEO runs (private communication). Most disturbing, and somewhat unbelievable, is the claim that DME eats MACOR, the machinable ceramic that we might use for the chamber end plates. We must investigate this immediately.

Apparently one should have a gas system with **no plastic parts**, including those plastics that are supposedly corrosion resistant. Also, the two ends of the straws should not be mechanically constrained to a fixed separation (as was the case in early West-Coast designs).

There are also reports of batch-to-batch variation in the purity of commercial dimethylether, with freon contaminants being especially harmful. S. Majewski (private communication) reports that good purity DME can now be obtained directly from DuPont.

Since dimethylether has the best all-around performance of any potential chamber gas, it is worthwhile to determine whether we can survive the aggressivity problem. We will need a gas chromatograph, such as the SRI Model 8610-003 at \$4k that interfaces to an IBM PC, to monitor the purity of the delivered DME. Also, we must buy the most 'corrosion resistance' regulators, valves, flowmeters, *etc.*, that exist. We estimate the extra cost to build a DME gas system, compared to that for a benign gas, as **\$7k**, and request funding for this in the 1990 budget.

d. Gas Distribution System

We need to construct a good-quality gas distribution system in the near future, and desire to adopt a standard suitable for eventual running in a collider environment. This certainly means use of mass-flow controllers, such as Matheson Model 8219 (\$2600 for a two-gas mixer), and electronic rather than mechanical flowmeters (one each of Matheson 8202-1413 and 8102-1413 per gas type, totaling \$2300 for two gases). We need two additional mass flowmeters (Matheson 8111, \$400 each) as well as various regulators, valves and plumbing. Eventually we will need a monitor chamber, although perhaps not in the first year. We also need a good leak detector such as the Matheson Model 8065 ($ 1300).

We request **$8k** for the gas distribution system (aside from the $7k requested above for special handling of DME).

e. Heat Load Due to Ionization

In Appendix B we also estimate that the heat dissipation due to the electron/ion currents in a straw tube that comes within 10 cm of the beams at 10^{32} luminosity is $\frac{1}{3}$ mWatt. The gas flow must be adequate to cool this heat load.

A very nice analysis of this problem was given by J. Kadyk and S. Whitaker at the Vancouver SSC Tracking Workshop last July. They concluded that for a one mWatt heat load in CO_2 gas, the gas must flow at 2 cm/sec in the tube to keep the gain constant to 5%. This was based on a model of the gas gain G as a function of temperature that

$$\frac{\Delta G}{G} = 5\frac{\Delta T}{T}.$$

However, it seems more reasonable to suppose that the gas gain depends linearly on the electron density, *i.e.*, $G \sim n \sim T/P$, as is supported by the Diethorn model[7] in the form given in sec. 2-a. Then

$$\frac{\Delta G}{G} = \frac{\Delta T}{T}.$$

This would reduce the require flow velocity to 0.4 cm/sec per mWatt, and hence 0.133 cm/sec if our estimate of $\frac{1}{3}$ mWatt is accurate. However, this does correspond to a 15°C allowed temperature rise, which is somewhat unpleasant.

The heat capacity per mole of DME is about three times that of CO_2, so if DME can be used, the estimated flow velocity is only 0.044 cm/sec. For a 2-m-long straw the time per volume change would then be 4500 sec for DME and 1500 sec for CO_2.

f. Heat Load of the Front-End Electronics

We anticipate that the front-end electronics must be mounted inside the chamber-gas manifolds. There are two feedthroughs per straw in the circuit board that supports the front-end electronics, and it may be asking too much that these all be gas tight.

The heat load of the AT&T bipolar front-end chip is about 25 mWatt per channel, far in excess of that considered in the previous subsection. Hence we cannot expect the flow of the chamber gas to be sufficient to cool the electronics.

Rather, the gas manifold on the ‘signal’ end of the straws should include a high-rate recirculating system that primarily cools the electronics, and incidentally bleeds a small fraction of the gas into the straw-tubes. We do not request funds for this part of the gas system in 1990, but will do so for 1991.

g. Pressurization

As has been mentioned in passing above, we envisage operating the straw tubes at only slightly above atmospheric pressure. While the spatial resolution obtainable in a gas varies, in principle, as $1/\sqrt{P}$, the low-mass gas manifolds are unlikely to be leak tight under pressure.

h. Lorentz Angle

The straws are in a magnetic field that is oriented along the anode wire. Hence the Lorentz force causes a deflection of the drift of an electron by

$$\tan\theta = \frac{(v/c)B}{E} = \frac{kB}{c} = 1.11kB[\text{Tesla}],$$

for gases in which the drift velocity obeys $v = kE$, and for which k is measured as in section 4-a above. This indicates that the Lorentz angle in a 1 Tesla field would be 21° for DME and 38° for CO_2. Clearly the corrections to the time-to-distance relation will be simpler for DME. On the other hand, the larger Lorentz angle for CO_2 will have the effect of increasing the drift time, which is not altogether unfavorable.

5. Front-End Electronics

The front-end electronics for the straw-tube system are to be based on the ongoing work of the U. Penn group,[9−11] who have been exploring ASIC's for SSC applications for several years. Their design of a fast bipolar preamp/shaper/discri is very well suited to be the front-end chip, and the Penn/Leuven design[9,12] of a CMOS TVC chip is a prototype of the digital processing that should also be located on the straw ends.

Sample quantities of the bipolar preamp are now available, as implemented in an AT&T semi-custom process. Tests of this chip show a pulse width of 10 nsec, and 1200 electron noise as measured by the shape of a discriminator curve (F.M. Newcomer, private communication).

Some 50-100 of these preamp/shaper chips will be available for use in test setups in Fall 1989.

a. Custom Run of the AT&T Bipolar Chip

A natural step in the development of the front-end electronics is a full-custom run of the AT&T chip in which a disriminator is included along with the preamp/shaper of the sample chips. In a full-custom run the layout can be arranged so that four channels are combined in a single die. Funding of $50k for the first full-custom AT&T run has been requested as part of the U. Penn Front-End Subsystem proposal.[11] This run should produce 1000-2000 chips on 3-5 wafers.

It is not guaranteed that the output of the first full-custom run will be satisfactory for actual use on detectors. Also, this first run will use certain design parameters (input impedance, tail-cancellation time, amplifier gain) not necessarily matched to the performance of the straw tubes of this proposal. We feel it prudent to anticipate the need for a second run to correct any processing errors in the first run, and to make small adjustments in design parameters.

The second AT&T bipolar run should be made no later than Spring 1990 to insure availability of chips towards the end of the 1990 Fermilab fixed-target run. We request **$50k** in 1990 for this. The chips should be mounted in suitable carriers at the foundry as part of the cost of the production run.

For the 1991 phase of this proposal a new bipolar run will be needed to bring the chip count to 10,000 or more, but we do not request funds for this at present.

b. Testing and Mounting of the Chips

As production quantities of thousands of chips become available we must test them and mount them on the straw-tube detectors. Then they must be tested in a setup to be constructed. We have recently purchased an Ortec 419 pulser that will be useful for this. In addition we would like to purchase a voltage control board that resides in an IBM PC-clone (such as yyy), and a fast oscilloscope (Tektronix 24xx, $??).

The chips are then to be mounted on a printed circuit board that will be attached to the gas manifolds of the straw-tube modules. This board will be designed at Princeton at made locally.

We request **$15k** in 1990 for the test instrumentation and the pc-board fabrication.

Westinghouse SIMOX Process

The bipolar preamp/shaper/discri is to be followed by a TDC chip, discussed further in sec. 6 below, also located on the chambers. The best apparent technolgy for this digital chip is CMOS. Given the eventual existence of the two types of chips, they must be bonded together to form a kind of hybrid for use on a detector.

It is worth exploring technologies that will permit the fast preamp and the digital section to be implemented in the same silicon process. In conjunction with our Pixel Detector Subsystem Proposal[13] we have learned that Hughes Aircraft has a ‘Bi-CMOS’ process that might be suitable for the present application. Discussions have not evolved to the stage of a definite proposal, but opportunity for such should readily occur in the next months if that proposal is approved.

Another exciting opportunity is the so-called SIMOX process of Westinghouse. In this a high-resistivity silicon wafer (high enough for the substrate to be a particle detector!) is bombared with oxygen ions to form an oxide layer about 2000 Å thick approximately 1000 Å below the wafer surface. The devices are implanted on this thin layer, and can be extremely fast because of the small number of electron-hole pairs involved in the current paths. This process was designed for gigaHertz RF applications, but has been somewhat underutilized in the commercial market to date. The device layers are implemented in a CMOS technology and hence will be rather low-power as well as very fast.

We propose to make a test of the suitability of this process for the straw-tube electronics by producing a preamp/shaper that is functionally equivalent to the existing U. Penn. bipolar chip. The design work would be performed at Westinghouse as well as the foundry run, and testing done at U. Penn. and Princeton.

We request **$???** for this in 1990.

6. TDC Development

While we intend tu use LeCroy camac TDC's to analyse the signals from the 1000-tube system in 1990, it is not practical nor pertinent to use this approach for later straw-tube systems, beginning with the 10,000-tube system in 1991. A VLSI TDC should be designed that resides on the detector, and eventually includes analog storage during a suitable trigger-delay interval.

a. The Penn/Leuven Design

As mentioned above, such a chip has been designed by the Penn/Leuven collaboration[9,12] although with slightly different parameters than would be optimal for a straw-tube system operating at 10^{32} luminosity. This work has been done primarily at Leuven. In these designs the time of arrival relative to a start pulse is converted to a voltage that is later digitized in an ADC. As such, this chip is often referred to as a TVC rather than a TDC.

The Penn group is now preparing[11] to implement a design that is closer to the needs of the 1991 tracking system of the present proposal:

0.5 nsec time resolution;
Analog storage for up to 5 μsec;
Time digitization of 8 bits = 128 nsec.

We make no request for funds in 1990 for this project, as it is covered in the Penn proposal, but will closely follow their progress. We anticipate the need for funding in 1991 for productions runs to yield in excess of 10,000 TDC chips.

b. The KEK TMC Chip

An interesting alternative to the Penn TVC chip is being developed at KEK.[13] This chip is a true TDC in that the time of arrival of the signal is directly digitized in 1 nsec intervals. However, the reference clock runs at only 60 MHz and the input signal is multiplexed 16-fold.

Sample quantities of this chip are now available, and we have a rather tentative arrangement to include some of these in the Fermilab fixed-target run in 1990. We do not request any funds for this at present.

7. Manufacturing Feasibility Study

The task of construction a straw-tube chamber system of 250,000 or more tubes is likely beyond the resources of a university group. Each tube requires several steps of hand labor, and there are only 120,000 minutes in a standard work year. We expect the large-scale production to be performed by industry and wish to explore arrangments to this end.

In 1990 the Westinghouse Science and Technology Center proposes to initiate a manufacturing feasibility study in based on the straw-tube design described above. A Statement of Work for this study follows (or put in an Appendix?)

8. Simulation of Physics Performance

A major effort will be made at Princeton during 1990 to develop a full GEANT simulation of the straw-tube system, and to write an analysis package that performs pattern recognition and track fitting. This work is in collaboration with physicists from Fermilab and U. Florida who have not signed the present proposal for organizational reasons. Figures 1-3 are from this effort.

A request of $25k for hardware improvements to our existing computing facilities was submitted as part of Princeton's 1989 Generic Detector Development proposal renewal. I interpret a recent telephone conversation with Tom Dombeck that this $25k was approved. **If not, we request the $25k as part of the present proposal.**

With funds from Princeton's 1988 Generic Detector Development contract we have purchased a DEC VAXstation 3100 and DECstation 3100. The latter will give us entry into the UNIX world while maintaining a VMS connection. In 1990 we wish to expand our computing power to about 50 MIPS, and anticipate purchasing a workstation(s) based on the Intel 80860 processor. This direction is suggested by our proposal to participate with Intel in the development of a large processor farm for online computing at the SSC.[14]

We have estimated that a 'full' simulation of the tracking in an SSC detector based on GEANT and having the ability to simulate 10^6 events per week will require 250-500 MIPS of CPU power. Even with our proposed expansion to 50 MIPS in 1990 we will only be able to perform simulations that take major shortcuts. Of course, this is exactly the way to start. But we anticipate the need for continued upgrades in computing power in the following years. Fortunately the trend in price/performance of RISC processors is so favorable that constant dollars will purchase nearly exponential increases in CPU power over several years.

9. Test Program

a. Gain Studies

We are current assembling a setup to test one to seven straw-tubes. A set of test electronics for a single channel has been purchased from Ortec for this. The emphasis here is studies of the gain in the straw tube for various gases.

In the present proposal we request **$4k** for gases to be tested in 1990: DME and isobutane approach $500 per bottle, and CF_4 is $2k per bottle. We will likely need to order DME from more than one vendor to examine the deliverable purity.

b. Resolution Studies

In Fall 1989/Winter 1990 we plan to construct a setup with 64 straw tubes to perform resolution studies using cosmic rays. A relatively large number of channels will be useful as the rates are low, as well as providing a prototype for the 1000-tube system to be built in Spring 1990.

The front-end chips for this test will sample quantities of the AT&T preamp/shaper now in exisitence (no discriminator). Discriminators, ADC's, TDC's, and trigger logic will be borrowed from PREP at Fermilab. The straw tubes and end plugs needed will be taken from supplies for the 1000-tube development descirbed above. We request $5k for miscellaneous supplies, Macor end plates, mounting fixtures, two trigger scintillation counters, *etc.*, and $5k for an 80836 IBM PC-clone computer system to control the test, for a total of **$10k** in 1990.

c. Pulsed X-Ray Test Facilty

We desire a reasonably quick method of measuring the time-to-distance relation in the straw tubes that does not require a high-energy charged-particle test beam. As the straw-tubes are opaque and sealed, it is not possible to use a laser to simulate particle tracks. This leaves x-rays as the main candidate. The problem here is that typically there is no timing signal associated with an x-ray source, so the time-to-distance relation cannot be reconstructed.

We have opened discussions with Kevex (Phillip Heskette, 408-438-5940) towards purchase of a custom pulsed x-ray source, and request **$25k** in 1990 for this. Such a source would be an extremely valuable addition to the diagnostic tools available for straw chambers, and could be installed in a collider experiment itself to provide continually updated timing calibrations.

d. Fixed-Target Test

We have mentioned several times our plans to test a set of some 1000 straw tubes at the M-Test line at Fermilab in 1990. The straw tubes and electronics for this are part of above requests. The test will also include a set of silicon strip detectors, and a primary goal is to demonstrate a tracking arrangement with a few silicon planes close to the vertex followed by a set of straw tubes with longer lever arm.

Here we request **$25k** in 1990 to cover construction of stands for the straws ($5k), and for travel to and operating expenses at Fermilab ($10k each for IIT and Princeton). As well as involving physicists and students in such tests, several techicians will participate in the setup phase at Fermilab, which requires sufficient operating funds.

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