I. Introduction

In considering the design of experiments for high energy colliding beam facilities one quickly sees the need for better detectors. The full exploitation of machines like ISABELLE will call for detector capabilities beyond what can be expected from refinements of the conventional approaches to particle detection in high energy physics experiments. Over the past year or so there has been a general realization that semiconductor device technology offers the possibility of position sensing detectors having resolution elements with dimensions of the order of 10 microns or smaller, with a detector could offer enormous advantages in the design of experiments, and the purpose of this paper is to discuss some of the possibilities and some of the problems.

To give a specific context to the discussion, I choose to focus on applications for ISABELLE experiments, where the requirements are particularly severe and there is a clear need for a qualitative improvement in detector capability. Experiments at ISABELLE are planned to begin in about 5 years.

II. Experimental Environment: The Need for Improved Detectors

In Figure 1 is sketched, in a schematic way, the elements of a general purpose detector facility which might be appropriate for many of the experimental programs contemplated for ISABELLE. A cylindrical geometry is shown, with the two beams of 400 GeV/c protons entering from opposite ends, each at a small angle to the cylinder axis, and crossing at the center. The crossing region, owing to the finite beam size and small crossing angle, extends several tens of centimeters along the axis and is the source from which the secondary products of proton-proton collisions emerge into the detector array: about fifty relativistic particles (both charged and neutral) for a typical inelastic collision, and possibly several times that number for the truly interesting events. The reaction products are not isotropic in their angular distribution but, on the average, exhibit a flat spectrum in the rapidity variable, as shown in the figure. Most particles emerge from the collision with very small angles relative to the incident beams.

This is the average behavior. The main physics interest lies with rare processes involving direct collisions of fundamental constituents of the incident protons, the signature for which is a large fraction of the incident energy being carried off at angles near 90° (i.e. into the so-called "central" region of small rapidity). Figure 2 shows an example from Monte Carlo simulation of one class of such events. Trajectories of charged particles are shown in a uniform magnetic field filling a volume 5 meters in diameter.

The first major point to notice about the detector array sketched in Fig. 1 is that it covers the full 4π steradians of solid angle around the interaction region. Its job (ideally) is to select with good efficiency the events of interest and to measure each of the secondary particles which results from the collision. Furthermore, the phenomena which we wish to study require not only high energies, but also the highest possible interaction rates. The term "rare processes" used above implies probabilities of occurrence as small as 1 per 1012 interactions. This, in turn, implies detectors with an extraordinary tolerance for high background rates.

The interaction rate is given by the product \( \sigma L \) where \( \sigma \) is the cross section (in cm²) and \( L \), the luminosity, is determined by the size, intensity and crossing angle of the beams. The design luminosity for ISABELLE is \( 10^{32} \text{cm}^{-2} \text{sec}^{-1} \). At this luminosity the rate for inelastic proton-proton collisions is \( \approx 50 \text{ MHz} \) (the beams have 100% duty fraction), and the rate of particles into each of the rapidity intervals indicated in Fig. 1 is on the order of 100 MHz. As indicated in Fig. 1, the rate of charged particles into a square centimeter of detector area is \( 35 \text{ MHz} / \text{cm}^{-2} \) where \( r \) is the distance from the beam (the dependence on \( r \) rather than the radial distance \( R \) is a consequence of the flat rapidity spectrum).

With these points in mind we return to the conceptual detector array of Fig. 1. The central chamber, which is immersed in a magnetic field, is a drift tracking chamber to measure the trajectories and momenta of charged particles emerging at relatively large angles. It may be a large, high precision cylindrical array of gas proportional or drift wires. The central track detector is surrounded by segmented total absorption calorimeters whose purpose is to detect and measure neutral particles, and to provide a trigger based on the detailed angular distribution of the total energy flux in each event. The forward detectors cover the small piece of solid angle close to the beams into which most of the secondary particles go. These forward arms may extend to considerable distances away from the interaction region, and incorporate tracking chambers, calorimeters and additional magnetic deflection.

The overall dimensions of the detector facility are largely determined by the requirements (or acceptable limitations) of the central track detector, both in its momentum resolution and in its capability for efficient pattern recognition in the face of complex events and high rates. These capabilities improve as the size increases, but the cost increases as well—not only the cost of the track detector itself, but the cost of filling its volume with magnetic field, and surrounding it with the next layer of detectors (e.g. the calorimeters sketched in Fig. 1).

Assuming state-of-the-art performance for large drift chambers, the detector volume and magnetic field indicated in Fig. 2a would suffice for the momentum measurement of isolated tracks, but it is probably too large a diameter for practical consideration, and it is unlikely that a drift chamber structure can reliably extract useful measurements from the densely clustered tracks ("jets") which characterize this type of event. Attempting to shrink the detector by increasing the magnetic field strength has distinctly adverse effects on the pattern recognition capability, as seen in Fig. 2b.

III. Why Semiconductor Detectors?

It is not to be implied here that the advent of semiconductor detectors will solve all the problems...
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of large acceptance spectrometry for colliding beam facilities, but rather that the introduction of a new class of fine grain, high resolution detector can significantly influence the design of experiments by improving our options for the inevitable trade-offs.

The interest in semiconductor detectors follows from two features: improved space resolution (by an order of magnitude over the wire chambers) and the potential for extremely high densities of resolution elements. In light of the discussion above we may list some of the ways in which these features can be exploited.

Rate Capability

The density of individual detecting elements would be at least 10/cm² and could be 10²/cm² or greater, with recovery times < 100 nsec. Such an array could operate in the high fluxes close to the beams (forward detector arm, inner radius of central detector) without loss of efficiency.

Pattern Recognition

Very fine grain detectors are clearly needed to reliably sort out individual tracks in events like that shown in Fig. 2. Good track pair resolution in two coordinates on a detector surface is especially important in the forward detectors as well as for observing jet structure in the central detectors. The pattern recognition capability of a large cylindrical drift chamber (for example) would be greatly enhanced by a small inner cylinder of very high resolution and grain density as indicated in Fig 1. Such a detector, with position accuracy ~ 10 µm, would also provide precise vertex positions, a powerful level in event reconstruction and a means of identifying short lifetime decays of charged particles and heavy leptons which may signify the presence of massive particle states.

Improved Triggering

Event selection at the trigger level must be extremely efficient in order to take full advantage of the high luminosity. With present day large detector systems of the type under consideration here it is not uncommon to record thousands of words of information per event. At this rate it is not possible to record more than 50 or so events per second (nor is it desirable: the off-line processing may require seconds of cpu time per event in a large computer). Sophisticated triggers involving on-line pattern recognition and momentum selection will be vastly improved with better position accuracy and a higher degree of detection segmentation.

Improved Mass and Momentum Resolution

The existence of machines like ISABELLE is primarily motivated by the search for massive, narrow particle states which ultimately will call for detailed spectroscopic measurements at the highest attainable energies. The accuracy of momentum measurement in the central and forward detectors scales linearly with the space resolution and with the magnetic field integral. As the scale of increasing masses and momenta increases with increasing machine energies it is economically unfeasible to keep pace by increasing the field integral in large aperture detectors. Hence the need for a big gain in the space resolution.

Miniaturization of the Central Detector

As pointed out above the overall size of the detector facility is largely governed by the size of the central detector. If the latter can be significantly reduced by virtue of fine grain, high resolution detection elements then the possibility exists for large economic savings.

IV. Some Possible Device Structures

Several avenues may be pursued once it is accepted that efficient detection of minimum ionizing particles can be achieved in very thin layers of silicon. (The signal consists of ~ 80 electron-hole pairs per micron of detector thickness.) A detailed discussion of charge collection and signal processing, addressing this question, is given by Radeka. Figure 4, taken from Radeka's analysis, shows that the limit of thickness is in fact very small provided the amplifier (plus leads and connections) can be matched to the detector capacitance.

Recently, position sensitive surface barrier strip detectors have been built and tested for possible high energy physics applications. These devices (dubbed "microstrip" detectors by the CERN group in Ref. 4) have strip densities of a few per millimeter, with a separate readout for each strip. Measurements with these prototype detectors in charged particle beams have given satisfactory results, with no unpleasant surprises, and have stimulated a great deal of interest in their possible applications and potential for further development. A natural evolution is toward a higher density of strips to achieve measurement accuracies at the level of 10 microns, some sort of interpolation is called for to keep the readout manageable. A microstrip detector incorporating resistive charge division to achieve very high resolution with a modest density of output connections is sketched in Fig. 3. The parameters and the optimization of such a device are discussed in Ref. 3. Strip detectors, of course, offer high resolution in only one coordinate: a miniature analogue of the multiwire proportional chamber. The possibility of planar arrays with high resolution in two coordinates is suggested by the advanced state of commercial development of charge transfer devices (Fig. 6). Charge coupled devices (CCD) have been used as position sensing detectors in applications involving x-rays, and it has been demonstrated for each element (pixel) of the CCD acts as a tiny solid state detector. As presently available, however, these devices are not suitable for high energy charged particle detection. The signal deposited in the thin depletion layer is insufficient to overcome the output noise level (resulting mainly from circuitry on the chip) of a few hundred rms electrons. Ionization produced in the thick substrate, far exceeding the signal charge, eventually drifts back to the active depletion layer. The readout is unacceptably slow for high rate applications: with the standard readout organization and a clock speed of 1 MHz the time to read out a full CCD frame (typically 300 x 300 pixels) is measured in milliseconds. Of course, these objections arise mainly from the fact that commercial CCD's are not optimized as particle detectors, but as video imaging devices. Special purpose CCD's are being constructed with characteristics suitable for particle detection in high energy beams. Nonetheless, a substantial development effort would be required to adapt the technology of charge transfer devices to meet the requirements of particle detection described here.

Microstrip devices and specially developed charge transfer devices appear to be the most promising means for achieving practical detectors in the near future, the first because of its relative simplicity and second because the technique is highly developed for other purposes. It is natural to consider what ultimately might be achieved if the capabilities of large scale integrated circuit technology were fully exploited.
A conceptual device of this type, which I shall refer to as a Micro Detector Array, has been examined by J. Sandweiss and R. Baringer.\textsuperscript{8} The concept is illustrated in Fig. 7. It consists of an array of very small detection elements, as in a CCD, with each element individually addressed and much of the circuitry for readout and data compaction integrated on the chip. Such a device would require substantial new developments, and further work is necessary to establish fundamental technical limits.

For most colliding beam applications the development of a detector and its readout must address the problems of constructing arrays covering relatively large areas - problems of mechanical assembly, high densities of output connections, and limitations of power dissipation, to name a few. Ideally, one would like to focus the development effort on the fundamentals of detector construction and electronics and test the result in a fairly simple but rigorous experimental environment. From this point of view there are very attractive applications where these detectors could be used with immediate benefit at fixed target accelerators in experiments where it is not necessary to cover areas larger than a few cm\textsuperscript{2}. Accurate Vertex location for short-lifetime particle searches in nuclear emulsions is one such example, and at least one group is actively pursuing the development of microstrip devices for this purpose.\textsuperscript{9} Such applications will offer an early opportunity to carry the development beyond the laboratory scale and give physicists and potential commercial manufacturers a chance to assess the merits of longer term R&D work.

V. Limitations: Multiple Scattering and Radiation Damage

Consideration of any detector for very high precision momentum determination must take account of the effects of multiple scattering. We may examine the limits imposed for silicon detectors by considering the following geometry:

\begin{center}
\begin{tikzpicture}
\draw[thick] (0,0) -- (0,4); \draw[thick] (0,0) -- (4,0);
\end{tikzpicture}
\end{center}

A charged particle in a uniform magnetic field (B) traverses n detectors each of which measures a point on the trajectory with accuracy \( e \), and each of which has thickness \( t \). The total path length is \( L \). The fractional momentum error is then given (approximately by

\begin{equation}
\Delta p = \frac{90 \Delta p}{7n} \frac{\mu B L}{L}
\end{equation}

\begin{equation}
\Delta p = 0.116 \text{ F.m.s.}
\end{equation}

The units are GeV, Tesla, meters. The product \( n \) is the total thickness of silicon, \( L \) the path length (0.06 m), and scattering in material between the detector layers is neglected (if necessary, the detectors can operate in a vacuum). It will be seen that for any given configuration there is some momentum, \( P_0 \), below which the error is dominated by multiple scattering:

\begin{equation}
P_0 = \frac{0.0013 L n t}{c R}
\end{equation}

The implications of these formulas is not easily distilled to a simple statement. Let us, by way of illustration, consider the measurement of 50 GeV/c particles in a 2 Tesla magnetic field. To be more specific, we assume a solenoidal field with 10 tracks measured in a cylindrical central detector. The dashed curve in Fig. 8 shows the best performance that is likely to be achievable with a large drift chamber, as a function of the chamber radius. The curve is calculated for \( c = 150 \mu \text{m}, t = 100 \mu \text{m}, \) and requiring at least ten measurement layers. The purpose of this illustration is to show that multiple scattering in silicon does not a priori vitiate the potential for exploiting the high space resolution of a single element to obtain very good momentum resolution in a multi-layer array. In fact, it is interesting to note that the multiple scattering limit for the silicon detectors of this example lies below that of the gas detector (argon at 1 atmosphere). This, of course, assumes that the silicon detectors are operated in a vacuum.

A crucial element in the development of semiconductor detectors for high energy colliding beam experiments must be an improved understanding of the radiation hardness of these devices. Most studies of radiation effects in silicon detectors have been carried out for low-energy environments, and evaluations of detector lifetime have generally been made with criteria based on requirements for high resolution measurements of deposited energy. For position sensing detectors, tolerable degradation is determined by consideration of efficiency loss due to loss of signal charge, through trapping, and increased noise due to increased leakage current.

From the point of view of radiation damage, the application of most critical concern is for detectors which immediately surround the beam pipes in high luminosity colliding beam facilities. Here the particle fluxes from beam-beam collisions are highest (Fig. 3), as is the additional radiation from beam-gas collisions and beam losses during filling and tuning. Furthermore, the innermost detectors in a compactly nested assembly such as that envisioned in Fig. 1 are the least accessible for frequent removal - either for annealing (if possible) or replacement.

Experience to date in high energy particle beams, in particular that of Heinje and co-workers at CERN,\textsuperscript{10} indicates that integrated fluxes as high as \( 10^{14} \) per cm\textsuperscript{2} of fully relativistic hadrons can be tolerated. As we have seen, the flux of collision products (mainly high energy protons) in the ISABELLE design is of order \( 10^{12} \) per cm\textsuperscript{2} as the beam pipes. At this rate a flux of \( 10^{14} \) cm\textsuperscript{2} is reached after about one year of machine operation. Studies at CERN\textsuperscript{10} and at BNL\textsuperscript{11} indicate, however, that the limit of detector lifetime may be set not by the direct flux of collision products, but by few-MeV neutrons which result from subsequent collisions in shield walls, support structures, etc. A fluence of \( 10^{14} \) cm\textsuperscript{2} of neutrons with energies in the fast fission spectrum results in a marked increase in leakage current in a standard surface barrier detector. The expected flux of such neutrons in a given experimental environment is not easy to calculate; reliable information must come from in situ measurements of the radiation field (some are now in progress at the CERN ISR) and experience with real detectors at real experiments.

VI. Epitome

The application of semiconductor devices as fine grain position sensing detectors for high energy physics experiments is within the reach of presently available technology. Existing prototype devices have demonstrated the capability for efficient detection of minimum ionizing charged particles with
sub-millimeter resolution, and there are no fundamental barriers to achieving individual resolution elements with dimensions ~ 10 microns. Such detectors, fully developed, could offer important new possibilities for the design of high energy colliding beam experiments: e.g. precise momentum measurements over very short track lengths to reduce the size (and cost) of large aperture spectrometers; excellent track pair resolution for improved pattern recognition; very high rate capability by virtue of a very high density of individual detection elements.

Of the several types of devices which seem attractive for development as particle detectors, the most straightforward consists of a surface barrier detector subdivided into closely spaced strips. Detectors of this sort are currently being planned for use in experiments. Experience thus gained should provide a basis for assessing the physical and economic factors which will determine the feasibility of developing a new line of particle detectors which may fully exploit the capabilities of large scale integration technology.

References

3. V. Radeka and R.A. Bolo, "Position Sensing With Semiconductor Detectors," these proceedings.
Figure Captions

Fig. 1. Schematic of a general purpose detector facility. This is a cutaway view showing the elements of a cylindrically symmetric assembly. Unit intervals of the rapidity variable are indicated, with $y = 0$ at 90° to the axis of colliding beams. The particle production spectrum as a function of rapidity is shown above, for colliding beams of 400 GeV protons.

Fig. 2. Monte Carlo simulation of an event with hard scattering of quarks in the collision of 400 GeV/c protons, as seen in a detector volume 5 meters in diameter. The axis of the beams is perpendicular to the page. The trajectories of charged particles are shown for a uniform axial magnetic field of (a) 0.5 tesla, (b) 1.5 tesla.

Fig. 3. Particle fluxes for the design parameters of ISABELLE. $n$ is the rate of charged particles through 1 cm$^2$ of detector area.

Fig. 4. The minimum detector thickness as a function of the area of each detection element, for minimum ionizing particles. The result assumes the optimal noise for an amplifier matched to the detector capacitance, with the requirement that the signal charge be 5 times the rms noise (from ref. 3).

Fig. 5. A microstrip detector with interpolation by charge division. $N$ is the number of outputs; $a_x$ is the position resolution. Reasonable dimensions would be $l = 2$ cm, $w = 1$ cm, $d = 1$ mm, with $N = 20-40$ and $a_x = 10 \mu$m.

Fig. 6. Schematic of a typical CCD.

Fig. 7. Conceptual layout of a microdetector array.

Fig. 8. Momentum resolution limits as a function of measured path length (detector radius) for 50 GeV/c tracks in a uniform magnetic field of 2 tesla. The dashed curve (drift chamber) is calculated for the case in which position measurements are made at 1 cm intervals with 150 $\mu$m rms accuracy. The shaded curve gives the multiple scattering limit in Argon gas at 1 atmosphere. The solid curve gives the multiple scattering limit for an array of silicon detectors each 100 $\mu$m thick with 10 $\mu$m rms accuracy. For comparison the (approximate) energy resolution for total absorption calorimeters measuring hadronic and electromagnetic showers at 50 GeV/c is indicated. The point $\Delta m = 500$ MeV indicates the accuracy of momentum measurement required to determine the mass of an object decaying to two 50 GeV/c particles with an uncertainty consistent with theoretical estimates of the width (lifetime) of particle states expected in this mass range.
Fig. 1
Fig. 2b
PARTICLE FLUXES AT ISABELLE

\[ L = 10^{33} \text{ cm}^{-2} \text{sec}^{-1} + 50 \times 10^6 \text{ interactions/sec.} \]

1 mb = 1 MHz

\[ n = \frac{35 \times 10^6}{r^2} \text{ cm}^{-2} \text{ sec}^{-1} \]

Fig. 3
MINIMUM DETECTOR THICKNESS VS. DETECTOR AREA

MIN. THICKNESS ($\mu$m)

1000

100

10

1

10$^{-6}$ 10$^{-4}$ 10$^{-2}$ 1 Cm$^2$/ELEMENT

TYP. CCD  STRIP 10$\mu$m x 1cm

Fig. 4
Fig. 5
Fig. 6
"Many Pads"

"few" gate, address, program---lines

Fig. 7
MOMENTUM RESOLUTION

P = 50 GeV/c
B = 2 TESLA

Δp/p (%) vs DETECTOR RADIUS (METERS)

- HADRON CALORIM
- EM CALORIM

ΔM = 500 MeV

Fig. 8