Proposal for Research & Development: Vertexing, Tracking, and Data Acquisition for the Bottom Collider Detector

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Abstract

We propose a program of research and development into the detector systems needed for a B-physics experiment at the Fermilab p-$\bar{p}$ Collider. The initial emphasis is on the critical issues of vertexing, tracking, and data acquisition in the high-multiplicity, high-rate collider environment. R&D for the particle-identification systems (RICH counters, TRD's, and EM calorimeter) will be covered in a subsequent proposal. To help focus our efforts in a timely manner, we propose the first phase of the R&D should culminate in a system test at the C0 collider intersect during the 1990-1991 run: a small fraction of the eventual vertex detector would be used to demonstrate that secondary-decay vertices can be found at a hadron collider. The proposed budget for the R&D program is \$800k in 1989, \$1.5M in 1990, and \$1.6M in 1991.

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1 Introduction

We have recently submitted a Letter of Intent[1] to inaugurate a study of B physics at the Tevatron collider with the goal of observing the strongest signals for CP violation in the B-$\bar{B}$ system. This experiment combines a rich physics program for the 1990's with the opportunity for development of detector technology needed in the SSC era. The program is ambitious and is not a direct extension of any existing experiment. We propose here to begin research and development of several critical detector systems as a means of dedicating our efforts towards the B-physics program prior to the approval of the full experiment.

One B-$\bar{B}$ pair is produced in every 1000 interactions at the Tevatron collider,[2,3] while each interaction produces about 60 'background' particles. To extract the B mesons from this background we will employ two techniques: reconstruction of a secondary decay vertex for the B's (whose lifetime, $c\tau$, is 360 μm,[4] and reconstruction of the invariant mass of the products of B decay into all-charged final states. In recent years, the development of silicon vertex detectors has permitted hadronic fixed-target experiments to compete favorably with e^+e^- colliders in the study of charmed mesons. We propose to demonstrate that silicon vertex detectors are also appropriate for a hadron collider.

CP violation is expected to manifest itself prominently only in rare ($\Gamma \sim 10^{-5}$) decay modes of the B mesons; some 10^8 reconstructible B's will be needed to establish the effect clearly.[5] Hence the experiment must be performed with a reasonably high collision rate, and we adopt $\mathcal{L} = 6 \times 10^{31}$ cm^{-2}sec^{-1} as the detector-design luminosity. This corresponds to an event rate of 2.5 MHz, and requires the experiment to have a very high rate data-acqusition system by present standards. We propose to develop a data-acquisition architecture based around a 'barrel switch' that can build 10^5 complete events per second, which events are then processed in a large 'farm' of numeric processors before archival storage of at most 10^3 events per second.

The issues of vertex detection and data acquisition are the most critical for B physics at a hadron collider, and are emphasized in the present R&D proposal. A discussion of the technical issues to be studied is given in section 2, which includes a number of secondary items to be covered by the present proposal, as well as important items beyond the scope of the initial effort. Schedules and costs are presented in section 3, with the rough scenario that 1989 is devoted primarily to bench tests with a budget of \$0.8M, leading to tests of individual devices in an external beam in 1990 with a budget of \$1.5M, followed by a system test in 1991 at the C0 intersect with a budget of \$1.6M.

2 Issues for Research and Development

The current vision of the Bottom Collider Detector is shown in fig. 1. The detector is comprised of 5 detector systems, plus the electronics for data acquisition. In this section we outline the technical issues related to these systems that require study, as well as several issues of the impact of the experiment on the accelerator operation.

While some discussion is given of R&D for the particle-identification systems (the RICH counters, the TRD's, and the EM calorimeter), work on this is not part of the initial proposal detailed in section 3. Our plans in this area should become much more well-defined following the upcoming Symposium on Particle Identification at High Luminosity Hadron Colliders, organized by J. Morfin and to be held at Fermilab on April 5-7, 1989.

The present detector design is based on the assumption that the Tevatron collider will operate with 44 bunches with a spacing of 21 rf buckets, so the time between bunch crossings is 400 nsec.

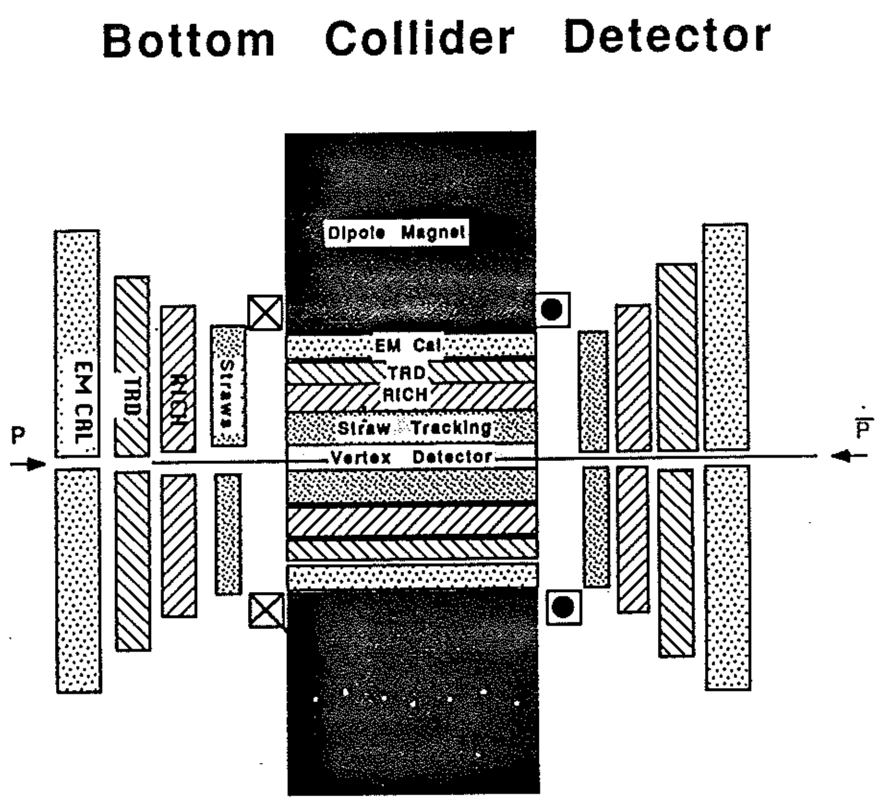

Figure 1: Overview of the Bottom Collider Detector.

2.1 Dipole Magnet

Reconstruction of B-decays requires magnetic analysis. The kinematics of B production and decay at the Tevatron collider indicate the need for coverage for particles primarily with $P_T < 5$ GeV/c and pseudorapidity $-4 < \eta < 4$ (lab angles $2° < \theta < 178°$). A dipole magnet with field transverse to the colliding beams is the best configuration, and provides good accuracy for high-momentum tracks in the forward and backward directions, at the expense of a small loss in useful solid angle around the direction of the magnetic field. This 'dead' region will be useful for cable paths out from the interior of the detector.

The magnet should have a field integral of $\int Bdl \approx 3$ Tesla-m out from the interaction point along the beam direction, and an integral of 0.6 Tesla-m outwards transversely to the beams. The central-detector systems should be entirely within the magnet (there is no hadron calorimeter), while in the forward/backward directions the particle-identification systems can be outside the field volume.

A magnet with circular pole tips (such as a cyclotron magnet) meets these requirements, while providing a field with circular symmetry to simplify the track-finding algorthm. Such a magnet is relatively open in both the forward and sideways directions, permitting great flexibility in configuring the detectors.

Design studies for such a magnet have been initiated at Fermilab by R. Wands and A. Wehmann, and should be continued. A magnet with pole tips 4 m in diameter and with a 4-m gap would weigh 2500 tons. With a central field of about 1 Tesla the stored energy is 100 mJoule. Superconducting coils are needed to keep the operational cost down, and represent the major design issue. A scenario to recycle the Livermore Magnetic Fusion Test Facility coils could be pursued, but an engineering study is needed to determine whether this option would be cost effective.

2.2 Silicon Vertex Detector

At a hadron collider, the intersection region is typically tens of centimeters long, and tracks of interest emanate in all directions from this line source. Thus the geometry of tracking is much more complicated than in a fixed-target experiment, where most tracks of interest have near-normal incidence on detector planes in the forward direction. Further, to obtain good reliability for finding secondary vertices, the vertex detector must provide all three coordinates of each intercept of a track with a detector plane. In the future this may be best accomplished with pixel detectors, but at present we are exploring the use of silicon strip detectors each with two strip orientations.

Because the collider intersection region is extended, the only practical arrangements of silicon detector planes are those in which some particles must be observed at angles up to 45° incidence. This leads to mechanical and electronic specifications somewhat beyond presently achieved values. The present proposal is to develop the technology to meet these specifications.

Silicon detectors have reduced sensitivity for tracks with large angles of incidence. We currently plan to use silicon strip detectors with 50-μm strip width, 200-μm thickness, and double-sided readout (a.c. coupled). A minimun-ionizing particle creates 80 electron-hole pairs per μm of silicon traversed, so the signal is 16,000 electrons at normal incidence, 5600 electrons per strip at 45° incidence, and only 4000 electrons at grazing incidence. We are setting a goal of an r.m.s. noise level of 600 electrons in the preamplifier, so that tracks of less than 45° incidence will have better than 9:1 signal-to-noise. The preamplifiers are to be implemented in VLSI technology and bonded directly to the silicon detectors. The R&D program to produce such amplifiers is already underway, and is elaborated upon in section 2.9 below.

The mechanical configuration of the silicon planes is sketched in fig. 2. Tracks with angles less than 45° to the beams are to be observed in detectors oriented perpendicular to the beams, which are called **disks**. Tracks with angles between 45° and 135° to the beams are to be observed in detectors arranged in **barrels** around the beams.

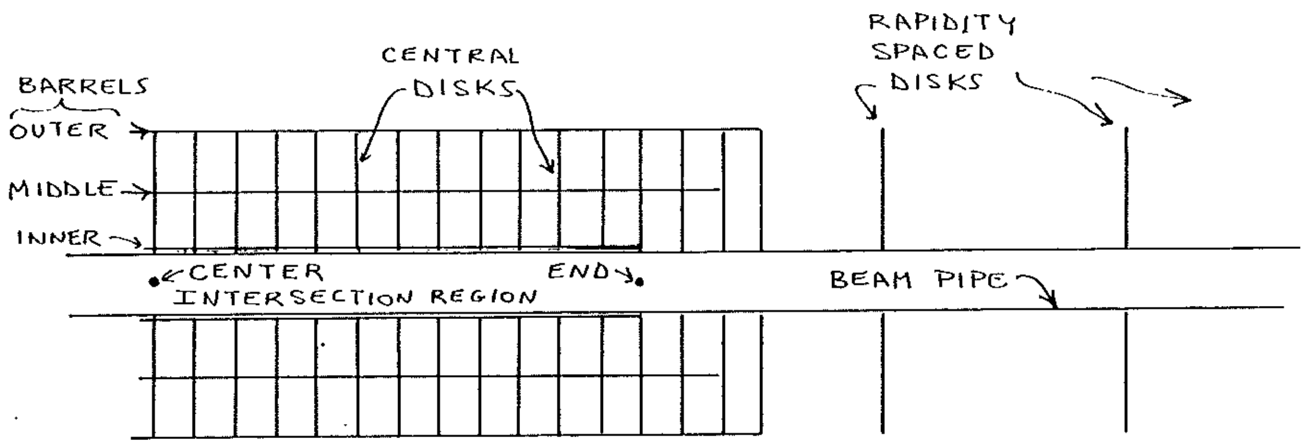

Figure 2: A section through the silicon vertex detector including the beam axis. In this view the **disks** are vertical and the **barrels** are horizontal.

If the intersection region were a point, there would be no overlap in the solid angle covered by the **disks** and **barrels**. But for a finite interaction length these two detector types must be interspersed, leading to significant mechanical complexity, especially for the cooling of the preamplifiers mounted on the silicon detectors.

In principle, each particle might pass through so many silicon detectors that the entire task of tracking could be accomplished with the resulting signals (although multiple scattering in the silicon would limit the accuracy). However, the cost of this is deemed prohibitive at present, and we plan for a configuration in which each particle penetrates at least 3 silicon detectors (each providing an x-y-z space point) at an angle of incidence less than 45°. Even so the number of silicon strips is roughly $2 \times 10^5 + (10^6 \times$ interaction length in meters). The task of pattern recognition of the tracks must be accomplished in the tracking system described in the next section; the silicon detectors provided an accurate measurement of the track segments in the vicinity of the beams.

Double-sided silicon detectors only 200-μm thick are used to reduce the multiple scattering in the detectors. The **barrel** detectors intermingle with the central **disks** to form a closed, layered structure. Penetrations must be provided for signal readout, and for cooling of the preamplifiers. This leads to a nontrivial mechanical structure which requires immediate study.

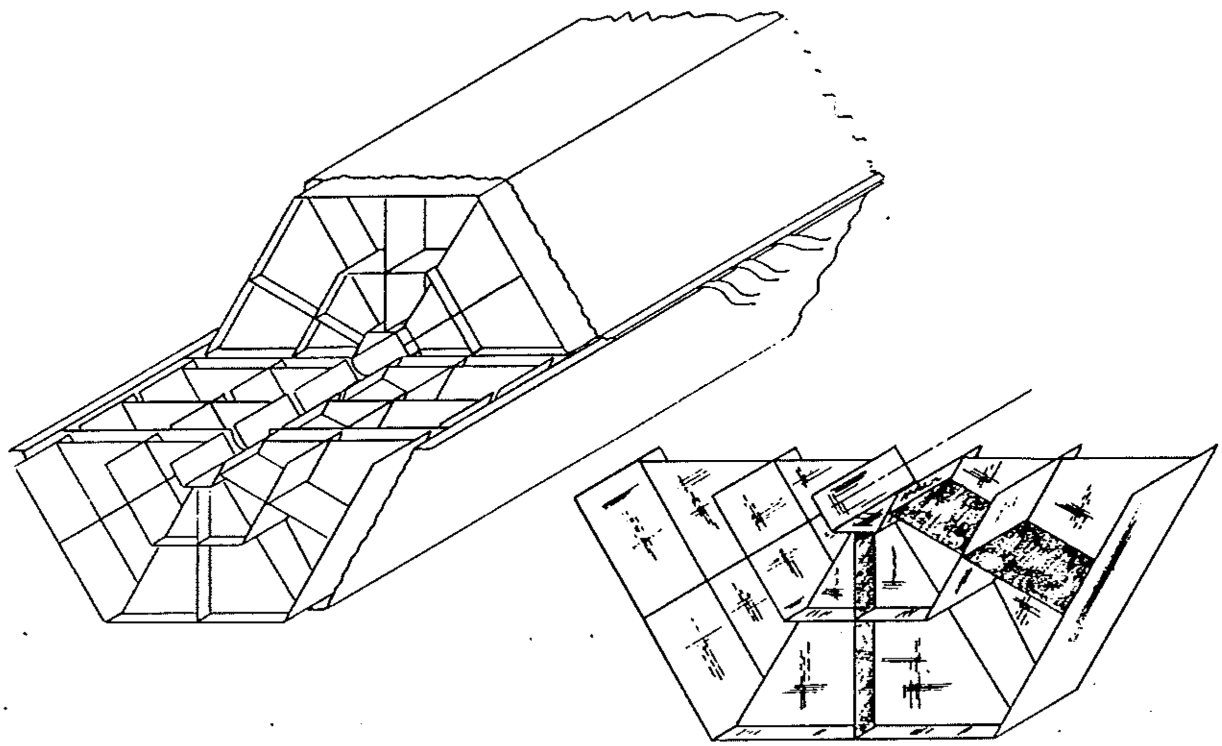

Figure 3: Sketch of a model built to study the assembly of the silicon vertex detector.

Two sets of models have been built to help characterize a suitable arrangement of the detectors into a largely self-supporting structure. These first steps must now be followed by more realistic models, eventually made of silicon, which include heat sources simulating the anticipated load of 2 mWatt per strip (about 2000 Watt for the whole silicon vertex detector).

If the detector is to be gas cooled a flow of order 100 cfm is needed, which flow must be channeled into the inaccessible interior of the detector without inducing vibrations. A scheme in which the **disks** of the central silicon detector are only partially implemented in azimuth is under study. An alternative scheme involving local cooling of the preamplifiers by liquid in small tubes is also under consideration.

The individual silicon detectors will be assembled into the overall structure via small channels of beryllium or kevlar, machined to a few μm accuracy, and glued to the silicon at a minimum number of points. The detectors may need to be cradled in an exterior trough to counteract sagging over its 1-m length, and to provided means of alignment of the vertex detector with the exterior tracking system. Figure 3 shows a preliminary conception of the assembly that was the basis for one of the models, and which revealed the need for continued evolution of the design.

The silicon vertex detector will be operated in the 1-Telsa dipole magnetic field. The effect of the Lorentz force on the drift of the signal electrons must be characterized for each of the several orientation of strips relative to the magnetic field.

2.3 Straw-Tube Tracking System

The outer tracking system must reconstruct charged-particle tracks unambiguously in three-dimensional space and extrapolate them into the silicon vertex detector, which functions as a vernier. The tracking system must measure the particles' momenta to $\pm 1\%$ in the dipole field of about 1 Tesla, and cannot have massive support structures such as end plates that would interfere with the particle identification systems which surround it. The tracking system should be configured so that a fast measure of the particles' P_T could be obtained for triggering.

The requirements of low-mass devices with high spatial resolution seem well met with straw-tube technology. A possible layout of some 2×10^5 pressurized straws is shown in fig. 4. The tubes are configured in 'superlayer' modules comprised of 8 layers of tubes each. Each track should pass through at least 8 superlayers, yielding a minimum of 64 measurements per track. With a tube diameter of 3 mm and a gas pressure of 4 atmospheres, a spatial resolution of 50 μm per hit should be achieved. To minimize multiple scattering in the walls of the tubes it is advantageous to use tubes of only 30-μm thickness, half of that achieved to date.

The straw-tube systems will bear the primary burden of pattern recognition for particle tracks. Further study is needed to confirm that our configuration of the straws has sufficient stereo-matching capability. We are exploring the possibility that 'neural-net' hardware processors might be developed which associate vector track segments with the patterns in each superlayer for use in the trigger. The front-end electronics for the straw tubes are relatively modest extrapolations of present designs, as discussed more in section 2.9.2 below.

A hardware R&D program for straw tubes should be initiated in the near future. We must determine whether thin-walled straws can be manufactured, and determine their mechanical stability under presssurized operation. Low-mass end plug must be developed with gas and electrical feed throughs. Spacers may need to be inserted into the longest straws, whose length might be 2 m. The effect of high radiation dose on the chamber gas must be studied along with the more usual aspects of optimizing the gas mixture. Assembly and alignment schemes are to be specified and tested. A lengthy scenario for

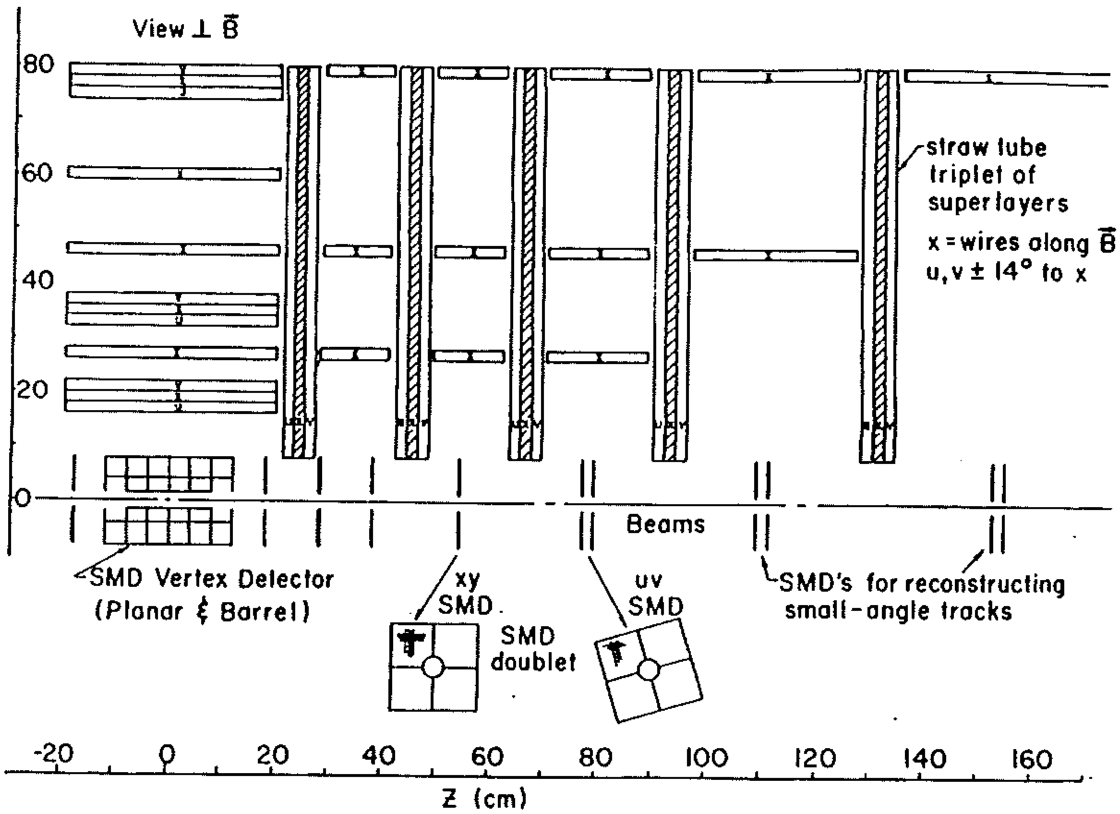

Figure 4: Plan view through the median plane of one quadrant of the tracking system, showing the configuration of the straw-tube 'super-layers' and the silicon strip detectors. The dipole-magnet field and the wires in the x straws are perpendicular to the page.

straw-tube development has been given by DeSalvo.[6]

2.4 Ring Imaging Čerenkov Counters

Identification of hadrons in the Bottom Collider Detector will be accomplished primarily with RICH counters, supplemented by a time-of-flight system in the central region. The goal is to provide flavor tagging for all hadrons of transverse momenta less than 5 GeV/c. This could be done with RICH counters with a liquid radiator in the central region, and gas + liquid radiators in the forward/backward directions. The desired ranges of momentum coverage are summarized in table 1.

The space available for the RICH counters permits a thickness of approximately 25 cm for the liquid-radiator counters, and 1 m for the gas-radiator counters. Complete coverage of the momentum ranges given in table 1 would require a position resolution of about 1 mm for detection of the Čerenkov photons. This implies the need for about 10^7 detector pixel elements. Readout electronics suitable for such large-scale implementation are currently being designed at the Rutherford Laboratory.[7]

	P (GeV/c) at $\gamma_t = 2$	γ at $P = 8$ GeV/c	P (GeV/c) at $\gamma_t = 17$	γ at $P = 120$ GeV/c
π	0.3	56	2.5	840
K	1	16	8.5	240
p	2	8	17	120

Table 1: Ranges of momenta and γ which should be covered by the RICH counters. $\gamma_t = 2$ for liquid C_6F_{14}, and $\gamma_t = 17$ for gaseous C_5F_{12}.

The detector for the UV Čerenkov photons needs R&D. The issue is complicated by the use of a liquid radiator, which absorbs photons of energy greater than 7 eV. These photons are to be detected in a photosensitive gas, such as TMAE, and the ionization electrons observed via the signals induced on cathode pads of a multiwire chamber. The drift velocity for the photoelectron is about 15 nsec/mm, so if the signal width is desired to be, say, at most 200 nsec, the active depth of the photodetector must be only 6 mm. However, the absorption depth for TMAE at room temperature is about 2 cm, so only 30% efficiency could be achieved within the desired time window, unless the TMAE is heated. There is a clear need for a 'designer molecule' whose photoionization properties are better matched to the experimental requirements. Some progress in this direction has been recently achieved by Ypsilantis in colloboration with a chemist, Alan Katzrik of the U. of Florida.[8]

Another problem which must be faced in a collider experiment is the large signals due to charged particles passing through the detector gas. The partial pressure of the photosensitive gas is only a few Torr, so operation at atmospheric pressure is obtained by adding a buffer-gas mixture such as argon-isobutane-methane. About ten times as many electrons are ionized directly by a charged particle as are ionized by the Čerenkov photons. With a high gas gain to observe the Čerenkov signal, there is risk of discharges due to the minimum-ionizing 'background.' A possible solution is to operate the photodetector at only a few-Torr pressure, which nearly eliminates the signal from minimum-ionizing particles, and actually improves the gas gain. However, considerable developement is needed on the mechanical configuration of a large-area, low-pressure detector.

2.5 Transition Radiation Detectors

While evidence for CP violation in B decays will likely come primarily from measurement of asymmetries in all-charged decay modes, it is important to tag semileptonic modes, $B \to e\nu X$, as well. The best modes for observation of CP violation are those where the final state f is a CP eigenstate, so the particle/antiparticle character of the parent B cannot be determined from measurement of this decay alone; the second B of the produced B-$\bar{B}$ pair must be tagged. This leads to the need for electron identification systems, comprised of TRD's and electromagnetic calorimeter.

Of all the technologies to be used in the BCD, the TRD's are the most well-developed at present.[9] However, it will be advantageous to use next-generation thin-sampling detectors,[10] in which some 30 detectors each 1.5-cm thick yield better pion rejection than the 15-cm-thick devices currently in use. An online rejection of 100:1 against pions should be achievable, presuming some processing of the 30 samples per track.

The BCD requires about 60 m^2 of TRD's. If the size of the cathode readout pad is taken as 1 cm^2, there are 6×10^5 pads per layer of TRD. Thus a 30 layer system of this granularity has about 2×10^7 readout elements. While the cost of VLSI electronics in such numbers is not excessive, the question of mechanical costs of mounting these chips on a low-density board must be explored.

2.6 Electromagnetic Calorimeter

The calorimeter functions primarily to aid in electron identification, rather than providing a precision energy measurement. As such, position resolution is more critical. We thus have the option to use a sampling calorimeter (as opposed to total absorption in BGO or lead glass, *etc.*).

The calorimeter should have tower geometry, with three longitudinal samplings per tower. This feature should permit an online rejection factor of several hundred for charged π's. The transverse size of the towers should be sufficient that the energy measurement is of only a single particle with 99% probability, leading to a tower count of 10^4 given an average multiplicity of 100. A position-sensitive detector will be placed between the first and second layers of each tower to reject overlaps of a charged pion with a photon from π^0 decay. For this a two-track resolution of about 1 cm is desirable.

Of the technologies available for calorimetry, liquid argon appears the most satisfactory in terms of performance, but is cumbersome to implement in a 4π experiment. A warm-liquid system could be advantageous if perfected. A calorimeter with scintillator as the sampling medium is adequate, if the difficulty of an optical readout in a magnetic field can be solved.

A speculative option is to read out the scintillating fibers of a 'spaghetti' calorimeter with to-be-developed devices called 'silicon phototubes.' In these, a small photodiode has a silicon pixel detector as its anode, which is bonded to a low-noise amplifier inside the vacuum. About 300 electrons would be liberated per photoelectron per 1000 volts across the diode. For a small pixel size the noise could be held to perhaps 500 electrons, so with a 3-keV voltage, the noise level is 0.5 photoelectrons. The silicon phototubes might have cathode areas of 1 cm^2, matched to a 2×2 cm^2 segment of the spahghetti calorimeter, assuming 25% coverage by area with the scintillating fibers. Because they are photodiodes with a small gap, the silicon phototubes are relatively insensitive to magnetic fields. A possible drawback is that the anode is sensitive to charged particles which pass through it, each such giving a signal equivalent to one photoelectron. It would require a large R&D program in cooperation with an interested vendor, perhaps Burle Industries, to develop the silicon phototube.

2.7 Signal-Processing Architecture

Because the B experiment is based on reconstruction of all soft charged tracks, a large amount of data is produced by each event. Each of 60 tracks will be sampled approximately 100 times for a total of about 6000 words per event. A word will typically consist of 4 address bytes and one data byte, for a total of 30,000 bytes per event. The detector is to operate at event rates of up to 2.5 MHz, so the potential data rate is 75 gigabytes/sec.

By utilizing the technology of modern telephone switches we can process this high data rate in 3 levels, as illustrated in fig. 5:

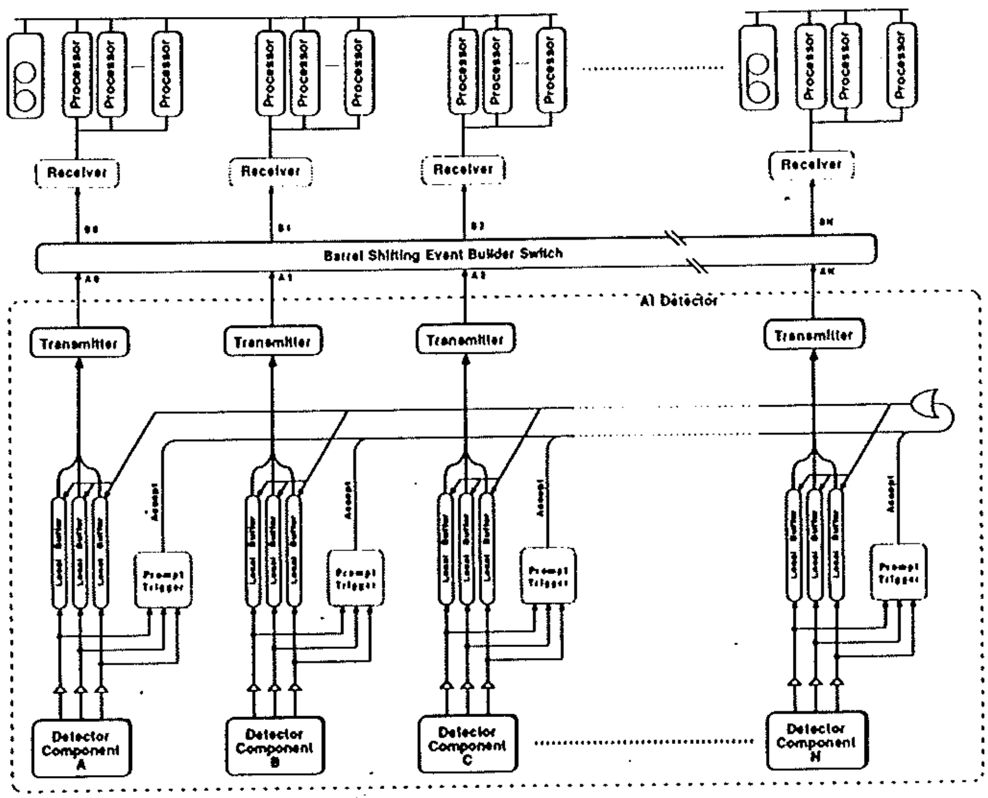

Figure 5: Schematic of the signal-processing architecture.

- A fast trigger reduces the event rate by a factor of 25, for a maximum of 100 kHz of surviving events. The fast trigger is based on analog signal processing; all trigger decisions based on numerical calculations are to be deferred to the second level.
- A 'barrel switch' organizes that data from up to 10^6 events/sec into individual event records, which are fed to a farm of perhaps 10,000 numeric processors. Each processor is about 50 VAX-780 equivalents, and must make a second-level trigger decision in 0.1 sec, with a desired reduction in the event rate of 100.
- The remaining event rate of up to 1 kHz is archived to some storage medium such as video cassette, or perhaps the new technology of 'digital paper.' The archival data

rate is then about 30 Mbytes/sec, which would require 120 present-day Exabyte cassette drives. The archived events would later be analyzed on the processor farm, whose combined processing power is about 0.5 TIPs (0.5×10^{12} instructions per second).

In the next three subsections we discuss issues relating to the fast trigger, the front-end electronics, and the data-acquisition system.

2.8 Fast Trigger

As discussed in our Letter of Intent,[1] two kinds of fast triggers are under consideration for the Bottom Collider Detector:

- A **topology** trigger which is satisfied whenever n or more tracks in an event have P_T above a cut value. For $n = 1$ the cut might be 3 GeV/c, while for $n = 2$ the cut could be at 2 GeV/c. Either could yield a factor of 25 reduction in the event rate according to preliminary Monte Carlo simulations. This trigger would be based on fast tracking, and could use coarse-grained position information from pad chambers (*i.e.*, the first and last pad layers of the TRD's) as well as signals from the straw-tube tracking system.
  - In addition, the fast-tracking system must have precise ($\sim \pm 1$ cm) z-coordinate information within a few hundred nsec after a collision. This component of the fast trigger would be provided by a scintillating-fiber tracking system located several meters upstream and downstream of the interaction region. One encouraging design consists of 4 identical 9-plane arrays of fibers positioned to cover the rapidity range from 4 to 6. Each detector plane consists of 200 fibers oriented in the nonbend plane.
- An **electron** trigger with a minimum-P_T cut of about 1 GeV/c. Since each event will have about three charged pions with $P_T > 1$ GeV/c, an online pion rejection of greater than 75:1 is needed to reduce the event rate by the desired factor of 25. This should be achievable using signals from the TRD's, and from the longitudinally segmented electromagnetic calorimeter.

Thus the fast trigger will be derived primarily from signals in the outer layers of the detector, but the design should preserve an option to incorporate signals from the inner tracking systems as well. This may be particularly important for rejection of electrons from photon conversions.

Continued study of the trigger scheme is needed, with emphasis in the near term on computer simulations.

2.9 Front-End Electronics

The front-end electronics will be in the form of custom, very-large-scale integrated (VLSI) circuits, permitting low-cost and low-power readout of the large number of detector elements of the Bottom Collider Detector. All of the various chips proposed here are straightforward extrapolations or reconfigurations of presently available devices, although they will necessarily be 'state-of-the-art' devices.

The experience of a number of high-energy-physics groups has shown that such chips can be successfully developed by a small number of people, but that turn-around times with the silicon foundries dictates a time scale of perhaps two years per chip. Resistance to radiation damage is of particular interest to us, and will require additional studies best performed once the chips are electronically operational.

For running of the Bottom Collider Detector at the Tevatron collider we take the bunch crossing time to be 400 nsec (compared to 16 nsec at the SSC). Hence any signals not requiring a fast timing pulse can be shaped to a full width of 400 nsec. This permits the use of low-power CMOS technology for most chips. The notable exception is the preamplifier for the straw tubes, which must use Bipolar technology to provide a time resolution of 0.5 nsec, corresponding to the desired 50-μm spatial resolution.

While the detector will have a channel count in excess of 10^7, only about 10^4 channels will be struck during an event of interest. The front-end electronics must include functions to sparsify the data, outputting only addresses and digitized data for the struck channels. Further, the data must be stored at its source until the fast trigger is formed, perhaps as long as 6 μsec, before passing it on to the data-acquisition system.

The flow of data out of the detector should be on fiber-optic cables whose higher rate capability will minimize the number of physical cables. This requires a class of data-collection chips on the detector which format and buffer the data before transmission off the detector.

The front-end electronics for the various detector systems will be designed with the maximum of commonality. Efforts will begin on chips for the silicon strip detectors. Only the straw-tube chambers will require electronics with considerably different features.

2.9.1 Silicon Strip Front-End Electronics

From the considerations outlined in section 2.2, we have arrived at the following specifications for the front-end chip (designated the BVX) for the silicon strip detectors:

- 1.25-μm CMOS technology.
- Power consumption: 1 mWatt/channel.
- R.m.s. noise $<$ 600 electrons.
- Signal shaped to 400-nsec full width at base.
- Adjustable discriminator threshold in the range 3000-6000 electrons, with option for a second discriminator threshold.

- On-chip storage of the analog signals for about 6 μsec = 16 bunch crossings.
- Six-bit ADC for signals above threshold, with digitization beginning only if the fast trigger is satisfied.
- Sparsified readout of the 128 channels which make up a physical BVX chip.
- Individual channel electronics sized for the 50-μm strip pitch of the silicon detectors.
- Radiation hardness to 100 krad, the expected yearly dose at 1 cm from the beam at a luminosity of 10^{31} cm^{-2}sec^{-1}.

These specifications are slightly beyond those met by the current generation of chips, such as the MPI CAMEX,[11,12] the LBL SVX[13] and the RAL MXI.[14] However, the relatively long bunch crossing time at the Tevatron, 400 nsec, should permit the stringent noise requirement to be met. Also, we plan to use a.c. coupling to the amplifiers, which renders them largely immune to leakage current, and eliminates the need for quadruple-correlated sampling.

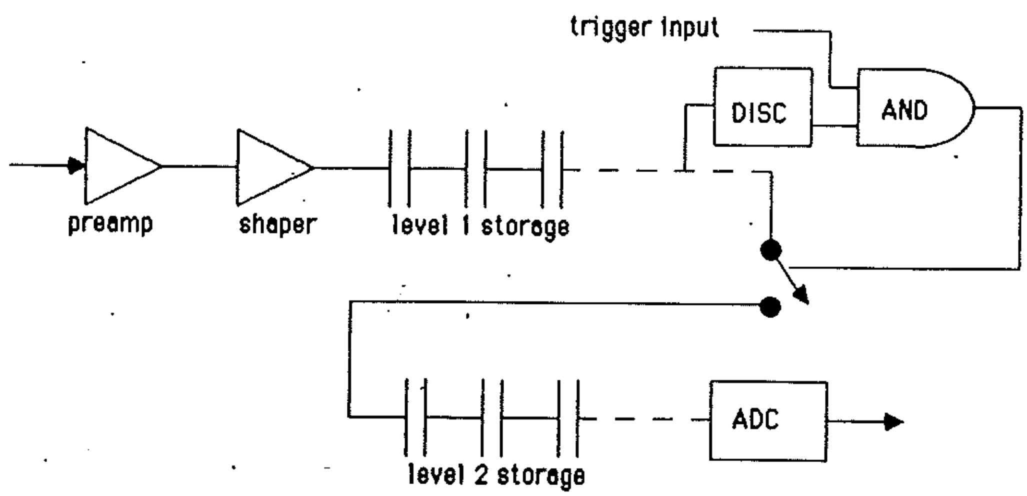

Figure 6: Block diagram of one channel of the BVX readout chip for the silicon strip detectors.

A block diagram of one channel on the BVX chip is shown in fig. 6.

Tracks with angle of incidence greater than 45° present an additional problem for the readout. Such tracks may deposit signals of greater than 4000 electrons into a large number of contiguous strips, called here a cluster. It is not necessary that these signals be processed further, because the silicon is arranged so that all tracks strike at least three detector at angles of incidence less than 45°. However, signals as low as 5600 electrons, due to tracks at exactly 45° incidence, must be kept. Because the r.m.s. noise is a substantial fraction of the difference between 5600 and 4000 electrons, it is dangerous to set a threshold in this region; because of noise fluctuactions the cluster of struck strips would be processed as a number of isolated hits, filling the event records with useless data.

If would be preferable if there were an on-chip capability to sense the number of contiguous struck strips above a threshold of, say, 4000 electrons, and suppress the readout of the entire cluster (or entire chip!) if more than 6 contiguous strips were struck.

The BVX chips are to be bonded directly to the silicon wafers, without requiring a dead space near the readout end of the wafer. Figure 7 sketches how this might be accomplished with a tab-bonding technique.

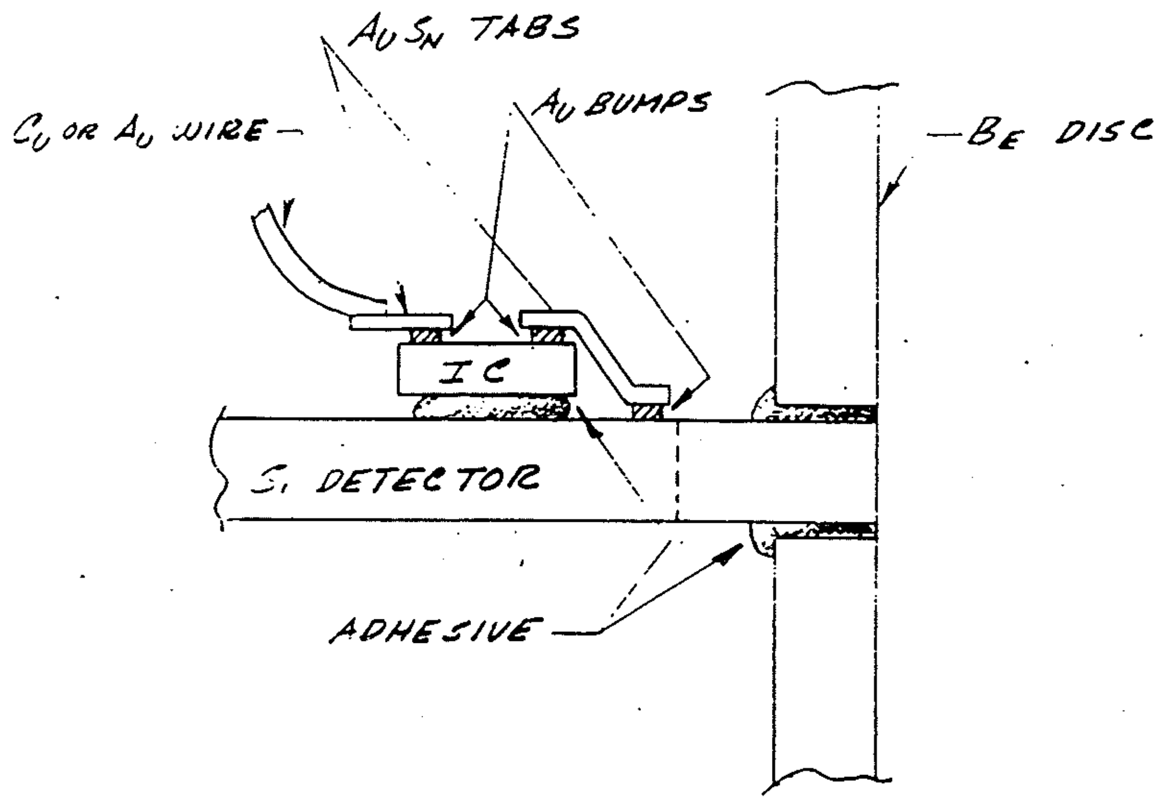

Figure 7: Possible scheme for bonding the BVX readout chips to the silicon strip detectors.

If there are 10^6 silicon strips serviced by the 128-channel BVX chips, then about 10^4 of the latter are required. If separate data lines emerge to the outside world from each BVX chip the cabling problem would be severe. However, the average occupancy of a BVX chip should be less than one channel per event (if clusters of greater than six strips can be suppressed). It will be advantageous to route the signals from 10 to 100 neighboring BVX chips into a 'data collection' chip, which further buffers the data until the data-acquisition system is ready to receive it. Details of the data-collection architecture need further specification; this architecture should be suitable for collection of signals from all systems of the Bottom Collider Detector.

2.9.2 Straw-Tube Electronics

The high spatial resolution of the straw tubes is obtained by measuring the time of arrival of the first ionization electron. A resolution of 50 μm requires a timing accuracy of 0.5 nsec. Hence the preamplifiers for the straw tubes must be fast devices even though the event rate is at most 2.5 MHz. The speed requirement dicates the use of Bipolar technology for the integrated circuits, at the expense of a heat load of about 15 mWatt per channel. Cooling the low density of straw-tube preamps is, however, a straigthforward matter. Once the electron-arrival time has been converted to a voltage, the rest of the signal processing (trigger delay and digitization) can be performed in CMOS circuitry very similar to that on the BVX chip

The block diagram of the proposed Bipolar/CMOS chip is shown in fig. 8, which closely follows the so-called TVC chip set developed at U. Penn for the SSC.[15] The Bipolar amplifier/shaper/discriminator of the TVC could be used directly, and the CMOS analog store could be used but with a slower clock, typically 5-10 MHz.

The system would consist of the Bipolar preamp/shaper/discriminator followed by the CMOS analog-store/ADC/readout-control chip. The Bipolar chip will have four channels and the CMOS chip will have 8 channels. In addition the system would need a data-collection chip (digital CMOS), similar to that for the silicon strip electronics, for every 8-32 front-end chips. Total power costs would be about 20 mW per channel.

A possible arrangement would have a thin printed-circuit board mounted on the ends of a group of 128 straws, with 32 Bipolar chips, 16 CMOS TVC chips, and one data-collection chip, in addition to discharge protection and bypass and coupling capacitors for the straws. The cost would be about \$2-3 for the Bipolar chip/channel, \$1-2 for CMOS, \$0.25 for the data chip and \$0.50 for mounting, for a total of < \$6/channel.

It will be useful to include segment-finding electronics for some of the straw-tube superlayers. This should be possible by adding a CMOS digital-logic chip in parallel to the CMOS TVC chip. Found segments would then be shipped to the trigger system. The increase in power cost should be only about 10% assuming a high level of multiplexing. An intriguing alternative possibility for the segment-finding chip is an anolog processor based on 'neural-net' concepts. This option is currently being explored for the Bottom Collider Detector by Bruce Denby.[16]

2.9.3 RICH-Counter and TRD Electronics

Both the RICH counters and the TRD's will have pad sensors whose signals will be similar in magnitude and shape to the signals from silicon strips. Thus we have the option that

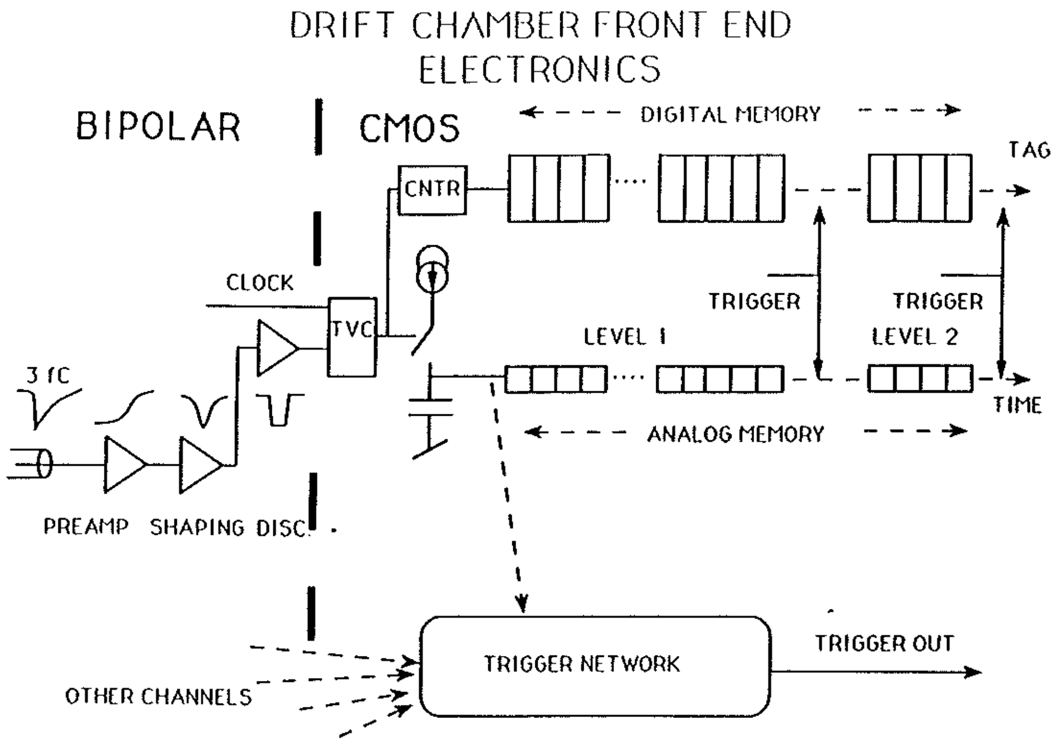

Figure 8: Block Diagram of the Bipolar/CMOS readout chip set for the straw-tubes.

the BVX chips may be used for these devices as well. However, the number of channels in the RICH counters and TRD is greater by at least an order of magnitude compared to the silicon vertex detector, so the major cost of electronics for the entire detector is likely that of the pad readout. Hence the pad readout may deserve a specifically optimized solution.

It should be possible to design pad-readout chips with rate capabilties significantly higher than those required at the Tevatron, but which could be suitable for the SSC. Very recently we have made contact with an electronics group at Rutherford Appleton Laboratory,[7] who may be interested in a collaboration towards this end.

In any case, the low density, large channel count, and large physical size of the pad readout mandates a large R&D program addressing cost-effective methods of chip mounting and signal routing, in additional to the development of the readout chips themselves.

2.9.4 Electromagnetic Calorimeter

The calorimeter could use a readout system similar to that of the straw tubes in the sense that a Bipolar front end would feed a CMOS delay-and-encode section. However, the calorimeter requires charge measurement over a large dynamic range and may or may not require an acurate time measurement. Thus the Bipolar chip will necessarily require rather more power (for the dynamic range) and the CMOS chip will require more area for storage capacitors (high- and low-charge ranges).

In addition the calorimeter will serve as one of the primary triggering detectors and must provide fast signals out of the detector to the central triggering system. These signals will require > 40 mW per output, but the trigger outputs will be sums of local channels so that the total power burden is not greatly increased. If a suitable clustering algorithm can be defined and tested, we could ship only cluster-position and -size information to the trigger system, greatly reducing the burden on and increasing the power of the trigger.

We estimate that the total power requirement per channel would be about 30 mW and the cost per channel would rise slightly to < $7. Mounting and cooling is least restrictive in this region and we anticipate no major problems for the calorimeter system.

2.10 Data-Acquisition System

The overall signal-processing architecture for the Bottom Collider Detector has been introduced in section 2.7 and illustrated in fig. 5. The data-acquisition system incorporates three new technologies which require an R&D program:

- Fiber optics for digital-data transmission.
- Barrel-switch event builder.
- Industry-supported numeric processors for the second-level trigger.

The design goal for the data-acquisition system is an input of 10^5 events/sec containing about 5 gigabytes/sec of data, and an output of 1000 events/sec to archival storage. A design to meet this goal has been prepared by the group of Ed Barsotti at Fermilab as part of the present proposal.[17,18]

2.10.1 Local Buffers and Transmitters

Figure 9 shows a portion of the data-acquisition system between the front-end electronics on the detector and the event-builder switch. The block labeled 'local buffer' resides on the CMOS data collection chips described in section 2.9.1. A fiber-optic link connects the local buffers to a smaller number of transmitters. The latter must organize the data from each event into units, called 'fragments,' whose format is suitable for processing by the event builder switch. A transmitter would receive data from the local buffers in parallel streams at a rate of 1 Mbyte/sec, and send out a serial data stream at a rate of 10 Mbyte/sec. About 512 transmitters will be required to accomodate the expected total data rate of 5 Gbyte/sec.

2.10.2 Barrel-Shifting Event-Builder Switch

The key section of the data path is the event-builder switch. This should organize the 512 event fragments from the transmitters into individual events at a rate of 10^5 events/sec (compared to 10/sec presently achieved in the CDF detector). This can be accomplished via the barrel-shifting technique used in the telephone industry.

A barrel-shifting event-builder switch is an N-input, N-output device with only N possible interconnects at any given moment (in contrast to a crossbar switch that has $N!$

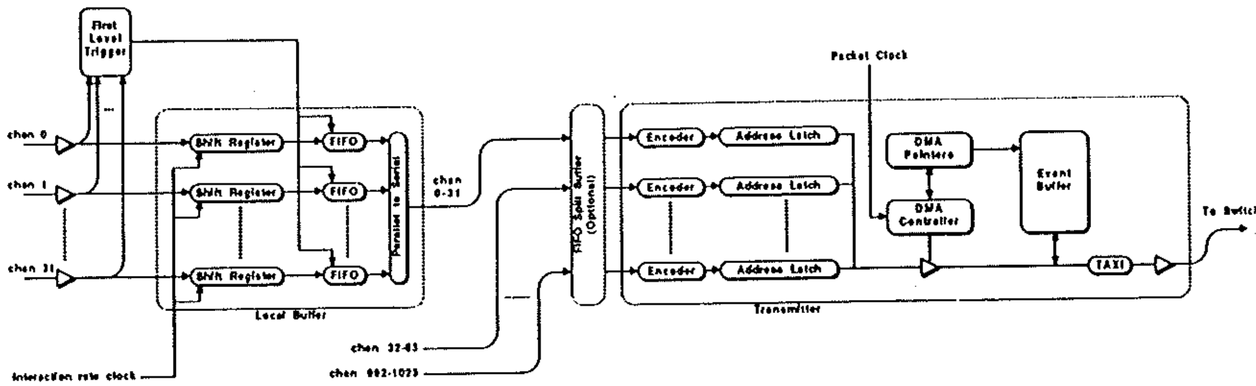

Figure 9: Block diagram of local buffers (data collection chips), 'event-fragment' transmitters, and their fiber-optic interconnections.

interconnections). The pattern of the N interconnections is altered at every cycle of a clock, so after N clock cycles all inputs have been connected to all outputs once. Since there are exactly as many interconnects as inputs, the switch can transmit the full input bandwidth.

To illustrate how the barrel switch organizes data fragments into whole events, consider a simple example in fig. 10. Fixed-length event fragments pass through the system with each input channel delayed by one clock cycle relative to the adjacent channel. With the switch-control word set to 00 (fig. 10a), the first fragment of event 1 (labeled 1A) passes directly through the switch along with three empty fragments. The switch-control word is the incremented by one (fig. 10b) and the second fragment of the first event (1B) and the first fragment of the second event (2A) are transmitted; because the pattern of the interconnects has changed, fragment 1B now follows 1A. During the next cycle of the switch (fig. 10c), fragments 1C, 2B, and 3A are transmitted. After one full rotation of the switch control, the system reaches a steady-state condition, shown in figs. 10e and 10f. Parallel event fragments are converted to assembled event streams with no low of bandwidth.

As a first step in the development of the barrel-shifter technique, a 16-channel demonstration system will be constucted, shown in fig. 11.

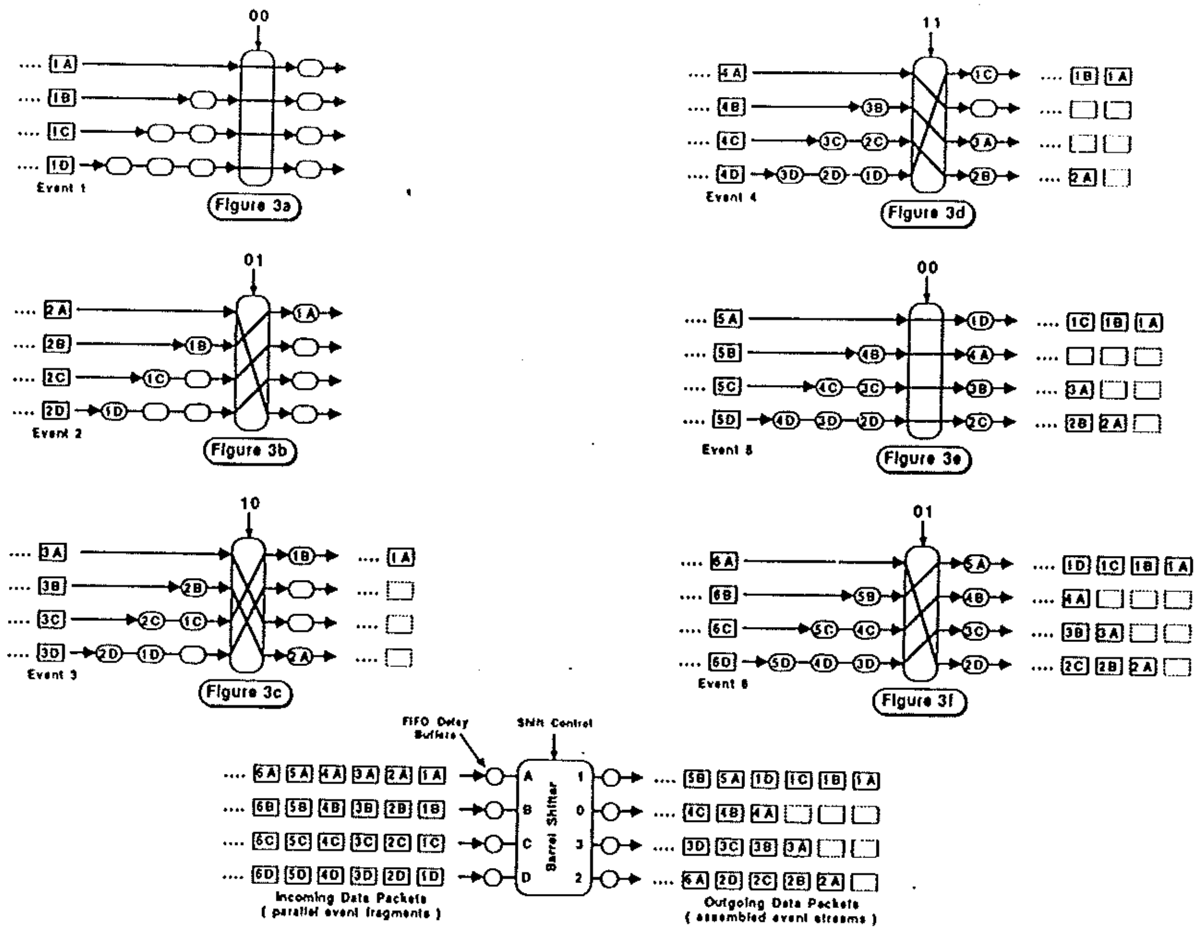

Figure 10: Principle of operation of a 4-input, 4-output barrel-shifting event-builder switch.

2.10.3 Numeric Processors and Archival Storage

The assembled events emerging from the event-builder switch are fed to a farm of numeric processors in which the level-2 trigger calculations are performed. No special-purpose numerical processors will be built; we propose to take maximum advantage of industry support of high-speed processors optimized for numerical calculations. Prototypes of 30-MIP processors will become available in Spring 1989, which we plan to incorporate them in the 16-channel demonstration system.

We anticipate the need for 5000-10000 processors in the eventual configuration of the Bottom Collider Detector. Then each processor would have about 0.1 second to make the level-2 trigger decision, with the goal of a factor of 100 reduction in the event rate.

The total archival data rate is expected to be 1000 events/sec, or 30 Mbyte/sec. This could be handled by an array of 120 Exabyte drives. Options for the use of fewer devices will emerge in the next few years. In 1989 the so-called 'digital paper' devices should become available from Creo.[19] In this, one terabyte can be stored on a 2400′ reel of write-only optical tape, with a data rate of 3 Mbyte/sec. A more virtual device is the Haystack drive, being developed for the radio-astronomy community, in which a magnetic drive with 100 heads should eventually be capable of writing 100 Mbytes/sec.

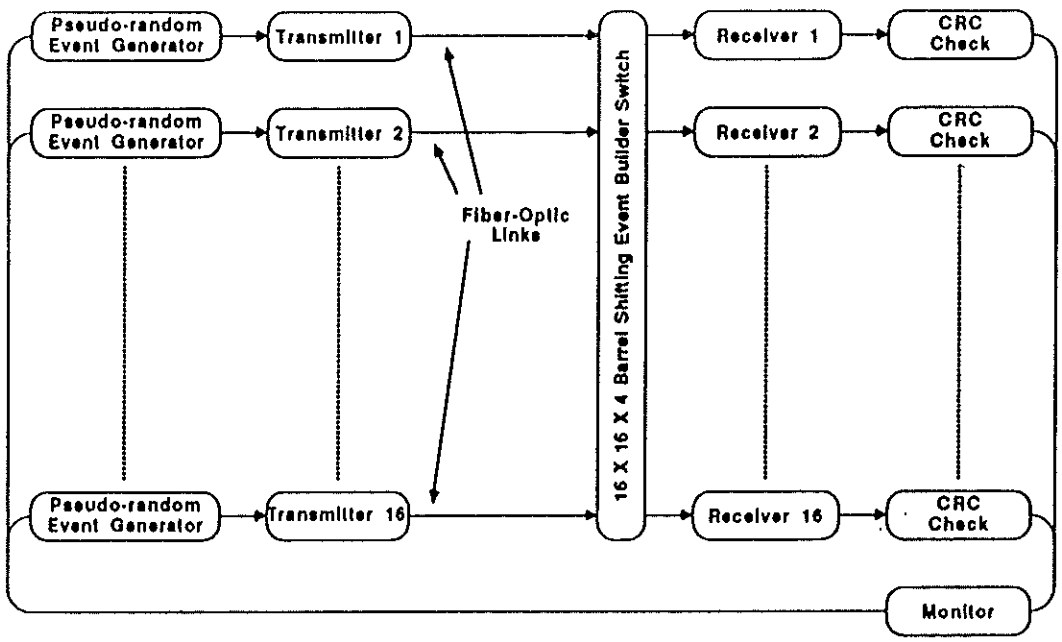

Figure 11: Proposed demonstration of a 16-channel barrel-shifting event-builder switch.

2.11 Accelerator Physics Issues

2.11.1 Luminosity

The window of opportunity for observation of CP violation in the B meson system at the Tevatron collider opens for luminosities above 10^{31} cm^{-2}sec^{-1}. We strongly support the Tevatron upgrade programs which would make this possible.

2.11.2 Beam Pipe

The resolution of a silicon vertex detector improves when the innermost detector is closer to the beam. We plan to use a beam pipe 1 inch in diameter with walls of 400-μm-thick beryllium.

2.11.3 Length of the Interaction Region

Most of the mechanical complexity of the silicon vertex detector arises because of the finite length of the interaction region which it must cover. We wish to explore the possibility of reducing the luminous region to a σ of 10 cm, down from the value of 35 cm in present running. Following discussions with Dave Finley, this might be accomplished in two ways:

- Reduce the β^* at the intersect with stronger quads. This might be possible because the 1-inch beam pipe would permit a smaller bore for the quads, and the experimental configuration might permit the quads to be closer than 7.5 m from the intersect. Of course, a lower $\beta^\star$ is also useful in raising the luminosity.

- Add a higher-harmonic rf system to bunch the beams more tightly. This has the bad effect of increasing the intrabeam scattering, leading to a shorter luminosity lifetime. Calculations should be made to judge whether this option can produce a net gain in useful luminosity for a shorter interaction region.

2.11.4 Bunch Crossing Rate

The time between neighboring bunch crossing sets the time scale for all readout electronics. We now assume that this time will be 400 nsec, which is well matched to the stated goal of a luminosity of several times 10^{31} of the p-$\bar{p}$ upgrade program.

2.11.5 Beam Halo

Halo associated with the beams will contribute to the radiation exposure of the vertex detector and thereby shorten its lifetime. Present data indicate that the silicon detector can suœ[Brvive about 10^5 rads. It is clear that catastrophic beam loss must not occur near the detector. The beam-loss level for abort may need to be lowered compared to present operation.

2.11.6 Compensation for the Dipole Field

The presence of a spectrometer dipole in the Tevatron would alter the beam trajectory unless compensating measures are taken. The scheme that has been chosen for compensation uses two dogleg bends, one at each end of the straight section and each 20 feet from the center of the interaction region, just downstream of the low-beta quads. The two magnets are both of opposite polarity relative to the spectrometer dipole, and run in series with it (that is, the currents run up together). The spectrometer dipole and compensating magnets are energized only after coasting beam has been established. The beams at the crossing region then move laterally a few mm as the magnets are energized.

2.11.7 The Detector Hall and Support Facilities

The Detector Hall required for this facility will be comparable in size to that at D0. The detector itself will fill about one half the space available in a straight section at the Tevatron. The compensating dipoles are placed at the outer ends of the straight section. The need for electron detection, calorimetry and particle identification will require the use of special gasses and liquids. The detector may use ethane, TMAE, or TEA. Additional cryogenic support may be necessary to service the main dipole magnet. The detector will require a substantial signal-processing area. The Detector Building must also provide for a control room, office and technician space and shop support.

An initial design of a new collision hall is shown in fig. 12, as prepared by Nestander's Engineering Services Group.

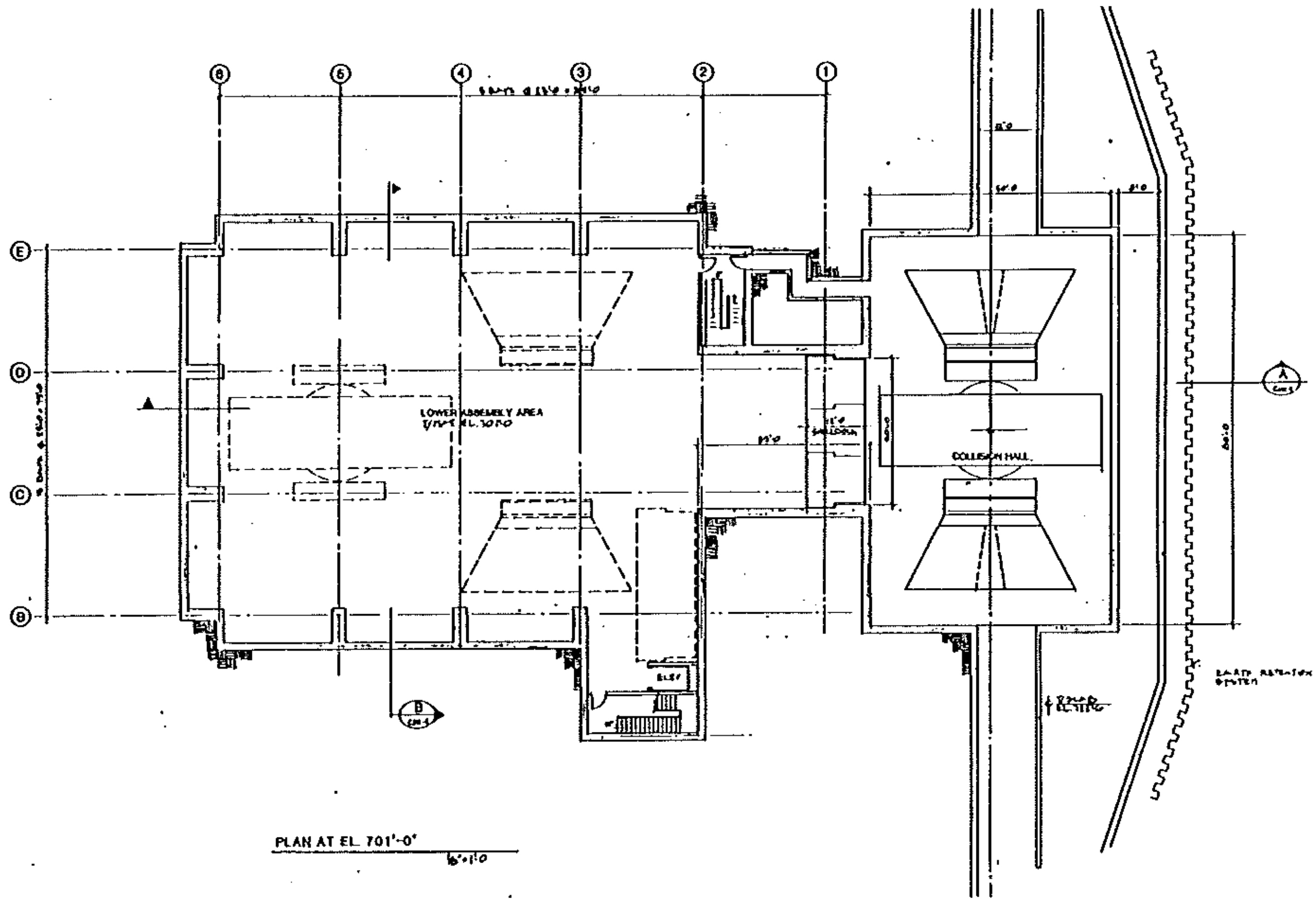

Figure 12: Layout of a new collision hall for the Bottom Collider Detector.

2.11.8 System Test at the C0 Intersect

We propose to test prototype versions of the silicon vertex detector, straw-tube chambers, and scintillating-fiber detector at the C0 intersect during the 1990-1991 collider run. This test will provide crucial evidence that secondary-decay vertices can be found at a hadron collider, and will also serve to focus the R&D efforts towards a timely measurement.

We can run at C0 in a parasitic mode in the sense that we would not require retuning of the beam for higher luminosity. But when we run, the electrostatic separators must be turned off so beams actually collide at C0.

In a run of 10^6 seconds at a luminosity of 10^{28} cm^{-2}sec^{-1}, about 100 $K^0_S \to \pi^+\pi^-$ decays would be observed (in the prototype apparatus) per each 100 μm of decay path. A study would then be made as to how close to the primary vertex the K-decay vertex can be reconstructed. This, of course, presumes the primary vertex can be located by the detector as well. A sample of about 50 decays $D^0 \to K^+\pi^-$ would also be observed in the test run.

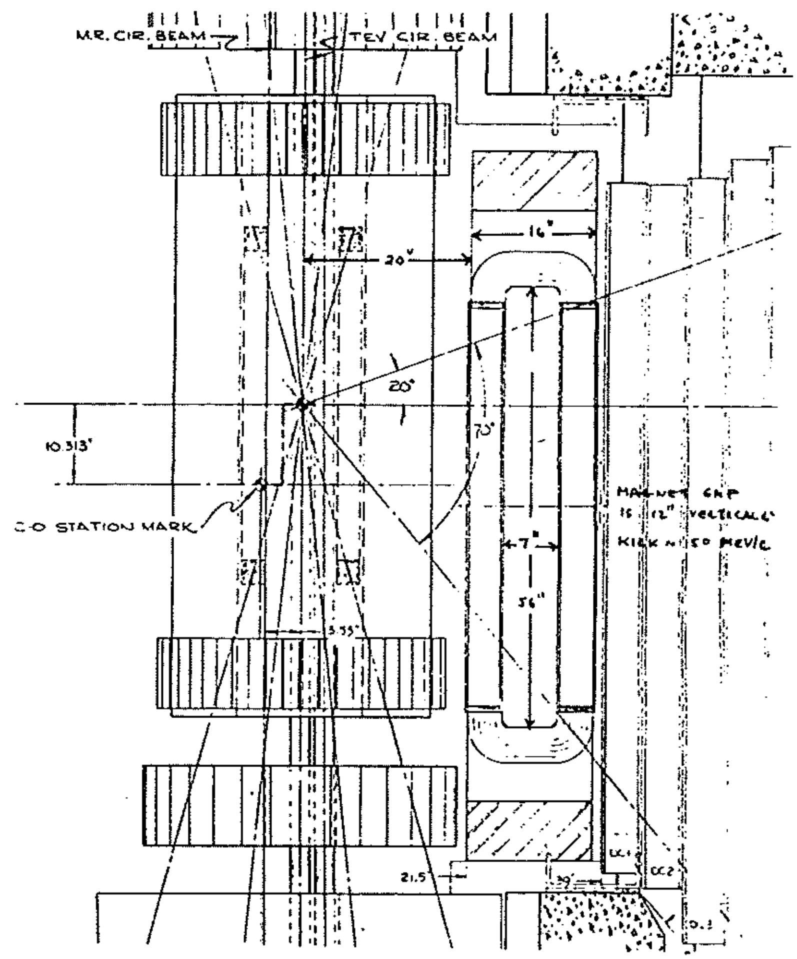

Figure 13: The existing layout of E-735 at the C0 intersect.

The existing configuration of E-735 in C0 is shown in fig. 13. We would need to replace the present central detector with our silicon vertex detector and straw tubes. A factor of about four in acceptance could be gained if the window-frame magnet were moved closer to the beams until it abuts the abort line of the 150-GeV ring. As mentioned in section 2.11.2, it is advantageous to have a small-diameter beam pipe for better resolution in the vertex reconstruction. The β^* is large in C0, so the pipe cannot be 1 inch in diameter. However, we would like the smallest pipe size compatible with the Tevatron beams.

3 Research & Development Program

The proposed research and development program for the Bottom Collider Detector is divided into three phases that overlap three fiscal years, 1989 through 1991.

- Phase I takes place in fiscal 1989 and consists of what might be called bench tests for each of the systems under consideration.
- Phase II takes place during fiscal 1990 and utilizes the fixed-target test beams available at the laboratory.
- Phase III takes place in fiscal 1991 and uses the C0 intersection region in a parasitic mode to perform system tests in the collider environment during the next collider run.

The three major systems addressed in this proposal are

1. The silicon vertex detector.
2. The tracking system.
3. The data-acquisition system.

The R&D issues for the silicon detector and straw-tube tracker are logically subdivided into mechanical and electrical parts, *i.e.*, construction and front-end electronics. The DAQ system includes everything after the front-end electronics including the fast trigger.

We outline below the R&D tasks and costs for each of the three systems, also breaking these down into the three phases.

3.1 Silicon Vertex Detector

3.1.1 Silicon: Mechanical & Electrical Tasks - Phase I

- Construct models of the silicon detector out of plastic and G-10 to explore assembly techniques.
- Continue modelling of the silicon cells and the supporting gutter structure using 'junk' (unprocessed) silicon and aluminum for the gutter. Survey various adhesives for resistance to creep, and for coefficients of thermal expansion matched to silicon. Add resistors to simulate the overall 2 kWatt heat load.
- Study the cable-plant issues with the silicon models. Develop techniques to cut slots in the silicon for cables (and cooling, possibly).
- Study the cooling requirements.
  - Can the device be cooled with a modest nitrogen gas flow?
  - Is liquid cooling an option?

- Is better electronic noise performance obtained at temperatures below ambient?

- Study alignment issues.
  - How accurately can the disks and barrels be assembled?
  - What is the long term stability?
  - How stable is the detector against thermal gradients?
  - Use the CORDAX (optical) measurement machine and proximity sensors for bench tests.
- Study the various techniques for bonding VLSI chips to silicon wafers now used by industry: bump bonding, tab bonding, and wire bonding.
  - Does the more robust procedure of tab bonding cause cracking of the silicon during heating?
  - Does the adhesive chemically damage the high-resistivity silicon near the bond?
- Test the performance of the double-sided silicon strip wafers. Obtain the a.c.-coupled detectors from Messerschmitt-Bölkow-Blohm GmbH, Munich and Senter for Industriforskning, Olso and test them.
- Design, build and test a VLSI readout chip set that permits a low cost, low power, and low noise readout system for the roughly 500,000 silicon strips.
  - Begin the front-end (BVX) chip design immediately.
    * Define the specifications and overall architecture for the chips.
    * Design the first chip in three parallel efforts: the amplifier/discriminator, the storage/delay array, and the digitization.
    * The hardest part of the design is the amplifier and this will determine the schedule.
    * Existing VLSI amplifier designs are excellent starting points.
    * Goal is to have a first version sometime during the summer.
  - Start the collection-chip design in February.
    * Specify the data-collection architecture for the whole detector, maintaining compatibility with the input formats for the data-acquisition system.
    * The actual chip design will be relatively straightforward digital CMOS.
    * Have first run back from MOSIS by summer 1989.

3.1.2 Silicon: Costs - Phase I

The mechanical costs and electrical costs are listed separately. An estimate of the salary costs are given for each category.

- Electronics: equipment/operating

- Chip-processing costs using MOSIS, 4 runs @ $15k $60k
- Test equipment $30k
- Travel to conferences and workshops on VLSI $10k

- Electronics: salaries
  - 1.5 FTE electrical engineer @ $45k $68k
  - 0.5 FTE electrical technician @ $25k $13k
- Mechanical: equipment/operating
  - Build gutter and alignment jigs using inside and outside shops $10k
  - Use of outside companies to test bonding techniques, glueing, welding and cutting of silicon. Purchase of junk silicon for mechanical studies and of silicon strip detectors for bonding studies $15k
  - Purchase power supplies and miscellaneous parts for thermal studies on junk-silicon model $5k
  - Lab-D clean-room space for this work $5k
- Mechanical: salaries
  - 0.5 FTE mechanical engineer @ $45k $23k

3.1.3 Silicon: Mechanical & Electrical Tasks - Phase II

This work will require the use of a test beam. Discussions with the laboratory are taking place on where (M-Test, M-Bottom or Lab-D) we could be located. We need a place where we can leave equipment set up over the period of the next fixed-target run. We require a low-intensity beam for single-track studies.

- Phase II of the silicon test involves the construction of two cells using junk silicon for alignment studies using the beam. This will require a support structure or jig that rotates and moves in such a way that alignment studies can be performed economically.
- We may need to build a partial beryllium support for the cells in order to study multiple-scattering effects.
- Some of the mechanical questions are:
  - How well is the silicon internally aligned?
  - How well is the silicon aligned with respect to the straws?
  - How large are the dead regions?
  - How robust are the bonds?

- We need to instrument (bond chips to and readout) about 10 double-sided wafers with 50-μm pitch or roughly 5,000 channels. This will allow several studies of detector performance, as well as alignment. We hope to use an early version of the BVX chip for this work.

- Measure the resolution of the device as a function of momentum with and without the use of pulse-height information. Compare this to the Monte Carlo predictions.

- Perform signal-to-noise, efficiency and pulse-height-correlation studies using the double-sided detectors.

- Correlate tracks in the silicon and the straws.

- Study the issues associated with radiation damage. It is believed that a radiation-hard process can be specified once the desired electrical performance has been achieved in a possibly soft process.

3.1.4 Silicon: Costs - Phase II

- Electronics: equipment/operating
  - Purchase 10 doubled-sided silicon detectors @ $1k each $10k
- Electronics: salaries
  - 1.5 FTE electrical engineer @ $45k $68k
  - 1 FTE electrical technician $25k
- Mechanical: equipment/operating
  - Glueing, cutting and bonding the chips to the wafers $15k
  - Beryllium mechanical work $8k
  - Miscellaneous supplies $20k
- Mechanical: salaries
  - Mechanical engineer: 4 months @ $45k $15k
  - Mechanical technician: 1 year @ $25k $25k

3.1.5 Silicon: Mechanical & Electrical Tasks - Phase III

- Design and assemble a portion of a full 4π vertex detector, using about 20 wafers or roughly 5000 channels.

- Instrument this detector for operation at the C0 intersect.

- Readout every beam crossing (as a test of the data-acquisition system).

- Study the multi-track environment, including effects due to dipped tracks and closely spaced tracks.
- Determine impact-parameter resolution in 2 and 3 dimensions for both the disk and barrel configuration together and separately.
- Determine vertex resolution of the system in the multi-particle environment.
- Reconstruct a sample of $K_S \rightarrow \pi^+\pi^-$.

3.1.6 Silicon: Costs - Phase III

- Electronics: equipment/operating
  - 48 silicon detectors (2 cells) $50k
  - BVX chips, data collection chips for above $50k
- Electronics: salaries
  - 1 FTE electrical engineer $45k
  - 2 FTE technician @ $25k $50k
- Mechanical: equipment/operating
  - Assembly of 2-cell prototype detector $50k
  - Mounting of prototype in C0 intersect $25k
  - Cooling, cabling for prototype detector $25k
- Mechanical: salaries
  - Mechanical engineer: 4 months @ $45k $15k
  - Mechanical technician: 1 year @ $25k $25k

3.2 Tracking System

3.2.1 Tracking: Mechanical & Electrical Tasks - Phase I

The goal of this phase is build an instrumented superlayer of straw-tube chambers and perform a cosmic-ray test. In addition, we will start a program of R&D for a plastic scintillating fiber detector whose role would be to provide a fast measue of the z coordinate of the primary interaction vertex.

- Compare samples of straws from two vendors.
- Study different sizes of tubes. First try the 3-mm-diameter tube.
- Study both a short- and long-straw design, the latter with spacers inside the straw.

- Study the mechanical properties such as roundness, sag, and the adherence of the mylar to the aluminum as a function of temperature and pressure.
- Design and test the feedthroughs electrically and as gas seals.
- Make drift-velocity measurments as a function of high voltage, pressure, gas composition and magnetic field.
- Study the mechanical mounting and glueing techniques for assembling a superlayer.
- Measure the resolution as a function of all variables, including the orientation in the magnetic field.
- Study radiation damage.
- Study the feasibility of small pads on the straws as a means of obtaining fast z-coordinate information.
- Construct a sample of test straws.
- Design a readout system.
- Perform studies to see how well one can align and calibrate the system, and maintain optimal position resolution over time.
- Develop the readout chip set (3 chips):
  1. Bipolar amplifier/discrimator. Begin with the Penn-Louven design underway for SSC Generic R&D.
  2. CMOS time-to-voltage converter, analog storage/delay, and ADC.
  3. Data collection chip. Might be the same as for the silicon vertex detector.
  4. Study options for a fourth chip–for segment finding. This might be an analog processor implementing a neural-net algorithm, or a more conventional digital design.

Some of the group are interested in the development of plastic scintillating fibers. We are considering the application for both small-angle tracking and calorimetry. We discuss the need below as it pertains to the prompt trigger envisioned for the DAQ system. Because of the dipole field, the fast-tracking trigger needs the z coordinate within a few hundred nanoseconds after the collision.

- Develop a plastic scintillating fiber optic system that separates a beam-beam collision from a beam-gas collision. The system would subtend the rapidity range 4-6 units and is located several meters downstream and upstream of the collision point.
- Also use this system to determine the z-coordinate of the beam-beam interaction to 1-cm accuracy by tracing the low-angle tracks back to a common vertex.
- Design a fast readout system that can provide this information to the trigger.

3.2.2 Tracking: Costs - Phase I

- Electronics: equipment/operating
  - Chip development: 3 MOSIS runs @ \$15k \$45k
  - Studies of pad readout of straw tubes \$10k
- Electronics: salaries
  - 1.5 FTE electrical engineer @ \$45k \$68k
- Mechanical: equipment/operating
  - Purchase straws, travel to vendors \$10k
  - HV supply, wire, and gas system \$15k
  - Prototype feedthroughs \$5k
  - Test fixtures, cables, jigs and supplies \$40k
- Mechanical: salaries
  - 1 FTE mechanical engineer \$45k
  - 1 FTE technician for the mechanical straw work \$25k
  - 1 FTE technician for the gas studies \$25k
  - 1 FTE technician for alignment studies \$25k
- Fibers: equipment/operating
  - Scintillating fibers, and readout tubes \$50k
- Fibers: salaries
  - 1 FTE technician \$25k

3.2.3 Tracking: Mechanical & Electrical Tasks - Phase II

Phase II of the straw-tube development requires constructing a two-superlayer system to be tested in a test beam (M-Test, M-Bottom or Lab-D Test Beam). The scintillating-fiber detector will be tested in the beam also.

- Straw-tube studies
  - Perform pattern recognition and track fitting for tracks traversing several superlayers.
  - Measure the single-hit, single-track and two-track resolution.
  - Study the alignment issues associated with the assembly procedure of an octant of a 4π tracking system.

- Correlate tracks in the straw tubes with the tracks in the silicon.
- Study multiple-scattering effects.
- Test the readout system.

- Fiber studies
  - Build and test prototype fiber-array system.

3.2.4 Tracking: Costs - Phase II

- Electronics: equipment/operating
  - 6 MOSIS runs @ $15k $90k
  - Readout chips at $7 per chip and 4 channels/chip $13k
  - Test equipment such as digital scopes, and logic analysers $50k
- Electronics: salaries
  - 2 FTE electrical engineer @ $45k $90k
- Mechanical: equipment/operating
  - Build 7000 straws with feedthroughs @ $5 each $35k
  - Cables, mounting boards, epoxies, and supplies $20k
  - Bonding of readout chips to straws $5k
- Mechanical: salaries
  - 1 FTE mechanical engineer @ $45k $45k
  - 2 FTE technicians @ $25k $50k
- Fibers: equipment/operating
  - Scintillating fibers $20k
  - Test equipment $30k
- Fibers: salaries
  - 1 FTE technician $25k

3.2.5 Tracking: Production R&D - Phase III

A four superlayer straw-tube system would be used in the system test in C0 during Phase III, along with a prototype scintillating fiber detector.

A separate but parallel effort is needed to pursue the techniques for producing the very large number of straws that any major system will contain.

- Design overall layout for the C0 test.
- Reconstruct K_S's in the straw-tube tracker.
- Devise tools and techniques for stringing the sense wires.
- Devise superlayer-alignment techniques.
- Design pressure-testing and voltage-testing devices and procedures.
- Design the assembly-line techniques in preparation for mass-production personnel.
- Design the overall electronics mounting scheme for the full system including the cooling.

3.2.6 Tracking: Costs - Phase III

- Electronics: equipment/operating
  - Test equipment such as digital scopes, and logic analysers $50k
- Electronics: salaries
  - 1 FTE electrical engineer @ $45k $45k
- Mechanical: equipment/operating
  - Prototype fixtures for large-scale production........................... $100k
  - Mounting of prototype straw-tube system in C0 .... $20k
- Mechanical: salaries
  - 1 FTE mechanical engineer @ $45k $45k
  - 3 FTE technicians @ $25k... $75k
- Fibers: equipment/operating
  - Prototype detector for the C0 test.. $50k
- Fibers: salaries
  - 1 FTE technician $25k

3.3 Data-Acquisition System

3.3.1 Data Acquisition: Tasks - Phase I

- Specify in detail the overall architecture of the DAQ system including the interface between front-end electronics and the DAQ system.
- Build the following nine modules to test this architecture:
  - 2 transmitter boards
  - 2 receiver boards
  - 2 barrel-switch boards
  - 1 optical link
  - 2 boards with 4 numeric processors each

3.3.2 Data Acquisition: Costs - Phase I

- Development: equipment/operating
  - 9 prototype boards at roughly $6k each $54k
  - Terminals and workstations $50k
- Development: salaries
  - 1.5 FTE electrical engineers @ $45k $68k
  - 1 FTE programmer $45k

3.3.3 Data Acquisition: Tasks - Phase II

- Bring up system in test-beam area and connect to online system.
- Readout the silicon vertex detector through to the processors.
- Readout the straw-tube system.
- Develop the necessary performance and debugging tools for the system.

3.3.4 Data Acquisition: Costs - Phase II

- Development: equipment/operating
  - Simple clock system for readout in test beam $10k
  - Alarms, crates, racks, power supplies $100k
  - Host computer system for numeric processors $30k
  - Terminals and workstations $50k

- Development: salaries
  - 1 FTE electrical engineer $45k
  - 1 FTE electrical technician $25k
  - 1 FTE programmer $45k
- Prototypes: equipment/operating
  - Board production $300k
- Prototypes: salaries
  - 3 FTE electrical engineer @ $45k $135k
  - 3 FTE electrical technician @ $25k $75k
  - 1 FTE programmer $45k

3.3.5 Data Acquisition: Tasks - Phase III

- Build up processor farm. Add racks and power supplies.
- Install hardware-protection system.
- Install network between racks and crates of processors.
- Develop downloading procedures for a large farm.

3.3.6 Data Acquisition: Costs - Phase III

- Development: equipment/operating
  - Terminals and workstations $100k
- Prototypes: equipment/operating
  - 25 numeric processors $400k
  - Racks, alarms $50k
  - Exabyte tape drives (18) $66k
- Prototypes: salaries
  - 3 FTE electrical engineers @ $45k $135k
  - 3 FTE technicians @ $25k $75k
  - 1 FTE programmer $45k

4 Cost Summary

	FY89 Phase I (Bench Tests)		FY90 Phase II (Beam Tests)		FY91 Phase III (C0 System Test)	
	Equipment/ Operating	Salaries	Equipment/ Operating	Salaries	Equipment/ Operating	Salaries
	Silicon Vertex Detector (FNAL)					
Electronics	$100k	$81k	$10k	$93k	$100k	$95k
Mechanical	35k	22k	43k	40k	100k	40k
	135k	103k	53k	133k	200k	135k
	Tracking System (Universities)					
Electronics	55k	68k	153k	90k	50k	45k
Mechanical	70k	120k	60k	95k	120k	120k
Fibers	50k	25k	50k	25k	50k	25k
	175k	213k	263k	210k	220k	190k
	Data-Acquisition System (FNAL)					
Development	104k	113k	190k	115k	100k	
Prototypes			300k	255k	516k	255k
	104k	113k	490k	370k	616k	255k
Total	**414k**	**429k**	**806k**	**713k**	**1036k**	**580k**

Table 2: Summary of costs of the proposed 3-year R&D program. Benefits, overhead, contingency, and escalation are not included.

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