DOE/ER/3072-46
August 31, 1989

Proposal for Generic Detector Development

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Abstract

We propose to initiate a program of generic detector R&D in two areas:

- Studies of silicon drift chambers as a near-term implementation of a pixel vertex detector (in collaboration with P. Rehak of BNL);
  - At Princeton we would:
  - A. Construct a bench-top test facility based on a Nd:YAG laser which can simulate the deposition of energy by a charged particle throughout a layer of silicon;
  - B. Use A to study effects of angle of incidence on a silicon drift chamber, and of double pulses as a function of separation in space and time;
  - C. Use A to study the effects of magnetic fields on the detector (Princeton will provide a magnet with a 10-inch gap and 1 Tesla field for this);
  - D. Perform additional studies of the drift detectors in charged-particle beams (at Fermilab);
  - E. Test a scheme to resolve overlapping events at high rate, and participate in the design of a new high-rate readout.
  - BNL will provide the detectors and readout electronics.
- Large-scale simulations of a B-physics detector, and of the online data-processing architecture.

The funds requested for this work in 1989 are

- \$45k to construct a laser test facility for the silicon drift chambers;
- \$20k for a color DEC μVAX 3200 workstation with RD54 disk which would be dedicated to simulations of the B-physics experiment, and to circuit design for item E above.

This project will occupy half of the research time of K.T.M., and one-fourth the time of M.V.P. It offers an excellent opportunity for graduate students to become involved in the current technology of high-energy physics, and two students will join the project during 1989. We would 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

In reviewing the opportunities at the SSC we and many others have become quite excited about the prospects for B-meson physics. The cross section for B-$\bar{B}$ production is estimated at close to 1 mb, so about 10^{12} B-$\bar{B}$ pairs are produced per running 'year' of 10^7 seconds with average luminosity of 10^{32} cm^{-2}sec^{-1}. This large sample, and a signal-to-noise of 0.01 B-$\bar{B}$ pair per event, will make possible a detailed investigation of CP-violation effects in the B-$\bar{B}$ system.

A detector concept for B-$\bar{B}$ physics at the SSC has been evolving during the SSC workshops in recent years towards a design with a central dipole magnet augmented with forward spectrometers. The detector requirements contrast somewhat with those for both jet experiments at the SSC and B-$\bar{B}$ experiments at e^+e^- colliders:

- Tracking and particle identification for all charged particles with $-6 < \eta < 6$ (η is the pseudorapidity);
- No need for an hermetic hardon calorimeter;
- A microvertex detector, with inner planes < 1.5 cm from the beam and useful for tracks with up to 45° incidence to a detector plane;
- A trigger on electrons with transverse momenta as low as 1-1.5 GeV/c;
- Online data processing for a 10-MHz event rate with multiplicities of 100 potentially interesting tracks per event.

The challenge of such a detector is very great, and cannot readily be met with 1988 technology. It may even be that two generations of detector development are needed prior to the SSC era, so we are strongly interested in becoming involved in such efforts now. In this startup proposal we plan to focus on two issues:

- Studies of silicon drift chambers as a near-term implementation of a pixel vertex detector, in collaborative effort with P. Rehak of BNL;
- Large-scale simulations of detector performance, and of the online data-processing architecture, in collaboration with physicists from Fermilab and U. of Penn.

The funds requested for this work in 1989 are

- \$45k to construct a laser test facility for the silicon drift chambers;
- \$20k for a color DEC μVAX 3200 workstation with RD54 disk which would be dedicated to simulations of the B-physics experiment, and to circuit design for item E above.

We anticipate that this programs will be expanded in the following years based on our initial experience.

This work is in the context of ongoing studies by various members of the so-called Fermilab B Collider Study Group,[1] which include hardware studies of silicon microstrip chambers at U. of Oklahoma and Yale U., straw chambers at Ohio State U., data-acquisition modules at Fermilab and U. of Penn., and detector simulations at Fermilab, Ohio State U., and U. of Penn.

2. Silicon Drift Chambers

The silicon microvertex detector has caused a small revolution in hadron physics, making it possible to extract the relatively weak signal of heavy-flavor decays in hadron collisions. The signal-to-noise for B mesons at the SSC will be comparable to that for charmed mesons in photoproduction at Fermilab. Thus while we can be optimistic that the B-meson signal will be extracted at the SSC, it is clear that the performance of the microvertex detector is critical.

Present thinking by proponents of B-physics at the SSC has concentrated on a vertex detector using double-sided silicon strip detectors.[1] Laboratory studies of such devices with particular emphasis on their utility for B physics are being made by G. Kalbfleisch of the U. of Oklahoma, and P. Karchin of Yale U.

In the meanwhile significant advances have been made towards pixel vertex detectors by members of the detector-development community. As a pixel device provides an unambiguous space point along a particle track it is clearly superior to any strip device in a high-track-density environment. The pixel devices under development by D. Nygren, and by S. Shapiro implement the pixel as silicon pads, leading to very large numbers of readout elements in a micrcovertex detector.

The multianode silicon drift chamber of E. Gatti and P. Rehak[2−5] implements 'virtual pixels' by recording the history of ionization electrons drifting towards a relatively small number of anode pads. The number of readout elements is similar to that needed for a silicon strip detector of the same area, although a TDC (and ideally an ADC) is needed for each anode. An on-detector preamplifier exists for the silicon drift chamber.[6] We judge the silicon drift chamber to be the pixel device closest to useful application in a physics experiment, and wish to gain experience with it in a realistic physics environment.

While the silicon drift chamber was invented in the U.S.A., lack of support for it here has led to its development primarily in Italy and Germany.[4,5] Indeed, very few physicists in the U.S.A. besides Rehak are presently working on this device, and he strongly encourages a collaboration with the present authors.

The moment is propitious for an increased effort. A set of 4 cm × 4 cm detectors, the largest to date, is now available, but the people working to produce them are primarily concerned with their design and electronic performance. Beyond a beam test in Sept. 1988, little is planned towards detailed characterization of the silicon drift chambers as particle detectors. We propose to:

A. Construct a bench-top test facility based on a Nd:YAG laser which can simulate the deposition of energy by a charged particle throughout a layer of silicon;

B. Use A to study effects of angle of incidence on a silicon drift chamber, and of double pulses as a function of separation in space and time;

C. Use A to study the effects of magnetic fields on the detector;

D. Perform additional studies of the drift detectors in charged-particle beams;

E. Test a scheme to resolve overlapping events at high rate, and participate in the design of a new high-rate readout.

The funding request of \$45k is primarily to construct item A, with minor operating funds for items B-E.

This effort complements the proposal by Rehak[7] for Generic Detector R&D to develop the on-chip preamp, the sparse write-in system, and to perform radiation-damage tests for the silicon drift chambers.

A. Laser Test Facility for Silicon Detectors

The silicon drift detectors appear caplable of position resolution of 5-10 μm.[5] Very few facilities exist which can provide a charged-particle beam known to such precision, and consequently rather few beam tests have been made of the silicon drift detectors.

Optical light can be focused on a silicon detector yielding a well defined spot, but all the photo-ionization occurs very near the surface and does not simulate 3-dimensional effects of the ionization by a charge particle.

However, silicon is almost transparent to infrared photons of energy only slightly above the 1.1-eV band gap. By a fortunate coincidence the photon energy of a Nd:YAG laser is 1.16 eV (wavelength = 1.064 μm), and the absorption length for such photons in silicon is 1 mm.[8] A Nd:YAG laser beam will then leave a line of essentially uniform ionization as it passes through a 300-μm-thick silicon detector.

A minimum-ionizing charged particle creates 80 electron-hole pairs per μm as it traverses silicon, while a photon from an Nd:YAG laser creates 10^{-3} pairs per μm. Hence a laser pulse of only 8×10^4 photons will simulate the average ionization of a charged track. It is important to note that the laser beam does not simulate the Landau fluctuations in ionization by a charged particle, and that these fluctuations limit some aspects of silicon-detector performance.

To be useful, the laser beam should have a small transverse dimension, and a short pulse length. The laws of diffraction limit a focused beam to have a transverse size (standard deviation, σ) which depends on longitudinal position z according to

$$\sigma^2 = \sigma_0^2 \left(1 + \frac{z^2}{z_0^2}\right),$$

where σ_0 is the transverse size at the focus, and $z_0 = 2\pi\sigma_0^2/\lambda$ is called the Rayleigh range, the distance over which the beam area grows by a factor of two. For example, if we choose $\sigma_0 = 5$ μm $\sim 5\lambda$, we have $z_0 \sim 150$ μm, which is well matched to a silicon detector. Hence the Nd:YAG laser should be capable of simulating a track thoughout the depth of a detector to 5-μm accuracy.

The electron drift velocity in a practical silicon drift chamber is about 10 μm per nsec. Hence the ionization created by, say, a 1-nsec laser pulse would form a sheet 10 μm long in the direction of the electric field lines (the drift direction). The centroid-finding readout electronics of a silicon drift chamber can locate the center of this sheet to a small fraction of its length. Hence even a several-nsec laser pulse would not degrade the postion accuracy beyond the nominal goal of 5 μm.

A laser pulse is readily split, yielding two pulses which may be offset in space and time by controlled amounts. Very detailed double-pulse studies can be made with the laser technique.

Commericial Nd:YAG lasers with nanosecond pulse lengths are priced from \$5k for a 'disposable' version good for only 300,000 shots, to \$30k for a 'workhorse.' We believe an adequate laser can be purchased for \$15k (but would welcome a recommendation to purchase a more robust and costlier version).

The laser pulse should be delivered to a test detector with 6 controllable coordinates: x, y, θ, ϕ, and double-pulse separations Δx and Δt. Each coordinate must be associated with a precision motion stage and motorized position controller. We need 'only' micron accuracy, so relatively modest components will suffice (by the standards of the laser community), for which the cost is about \$2.5k per coordinate.

In addition we need a lens, beam splitter, and two roof-top prism reflectors for the double-pulse preparation. These items and various machining costs to build an integrated facilty are estimated at an additional \$5k.

The facility is to be controlled by an IBM PC-clone computer. We estimate \$5k for an 80386-based machine, with printer and software packages.

The silicon detectors and associated readout electronics will be provided by Brookhaven Lab.

We estimate the operating costs for performing studies B-E with the test facility to be another \$5k. The total proposed budget for the silicon drift chamber studies is then \$45k.

B. Studies of Angle of Incidence, and of Double Pulses

We first recall the basic principle of the silicon drift chamber. A plane of silicon has a grid of field-shaping strips (oriented along the x axis) deposited on each surface (see Figure 1). When the strips are maintained at a sequence of voltages, a drift field is established parallel to the surface (along the y direction), driving the ionization electrons towards the anode. The latter is a row of pads on one surface, and at either end of that surface (in y) in present designs. In addition, the field strips set up fields perpendicular to the surface (along the z direction) which drive the electrons to the midplane (in z) of the silicon shortly after they are liberated. Because of the very small area of the anode pixels, their capacitance is low, and the noise signal is less than 100 electrons.

Note that the y component of the drift velocity is independent of the x component. Then if a charged particle is incident along the z axis it liberates a line of charge, which quickly coalesces into a point in the detector midplane (in the absence of diffusion and Coulomb repulsion). The time of arrival of a

Fig. 1. Illustration of the principle of operation of a silicon drift chamber.

point charge of 20,000 electrons can be measured extremely well; the silicon drift chamber is capable of very high resolution in principle.

Because of diffusion the ideal point charge is actually a cloud of radius (standard deviation) $\sigma = \sqrt{2Dt}$, where t is the drift time, and $D = 35$ cm^2/sec is the diffusion constant for silicon. For a drift time of 1 μsec, we then have $\sigma_x = \sigma_y \sim 84$ μm. With a typical drift velocity of 10 μm/nsec, the charge cloud arrives at the anode with a gaussian time profile with $\sigma_t = \sigma_y/10 = 8.4$ nsec. Good position resolution in x can be maintained if the anode pixels have length $\sim \sigma_x$, and the pulse centroid is found by charge sharing among the anodes. Similarly, good position resolution in y can be obtained using time bins of size $\sim \sigma_t$, if the charge in each bin is recorded.

i. Angle of Incidence

The interaction region in a collider experiment extends over many centimeters. Hence vertex detector elements located closer to the beam axis than this will observe tracks incident from a large range of angles. With a detector geometry which minimizes the number of elements, some silicon planes must contend with tracks of up to 45° incidence.

This is a challenge for silicon strip detectors if, as is typical, the strip width is less than the detector thickness. For example, in a strip that is 300-μm thick and 50-μm wide, a track of 45° deposits only 1/4 the charge of a normally incident track. Thus a silicon strip detector for a collider experiment must operate down to much lower signal levels than in a fixed-target experiment (where normal incidence is the rule).

The silicon drift chamber has a somewhat different response to a tilted track. The confining fields (along the z direction) project the tilted line of ionization electrons onto a line in the z miplane of the detector. This line charge then drifts to the anode and its centroid is determined. When the angle of incidence is 45°, the length of the projected line charge is just the thickness of the silicon, 300 μm in present detectors. The centroid-finding electronics can locate the center of the line charge to an accuracy similar to that for the case of normal incidence. The charge density in the pulse as it nears the anode is less for tilted tracks than for normal ones, but as mentioned above, there is no problem detecting the smaller signals given the low capacitance of the anode pads.

The preceding argument will be tested with the proposed laser test facility, which includes rotary stages to orient the test detector at arbitrary angles.

Landau fluctuations degrade the position resolution for tilted tracks in any silicon detector, and in a manner which will not be explored with the laser test facility. Tests in a charged-particle beam will be needed to complete the studies of tilted tracks. The distribution of liberated electrons along a charged-particle track is nonuniform because of the Landau fluctuations, and any centroid-finding algorithm will make an error which is estimated to be $\Delta x \sim 0.2 L_{\rm proj}$, where $L_{\rm proj}$ is the length of the tilted track as projected onto the detector surface.[4,5] Clearly the best weapon against this loss of resolution is to use thin detectors.

ii. Double-Pulse Resolution

Because of the considerable diffusion of the electron cloud in a silicon drift detector, the minimum separation at which two tracks can be resolved is greater than the typical strip width of a silicon strip detector. However, as the silicon drift chamber is a pixel device, two tracks are confused only if their separation is small in both x and y. This is an important advantage of pixel devices over strip detectors for the SSC, where tracks densities will be high in the inner layer of the vertex detector.

The laser test facility will generate pairs of pulses of controlled separation in space (and time, if desired), which can be used to make a thorough study of double-pulse resolution. As this issue is governed by diffusion rather than by Landau fluctuations, the laser technique should give a complete simulation of closely spaced charged particles.

C. Detector Performance in a Magnetic Field

Most silicon detectors now in operation are located in a magnetic-field-free region. However in a collider configuration the vertex detector should operate in a magnetic field typically of 1 Tesla. The 4π geometry of the detector will require silicon planes at various orientations with respect to the magnetic field.

The laser test facility will be placed in a large magnet to study its effect on position resolution. Qualitative arguments allow us to anticipate the general nature of the results for fields oriented along the axes of the detector:

B_x: In a silicon drift chamber the principal drift direction is along the y axis, but initially there is a drift along the z axis as well, until the charge reaches the midplane in z. The v_y drift couples with B_x to give a force in z. This is compensated by the confining field along z once the electrons have moved out of the detector midplane. That is, the y drift now occurs at some z other than the midplane, which has no effect on detector performance. But the v_z of the electrons shortly after their liberation couples with B_x to tilt the line of charge in the y-z plane. Even for normal incidence the charge coalesces to a line rather than a point, as if the charged track actually had a tilt. A short argument leads to the result that the effective angle of the tilt is μB where μ is the electron mobility in silicon, whose numerical value is conveniently stated as $\mu = 0.133/\mathrm{Tesla}$.

B_y: In this case the principal drift v_y does not couple to the magnetic field. But the initial drift v_z couples to give an effective tilt to the track in the x-z plane, with magnitude as estimated above.

B_z: In this case the v_z does not couple. However, the principal drift v_y couples to B_z to give a tilt to the drift path in the x-y plane. Again the drift angle varies as μB_z. The charge cloud arrives at the anode pixels displaced in x by an amount proportional to the drift distance in y. This should be correctable with little loss in resolution, but deserves to be tested.

Landau fluctuations aggravate the slight loss of resolution in the case of B_x or B_y of order 1 Tesla. Again, this effect cannot be studied with the laser test facility.

For the magnetic-field tests, a 1-Tesla magnet of gap approximately 10 inches is needed. Princeton has an idle cyclotron magnet meeting these specifications that can used for this.

D. Tests in a Charged-Particle Beam

The laser test technique should be calibrated by direct tests in a charge-particle beam. This is most critical for tracks of large angle of incidence, where Landau fluctuations contribute an important uncertainty to the position measurement. Once the laser test facility is constructed, we would have the opportunity to place it (minus the laser) in the beam of Fermilab E-791 (for which M.V.P. is the spokesman) during the fixed-target run of 1989-90.

E. Design and Tests of a High-Rate Readout

If the time between primary interactions in an experiment is less than the drift time of the silicon drift chamber one has the problem of overlapping events. A solution exists in principle: mount the detectors in pairs, with opposite drift directions, as is often done to resolve the left-right ambiguity in gas drift chambers. Then $t_1 + t_2$ is a constant for all tracks associated with a given interaction time.

Tests of this scheme will be made at the laser test facility using two existing detectors. [Such tests are very difficult using low-energy x-ray or particle sources.]

The challenge is to design a readout that incorporates this trick at the trigger level, and that operates at the high event rates which require the trick in the first place. We plan to initiate a design effort for the readout electronics, which requires a color-graphics workstation in order to run a multilayer circuit code such as KIC. Therefore the VAX workstation for the studies of part 3 of this proposal should be a color version, adding $5k to the cost.

3. Simulation of a *B*-Physics Experiment at the SSC

Although a B-physics experiment at the SSC will be modest in cost (perhaps \$50-100 million) compared to a large jet detector, this is still a sizable investment. Any SSC experiment deserves detailed simulation prior to its approval. But the Catch-22 is that funding for simulations comes only after the experiment is approved.

Here we ask for early support of the massive task of computer simulation of an SSC experiment in the form of a workstation that would be dedicated to that purpose at Princeton.

One of us (K.T.M., in collaboration with N. Lockyer of U. of Penn.) has made small-scale use of ISAJET in the last year to study a possible electron trigger for a B-collider experiment.[1] Other computer-aided studies of this experiment are in progress, most notably a somewhat-idealized simulation of the vertex detector by Lee Roberts,[9] and by Paul LeBrun. However, it is clear the significantly greater effort must be made before sufficient results will become available to convince a skeptical program committee of the merits of the experiment.

A large-scale simulation must include realistic a detector configuration, and most importantly, a realistic simulation of the limitations of detector elements. The typical vehicle for this stage of the simulation in the very time-consuming program GEANT. The mere generation of a sizable sample of simulated events will saturate a μVAX III workstation for many weeks. Greater physicist time is then required to write reconstruction alogrithms that are a substantial fraction of a final-event-analysis program.

This effort must be made soon, and deserves significant support as a critical aspect of detector development in the 1990's.

Another vital concern is to provide a simulation of the trigger scheme and online data processing. It is anticipated that the next generation of online trigger processors will have the power of 10,000 VAX's. It is mandatory that a few VAX's be dedicated to the advance study of such online processors.

We will work in the next year in collaboration with the Barsotti electronics group at Fermilab, and with N. Lockyer, to develop prototype trigger-processing alogrithms. Here the electronic engineers provide a realistic statement of future processing power, but the physicists must explore ways to utilize that power. Again, a dedicated VAXstation would be very timely for this effort.

Finally, as noted in section E of part 2 above, a color workstation is needed for the circuit design of the high-rate readout of the silicon drift chambers.

We propose to meet all these needs with a VAXstation 3200, with 8-plane color graphics, and a 159-Mbyte RD54 disk drive. The VAXstation consortium price for this item is \$20,195. It would be hosted by an existing VAX 3600 server belonging to the Princeton high-energy physics group.

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