Optimisation of a silicon microstrip telescope for UA9 crystal channeling studies

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Abstract: A charged particle telescope based on silicon microstrip sensors has been used for several years for data taking at high rates in the CERN H8 beam line using a range of different incident particles. The electronic readout and data acquisition system is based on that developed for the CMS Tracker, and provides almost deadtime-free operation at trigger rates of up to about 10 kHz. The telescope was designed to characterise crystals in channeling studies by the UA9 experiment with the primary objective to validate them for use in a future LHC beam collimation system, hence is optimised for measurement of a single particle in the outgoing arm. The telescope has also been used for other studies of fundamental phenomena associated with the channeling process and further LHC applications. Some of these require a different layout of the telescope, for example to achieve a larger angular acceptance to study longer channeling crystals, or modifications to sensor operating conditions because of the very large electric charge and consequent ionisation energy loss associated with heavy ions. The telescope and its performance are described. Possible improvements are discussed.

Keywords: Particle tracking detectors; Si microstrip and pad detectors; Beam-line instrumentation (beam position and profile monitors; beam-intensity monitors; bunch length monitors); Performance of High Energy Physics Detectors; Beam-line instrumentation (beam position and profile monitors; beam-intensity monitors; bunch length monitors)
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1 Introduction

A charged particle telescope based on silicon microstrip sensors has been used for several years for data taking at high rates in the CERN H8 beam line using a range of different incident particles [1, 2]. The electronic readout and data acquisition system uses the APV25 readout ASIC [3] and other components originally developed for the CMS Tracker [4]; it allows almost deadtime-free operation at trigger rates of up to about 10 kHz.

The telescope was designed to characterise silicon crystals for channeling studies [5, 6] by the UA9 experiment [7, 8], initially with the primary objective to validate them for use in a future LHC beam collimation system, hence the telescope was optimised for measurement of a single particle in the outgoing arm with a limited downstream angular acceptance. The telescope has also been used for other studies of fundamental phenomena associated with the channeling process and further applications, such as beam focusing [9] or extraction [10, 11]. Some of these require a different layout of the telescope, for example to achieve a larger angular acceptance to study longer channeling crystals, or modifications to sensor operating conditions because of the very large electric charge and consequent ionisation energy loss associated with heavy ions.

Further development of the telescope is under consideration for future studies. As will be discussed it is challenging to improve the angular resolution significantly but other improvements are possible, making use of more modern technologies than available when the telescope was originally built. Much faster digital optical fibre links are now available and our group has developed a new front-end ASIC and off-detector processing electronics for CMS upgrades. Low latency online track finding in FPGAs has been proven for future operation in CMS using current state of the art digital electronics and more advanced boards intended for CMS upgrades are now available. These could be deployed to increase the UA9 data taking rate or carry out online track reconstruction which would provide faster feedback to the channeling studies or allow triggering on specific types of event.
2 Telescope layout and operation

The “standard” layout of the apparatus is shown in figure 1; each arm has a length of approximately 10 m. Each station has two orthogonally oriented microstrip detectors to measure the two transverse spatial coordinates, denoted \( x \) (horizontal) and \( y \) (vertical); \( z \) is the beam direction. The upstream section for measurement of incoming tracks is formed by stations 1 and 2 while outgoing tracks are measured using stations 3, 4 and 5. Station 4 is usually oriented at a different transverse angle than the other stations, to provide \( u \) and \( v \) measurements to resolve combinatorial ambiguities, since background hits are present at a modest level. Each of the sensors has an active length of 98 mm and there are 639 strips on a 60 \( \mu \)m pitch so the effective aperture for \( x-y \) measurements in each station is \( 38 \times 38 \) mm\(^2\).

Vacuum pipes are included in the arms to minimise the multiple scattering in air. The position of the planes can be changed; this usually applies to the downstream arm to optimise the angular acceptance. A precise goniometer is provided at the centre of the apparatus between planes 2 and 3 to perform angular scans of a crystal mounted on the goniometer, to orientate it for channeling in the horizontal plane, with an accuracy of 1 \( \mu \)rad.

In this configuration, the dominant contribution to the angular resolution is from multiple scattering in the sensors while the position resolution of the microstrips closest to the crystal determines the impact parameter resolution at the crystal. The sensor thickness is nominally 320 \( \pm \) 20 \( \mu \)m, but measurements made on 24 samples of the wafers provided with the sensors give a more precise value of 328 \( \pm \) 2 \( \mu \)m. Thin aluminium windows are included in the mechanical mounts so each station of two planes contributes material equivalent to approximately 716 \( \mu \)m of silicon. The sensor readout pitch is 60 \( \mu \)m but an electrically floating intermediate strip is present which enhances charge sharing to improve the spatial resolution. Previous studies [1] showed that an overall spatial resolution of \( \sim 7 \) \( \mu \)m is achieved in each sensor plane. The location of each of the planes is known from direct measurement using a laserometer, with a precision of about 1 mm, which is more than adequate for estimates of performance from calculations or simulations.

A narrow, low divergence 400 GeV/c proton beam with no radiofrequency structure is available in the external H8 beamline of the CERN SPS; other types of particle and energy can also be pro-

![Figure 1](image_url)
vided. The beam is ejected with a time structure consisting of a flat top when particles are present, lasting about 10 s, followed by about 35 s of no beam. Events are triggered on the coincidence of signals from a pair of plastic scintillators placed outside the telescope. The goniometer angle is adjusted in steps in the intervals when no particles are present. The data capture rate must be high enough to capture typically a few thousand events at each angular position to provide adequate statistics.

Data taking by UA9 in H8 has often required parasitic operation with other users to share beam time. Hence a significant amount of data has been taken at 180 GeV/c as well as with various ion species. This provides an opportunity to study the performance of the telescope as a function of momentum.

The original objective was to measure performance of crystals to be used for LHC beam collimation. This requires excellent angular resolution, sufficient to select particles within the critical channeling angle $\theta_c$ [5], hence the long lever arms. Since the beam was generally narrow and in many cases the channeling deflection angle was $\sim 100–200 \mu$rad, a limited angular acceptance, both upstream and downstream, was sufficient. Automated scans from incident direction to the channeling angular region, with (mostly) a single particle in the telescope, were required to achieve high statistics, and rapid location of the channeling angle. In practice this was speeded up by precise laser alignment of the crystal on the goniometer which simplified the identification of the channeling peak. A high data rate during the spill was required to acquire sufficient events, with rotation of the crystal by the goniometer between spills.

Since channeling does not involve production of secondary particles, events of interest should have only one hit in each sensor. Background from the accelerator in the experimental area or noise hits in the electronics give rise to a small fraction of multiple hits. The location, acceptance and alignment of the scintillator trigger, which has changed several times, also has an influence, and also permits missing hits. Only events with a single hit in each plane are accepted for analysis, which are the large majority. Because of the short resolving time ($\sim 25$ ns) of the APV25 electronics, pileup from beam particles is not significant.

To allow the telescope to be implemented reasonably quickly, it was required that detector modules and DAQ be based on existing, or easily acquired, hardware, and software should be derived from an existing system. This was achieved by profiting from developments made for the CMS tracker system, but with customised modules using sensors originally designed for an upgrade of the D0 silicon tracker [12, 13], which did not eventually take place. This strategy was quite successful and the tracker was first commissioned in H8 in mid-2010. The main changes since then have been to the DAQ and track reconstruction software to increase as much as possible the data taking rates, and to handle different beam conditions, as well as improve the user-friendliness of the system.

3 Track reconstruction and telescope performance

In such a simple system, sophisticated track reconstruction is not possible or needed. It generally uses a minimisation of two straight line fits [1], between station 1 and 2 and between stations 3, 4 and 5. Both fits are required to have a common impact point at the crystal origin. There are three free parameters per track per x or y projection denoted $\theta_{in}$ (incoming angle), $\theta_{out}$ (outgoing angle) and $d_0$ (impact parameter at $z = 0$), figure 2. The deflection of each beam particle relative to the incident particle direction, $\theta_{def} = \theta_{out} - \theta_{in}$, is the quantity of interest for channeling measurements.
The $z$-axis is defined by alignment runs with no crystal present. For measurements of the channeling properties of the crystal sample, it is desirable to exclude incident particles which arrive outside the channeling acceptance, i.e. to make a cut on the incident angle $\theta_{\text{in}}$, and the cut is usually chosen to be less than the critical angle $\theta_{\text{c}}$.

![Figure 2](image_url)

**Figure 2.** Schematic layout of the telescope showing the parameters used for track reconstruction, indicating how the multiple scattering deviations are included.

For some measurements an increased downstream angular acceptance was required. In this case, station 4 used an $x$–$y$ orientation instead of $u$–$v$ and the positions of the stations were adjusted, usually to achieve the largest compatible lever arm. However, restrictions on the station positions arose from the location of other components, such as the vacuum pipe, or the length of the granite support table. For measurements using only four stations, the angular deflection was measured simply from two 2-point track reconstruction in each arm. The constraint on the common impact point was dropped, especially because it was an oversimplification when the channeling crystal had a significant length, which was the case for large angle channeling, $\sim 1–10$ mrad.

The performance of the telescope for different configurations has been estimated in two ways; first by a calculational method originating with Kärimaki [14] but which includes multiple scattering terms in the covariance matrices used and secondly by a direct Monte-Carlo simulation. The two methods are in good agreement. The quantities of most interest are the angular resolution in the upstream arm, $\sigma(\theta_{\text{in}})$, and the resolution on the deflected angle, $\sigma(\theta_{\text{def}})$, which includes contributions from the upstream arm and the downstream arm. It is worth noting that $\sigma(\theta_{\text{def}})$ cannot be obtained by combining $\sigma(\theta_{\text{in}})$ and $\sigma(\theta_{\text{out}})$ in quadrature as multiple scattering deflections lead to correlations between the measurements in different planes which must be taken into account in calculations; in a simulation they are automatically present. The resolution on the impact parameter at the channeling crystal is usually very similar to the spatial resolution of the closest plane, except for very low momenta. Figure 3 and table 1 show results for a typical “standard” layout; the results are insensitive to modest changes in the station locations because the results are determined mainly by multiple scattering and the long lever arms. In this case the upstream arm was a little shorter, 9,934 m, than shown in figure 1. Not all of the tabulated momentum values correspond to measurements with hadron beams; however, some of the values are relevant for comparison with data taken with different ion species.
Table 1. Calculated performance of the standard configuration of the telescope for selected beam energies, compared to the critical channeling angle $\theta_c$. $\sigma(\theta_{\text{in}})$ is the resolution in the upstream arm only, and $\sigma(\theta_{\text{def}})$ is the resolution of the deflection angle.

| $p$ [GeV/c] | $\sigma(\theta_{\text{in}})$ [\mu rad] | $\sigma(\theta_{\text{def}})$ [\mu rad] | $\theta_c$ [\mu rad] |
|-------------|----------------------------------------|----------------------------------------|---------------------|
| 30          | 34.1                                   | 51.2                                   | 36.5                |
| 100         | 10.3                                   | 16.9                                   | 20.0                |
| 150         | 6.9                                    | 11.4                                   | 16.3                |
| 180         | 5.8                                    | 9.6                                    | 14.9                |
| 400         | 2.8                                    | 4.5                                    | 10.0                |

Figure 3. The calculated angular resolution of the incident angle $\theta_{\text{in}}$ and deflected angle $\theta_{\text{def}}$ for a 5-station configuration of the telescope, with the critical channeling angle $\theta_c$ shown for comparison.

When only four stations are present, the results are sensitive to the location of the downstream stations, as spatial constraints in the beam area limit the length of the downstream arm for configurations of interest, i.e. with sufficient angular acceptance. As an example, table 2 shows the performance at two beam energies of interest, with the stations located at $z = 0$, 10 m, 10.6 m and 11.1 m, i.e. with a 10 m upstream arm, a downstream arm of 50 cm, and both the stations closest to the channeling crystal (at $z = 10.3$ m) having a 30 cm gap between the station and the crystal. It is clear that the resolution on the deflected angle is now dominated by the spatial measurement errors in the downstream planes, and no longer by multiple scattering, because of the short arm length.

Table 2. Calculated performance of a simplified 4-station configuration of the telescope for different beam energies, compared to the critical channeling angle $\theta_c$. $\sigma(\theta_{\text{in}})$ is the resolution in the upstream arm only, $\sigma(\theta_{\text{def}})$ is the resolution of the deflection angle.

| $p$ [GeV/c] | $\sigma(\theta_{\text{in}})$ [\mu rad] | $\sigma(\theta_{\text{def}})$ [\mu rad] | $\theta_c$ [\mu rad] |
|-------------|----------------------------------------|----------------------------------------|---------------------|
| 180         | 5.4                                    | 21.2                                   | 14.9                |
| 400         | 2.6                                    | 20.1                                   | 10.0                |
Results from measurements in a series of different beam studies are listed in table 3; those with ions are described in [2], while the 400 GeV/c proton results were derived in [1]. Other measurements from 180 GeV/c hadron beams are under study, for an expected publication [15]. Because of the very large signal sizes with ions, the sensors in the telescope must be operated under special conditions as explained in [2], hence it is not expected that the estimated achievable resolution will be obtained, since the analogue front-end electronics is often saturated and the charge sharing is expected to be non-optimal. However, the measured angular resolutions were sufficient for channeling studies.

Table 3. Measured angular resolution of the deflection angle for different configurations of the telescope with different beam particles and energies. Except where stated, measurements were made with a 5 plane telescope. $\sigma_{\text{meas}}$ is the measured result, $\sigma_{\text{scaled}}$ is the experimental value scaled from 400 GeV/c protons, and $\sigma_{\text{calc}}$ is the numerically calculated resolution for that layout. (The performance of the 4 plane telescope cannot be estimated by scaling from the 5 plane layout.) Small differences compared to values in tables 1 and 2 are due to different plane positions.

| beam | Z | A | p [GeV/c] | $\sigma_{\text{meas}}$ [µrad] | $\sigma_{\text{scaled}}$ [µrad] | $\sigma_{\text{calc}}$ [µrad] |
|------|---|---|----------|-------------------------------|-------------------------------|-------------------------------|
| p    | 1 | 1 | 400      | 5.2                          | 5.2                          | 4.4                           |
| Xe   | 150 GeV/n | 54 | 131.2 | 19680 | 7.8 | 5.7 | 4.7 |
| Pb   | 30 GeV/n | 82 | 207.2 | 6216 | 29.6 | 27.4 | 20.3 |
| $\pi/p$ | 1 | 1 | 180 | 11.3 | 12.0 | 9.6 |
| $\pi/p$ | 4 plane telescope | 1 | 1 | 180 | 22.1 | 19.7 |
| $\pi/p$ | 8 cm Si & 4 plane telescope | 1 | 1 | 180 | 82.2 | 72.2 |

For the hadron (p and mixed $\pi/p$) beams there appears to be a trend that the estimated angular resolution is somewhat less than achieved in measurements. A series of measurements were made with very long channeling crystals (e.g. last row in table 3 where an 8 cm long crystal was used to deflect the beam by about 12 mrad) which show the same trend.

Although the discrepancy is not dramatic, ∼10–15%, multiple scattering is such a well-established phenomenon [16], that this difference remains the subject of more detailed investigations. Non-Gaussian tails are present in the data but do not explain the results. Some additional material is present in the beam as well as the sensor plane and vacuum tank windows, but this is believed to be included in the calculations and simulations. The interpolation of the signal pulse-heights has been simulated, since the charge sharing is not trivial, but again does not seem to account for the differences. A systematic uncertainty could arise from the beam energy but, although this does not seem to have been directly measured for any of the North Area beam lines, it is considered unlikely that the beam momentum differs from its nominal value by more than about 1%. At present it seems that the most likely explanation is that the pressure in the long vacuum chambers in the beam line was not as low as assumed.

4 Possible future developments

An obvious target for modifications would be to improve the angular resolution, which for a telescope with long arms requires reduction in the material budget which can only be achieved by thinner sensors. For such configurations, calculations show that, as expected, the deflection angle resolution...
changes as $\sim \sqrt{t}$, where $t$ is the sensor thickness, if all the planes are changed in thickness by the same factor. In practice, reducing the sensor thickness considerably is not easy, just because of lack of availability and that thin sensors are less easy to manufacture without risk of breakage. There is little advantage to be gained from improving the intrinsic spatial resolution of the sensors, compared to the existing ones.

Alternatives might be to deploy double-sided sensors, provided the readout pitch is comparable with the sensors in use. This would represent a relatively easy means of upgrading the system, since it would not require much change to the readout and DAQ systems. The most profitable place to deploy improved sensors, if only some of them were to be replaced, would be in the upstream arm. Improving the angular resolution there would enable tighter cuts to be placed on the incident angle. This would be most worthwhile if the beam has limited dispersion, which is not always the case.

Other sensors which have been considered are pixel detectors. In principle, both coordinates can be measured with a single sensor layer, which saves material. However hybrid pixel sensors are inevitably supported on the readout ASIC, which is often rather thick, $\sim 750 \mu m$, and, even if thinned, usually not less thick than the existing sensor layers. In addition, the pixel sizes in common use, e.g. in ATLAS and CMS, would not provide the same spatial resolution as the existing sensors in the H8 telescope. In the LHC experiments, charge sharing from Lorentz drift in the sensors due to the magnetic field, and non-normal incidence of many of the particles, which typically have a much softer momentum spectrum than in H8 beams, overcome these difficulties.

Other types of pixel sensor are becoming more readily available, in particular MAPS devices, which have made much progress in recent years. Typically these have much smaller pixel sizes and, since they do not have an ASIC substrate, can be made very thin. Individual sensors are not very large however, being limited in size by the manufacturing reticle, of order $2 \times 2 \text{ cm}^2$. This would not be adequate for a downstream arm, without some dead regions intervening. However, such sensor areas would be very suitable for the upstream arm with potentially big gains in the angular resolution.

Other potentially profitable improvements can be made in other ways. The readout system remains unchanged since it was built, although more data can now be stored at higher rates due to technology improvements, which allows larger statistic measurements to be acquired more rapidly. If the readout system were to be rebuilt, there are several ways in which it could be improved, especially in the data transfer and acquisition. The optical links would be replaced with digital links, which are now available at multi-Gbps speeds. This would require an ADC and extra layer of electronics preceding the DAQ but this is not considered to be difficult.

For the DAQ itself, the present VME Front End Drivers [17] developed for CMS, were based on state-of-the-art technology about fifteen years ago, which has progressed immensely since then. New digital electronics would allow much fast signal processing to take place on the DAQ boards, such as for track selection or triggering. For example, real-time low latency online track finding in FPGAs has been proven [18] for the planned upgrade of the CMS tracker for HL-LHC using the $\mu$TCA MP7 board [19]. They will be replaced in CMS by even more powerful digital electronic boards, known as Serenity, [20] using an ATCA form factor. Special modules have been developed for CMS [21] to allow such data processing. Although these modules would increase multiple scattering because of the extra layers, they could be deployed in the downstream arm without much penalty for online track finding. This offers opportunities to improve rejection of background hits, and provide online cluster-finding and track reconstruction including triggering on event topologies of particular interest.
5 Summary

Based on about ten years of operations, considerable experience has been gained using a silicon microstrip telescope whose performance is mostly well understood, although calculations seem presently to underestimate slightly the achievable performance compared to measurements.

For the future it seems that only modest gains are easily possible by reducing the material budget, which arises mainly from the sensors. However, significant potential improvements in data throughput are possible from exploiting progress in digital electronics. This might be combined with new double-layer module types to permit background hit rejection, online cluster-finding and track reconstruction and triggering on interesting event topologies.

Acknowledgments

We gratefully acknowledge financial support from the U.K. Science and Technology Facilities Council. We thank our collaborators in the UA9 experiment, especially M. Garattini, R. Rossi and W. Scandale for valuable discussions, and CERN for support with the H8 beams.

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