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Microscopic imaging of muons and 120 GeV/c pion interactions in a single, low-noise 256x256 Si pixel detector

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Abstract

With a 256x256 pixel matrix on a 300μm thick silicon sensor, placed parallel to the particles in the CERN H6 beam, it proves possible to record electronically in real time the microscopic details of particle trajectories and interactions. The Medipix2 readout chip, matched to this matrix of 55μm square pixels, contains a tuneable discriminator and a pulse counter in each pixel. The noise of the signal processing chain in each pixel is on average 135e^- (equivalent electrons) r.m.s. A threshold not much higher than 800e^- allows discrimination of full signals ~3800e^- as well as partial signals from a minimum ionizing particle in adjacent 55μm thick pixels. With binary pixel information, exploiting charge diffusion and redundancy in the large matrix, the vectors of trajectories can be reconstructed with angular accuracy <1mradian and positions with respect to the detector coordinates often with sub-μm precison. Close tracks can be resolved down to 100μm distance. The width of the trail in the matrix sometimes can provide information on the energy deposition as well. A variety of applications can be imagined, the more so if several such detectors could be stacked to create a true 3-dimensional position-sensitive volume.

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1. Introduction

Fine-grained silicon (Si) pixel detectors are conceived to register positions of many simultaneous tracks of ionizing particles in high-energy physics experiments [1]. Usually, the thin chip with the matrix of pixels is perpendicular to the main direction of the particles. However, if the Si chip with 256x256 cells is exposed parallel along a beam one obtains position information from many consecutive pixels. The particles leave characteristic trails in the detector, from which the trajectory can be reconstructed, occasionally even in three dimensions. One can visualize interactions of beam particles with protons or neutrons in the detector itself. This situation resembles that in bubble chambers or nuclear emulsions, but in silicon much higher event rates can be handled fully electronically. The sensor chip is a continuous medium for the ionization, and the charge is collected on successive electrodes without losses between elements. The silicon pixel thickness of 55μm traversed by a particle is quite sufficient for reliable detection. Small, square pixels are essential and the thickness of the sensor layer must be sufficient (300 μm may be optimal) to contain a fair part of the tracks that come out of the interaction vertex. Low noise of the pixel electronics in combination with charge diffusion is needed to achieve sub-micron precision.

An investigation of this approach has recently been made using a Medipix2 ¶ detector in the H6 beam at CERN and results are presented in this first article. Work is in progress on several detailed aspects which will be reported later. The instrumentation and layout are described in section 2. The system is based on standard USB (Universal Serial Bus) and the miniaturized setup is so small that all of it can be transported in a briefcase. Yet, unprecedented precision in electronic tracking is achieved. In a single Medipix2 instrument position coordinates in space are electronically recorded and vectors and angular distributions measured. The 120GeV/c particle beam contains mostly pions and protons and interactions are shown in section 3. With beam stoppers in place, a low intensity but high energy muon flux was also recorded and results are shown in section 4. The concept of 'auto-residuals' is introduced and a first estimate gives a precision of 0.5 to 0.8 μm. Section 5 closes the article with a discussion and conclusions

Some applications come immediately to mind, but a better adapted and more sophisticated readout chip design is needed to fully exploit this new approach. For example, it may be possible to achieve particle identification for some of the tracks, with the large number of ionization samples along a typical track, and when a magnetic field allows momentum measurement. In the future, measurements in a larger volume may be achieved by 3-dimensional stacking of several sensor assemblies in parallel, a technology that is currently being developed in microelectronics [2,3], e.g. for high-density memory sticks.

¶ The Medipix2 readout chip and detector assembly have been developed by CERN and the Medipix collaboration, Spokesman and CERN team leader is Michael Campbell, see http://medipix.web.cern.ch/MEDIPIX/

2. Instrumentation and layout

The Medipix2 pixel matrix readout chip and its matching silicon sensor with 256x256 contiguously sensitive cells has been designed for a variety of quantum imaging applications, in particular for X-rays [4]. Each pixel, with dimensions 55μm x 55μm contains a complete nuclear electronics signal processing chain, with a tuneable energy threshold discriminator connected to a 13-bit counter that accumulates the number of hits in the pixel during a programmable shutter 'open' time. This active time can be selected to be as short as a few μs or as long as hours. Once this electronic shutter is closed, the counting registers are disconnected and a serial or parallel readout is initiated of the number of hits recorded in each pixel. The data, a string of 65 536 words of 16 bits, can be transferred off-chip in <10 ms in serial mode, and in <1ms in parallel mode. Different serial readout systems have been implemented for the Medipix2 chip at NIKHEF, Amsterdam [MUROS, 5], and at the CTU, Prague [USB, 6] while the parallel system DEMAS is made at IFAE, Barcelona [7] and another one at ESRF, Grenoble. The miniaturized USB modules designed at the Czech Technical University have been used in this beam test, and a photograph of a complete module is shown in Fig.1. The Pixelman readout software, also developed in Prague [8], has been used in conjunction with this USB module. This experimental software package provides all needed control signals, data acquisition, data recording and on-line display. It can run on a portable PC, but with a distance of 10m the USB needs a cable with signal restoration and additional USB power supply.

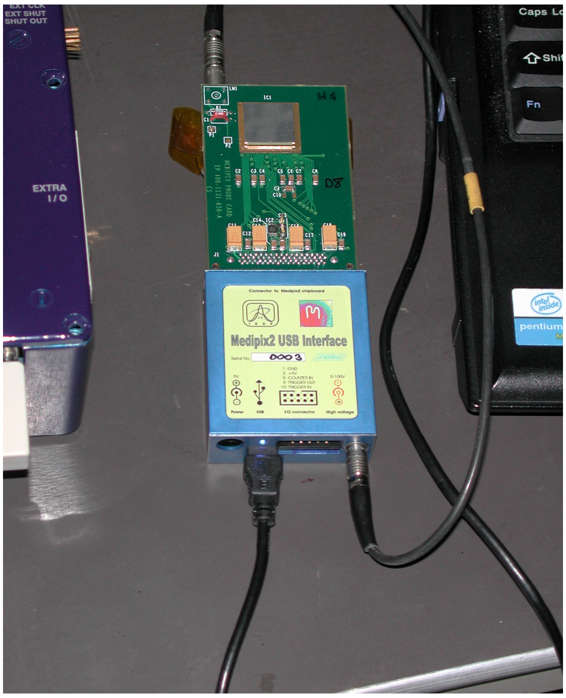

Fig. 1 Photograph of a complete module with sensor board and USB readout box in the middle. The USB cable at lower left connects to the portable computer at the right. The high voltage for the Si sensor, usually 100V, is provided from the USB module below to the top of the sensor board via the other cable with LEMO™ connectors. The undivided rear side of the 14x14mm^2 sensor is facing you, while the matrix of contacts and the Medipix2 readout chip are behind the sensor. The assembly is glued on the green printed circuit board which also contains decoupling, of which 4 large capacitors are seen. A 120 contact, flat connector in the USB box holds this circuit in place, and provides communication between the USB circuits and the Medipix2 chip. All control signals and data are transmitted back and forth to the computer via the standard USB cable. To the left one can just see a small corner of the earlier serial readout system MUROS, which illustrates the progressive reduction in size of the readout electronics.

The layout in the H6 beamline at CERN is sketched in Fig. 2 with the choice of coordinate system. The setup was placed for a brief period parasitically in front of the beam hodoscope of the EUDET Calice calorimeter experiment. Two detector modules have been exposed simultaneously but results obtained with the upstream device at an angle of 45° with the beam axis are not discussed here. The second Medipix2 assembly could be rotated on a goniometer, and most data were taken with the module positioned parallel to the beam along the z-direction. The 300μm thin side was facing the beam and 256 pixels with a length of 14.08mm of silicon are then available for imaging. Insensitive Si edge regions of ~0.5mm precede and follow the sensitive volume. Well-aligned particles travel through many pixels of the matrix and they are incident from the left in the frames shown. The bumps and readout chip were on the far side behind the sensor, when looking at the picture frame, just as in Fig.1. A small tilt of the sensor board around the y-axis is arbitrary, as it depends mostly on the insertion of the board in a flat electrical connector, so that in the first data run the particles seem to travel slightly upward, while in the second run they travel downward. This might be better controlled by fixing the sensor board itself on the reference mechanics, rather than the USB box. The beam spill from the SPS was 4.8 s and several tens of frames could be written for each spill. The limitation in the data acquisition rate is currently the real-time display function. The implementation of the software has not yet been optimized for high-speed frame recording. Nevertheless, thousands of frames with beam data have been accumulated in a few hours.

The assembly used is not a very high quality one, as ~700 pixels or ~1% were not connected to the sensor elements, mostly in rows 130 to 256. Seven pixels were turned off with the mask-bit because of high noise count rate. The Si sensor was overdepleted with a bias voltage of 100V, generated in the USB module.

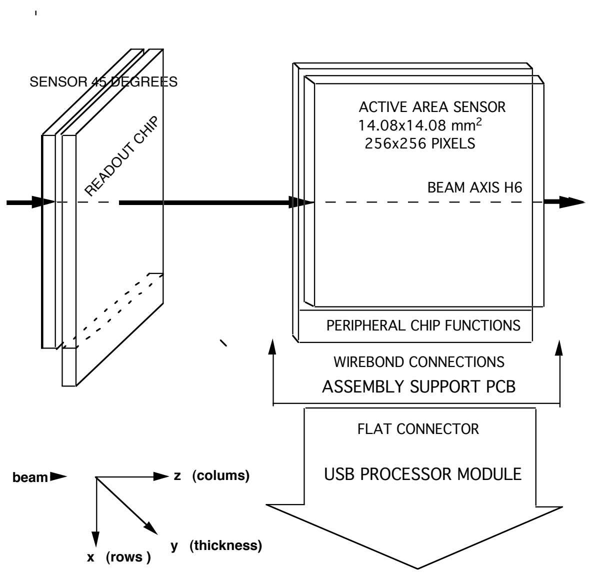

Fig. 2 Schematic layout of the two pixel 14.08mmx14.08mm matrices in the H6 beam, with the upstream under ~45° and the second one parallel to the beam particles. The sensor chip is assembled with bump bonds (not shown) on the readout chip, which has a 3mm extension for peripheral functions at the lower edge. This assembly is glued and wirebonded on a supporting printed circuit board PCB, of which only the lower part is schematically indicated. The PCB conducting lines match the receiving flat connector in the USB module, as may be seen in Fig. 1. The positioning of the two assemblies in the beam is achieved by fixing the USB boxes in holders, with the 'parallel' unit on a manually turned goniometer. The coordinate axes as used in the analysis are shown, with z along the particle beam. The 300μm thickness of the parallel sensor is in the y direction, the rows are numbered in negative direction along x from top to bottom and the columns from left to right along z.

3. Interactions in a 120 GeV/c beam

The downstream detector with parallel exposure of the Medipix2 sensor delivers detailed pictures of tracks, and also occasionally a particle interaction. The nuclear interaction length in silicon is 106 gcm^{-2} corresponding to 455mm and a fair number of interactions may be expected in the 14.08mm of sensitive length. Frame 02-0668 taken with a shutter time of 1s is shown in Fig. 3.

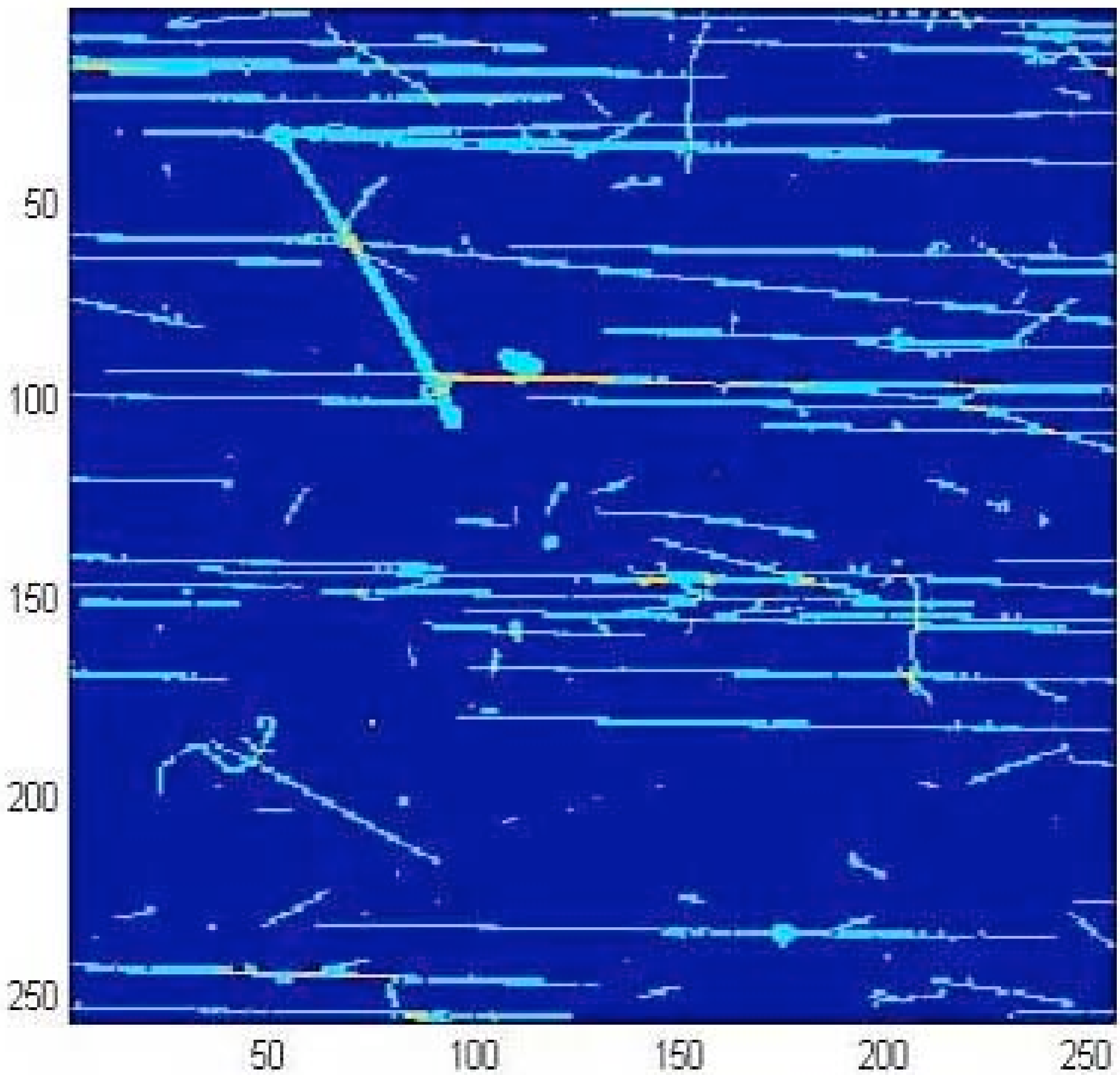

Fig. 3 Frame 02-0668 recorded with a Medipix2 detector with 1s shutter time exposed parallel in the H6 beam at CERN. The trails of the beam particles (mostly 120 GeV/c pions) point slightly downward. From interaction vertices some heavily ionizing trails emerge with several adjacent hit pixels on each row.

We propose to call 'trails' the sequences of pixels which are hit along the trajectory of the particle, and which are one, two or sometimes three or four pixels wide. A large number of trails are mostly parallel and in this experiment they tend to point slightly downward. Several interactions can be recognized and in most cases the incoming particle is identified. Also, one can see some erratic trails, presumably of electrons, which have fairly high energy, as they run through several mm of Si. In such a long exposure it is difficult to identify all the tracks associated with one interaction.

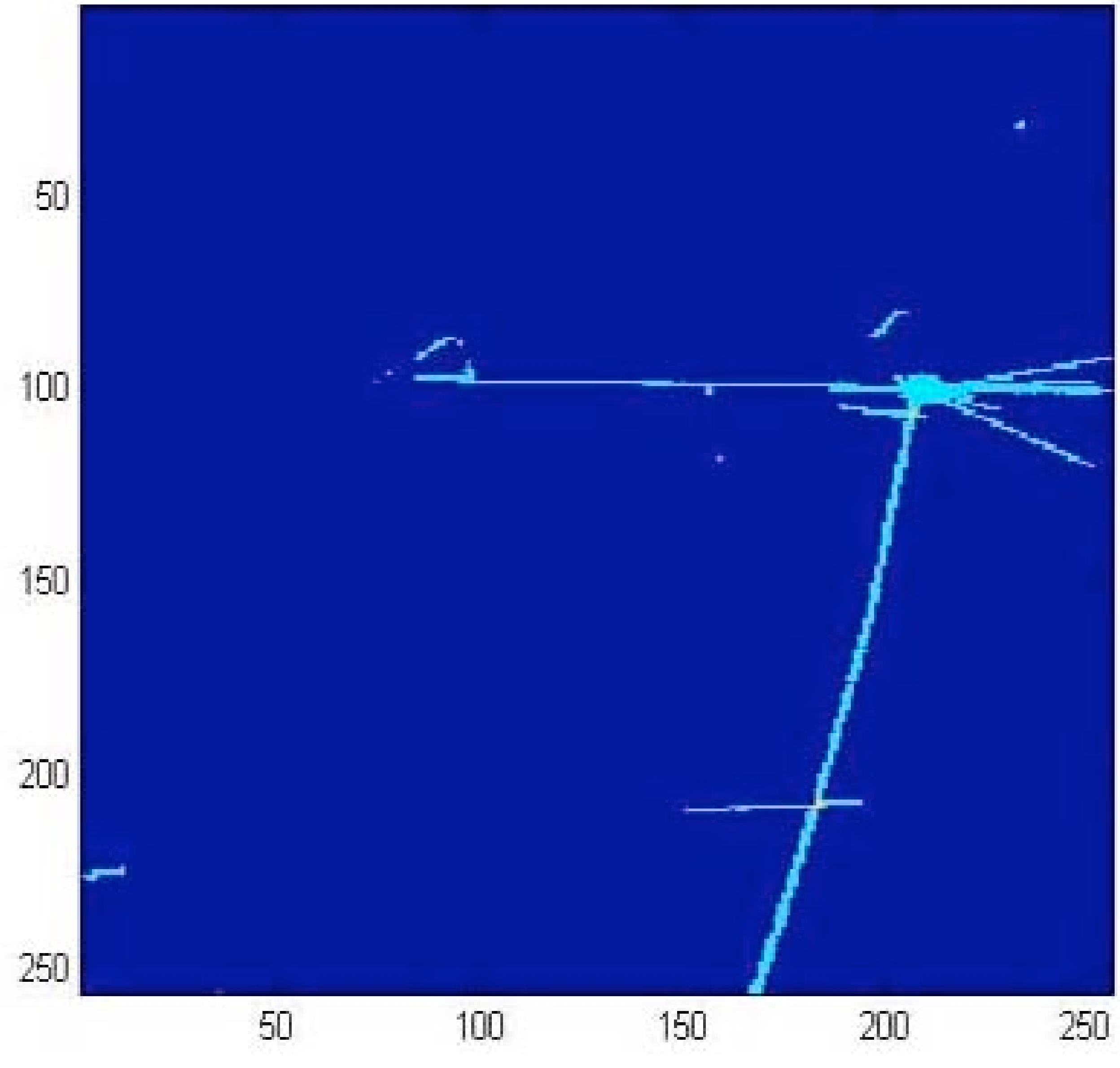

Fig. 4 Frame 04-0356 with 50 ms exposure. One long and three short trails and a single interaction are recorded.

Shorter shutter times of 50ms or 100ms have been used, and a few thousand frames have been recorded consecutively, without external trigger, during the beam spills as well as in between. Interactions are seen in ~200 of these frames. The signal from a minimum ionizing particle in a 55μm pixel should be between 3000 and 6000 e^- (electron-hole pairs) corresponding to an energy deposition of 10 to 20 keV. The threshold setting of the comparators is between 800e^- and 1000e^- as discussed later. Therefore, divided signals with charge sharing down to 30%-70% between two pixels can be seen.

The frame shown in Fig. 4 has an easily recognizable interaction by an incoming particle. A typical feature is the large energy deposition closely around the apparent vertex. The precise vertex point in the upper half of pixel (100,208) can be determined here by backtracking of the outgoing reaction products. One of these is a heavily ionizing, recoiling fragment, which remains within the sensitive

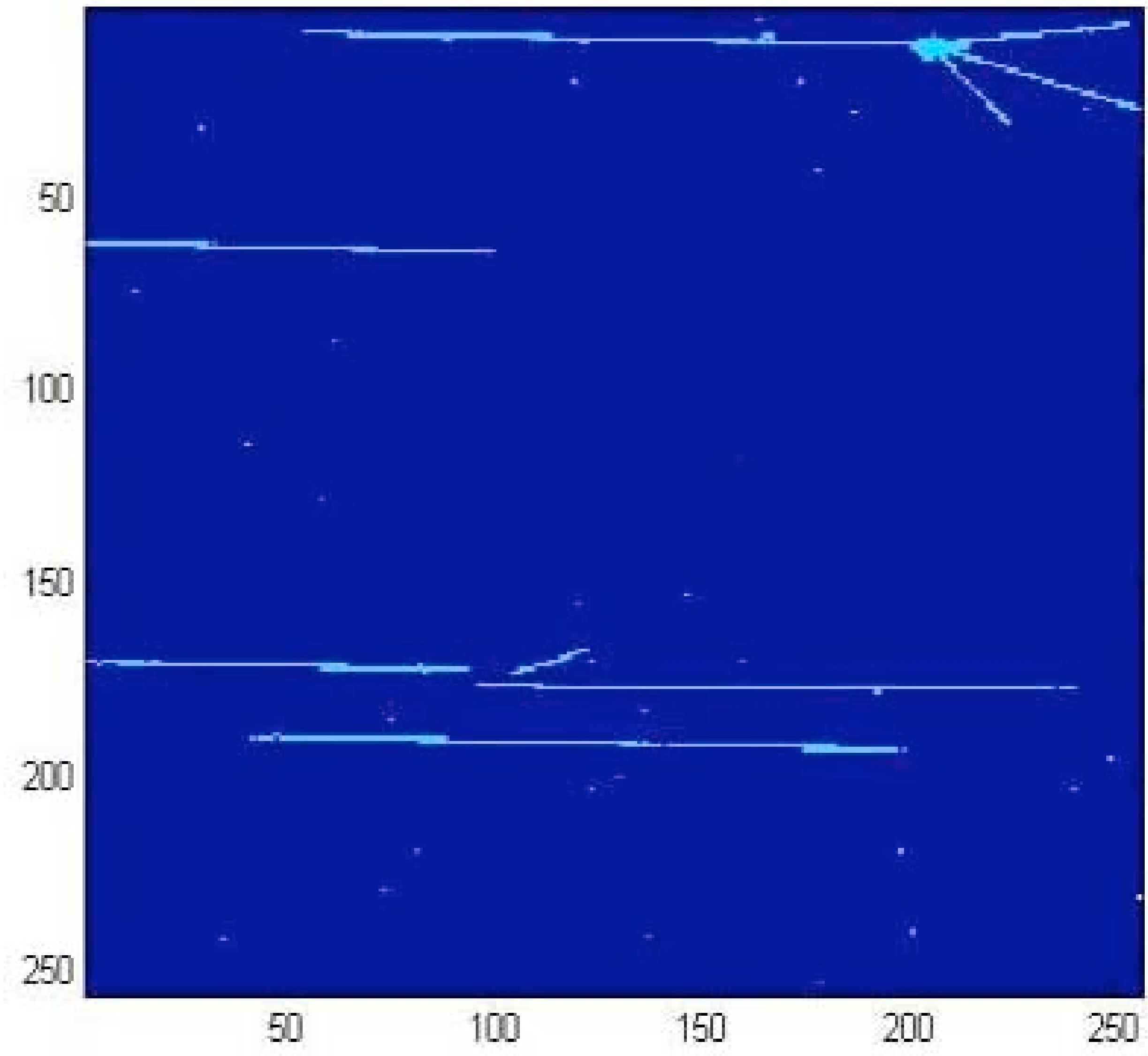

Fig. 5 Frame 02-0200 with 100 ms exposure.

volume all the way until the lower edge of the sensor. The trail consists in the beginning of two pixels on each row, but by the end it is mostly three pixels wide. Moreover, at row 160 this trail has a slight but recognizable kink. It is not possible to determine which secondary trails come out of the sensor towards you, and which leave away from you.

Another frame is shown in Fig. 5. At the top of the matrix an interaction has occurred with three registered outcoming particles. Again, a significant energy deposit surrounds the vertex in the right top corner of pixel (11,205) and this may 'hide' particles produced at ~right angle, which travel along the y direction all the way in a single pixel. A few other particles pass through the detector during this shutter time. It is not clear if the long tracks 2 and 3 counted from the bottom are coincident and also related with the wiggling track that seems to point to an 'offset point'. If time-tagging were available in the chip, such a question might be easier resolved. Note also that all particles have additional hit pixels along the trail, which indicate large energy transfers, or delta electron generation.

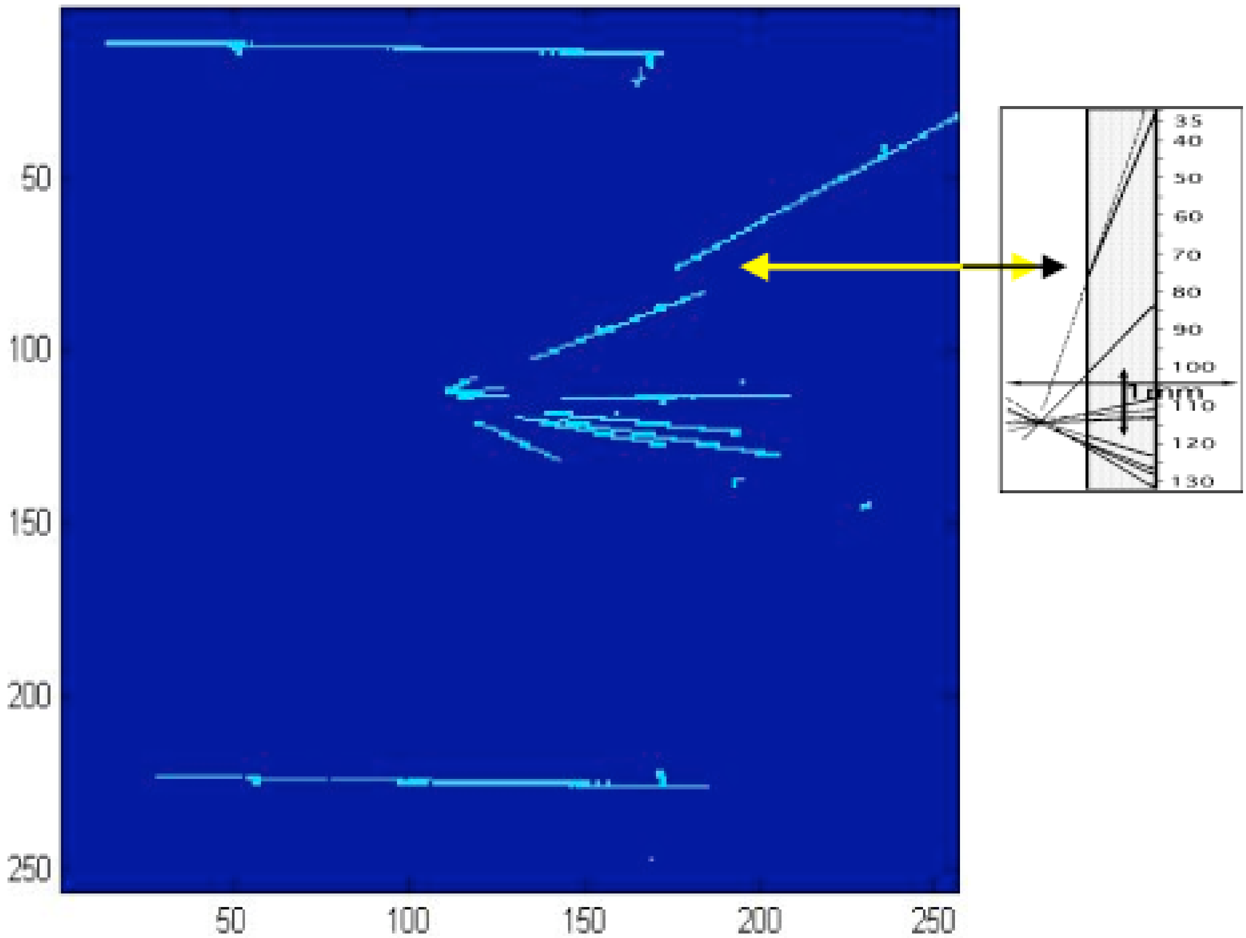

Fig. 6 Frame 03-0016, 100 ms exposure, interaction just outside the sensor volume. A reconstruction of the trails projected in the sensor thickness is shown besides. The pixel number scale is shown on the right with a 1 mm arrow for comparison, the Si thickness is multiplied in the drawing by a factor 2.

Sometimes, as in Frame 03-0016, Fig.6, the interaction takes place just outside the sensor, most likely in the silicon readout chip. Then for all recorded trails there is no ambiguity about entry and exit points and a reconstruction of the interaction in space is feasible. Even without an iterative procedure most trajectories intersect within ~5um of a spacepoint close to pixel coordinates (114,106), at a distance of 190 μm outside the sensor plane.

4.1 High energy muon trails

With a beam stopper in place upstream in the H6 beam one observes a small number of high energy muons coming from pions that decay before the dump. These muons produce typical minimum ionizing particle trails in the sensor, which look similar to those of the pions but they are more regular due to absence of nuclear interactions. A frame with a ~16s shutter time covering the full 4.8s spill is shown in Fig.7. Trails are continuous and monotonously tilted upward, crossing the rows of pixels

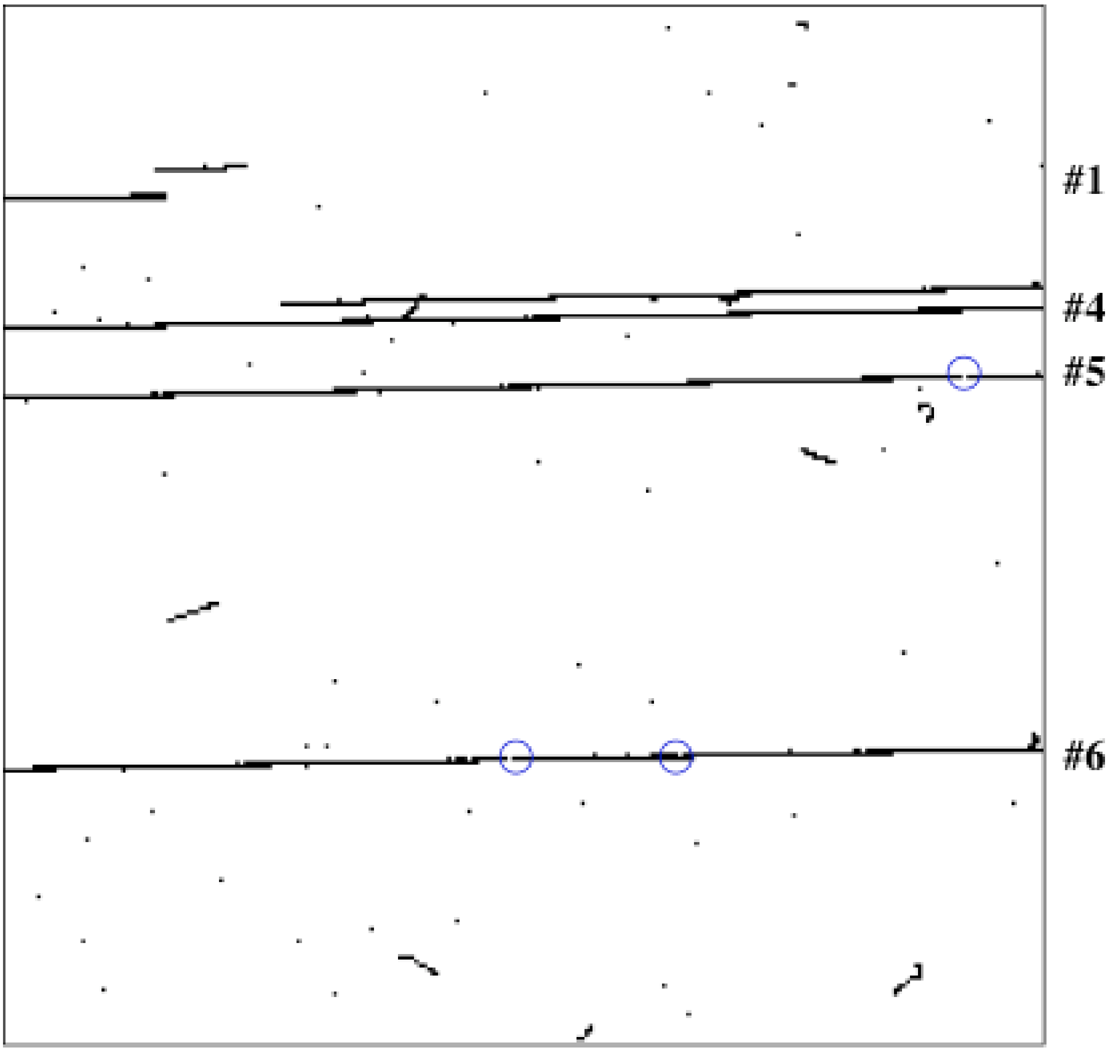

Fig. 7 Frame M01-013 with muon trails in the Medipix2 sensor assembly. Muons were coming in from the left. The parallel trails can be numbered #1 to 6 from top to bottom. Trail #5 is discussed in the text, the 1-pixel interruption is due to a dead pixel. Circles indicate 3 dead pixels which should have had a signal.

of the detector matrix with regular stretches of overlapping rows. One empty pixel in trail #5 and two in trail#6 have been identified as dead pixels, so the inefficiency for these 6 trails is 3/1019 detection points. Trails in the lower half of the matrix sometimes have a couple of missing pixels (maximum 5 on 256), but for the parallel exposure a particle passing through the detector is never completely missed.

The comparator thresholds for the input signals in all pixels of the Medipix readout chip have been tuned to an identical, fairly low value estimated between 800-1000e$^-$ (equivalent electrons at the input). A precise absolute calibration for the used chip is in progress. Typical performance for the Medipix2 chips has earlier been simulated and measured by Tlustos [9]. Electronic noise was measured at 135e$^-$ rms using the comparator response curves for several monoenergetic synchrotron beam energies, and he found an overall chip noise floor of 2.2keV, corresponding to 610e$^-$. Then a lowest threshold value setting ~800e$^-$ can be used and only a few of the 65000 pixels show occasional noise counts, while systematically noisy pixels, 6 in our device, have been switched off. Such a low threshold value allows imaging with a ^{55}Fe radioactive source, which emits K_α photons of 5.895 keV, corresponding to signals of 1628 electron-hole pairs on average. For minimum ionizing particles one expects energy deposition in thin silicon sensors of ~250eV per μm, corresponding to 13.8keV or 3800e$^-$ in the 55μm pixel length. Even if this signal is shared between two adjacent pixels, both respond as long as the threshold is below 1900e$^-$.

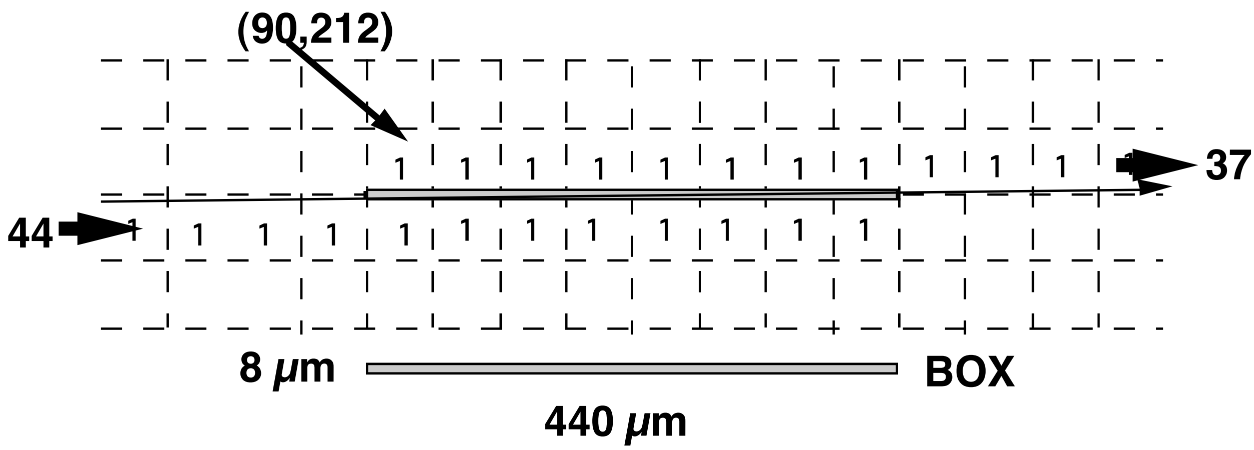

Fig. 8 Detail of muon trail #5 in frame M01-013 between pixels (91,212) to (90,219) from Fig.7. Row overlap with a sequence of double hits allows a very precise position reconstruction of the trajectory in terms of the sensor coordinates. The particle enters a virtual box of 8μm x 440μm from the bottom left, and leaves this box at the top right. In each pixel the position shifts monotonically by ~1 μm, and the trajectory at intermediate points can be interpolated to ~1/50th of one μm.

4.2 Submicron precision using charge sharing in binary system

With a low threshold setting, the diffusion of the signal charge and the sharing between neighbouring pixels allows enhanced precision, even in a binary readout system. For 18 trails in different frames we found 522 'double hits' (in stretches from 1 to 12 in adjacent rows), an occurrence of 13 % on a total of 4006 pixels. The boundary region then corresponds on average to 13% or ~7-8μm of the 55μm linear pixel dimension. Where the trail shows a series of double hits, the particle is at most 4μm away from the pixel border, and we assume that it crosses to the next pixel row in the middle of such a series of pixels. This defines a box-like boundary region and an example is drawn in Fig.8. The trajectory shifts up by ~one μm every pixel and particularly precise positions can be reconstructed within this box of 8μm x 440μm.

Charge sharing and the importance of the low threshold are confirmed by increasing the threshold value. In Fig. 9 a and b the frames M02-17 and M04-09 are shown with resp. 2 and 4 steps increase of threshold. In Fig 9a there are still a few 'double hits' but in Fig 9b they are practically absent, and already some pixels on the regular row segments have disappeared as well.

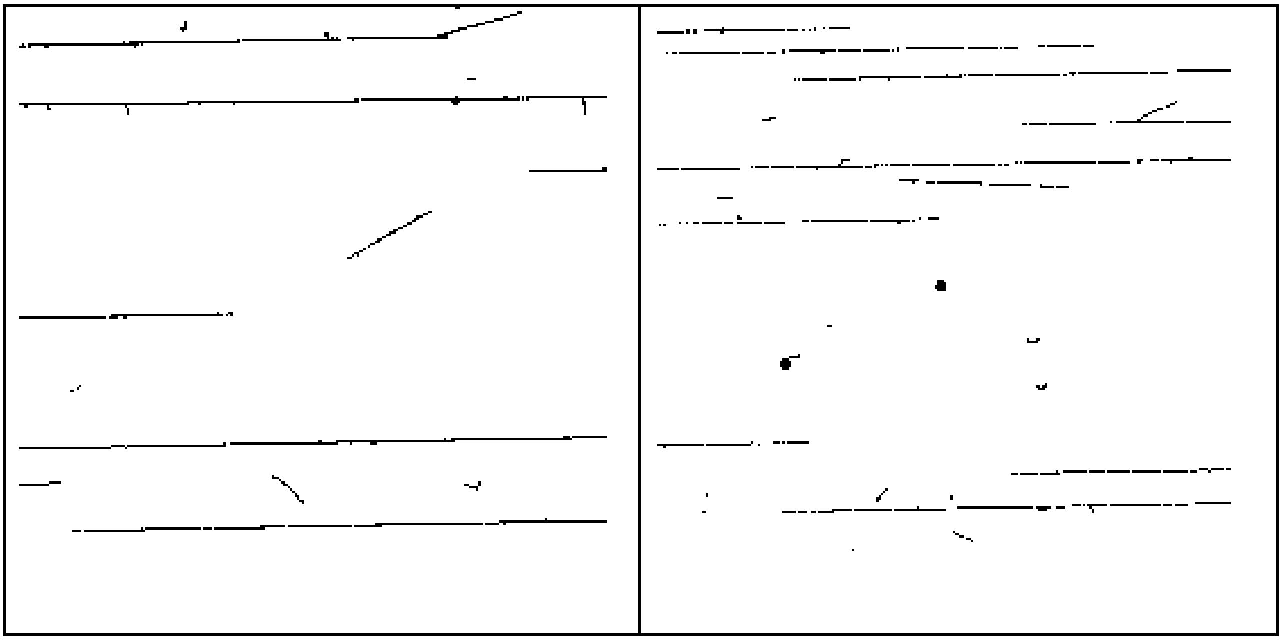

Fig. 9 a and b Muon frames M02-17 left with a threshold increase of two steps, and M04-09 with four steps. The overlap regions become shorter and pixels with shared charge around the jumps from row to row drop out the first. In Fig 9b there are also recorded two alpha particle impacts, the dark dots, probably from a neutron interaction.

The average value of diffusion distance of 8μm experimentally found here, can be compared to the values of signal charge diffusion which have been determined with a 280μm thick silicon microstrip detector by Belau et al. [10]. By a statistical analysis of a few thousand events using analog readout of a 20μm pitch sensor they found a FWHM (Full Width at Half Maximum) of 6μm at 120V detector bias and 4.5μm at 200V.

In the parallel exposed pixel detector one could use the effect of charge diffusion not only in a statistical way, but even on individual trails. If a particle travels close to the segmented pixel contacts, the diffusion would be small and only few double hits occur near the row crossing, while much more diffusion will be observed when the particle travels close to the rear of the sensor. Additional hodsocopes are needed in order to study this effect.

4.3 Vectors and autoresiduals

Thanks to the large number of precise measurement points, the detector allows a determination of the particle directions. The vector in the vertical plane for each trail can be determined simply from the number of rows, divided by the distance between exit and entry pixels. However, a more precise vector can be found if only 'closed' segments are considered in between series of double hits, where a better precision in x is available. As an example, in Table1 a comparison is made of the values of the separately determined tilt angles of the 2 open and 4 enclosed segments of trail #4 in frame M01-013

Table 1 Comparison of Tilt Angles for segments of Trail #4 in frame M01-013

SEGMENT	SINGLE HIT PIXELS	INCL. OVERLAP	TILT mradian
1 open left	37	38.5	26.0
2	43	48.5	20.6
3	37	45.5	22.0
4	41	48.5	20.6
5	41	49.5	20.2
6 open right	20	25.5	39.2
ALL 256 pixels	219	256	23.4
FIT on 5 pts			20.92

from Fig.7. The open segments left and right deviate from the values for the enclosed segments. The least squares straight line fit through the 5 high precision mid-points results in 20.92 mrad and apparently the precision is better than ±1 mradians. Variance of the residuals with this fit is 1.38μm.

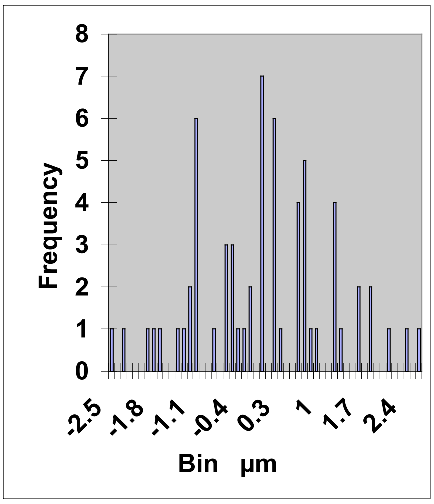

Fig. 10 Histogram of the distribution of autoresiduals of 88 closed segments in muon tracks. The predicted positions are based on the extreme points in a trail and the differences between measurements and predictions at the other row cross-over points in the trail are shown here.

Taking several segments of one trail, one can determine what we call 'autoresiduals'. We make here a first evaluation by taking the extreme points from closed segments and predict the other cross-over points between rows with the angle of this hypothetical trajectory. For 88 segments a distribution is obtained in Fig. 10. Most values remain between ±2.5μm and a preliminary precision between 0.5 and 0.8μm can be estimated from this small statistics. Improved fitting procedures are being studied.

5. Discussion and conclusion

Finally, nearly 20 years after the first dreams about micropattern pixel detectors [11] it has been shown here that even a single silicon pixel detector can produce detailed images of particle interactions. Imaging is 'quasi 3-dimensional' and a projection is obtained of particles as they travel in a thin slice of space. Making use of the redundancy in the measurement and the montonous character of the particle trails through the regular matrix of pixels one can achieve submicron precision on particular space points in the reconstruction of the particle trajectory. Such sub-μm precision can be achieved with small, square pixels and if the amplifier-comparator chain has sufficiently low noise ~100 e^- rms, so that one can make use of the tails in the charge diffusion. In the Medipix2 detector at a threshold between 800 e^- and 1000 e^- we register hits in adjacent pixels when the particle is within a small distance (3 to 5μm) of a pixel border. Scattering and large energy transfers can be recognized. The detector is beam hodoscope, target and analyzing detector at the same time, as it was with bubble chambers or nuclear emulsions. It is also essential that the sensitive thickness of the sensor wafer is not too small, so that a fair part of the trajectories can be contained. In this mode of operation one obtains a continuous chain (~20 per mm) of measurement points and the direction of the trajectory can be determined with better than ± 1 mradian precision in the sensor plane (here it was vertical). At the same time the perpendicular component of the vector also can be estimated, but with less precision. Residuals can be determined in the detector itself, and a preliminary evaluation of such 'autoresiduals' resulted in a distribution with sigma <0.8μm.

For this type of longitudinal application of a pixel matrix it may not be necessary that the sensor is as long as 14mm. From the closed segments measurements it appears that ~3mm might be already sufficient, as long as particles cross the border between several rows or columns of pixels. Increased coverage of solid angle or larger area would need three-dimensional stacking of several sensor chips (300μm), with thinned CMOS readout chips (~20μm) in between. Also a cooling mechanism must be provided, either with microchannels and liquid coolant in the 3-D stack itself, or nearby with a heat conductor such as diamond-like film.

Application of stacked pixel detectors for tracking in collider experiments would require much more study and development, and tradeoffs are not obvious. If analog information could be provided in pixels, it may be possible to achieve particle identification in Si in many more cases than now. We do not doubt that a variety of special applications will be found. A suggestion has already been made to use this principle as a guideline for neutrino factory detectors.

Acknowledgements

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REFERENCES

[1] F. Anghinolfi et al., A 1006 element hybrid silicon pixel detector with strobed binary output IEEE Trans. Nucl. Sci. NS-39 (1992) 654 also: CERN/ECP 91-26 or Nucl. Instr. Meth. A305 (1991) 527 presented 2nd Pixel Workshop Leuven

[2] Erik H.M. Heijne, Future semiconductor detectors using advanced microelectronics with post-processing, hybridization and packaging technology, Nucl. Instr. Meth. A541 (2005) 274, presented STD5 Hiroshima

[3] Advanced Silicon Technology, W. Haensch and M. Ieong, Special Issue, IBM J. Res. Dev. Vol 50, Number 4/5, July/September 2006

[4] X. Llopart and M. Campbell, First test measurements of a 64k pixel readout chip working in single photon counting mode, Nucl. Instr. Meth. A509 (2003) 157, presented IWoRID 2002, Amsterdam

[5] David San Segundo Bello, Martin van Beuzekom, Peter Jansweijer, Hans Verkooijen and Jan Visschers, An interface board for the control and data acquisition of the Medipix2 chip, Nucl. Instr. Meth. A509 (2003) 164, presented IWoRID 2002, Amsterdam

[6] Z. Vykydal, J. Jakubek and S. Pospisil, USB interface for Medipix2 pixel device enabling energy and position-sensitive detection of heavy charged particles, Nucl. Instr. Meth. A563 (2006) 112

[7] M. Maiorino, R. Martinez, G. Pellegrini, G. Blanchot, M. Chmeissani, J. Garcia, M. Lozano, C. Puigdengoles and M. Ullan, A read-out system for the Medipix2 chip capable of 500 frames per second, Nucl. Instr. Meth. A563 (2006) 96

[8] T. Holy, J. Jakubek, S. Pospisil, J. Uher, D. Vavrik, Z. Vykydal, Acquisition and data processing software package for Medipix-2 device, Nucl. Instr. and Meth. A563 (2006) 254, see also http://www.utef.cvut.cz/medipix/

[9] L. Tlustos, Performance and limitations of high granularity single photon processing X-ray imaging detectors, PhD Thesis, TU Wien, 2005 (CERN Thesis 2005-003)

[10] E. Belau, R. Klanner, G. Lutz, E. Neugebauer, H.J. Seebrunner, A. Wylie, T. Böhringer, L. Hubbeling, P. Weilhammer. J. Kemmer, U. Kötz and M. Riebesell, Charge collection in silicon strip detectors, Nucl. Instr. Meth. 214 (1983) 253

[11] E.H.M. Heijne, P. Jarron, A. Olsen and N. Redaelli, The silicon micropattern detector: a dream ? Nucl. Instr. Meth. A273 (1988) 615 (London Conf.1987)

[12] sheet 84 in http://indico.cern.ch/contributionDisplay.py?contribId=125&sessionId=47&confId=0510