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Proposal for Generic Detector Development in FY 1990

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Abstract

We propose to continue our program of generic detector R&D in the two areas approved in 1988, and to add a new project:

1. Studies of silicon detector performance using the infrared-laser test facility now under construction. New funds are requested for test detectors and readout electronics:
   A. Silicon Strip detectors and VLSI electronics $5k
   B. Silicon drift detector and 8 channels of discrete electronics........ $20k
   C. CCD Detector and Readout $10k
   D. General-purpose electronic test equipment $10k

2. Large-scale simulations of a B-physics detector. This work requires considerable cpu power, and in 1990 we propose to increase our capacity to approximately 50 MIPS via a RISC processor........................ $25k

3. Development of a straw-tube tracking system for an SSC detector. This work has been approved as part of an R&D project at Fermilab (E784) which provides the opportunity for beam tests, but no direct funding. To begin a substantial effort in 1990, we seek $110k for parts, supplies and labor, plus $95k for improvements to our shop facilities $205k

   Total budget for this proposal.. $275k

This project will occupy 100% of the research time of L.C., 75% of the time of K.T.M., and 25% the time of M.V.P. We will make some use of the technical support available through our regular high-energy physics contract, DOE-AC02-76ER-03072.

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1. Introduction

We propose to continue and expand our involvement in detector development for the SSC. In this we are guided by our interest in building a B-physics experiment which might operate intially at the Fermilab Tevatron but which would reap its greatest physics harvest at the SSC.

The critical technique in a B-physics experiment at a hadron collider is secondary vertex detection which can isolate the decay products of the B mesons from the rest of the event. Accordingly our intial R&D proposal concerned itself with hardware and software aspects of this technique. While the $65k approved for this last year by the SSC has not arrived at Princeton yet, we have spent about half of it via loans from the Princeton Physics Department. Some initial results are available, but the main work remains to be done. To continue this work in 1990 we seek $70k: $45k for the silicon detector studies, and $25k for expansion of our computing capabilities.

Since the writing of our 1988 Generic R&D proposal, we have been involved in the preparation of two documents: "Letter of Intent for a Bottom Collider Detector at the Fermilab Tevatron,"[1] and "Proposal for R&D: Vertexing, Tracking and Data Acquisition for the Bottom Collider Detector."[2] These documents signal our interest in going from the generic to the a specific physics context, but also indicate the need for considerable work at the prototype stage.

In reviewing the resources in the community that might be dedicated towards a B-physics experiment, it became appropriate that we at Princeton take on a major commitment to the hardware of the tracking system. It is expected that this commitment will grow into a major project, and we seek $205k funding in 1990 to launch this effort.

The $205k for the tracking project includes $95k for improvements to our shop facilities. Such improvements are vital if the shop is to have continuing competitiveness in the coming years. In submitting the request for these funds here, we hope that the SSC Division can invest in long-term support of laboratory facilites as well as items produced or consumed on a one-year basis.

2. Silicon Detector Studies

A. Laser Test Facility

We are now constructing a test facility that uses an infrared laser beam to simulate the creation of electron-hole pairs in silicon by the passage of a charged particle. This is possible because the band gap in silicon is 1.1 eV, so that photons of slightly lower energy have a long attenuation length and are absorbed almost uniformly across the thickness of a silicon wafer. The laser-pulse intensity can be adjusted to yield an absorption of 80 photons per micron, mimicking the ionization yield of a charged particle.

We have purchased (from RCA Quebec) an infrared diode laser operating at the slightly nonstandard wavelength of 1090 nm. The power supply (from Avtec) is capable of a 1/2 ns pulse, so that the drift of the liberated electrons (10 μm/ns) does not spread the effective size of the ionization region beyond 5 μm (plus the size of the laser spot).

Associated with the laser will be a microscope for precision alignment and viewing of the laser focus. A set of x-y-z and rotation stages will permit testing of detectors in various orientations and offsets. A PC-clone computer will control the test facility. The facility will be portable, and is expected to be used at BNL, Fermilab, and other universities as the opportunity arises.

The test facility can be used with any silicon detector whose surface is transparent to infrared light. Tests that we will conduct include:

- Evaluation of signal-to-noise for minimum-ionizing particles.
- Study of x-y dependence of spatial resolution.
- Study of spatial resolution as a function of angle of incidence of the particles.
- Study of detector performance in magnetic fields.
- Study of double-pulse resolution in both space and time.

The present proposal seeks funding for several silicon detectors and associated electronics that will be tested with the laser facility.

B. Silicon Strip Detectors

In thinking about detectors for B-physics in the mid 1990's,[2,3] we conclude that silicon drift detectors offer a good compromise of signal quality and maturity of technology. Nonetheless, the use of these detectors for full 3-dimensional vertex reconstruction at a hadron collider is a considerable challenge. No silicon vertex detector has yet operated at any collider (although several are scheduled for use soon).

Particularly interesting configurations are the double-sided, a.c. coupled detectors now available from Messerschmitt-Bölkow-Blohm GmBH, Munich, and Center for Industrial Research, Oslo. These offer both x and y measurements in a single 200-micron-thick detector, with some correlation of hits on the two detector faces via pulse-height matching. The a.c. coupling renders the detectors less vulnerable to leakage currents due to radiation damage.

VLSI readout chips for such detectors are becoming available, to met the needs of CDF, and of LEP. In particular, the CAMEX64 chip can now be purchased from ELMOS, Dortmund, and the MX3-128 chip from Rutherford Lab. Although the specifications of a chip for the Bottom Collider Detector[3] call for a new generation in chip development, it is desirable to gain operational familiarity with the present generation.

Considerable effort to this end is being made by G. Kalbfleish of U. Oklahoma, and by P. Karchin of Yale as part of the R&D for the Bottom Collider Detector. We will interact with these groups in use of the laser test facility, and build on their experience in use of the silicon detectors. Here we propose to spend $5k in 1990 for hardware support of these tests:

- Strip detector from MBB GmBH, Munich $1500
- Strip detector from Center for Industrial Research, Oslo $1300
- CAMEX64 readout chip from Elmos, Dortmun $60
- MX3-128 readout chip from Rutherford Lab $250
- Digital pattern generator for IBM PC computer .... $2000.

C. Silicon Drift Chambers

As a conceptual advance on the silicon strip detector, we are evaluating the use of silicon pixel detectors. These provide unambiguous x-y-z space points along a particle's trajectory, at the expense of a massive readout task.

An interesting approach to pixel technology is the silicon drift chamber of E. Gatti and P. Rehak.[4−7] In this, the detector is laid out with stripes held at graded potentials, creating a drift of ionization electrons towards one edge of the detector. An array of anode pixels along this edge collects the charge; time-of-flight measurements yield the orthogonal coordinate.

A very limited number of these detectors are available at present, along with a shortage of manpower to test them. From discussions with Rehak, it appears a more practical use of personnel if we obtain a detector and build the associated readout than transporting our base of operations to BNL for an extended period of time. For this we seek \$20 in 1990 to instrument 8 channels of a silicon drift detector via discrete electronics:

– Procurement of detectors from Kemmer in Munich \$5k
– 8 channels of hybrid preamplifiers (RAL Co.) \$1k
– 1 data buffer (BNL design) \$1k
– 8 channels of shaping amplifiers (BNL design) \$1k
– 8 channels of zero-crossing discriminators (BNL design) \$1k
– 8 channels of peak sensing ADC (LeCroy 2259) \$3k
– 8 channnels of TDC, 1 μs in 1 ns steps (LeCroy 2228A) \$2.5k
– NIM crate \$1.5k
– CAMAC crate \$2k
– IBM PC-CAMAC interface and single crate controller (DSP) \$2k

D. CCD Detector and Readout

Silicon pixel detectors are available commericially in the form of CCD sensors used in home-video cameras. As a spin off from this market there are some devices of scientific interest. In particular, a new camera, Model MC-1134GN, is about to be released by Texas Instruments with impressive specifications: 30-electron-noise readout in 1/30 sec at room temperature. The sensor is the TC217, which has 1134 $\times$486 pixels each $7.8 \times 13.6\ \mu\mathrm{m}^2$ in area, with 30,000 electrons full-well. A minimum-ionizing particle will deposit about 1000 electrons in this device; it is clearly useful as a charged-particle detector. While the readout rate is too slow for use at the SSC interaction rate, this device is of the same quality (on paper) as those being prepared for the SLD detector without the drawback of operation at liquid-nitrogen temperature.

We propose to test one of the TI cameras (\$6k), using for the readout a flash-adc framegrabber such as the 12-bit Imaging Technology VS-100-AT (\$4k).

E. General-Purpose Electronic Test Equipment

In support of the specific development efforts we need to augment our meager supply of general-purpose test equipment. With \$10k we would purchase a nansecond pulser, 300-MHz oscilloscope, PC-GPIBbus interface plus compatible DMM, and Electrometer. Without some flexibility in diagnostic equipment, the test program will surmount the inevitable obstacles only with great difficulty.

3. Simulations of a B-Physics Experiment

A. Progress and Projections

A sizable program of computer simulation of future detectors is needed in parallel with hardware development efforts. In the past year we have begun detailed simulations of vertex pattern recognition with silicon detectors. In the next months these studies will be expanded to include pattern recognition in the tracking system.

The first phase of computer studies was reported by L. Roberts of Fermilab.[8] He and P. Karchin of Yale examined the efficiency of various silicon vertex detector configurations for identifying the B-decay vertex, assuming perfect pattern recognition. The issue here was geometric coverage, and the fraction of B's that decayed with a vertex distinguishable from the primary vertex. An encouraging result that about 45% of B decays to all-charged final states would be reconstructible in principle.

The studies we have conducted in recent months add some experimental realism in the form of multiple scattering and finite detector resolution. These studies do not yet address the important question of pattern recongnition in tracking, *i.e.*, whether hits can be properly attached to tracks. Rather, we addressed the question of whether tracks can be properly associated with the vertices from which they emanate.

The events were generated using ISAJET, and the silicon vertex detector containing some 10^6 channels was simulated using GEANT. The primary vertex had to be found first, and the pool of tracks failing to be associated with the primary were searched for secondary-vertex candidates. How often do false secondary vertices simulate a rare B decay?

We studied the decay $B \to \pi^+\pi^-$ because it is the most difficult in terms of combinatoric background, and because it is potentially interesting for having a large CP-violating decay asymmetry.

The technique of vertex pattern recognition involves forming a χ^2 measure of tracks to a vertex hypothesis; minimizing the χ^2 to find the vertex, and then throwing out tracks with excessive contributions to the χ^2. Two vertex algorithms were tried: one in which both the vertex and track slopes are fit simulataneously, and another in which tracks were fit separately first, and their track parameters and error matrices used in a constrained fit to a single vertex hypothesis. The latter method offers the prospect of generalization to complex detector toplogies with well-defined error propagation, at the expense of some abstractness of approach.

A number of conclusions have emerged from our preliminary investigations;

- The vertex algorithms operated somewhat erratically if the silicon detector resolution was greater than 10 μm (for the assumed detector geometry with

the inner detector layer 1.5 cm from the beams). For detector resolutions of 10 μm or better, the two algorithms were largely equivalent.
- The vertex resolution had a most probable value of 25 μm in space, with a mean of 40 μm; a tail of poor resolution deserves further study. With a 4π detector geometry, the vertex resolution in z (the beam direction) was only slightly different from that in x or y.
- Only tracks with transverse momentum greater than about 500 MeV/c will be useful in vertex finding (as known from fixed-target experiments).
- Secondary vertices more than 100 μm distant from the primary will be reconstructed with good efficiency.
- A useful cut is the requirement that the momentum vector of the secondary vertex point back to the primary vertex.
- The greatest source of fake B decays is events containing B's that are misanalyed; a track from is B decay is mistakenly grouped with a track poorly fit to the primary vertex, yielding a high apparent mass for the fake secondary vertex.
- In the present study, about 1 B decay in 10^5 yields a false $\pi^+\pi^-$ secondary vertex with mass within a 100 MeV window about the B mass. The latter is a $\pm 2\sigma$ cut based on the estimated momentum resolution of the tracking system.
- The efficiency for finding $B \to \pi^+\pi^-$ decays with the present vertex algorithms is about 20%.
- Without explicitly simulating other decay modes, we infer that they will all have better signal-to-noise, due to assumed use of particle indentification, or to the reduced probability of falsely associating more than two tracks to a secondary vertex.
- Simulation of events with two primary vertices (distributed in space according to the expected size of the collision region) shows that if the tracking pattern recognition remains of high quality, the vertex algorithms will continue to separate the vertices to the above accuracy.

Such studies must be expanded to include simulation of more details of detector performance. The next obvious step is to incorporate the tracking pattern recognition.

It is readily anticipated that overlapping hits will result in skewed track fits that in turn lead to poor fits to the proper vertex. Clearly the tracking system must operate at lower channel occupancy than typical in existing detectors if the B vertices are to remain isolated in the hadron collider environment. It remains to be verified that a tracking system of 250,000 channels is adequate to the task.

B. Hardware Needs

The simulations of the vertex detector alone have consumed about 75 hours of cpu time on the Fermilab Amdahl, a value typical of the analysis of a contemporary experiment. We project that eventually a Bottom Collider Experiment will require processing power about 1000 times the total now existing at Fermilab, but that this will be typical of an SSC experiment.

Funds from the SSC Division have already been spent at Princeton to purchase a VAXstation 3100 workstation. This is proving to be quite effective; it has 1/8 the speed of the Amdahl, but we have it 100% of the time compared to 25% at best on the Amdahl.

In simulations of the tracking system (see section 4 of this proposal), we will now have an average of 64 hits per track, compared to 5 in the vertex detector alone. A full simulation would likely require $(64/5)^2 \sim 150$ times as much cpu power, nearly beyond the reach of any existing facility. However, we will organize the simulation to take advantage of the 'superlayer' concept in the straw-tube system, so the cpu load over the next year will be only about 10 times greater than the present.

As a first step in meeting this need, we are spending FY 1989 SSC funds on a DECstation 3100 workstation with the MIPS R2000 processor. This may yield a fourfold improvement in throughput over the VAXstation 3100, at the expense of converting to the UNIX enviroment. We judge this conversion to be inevitable, and welcome the opportunity to explore it now.

In FY 1990 we seek another fourfold expansion in our local cpu power, to some 50 MIPS. We anticipate this will be possible in the next year in a single workstation, based perhaps on the Intel 860i, or the MIPS R6000. It will certainly be possible to obtain this in a 3-workstation cluster.

We feel it is vital to keep pace with the rapid development of commericial computer technology, and are driven by the expanding needs of our detector simulation program. We seek $25k for computer systems in FY 1990.

4. Development of a Straw-Tube Tracking System

A. 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. 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 Tevatron or 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 dipole magnet.[2]

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** 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 $B \rightarrow eX$.
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.

A collaboration is being formed[2] to undertake this experiment. Our initial goal[3] is R&D on items 1, 2 and 6, which are the key ingredients of a phase-1 version of the experiment. Princeton is taking the major responsibility for the hardware of the straw-tube tracking system.

B. Straw-Tube Chambers

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 as well as cost in resolution due to the multiple scattering in the silicon.

Thus we 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[9] has been influential in thinking about large tracking systems for colliders.

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 H. Kagan of O.S.U.). By operating the straw tube as a drift chamber with dimethyl-ether gas, resolutions of 50 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, 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.

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.

C. Phased Prototype Studies

Our development of a straw-tube stracking system for a hadron collider experiment is part of an R&D project approved at Fermilab for use of a fixed-target test beam in 1990, with a test in the C0 intersect in 1991 pending approval.

In 1990 we should produce a prototype of some 1000 tubes for the test in a fixed-target beam at Fermilab, and in 1991 we should have produced some 10,000 tubes for a system test at the C0 intersect at the Fermilab Tevatron. The full chamber system for the Bottom Collider Detector will consist of about 250,000 tubes. As no existing straw-tube detector exceeds 1000 tubes, this will be a sizable project.

Some of the major tasks in constructing the straw-tube chambers are:

1. Economical and reliable production of the tubes, which are 3 mm in diameter, with 1 mil walls, and which must hold 4 atmospheres pressure.

2. Production of low-mass end plugs for the tubes, which include feedthroughs for the sense wire and the chamber gas.
3. The high-pressure gas-distribution system.
4. The low-mass end plates that provide mechanical alignment (but not structural rigidity) and distribution of electrical signals.

The readout electronics are being prepared at U. Penn in close collaboration with the mechanical work at Princeton.

Work to date at Princeton on this project has been primarily concerned with the manufacture of the straw tubes. The main present source of tubes, Precision Paper Tube of Wheeling, Il, now charges rather high prices: at least $10 per tube in large quantities. We are evaluating two new vendors: Electrolock of Chagrin Falls, OH, and Stone Industrial (the inventor of the sprial-wound straw) of College Park, MD. In addition, we have contacted a manufacturer of straw winding machines, Rockport of Cleveland, OH; the basic machine is an elegant application of 19th century technology, and costs about $10k. Some skill is required in the winding of multilayer small-diameter tubes!

We have found the work of Kagan *et al.* of O.S.U. quite useful in pointing the way for future straw-tube development, and we have obtained a 7-tube 'kit' from them for initial bench tests. The next chamber will be of our own design, and will be built over the summer of 1989.

Funding needs in FY 1990 for the straw-tube development include

1. Parts and supplies for tube construction $25k
2. 1/2 year of a mechanical technician $25k
3. Parts and supplies for the gas-distribution system $10k
4. Parts and supplies for chamber end plates, frames and mounting $10k
5. Parts and supplies for tube endplugs $10k
6. 1/2 year of an electrical technician $30k
7. Class-100 clean room for chamber assembly $60k
8. AutoCad system for mechanical design $10k
9. Toolroom lathe for parts fabrication $25k

Total **$205k**

Items 7-9 are of long-range utility, but needed now to insure a strong capability for work on the very large straw-tube system in the following years.

The inclusion of labor costs in the above list indicates the need for technical support beyond that provided in our present DOE contract base. Labor at the level indicated can be obtained through hourly wages paid to Departmental Shops.

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