TRACKING AT THE SSC/LHC

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We present the design of a tracking system for the SSC/LHC based on silicon microstrip technology with excellent momentum resolution and good multitrack resolution. The parameters of the tracking device are based on an analysis of the requirements of 1 TeV physics. The performance of the silicon tracker has been investigated in a Monte Carlo study. An ongoing R&D program to develop radiation-hard fast readout chips for the silicon microstrips is described.

1. Introduction

In the past [1,2] the discussion of detector capabilities at the next generation large hadron collider (SSC/LHC) has been biased towards calorimetry. In most physics studies, information from calorimeters has been used to define the topology of the event (number of jets, missing $E_t$, etc.) and to measure the energy of the electrons and the mass of jets. In contrast, tracking has been reduced to a minimal role as a backup for the calorimeter, to detect detached vertices and identify multiple interactions within one beam crossing. Only a modest momentum resolution was required. Inspired by the work of the Compact Detector Subgroup of the 1987 SSC Detector Workshop [3], we propose to extend the function of the tracking to include resolving tracks inside dense jets and measuring momenta of isolated high energy leptons with precision comparable to the calorimeter in order to momentum-analyze both electrons and muons with the same resolution.

2. Physics motivation for high precision tracking

One can measure the performance of general purpose SSC/LHC detectors on their ability to discover the Higgs boson, if its mass is in the 100 GeV to 1 TeV range, and to study its decays. Depending on its mass, the Higgs search will focus on different signatures and thus will require different detector capabilities. This is shown in table 1 [3], where as a function of Higgs mass

![Fig. 1. Charged multiplicity $n_{ch}$ in jets recoiling against W bosons in pp collisions (PYTHIA 4.8): (a) W+W events from a Higgs with 1 TeV mass, (b) W+QCD jets events with 1 TeV mass.](image)

![Fig. 2. Mass of jets recoiling against W bosons (solid histogram: W+W events from a Higgs with 1 TeV mass, dotted histogram: W+QCD jets events with 1 TeV mass, both normalized to one SSC year): (a) all events, (b) events with $n_{ch} < 40$.](image)
the detector requirements are shown. For the light Higgs decaying into $b\bar{b}$ one must have excellent vertex reconstruction to tag $b$ decays [4]. For the intermediate Higgs, which decays to $ZZ$ pairs leading to a 4-lepton final state, good pair mass resolution in both electrons and muons is necessary to increase the rate by a factor of four over the electron-only case [5]. At large Higgs masses, where in the $WW$ decay one of the $W$'s is detected in its hadronic decay, the ability to track efficiently charged particles of the underlying event allows one to discriminate between the signal ($WW$) and the major background ($W + QCD$ jet). To quantify this, we show in fig. 1 the charged event multiplicities $n_{ch}$ from PYTHIA 4.8 [6] for the two cases (only tracks with rapidity $|Y| < 2.5$ and transverse momentum $p_T > 0.5$ GeV in events containing a jet with the mass of the $W$ are counted). Fig. 1a is the charged multiplicity for $H \rightarrow (W \rightarrow l\nu) + (W \rightarrow jets)$ with a mean multiplicity of $\bar{n}_{ch} = 32$, and fig. 1b shows $n_{ch}$ for the background ($W \rightarrow l\nu$) + QCD jets with a mean of $\bar{n}_{ch} = 75$. A cut at $n_{ch} < 40$ retains 78% of the signal while rejecting 92% of the background. Fig. 2 shows the effect of this multiplicity cut on the mass distribution of the jets recoiling against the leptonically decaying $W$. Fig. 2a shows the signal around 84 GeV and the background before the cut (signal/background $= 1:7$), and fig. 2b shows the result of the multiplicity cut (signal/background $= 1:0.7$).

A precision tracking device which allows the determination of the charged multiplicity down to $p_T = 0.5$ GeV thus provides crucial information complementary to the calorimeter to suppress the background sufficiently. This is possible because the tracking device has potentially more sensitivity to the soft component of the event (tracking is possible down to 250 MeV) and has much better spatial resolving power.

Table 1

<table>
<thead>
<tr>
<th>$M_{P^0}$ (GeV/c$^2$)</th>
<th>Signature</th>
<th>Advantages of Compact Solenoid Detector</th>
<th>Detected Rates Per Year ($10^{35} \text{ cm}^{-2}$)</th>
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<tr>
<td>60</td>
<td>$H^0 \rightarrow \gamma\gamma$</td>
<td>Good $\pi^+/$ separation in microconverter</td>
<td>500</td>
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<tr>
<td>100</td>
<td>$H^0 \rightarrow e\nu$</td>
<td>Vertex detection ($b$ tag)</td>
<td>400</td>
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<tr>
<td>150</td>
<td>$H^0 \rightarrow b\bar{b}$</td>
<td>Good $\mu/e$ ID in Jets</td>
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</tr>
<tr>
<td></td>
<td>$H^0 \rightarrow ZZ'$</td>
<td>Good $Z$ mass reconstruction</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$2M_Z$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>300</td>
<td>$H^0 \rightarrow ZZ \rightarrow 4\ell^\pm$</td>
<td>Good $Z$ mass measurement in both $ee$ and $\mu\mu$ up 1 TeV</td>
<td>140 ($Z \rightarrow e$ only) 160 ($Z \rightarrow \mu, \nu$)</td>
</tr>
<tr>
<td></td>
<td>$WW \rightarrow \ell\nu\ell\nu$</td>
<td>Good $p_T$</td>
<td></td>
</tr>
<tr>
<td>500</td>
<td>$H^0 \rightarrow WW \rightarrow q\bar{q}$</td>
<td>Best jet capability: Calorimetry Precise, high resolution analysis of charged tracks and neutrals inside jets</td>
<td>29 ($Z \rightarrow e$ only) 116 ($Z \rightarrow \mu, \nu$)</td>
</tr>
<tr>
<td></td>
<td>$ZZ \rightarrow \ell^+\ell^-\ell^+\ell^-$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>700</td>
<td>$W^+W^-$</td>
<td>Precise lepton measurement in TeV range</td>
<td></td>
</tr>
</tbody>
</table>

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3. Design of a 1 TeV tracking system

The environment at the SSC/LHC will be a challenge to a tracking device. It can be characterized by large multiplicities, dense jets, stiff tracks and a high collision rate. Jets with an energy of 1 TeV will have a charged multiplicity of \( n_{ch} = 50 - 100 \) and a mean angular track separation in the core of \( \langle \theta \rangle = 0.5 \text{ mrad} \) (i.e., 500 \( \mu \text{m} \) at 1 m radius) [5]. On the other hand, isolated leptons from Z or W decays will have transverse momenta of the order up to \( p_t = 1 \text{ TeV} \). Additionally, if the readout is not accomplished within the time between beam crossings (16 ns at the SSC) so-called minimum-bias events will be added to the interesting events, increasing the occupancy. This calls for a detector which has small cells commensurate to the track separation, good intrinsic position resolution, and fast collection time.

A tracker consisting of Si microstrips with 25 \( \mu \text{m} \) pitch fits these requirements. It was shown [7] that a double hit resolution of 100 \( \mu \text{m} \) and an intrinsic resolution of better than 5 \( \mu \text{m} \) can be achieved. The collection time can be made as small as 10 ns.

A model for the organization of such detectors is the vector tracking chamber, made of jet cells. The jet cell geometry was introduced by the JADE collaboration. The first of such chambers incorporating stereo wires, and smaller jet cells to aid in pattern recognition, was used by the MARK III detector. Subsequent examples are the trackers for the MARK II, CDF, SLD and ZEUS. Note also, that the use of a vector tracking chamber allows a crude local calculation of the transverse momentum, using track segments; this allows the reconstruction of high transverse momentum tracks only, in an efficient manner. This would vastly shrink the computer time needed for track reconstruction for events in which only high \( p_t \) tracks are desired.

3.1. Parameters of the tracking chamber

The parameters of the tracker are as follows (see fig. 3):

(1) It is made of 16 layers of silicon strips (25 \( \mu \text{m} \) pitch) organized into 8 pairs (superlayers) of detectors. The detectors are assumed to be double sided (one side with axial strips, the other with small angle stereo) so the total number of measurements is 32. Thus the detector can be thought of as 8 axial and 8 stereo superlayers, although the axial and stereo measurements are grouped together locally. This can be compared to typical vector drift chambers, such as the new MARK II chamber, which has 6 superlayers of each type.

(2) The radius varies from 8 to 50 cm. The inner radius is determined by the amount of radiation damage that can be tolerated. For the SSC operating at a luminosity of \( 10^{33} \text{ cm}^{-2} \text{ s}^{-1} \), this inner radius corresponds to about 0.6 Mrad per year [8]. Clearly, the design of sufficiently radiation-resistant electronics is critically important. Note that for high momentum tracks, the impact parameter error is still ~ 5 \( \mu \text{m} \), even starting 8 cm from the origin, since the long lever arm of the tracking device provides a very well measured angle and curvature.

(3) We assume each layer is 150 \( \mu \text{m} \) thick and has double sided readout, a technological development which seems to be realistic [9]. This gives 2.5% of a radiation length of material for the silicon and probably about 4–5% \( X_0 \) in total if we include a support structure. It is of great importance to keep the amount of material in this range to avoid creating many soft electron–positron pairs from photon conversions (see section 5). In addition, B meson vertex reconstruction for the light Higgs scenario involves lower momentum tracks and is sensitive to multiple scattering errors. For our design the multiple scattering contribution to the impact parameter error is about 80 \( \mu \text{m/p} \) with \( p \) in GeV. Requiring an error \( \leq 20 \mu \text{m} \) implies B tagging using tracks with \( p > 4 \text{ GeV} \). For the light Higgs search discussed above, we find that the efficiency for reconstructing a 100 GeV Higgs → b\bar{b} with at least two charged tracks falling within the central ± 2 units of rapidity is reduced by only 14% if we do B tagging requiring two tracks with \( p > 4 \text{ GeV} \).

3.2. Pattern recognition requirements

We show in fig. 4 two pairs of detector layers. The detector arrangement is specified by the distances \( \delta \) and \( \Delta \), which are the separation between pairs in a superlayer and between superlayers, respectively. The conflicting demands on \( \delta \) and \( \Delta \) are as follows:

(a) would like \( \delta \) small enough to make matching of points on a track simple;

Fig. 3. Beam view of silicon tracking system. The outer radius is 50 cm.
Fig. 4. A track passing through two adjacent layer pairs.

(b) would like \( \delta \) large enough that the track angle (tangent vector) is well measured;
(c) would like \( \Delta \) big enough to fill a given space; and
(d) would like \( \Delta \) small enough to allow frequent sampling.

For the pattern recognition we require that:
(1) different tracks give distinct hits;
(2) hits in the paired layers, separated by \( \delta \), can be locally associated into correct vector segments; and
(3) vector segments from different pairs can be correctly linked into tracks.

We define:
- \( \rho_{\text{track}} \) = track's radius of curvature;
- \( \langle \theta \rangle \) = typical track separation angle;
- \( \sigma_m \) = position resolution of measuring element;
- \( \epsilon_m \) = two track resolving power in space, locally, for a measuring element;
- \( \delta \) = separation of elements used to measure track vectors;
- \( r_m \) = outer radius of device; and
- \( r_i \) = mean radius of the \( i \)th pair.

From the physics considerations discussed earlier, \( \langle \theta \rangle = 0.5 \text{ mrad} \). For a silicon strip detector with 25 \( \mu \text{m} \) pitch, \( \sigma_m = 5 \text{ \( \mu \text{m} \)} \) and \( \epsilon_m = 100 \text{ \( \mu \text{m} \)} \). Suitable signal processing could distinguish tracks entering adjacent microstrips, giving \( \epsilon_m = 25 \text{ \( \mu \text{m} \)} \) at the expense of a slightly degraded position resolution.

We now quantify the relation between parameters so that the three pattern recognition requirements can be met:

1. To see distinct hits from different tracks in layer \( i \) we need:
   \[ \epsilon_m < r_i \langle \theta \rangle. \]
   This is a very stringent requirement, which even for the excellent double track resolution of the silicon strip tracker is fulfilled for only the outer 5 superlayers (out of 8 total) with radii \( r_i \geq 20 \text{ cm} \). Thus the device should be able to yield a sufficient number of distinct hits for nearly all of the tracks.

2. To match points into a segment we choose the simplest algorithm illustrated by the dashed line in fig. 4. To each point in the inner layer of a pair we associate the point with the closest \( \phi \) angle in the outer member of the pair. For a curving track the deviation in space from a perfect match, using this algorithm, is given by:
   \[ \frac{r_i}{2 \rho_{\text{track}}} \delta. \]
   However, in the jet core we can expect nearby hits from very stiff tracks with a mean spacing of \( \langle \theta \rangle r_i \). These can cause incorrect associations in segment formation. Thus, the simple algorithm for matching points into vectored segments will work provided:
   \[ \frac{r_i}{2 \rho_{\text{track}}} \delta < \langle \theta \rangle r_i, \]
   or
   \[ \frac{\delta}{2 \langle \theta \rangle} < \rho_{\text{track}}. \]
   This relation needs to be valid for all momenta within the jet core and provides the motivation for a small \( \delta \).

3. The basis for linking vector segments [10] is illustrated in fig. 5. The angle between the tangent vectors and a chord connecting the segments is the same for both vector segments belonging to the same circle. Each angle \( \theta_1 \) or \( \theta_2 \) is measured with a precision given by \( \sqrt{2} \sigma_m / \delta \). Linking can be done if this accuracy is adequate. We show in fig. 6 the trajectories of two very high momentum tracks separated by a production angle of \( \langle \theta \rangle \). An incorrect link yields the dashed track whose

Fig. 5. Relation for vector segments lying on one track.
Fig. 6. Angular relations for a spurious track (dashed) created from hits from two real tracks.

angles do not match by an amount $\langle \theta \rangle$. Thus, the goal for the linking to work is:

$$\sqrt{2} \frac{\sigma_m}{\delta} \leq \langle \theta \rangle.$$  

This provides the motivation for a large $\delta$.

For $\sigma_m = 5 \mu m$ and $\delta = 1 \text{ cm}$, we get $\sigma_m/\delta = 0.5 \text{ mrad}$, which is $-\langle \theta \rangle$. We will see below, using a full Monte Carlo simulation, that $\delta = 1 \text{ cm}$ is indeed close to optimum.

In the above we have assumed that tracks come from the origin when we match the two hits into a vector segment (but not in the vector segment linking). We show in fig. 7 what happens for a track with an impact parameter $b$.

The displacement of the second hit in a closely spaced pair of detectors at radius $r_i$ for a very stiff track with impact parameter $b$, with respect to a straight line through the origin, is $d = b \delta / r_i$. For the decay of D or B mesons, $b \leq 300 \mu m$. To avoid errors in association for pairs, we require as before:

$$d = \frac{b \delta}{r_i} < r_i \langle \theta \rangle \quad \text{or} \quad b < \frac{r_i^2 \langle \theta \rangle}{\delta}. $$

Taking $\delta = 1 \text{ cm}$, and $r_i > 8 \text{ cm}$ implies that there is no problem for $b < 320 \mu m$ even for the innermost layer. There is a problem $K_S^0$, which might have to be picked up in a second pass, if they are close to the jet axis.

### 3.3. Monte Carlo studies

In ref. [5], we have looked in more detail at the ability to do tracking in 1 TeV jets with a silicon tracker. The program ISAJET [11] was used to generate events with two quark or gluon jets, each with $p_t \geq 1 \text{ TeV}$. The mean multiplicity within $|Y| < 2$ in these events is 330, of which 118 have $p_t \geq 1 \text{ GeV}$. Fig. 8 shows a high $p_t$ event in a 3 T magnetic field. A region near the core of the tight 1.5 TeV jet in the lower left quadrant of the event, at a radius of 26 cm, has been blown up as fig. 9. The scale is matched to the size of a single strip detector containing 1024 25-\mu m elements. (Note the strips have been tilted to compensate for the Lorentz angle due to the magnetic field.) At this scale, which is the one relevant to track finding, the stiff tracks are not confusing.

To quantify this further, we have performed the first two steps of the pattern recognition for events with 1 TeV jets as outlined in section 3.2. Details can be found in ref. [5]; we report here only the results. For tracks with $p_t > 1 \text{ GeV}$, we evaluate the efficiency vs $p_t$ for finding tracks if we require at least $\text{NVEC} = 4, 6, \text{ or } 8$.

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correctly found vector segments to call the track found. The results for $\delta$ chosen equal to 1 cm are shown in fig. 10, where the last bin includes overflows. The efficiency approaches 100% for high momentum tracks. In contrast to conventional drift chamber trackers, which are most efficient for low-$p_t$ tracks which separate from jets, the silicon tracker we describe is most efficient for the high-$p_t$ tracks in the core of jets. We find that a $\delta = 2$ cm is noticeably worse than $\delta = 1$ cm. Choosing $\delta = 5$ mm would give about a 10% increase in efficiency if all 8 segments are required and little change for the case of 6 or 4 segments found.

Once vector segments are found, they must be unambiguously linked together to form tracks. One way to do this is to use a technique employed successfully with the Mark II jet-cell central drift chamber at the SLC [12]. The idea is to calculate the curvature ($\kappa = 1/2p_{\text{track}}$) and azimuth at the origin $\phi_0$ of a track passing through the origin and tangent to the vector segment. A vector segment provides a measure, at average radius $r$, of the track azimuth $\phi$ and rate of change of azimuth $d\phi/dr$.

We thus calculate

$$\kappa = \frac{-d\phi/dr}{\sqrt{1 + (r d\phi/dr)^2}},$$

$$\phi_0 = \phi + \arcsin \kappa r.$$

This will produce a mapping in which all vector segments found for a given track should lie near one point in the $\kappa-\phi_0$ plane. The vector segments found for the event shown in fig. 8 have been plotted in fig. 11a. Up to eight vector segments are plotted for each track.

![Fig. 9. Blowup of high $p_t$ event showing the jet core.](image)

![Fig. 10. Tracking efficiency vs $p_t$ as a function of number of segments reconstructed ($\delta = 1$ cm). The error bars are 95% confidence level limits, from the statistics of the Monte Carlo run.](image)
One can immediately see the two jets in the event. The effect of resolution in curvature is also seen from the spread in points for each track. For this plot we have used $\sigma_m = 5 \, \mu\text{m}$ and $\delta = 5 \, \text{mm}$.

Fig. 11b is a blowup of the region around the jet at $\phi_0 = 3.9$ rad. The effect of resolution is now more obvious, and it is also clear that the error in $\kappa$ is strongly correlated with the error in $\phi_0$. The improved vector segment resolution obtained by increasing $\delta$ from 5 to 10 mm results in clearly separated tracks within the jet, as shown in Fig. 11c. Note the spread in measured $\phi_0$ values is $\sqrt{2} \sigma_m/\delta$, the parameter introduced earlier to quantify the ability to link vector segments. After looking at plots for many events with 1 TeV jets, it becomes clear that 1 cm is a good choice for $\delta$ and will usually allow vector segment linking for the tracks in the jet core.

### 3.4. $z$ Measurement

In ref. [5] we have looked at the use of stereo measurements to determine the $z$ coordinate. Since each strip detector is double sided, we orient the strips on one side of the detector at a small angle (the stereo angle $\alpha$) with respect to the axial direction. For detectors of length $l = 10 \, \text{cm}$, a stereo angle of $\alpha = 5 \, \text{mrad}$ yields a “stereo displacement” $s = l \alpha = 500 \, \mu\text{m}$. We assume each pair of strips is organized as shown in Fig. 12, with $u$ stereo strips on one detector of a pair and $v$ stereo on the other ($\alpha_u = -\alpha_v$).

The goal for the pattern recognition is to measure $z$ coordinates locally within each pair. Each of the 8 pairs making up the full detector would then have space coordinates and tangent vectors assigned locally to each track. These would then have to be matched from layer to layer, as discussed above.

Tracks separated by more than the stereo displacement $s$ in the axial projection do not interfere with each other at all. A value of $s = 500 \, \mu\text{m}$ is probably small enough to guarantee that most stereo hits can be associated by selecting from a small number of alternative assignments.

The matching problem in $z$ locally can come from two tracks which can be confused or from many tracks causing accidental matches.

In general, we can minimize the $z$ matching confusion by taking a very small stereo angle $\alpha$, trading off resolution in $z$. This does not significantly degrade the momentum or mass resolution for a solenoidal field. In addition, we only need 1 mm resolution in $z$ at the vertex to separate most multiple interactions. The very good 5 $\mu$ m resolution of the strips, giving $\sigma_z = 1.4 \, \text{mm}$ for $\alpha = 5 \, \text{mrad}$, will yield a resolution in $z$ at the vertex of 835 pm.

The confusion from many tracks can be quantified in terms of the detector and physics parameters. Recall that within a jet, the mean displacement between tracks at a radius $r$ is $r \langle \theta \rangle$. If a pair of axial strips have been successfully associated within the jet, all tracks within the stereo displacement region $s$ (defined above) will leave stereo hits which can confuse the $z$ matching. The number of tracks entering this region is $N_s = s/(r \langle \theta \rangle)$. All of these tracks will leave stereo hits in the $u$ plane which could accidentally associate with another hit in the $v$ plane falling within a region of full width $2 \sigma_m$.

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**Fig. 12. Orientation of strips for a closely spaced pair of detectors.**

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which is the resolution characterizing the correct choice. The probability of there being such a hit in the $v$ plane is therefore $P = N_\phi \frac{2\sigma_m}{s}$, and the number of potential incorrect $z$ pairings is $N_{inc-z} = N_P$. Thus we arrive at the scaling rule for stereo association to work well

$$N_{inc-z} = N_\phi \frac{2\sigma_m}{s} = \frac{2\sigma_m s}{(r(\theta/))} < 1.$$
want to minimize the tracking inefficiency and the Lorentz angle for electron motion in the silicon, 2.5 T is probably an optimum choice for the field.

For such good resolution the multiple scattering contribution to the resolution will dominate up to rather high momentum. Assuming 5% of a radiation length and a 50 cm path length the multiple scattering contribution is approximately $\sigma_p/p = 0.8\%$ for $B = 2.5$ T. This number is comparable to the number typical of present day central drift chamber systems.

Fig. 14 shows a possible arrangement for the tracking detector in $r$ vs $z$, having azimuthal symmetry. It contains about 40 m$^2$ of silicon detectors. Going out in $\theta$ this arrangement gives:

(a) tracking with $\geq 6$ superlayers for $170^\circ \geq \theta \geq 10^\circ$ ($|Y| \leq 2.3$);
(b) tracking with 8 superlayers for $160^\circ \geq \theta \geq 20^\circ$ ($|Y| \leq 1.75$);

Table 2
Detector parameters and scaling rules

<table>
<thead>
<tr>
<th>Physics parameters for:</th>
<th>1 TeV jets</th>
<th>50 GeV jets</th>
</tr>
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<tbody>
<tr>
<td>Track angular separation $\langle \theta \rangle$ (mrad)</td>
<td>0.5</td>
<td>10</td>
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<tr>
<td>Jet angular width $\theta_{1/2}$ (mrad)</td>
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<td>40</td>
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<tr>
<td>Track $p_t$ in jet core (GeV)</td>
<td>50</td>
<td>10</td>
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<table>
<thead>
<tr>
<th>Detector parameters</th>
<th>Si tracker</th>
<th>Drift chamber</th>
<th>Mark II/SLC</th>
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<tbody>
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<td>Magnetic field $B$ (T)</td>
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<td>2.5</td>
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<tr>
<td>Radius of curvature $\rho = 3.3 \ p_t / B$ (m)</td>
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<td>66</td>
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<tr>
<td>Radial detector spacing $\delta$ (cm)</td>
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<td>1</td>
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<td>Superlayer thickness $\delta_{SL}$ (cm)</td>
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<td>Maximum radius $r_m$ (cm)</td>
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<td>Double track separation $\epsilon_m$</td>
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<tr>
<td>Stereo angle $\alpha$ (mrad)</td>
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<td>50</td>
<td>74</td>
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<tr>
<td>Position resolution $\sigma_m$ ($\mu$m)</td>
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<td>100</td>
<td>100</td>
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<td>$z$ position resolution $\sigma_z = \sqrt{2} \sigma_p / \alpha$ (mm)</td>
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<td>2.8</td>
<td>1.9</td>
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<td>Momentum resolution $\sigma_{p_t} / p t^2 (1/\text{TeV})$</td>
<td>0.09</td>
<td>0.26</td>
<td>1.0</td>
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<td>Occupancy from min bias (TeV$^{-1}$)</td>
<td>0.003</td>
<td>0.26</td>
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Scaling rule requirements

| Resolve hits: $\epsilon_m / \langle \theta \rangle < 1$ | 0.7 | 6.0 | 0.45 |
| Find vector segments: $\delta / (2 \rho \langle \theta \rangle) < 1$ | 0.15 | 0.15 | 0.006 |
| Link vector segments: $\sqrt{2} \sigma_m / (\delta_{SL} \langle \theta \rangle) < 1$ | 1.4 | 7.1 | 0.4 |
| Match $z$ hits: $2 \sigma_m \alpha / (\rho \langle \theta \rangle)^2 < 1$, or: | 0.24 | - | - |
| $| \alpha > 2 \theta_{1/2} / 4 \sigma_m \theta_{1/2} / (\rho \langle \theta \rangle)^2 < 1$ | - | 16.0 | 0.2 |

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(c) tracking over a fixed radius of 50 cm for $154^\circ \geq \theta \geq 26^\circ$ ($|Y| \leq 1.44$); and
(d) tracking with axial strips for $143^\circ \geq \theta \geq 37^\circ$ ($|Y| \leq 1.10$).

Assuming $p_T/p_t = 8\% p_t$ (TeV$^{-1}$) at $90^\circ$ and ignoring multiple scattering, fig. 15 shows $\sigma_p/p^2$ vs rapidity, for $p$ in TeV.

The use of silicon, combined with a moderately large magnetic field, allows very good resolution. It is essential, however, to align the silicon to an accuracy of a few microns in order to achieve this resolution in practice.

A comparison of the parameters of the proposed Si tracker with the scaling rules (see table 2) shows that the SI tracking chamber is well suited to the requirements of physics at 1 TeV. On the other hand, a tracker based on conventional technologies like the one proposed for the large solenoid [13] will not be suited for the TeV scale due to problems with occupancy (see below) and double track resolution $\epsilon$. For comparison, the performance of the MARK II chamber at the SLC is shown, which is designed for physics at 100 GeV and very low duty cycle.

5. Occupancy of the tracking chamber

The occupancy of the tracking chamber is deteriorated by (a) pile-up of minimum-bias events, (b) trapped tracks, and (c) photon conversions.

If the collection and readout time of the tracking device is larger than the time between beam crossings, several events will pile up in the detector, thus increasing the occupancy correspondingly. The presence of a large magnetic field tends to trap particles in the field increasing the occupancy and radiation damage.

Fig. 16 shows the transverse momentum spectrum from ISAJET for minimum bias events. A track will be trapped in the field if the diameter of curvature is less or equal to the outer radius of the chamber: $2\rho_{\text{track}} \leq r_{\text{m}}$.

Thus, for example, trapping will occur for: $p_T \leq 190$ MeV for the compact solenoid [3] with $r_{\text{m}} = 50$ cm, $B = 2.5$; or $p_T \leq 600$ MeV for the large solenoid detector with $r_{\text{m}} = 160$ cm, $B = 2.5$ T [13]. A large fraction of the tracks in minimum bias events occur in this momentum range, so trapping can be important. The ranges for trapping are indicated in fig. 16 for the two detector configurations with 2.5 T fields. (Tracks with diameter of curvature less than the inner radius, $2\rho_{\text{track}} < r_{\text{inner}}$, are curled up without reaching the chamber.)

To estimate the effect we have calculated the effective track length seen in the detector per minimum bias event using the ISAJET MINBIAS model (with $\approx 5.1$ charged tracks per unit rapidity at SSC energies, which may be a significant underestimate). We have looked at both a compact and large solenoid [13].

We have found that the occupancy is increased by a factor between 2 and 2.5, as compared to $B = 0$, for both detectors at $B = 2.5$ T. For the compact solenoid the occupancy is not a problem because of the large segmentation and excellent time resolution. Silicon detectors are able to resolve the hits from every beam crossing separately. Even at the innermost radius of 8 cm, with a luminosity of $10^{33}$, the occupancy is $\approx 2 \times 10^{-3}$ in a two-hit resolution element of 100 $\mu$m (4 strips) of 10 cm length. This contrasts with an occupancy of about 20%, at a 50 cm radius, for a 4 mm diameter cell in a large solenoidal detector covering $|Y| \leq 1.5$, assuming a pileup of only 4.8 events (3 beam crossings). In the central rapidity region $|Y| \leq 1.0$, containing the silicon strips nearest the beam in fig. 14, the spiraling tracks would increase the occupancy and radiation damage by 40% for a 2.5 T B field. The radiation damage issue would argue for the smallest magnetic field consistent with the physics goals of the detector.

Finally, we consider the effect of photon conversions in the tracking system. This will be a serious problem for a tracking detector containing a substantial fraction of a radiation length of material. The converted electron spectrum is very soft since each $\pi^0$ decays into two photons and each photon converts into two charged particles. We assume that because the conversion electrons are so soft, they all spiral in the detector for nearly any radius of conversion. There are roughly half as many $\pi^0$'s as charged particles, giving $2X_0$ converted electrons per primary charged track, where $X_0$ is the amount of material in the tracking system in radiation lengths. We estimate the number of track lengths per spiralling track $r = 4$ for both detector configurations. This results in a track length due to photon conversions of $8X_0$ for every charged primary for both detector configurations. Clearly a value of $X_0 \leq 5\%$ is very desirable. Note that

Fig. 16. Transverse momentum spectrum for minimum bias events. The ranges indicated by arrows are described in the text.
the 20% occupancy for the large solenoid detector, with \( X_0 = 8\% \) [13], will increase to 26\% due to photon conversions.

6. R&D program

The tracking system based on silicon microstrips described above poses many challenging problems for research. Questions concerning alignment and power dissipation have to be solved soon.

The other area of needed research is the development of fast, low power and radiation hard readout electronics. It is important to note that these characteristics are already met by today's silicon microstrip detectors, which have collection times of the order 10–20 ns and are essentially radiation hard. The only degradation observed is an increased dark current \( I_d \) in the volume \( V \) after irradiation with a fluence \( F \)

\[ I_d = \alpha F V, \]

where \( \alpha = 3 \times 10^{-17} \text{ A/cm for 12 GeV protons, and } \alpha = 1.6 \times 10^{-16} \text{ A/cm for thermal neutrons.} \) (Different experiments [14] agree to these numbers within a factor of 2. A potentially large annealing effect is observed [15] for realistic dose rates, which could lower the damage factor \( \alpha \) considerably.) The fluctuations of this increased dark current leads to an increase in noise and limits the ultimate fluence \( F \) or useful lifetime of the detector for fixed signal/noise ratio \( R \). The fluence limit \( F_i \) for a detector of area \( A \) and thickness \( w \) is given by

\[ F_i = \frac{I_d}{\alpha w A}. \]

while the signal/noise ratio \( R \) is given by the ratio of signal electrons from a minimum ionizing particle (25000 in 300 \( \mu \text{m} \) Si) divided by the fluctuation on the noise charge \( I_d \Delta t \) collected in the shaping time \( \Delta t \),

\[ R = \frac{25000 \sqrt{I_d \Delta t}}{0.03 \times 1.6 \times 10^{-19}}, \]

with \( w \) in \( \mu \text{m} \) and \( I_d \) in A. This leads to the fluence limit \( F_i \) at which the signal/noise ratio \( R \) is dominated by the dark current

\[ F_i = 1.1 \times 10^{-7} \frac{w}{R^2} \Delta t A \alpha. \]

The fluence limit can be increased in different ways: pixel devices decreases the area \( A \) of an active element drastically, but require a large signal/noise ratio \( R \) and longer shaping time \( \Delta t \); microstrip detectors have relatively large area but can operate with smaller signal/noise ratio and shaping time. The fact that the fluence limit can be raised by decreasing the shaping time of the readout was pointed out by Kondo et al. [16].

In table 3, the fluence limit of both protons and neutrons for silicon microstrip detectors and for pixel devices [17, 18] are shown. Also shown is the expected yearly fluence [8] at the projected closest radial distance from the beam (\( r = 3 \text{ cm for pixel, } r = 8 \text{ cm for Si strips} \)), and corresponding expected lifetimes for the different devices. Lifetimes of more than 10 years for all devices are expected, making a combination of silicon microstrip tracker with a pixel device inside possible. As a caveat, it should be pointed out that the composition of the calorimeter and its size can increase the expected yearly neutron fluence by factors of 3 or 4 [8]. On the other hand, as mentioned earlier, annealing effects are not taken into account in the damage factors.

The requirements of radiation hardness, speed, and low power consumption are not necessarily met by present day readout electronics [19–21] and have to be the focus of intensive R&D efforts. Because of the density of strips, the readout has to be in VLSI, directly coupled to the detectors. For the high rate future col-

| Table 3 | Expected lifetime of silicon microstrip detectors and pixel devices |
|---------------------------------|-------------------------------------------------|-------------------------------------------------|
| **Si \( \mu \) strip detector** | **Pixel devices** |
| Area \( A (\mu \text{m})^2 \) | Area \( A (\mu \text{m})^2 \) | |
| **Thickness \( w (\mu \text{m}) \)** | 25 \times 10^5 | 100 \times 100 |
| **Shaping time \( \Delta t (\text{ns}) \)** | 150 | 300 |
| **Signal/noise \( R \)** | 16 | 100 |
| **Fluence limit \( F_i (p) \text{ (protons/cm}^2 \)** | 20 | 100 |
| **Yearly fluence \( \text{protons/cm}^2 \)** | 3 \times 10^{14} | 1 \times 10^{15} |
| **Lifetime (protons) (years)** | 2 \times 10^{13} | 1 \times 10^{14} |
| **Fluence limit \( F_i (n) \text{ (neutrons/cm}^2 \)** | 15 | 10 |
| **Yearly fluence \( \text{neutrons/cm}^2 \)** | 6 \times 10^{13} | 2 \times 10^{14} |
| **Lifetime (neutrons) (years)** | 2.4 \times 10^{12} | 2.4 \times 10^{12} |
| | | 24 | 80 |

V. TRACKING DEVICES
Fig. 17. Block diagram of the fast readout system for Si microstrip detectors: AACC = Analog Amplifier–Comparator Chip, DTSC = Digital Time Slice Chip.

Fig. 18. Block diagram of the Digital Time Slice Chip (DTSC). The chip has 64 parallel channels.

We have designed a readout system shown schematically in fig. 17 which consists of an analog amplifier–discriminator chip (AADC) and a digital time slice chip (DTSC). A more detailed description of the system is given in ref [22]. The analog chip is designed in dielectric isolated bipolar technology for low noise and potential radiation hardness, which we will test soon. The main design aim is low power consumption. The pipelining of the events is done digitally in the DTSC (shown in fig. 18), which is 64 levels deep in the level 1 buffer and 16 deep in the level 2 buffer. To save power, the buffer is an SRAM and the chip is being built in CMOS.

We are building first a scaled up (100 μm instead of 25 μm pitch) and slower (10 MHz instead of 60 MHz) version in 2 μm CMOS and plan to test the principle of operation of this prototype in the Leading Proton Spectrometer (LPS) of the ZEUS detector at HERA. Another very important development will be tested there: the radiation hardening of the chips. We have started a collaboration with both a rad-hard foundry in the U.S. and with Los Alamos National Laboratories to test and evaluate rad-hard processes and the final rad-hard product. Initial data are very promising, because radiation resistance of up to many Mrad have been achieved [23].

7. Conclusions

We propose a tracking device consisting of silicon microstrip detectors with 25 μm pitch to do 1 TeV physics at the SSC/LHC. The parameters have been optimized for high efficiency for transverse momenta between $p_t = 0.5$ GeV and 1 TeV. Excellent double track resolution (100 μm) and momentum resolution ($\sigma_{p_t}/p_t = 8\%$ at 1 TeV) can be achieved. The performance of the tracking chamber has been checked using Monte Carlo events containing 1 TeV jets and a realistic, albeit simple, tracking algorithm. The effects of event pileup, trapped tracks and photon conversions have been investigated for the proposed silicon tracking chamber, where they have minimal effects and alternatively for a conventional tracker based on drift tubes, where they produce significant increase in occupancy. Finally, our R&D program to develop radiation hard, fast and low-power readout chips is outlined.

References


[23] R. Woodruff (United Technologies Microelectronics Center), private communication.