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DOE FINAL REPORT

Silicon Drift Chamber studies for Possible use at RHIC

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Summary

This is the final report for the DOE project "Silicon Drift-Chamber studies for Possible use at RHIC" carried out at the University of Pittsburgh by T. J. Humanic (principal investigator), two graduate students and two post-doctoral researchers. This study was carried out during the period 3/89-4/93 under DOE Grant No. DE-FG02-89ER40503. The termination of this grant was caused by the movement of the principal investigator from the University of Pittsburgh to Ohio State University, where this work is continuing under a different grant. During this period we investigated various aspects of silicon drift chambers including two-track resolution, effects of external magnetic fields and different detector designs.

I) Introduction

In 1989 we received RHIC R&D funding to begin a study of the suitability of silicon drift chambers (SDC) for use in RHIC detectors. Within one year we were able to set up a testing laboratory at Pittsburgh, obtain (from P. Rehak at BNL) one of the few working SDC's in the world at that time (a $1 \times 1.8 \text{ cm}^2$ prototype) and carry out some preliminary base-line measurements with this detector. In the following year we made the first two-hit resolution measurements and first measurements in a magnetic field with an SDC. This work has resulted in a recent publication¹ based on the two-hit resolution measurements .

In the Summer of 1990, the decision was made to use SDC's in the vertex detector for the RHIC OASIS detector. The Pittsburgh group played a leading role in designing this detector which eventually led to the design, in collaboration with BNL, of a prototype $4 \times 4 \text{ cm}^2$ SDC. With the decision by the RHIC program advisory committee not to approve OASIS, Pittsburgh decided to join the RHIC STAR collaboration which was also planning to use SDC's in its Silicon Vertex Tracker (SVT). The "OASIS prototype SDC" was renamed the "STAR prototype SDC" (designated "STAR1").

In August 1992 the principal investigator moved from Pittsburgh to Ohio State University, taking with him the graduate students and equipment involved in the SDC work. We have since set up a testing laboratory at OSU and are planning to continue testing detectors for the STAR experiment. The first STAR1 detectors have now been fabricated at BNL and are being distributed to the various laboratories (LBL, OSU, and WSU) for testing. One detector has already undergone some preliminary testing at LBL. For this effort OSU is playing an important role. Two other prototype designs are also in the process of fabrication. One is based on dividing the detector up into two drift sections for faster readout times and lower applied voltages (designated "STAR2") and another is based on p type silicon for lower cost and possibly better radiation damage characteristics. Both of these designs will be available for testing by the end of 1993.

In addition to the principal investigator, two graduate students and two

post-doctoral researchers have worked on this project. The two graduate students have been G. Vilkeli (1990-present) and R. Jayanti (1991-present). The two post-doctoral researchers were M. Clemen (1991-1992) and D. Kraus (1990-1992).

SDC studies carried out by the Pittsburgh group during the period of this grant will now be described below. Section II gives a brief discussion of the principles of operation of SDC's. Section III describes the experimental test setup at Pittsburgh. Sections IV, V, and VI describe measurements of position versus time, two-track resolution, and magnetic field effects, respectively. Finally, Section VII discusses new designs for SDC's in which the Pittsburgh group participated.

II) Principles of Silicon Drift Detectors

Silicon drift detectors are a relatively new kind of semiconductor detector able to provide very precise position and ionization measurements with a very modest amount of electronics. A perspective view of the drift detector is shown in Figure 1.

Figure 1. Perspective view of a silicon drift detector. Electrons created by an ionizing particle are transported parallel to the detector surface. The anode is divided into short segments to measure the coordinate perpendicular to the drift direction

In principle, the electric field of the drift detector forces electrons liberated by an ionizing particle to drift parallel to the large semiconductor surface to the anode. The transit time of electrons inside the

detector measures the distance of an incident particle from the anode.

As a direct consequence of this electron transport method the anode capacitance is much lower than the anode capacitance of the classical semiconductor detector for the same dimensions. The amplifier noise can be made much smaller which is the main reason behind the excellent position resolution of silicon detectors. The measured position resolution in a test beam was 10 micro-meters on the drift distance of 4000 micrometers. These results² were achieved with external amplifiers which were not matched to the very low anode capacitance. As an example, the drift detector to be used in the UA6 experiment at CERN SPPS has an area of 4cm x 4cm, maximum drift time of 1.5 microseconds, total number of anodes 332 and an unambiguous x-y position resolution of 10 micro-meters in both directions.

It should be stressed that the maximum drift time is not the dead time of the silicon drift detector. Due to the fact that all electrons are continuously drained at the anode the silicon drift detectors have no dead time. Electrons drifting toward the anode have their charges screened by the electrode structure of the silicon drift detector and do not interfere with the other signals or with the signal processing at the anode. The signals are stored within the detector for the duration of their drift.

Figure 1 shows the collection anode divided into individual pad-anodes. The position of the responding anode(s) measures the coordinate perpendicular to the drift direction. Due to the transverse diffusion, the electrons produced by the ionization arrive as a gaussian shaped charge cloud in the anode region. Charge will be usually collected on more than one anode. The charge division method yields the position of the crossing particle in the second coordinate with a precision down to about 4% of the anode-pad pitch. This multi-anode silicon drift detector provides an unambiguous two dimensional position information. The position information is similar to one which is to be expected from proposed silicon pixel devices. The multi-anode silicon drift detector gives better resolution with four orders of magnitude less read-out channels.

III) Experimental test setup at Pittsburgh

In March of 1989 we received RHIC R&D funding to begin our study of silicon drift-chambers. Since then we have established a collaboration with P. Rehak of BNL, set up a testing lab at Pittsburgh, and carried out tests on an actual device. Most of the tests we have made have been performed on a developmental detector which served as a prototype for a CERN/Milano effort to develop a practical device for use in the UA6 experiment. Although the prototype detector is smaller in area (1x1.6 sq.cm) compared with the UA6 detector (3.2x4 sq.cm) its performance characteristics are considered, at this point, to be better than the UA6 detector and thus better suited for our tests to see if such a device is useful for the RHIC environment. The detector, one of five such detectors in existence, was obtained from Rehak at BNL. After some initial dark current testing at BNL, we brought the detector to Pittsburgh to electrically bond it to a pc-board for the further tests (two other detectors were also bonded at Pittsburgh for BNL). We also borrowed some readout electronics from BNL consisting of preamplifiers and gaussian shapers. The rest of the equipment for the test lab was purchased with DOE and University money, and consists of:

- a 4x6 sq.foot optical table for mechanical stability and easy fixturing
- a pulsed Nd:Yag laser producing a fast (6ns width) pulse in the infrared (1064nm) suitable to simulate the effects of a minimum ionizing particle in the detector
- six channels of 200Mhz time digitizers to digitize the signals from four readout anodes of the detector in 5ns bins to study their pulse shapes
- a PC that is connected to the digitizers via an RS-232 link that is used for further pulse shape analysis
- optics to focus the laser beam to a several micron spot on the detector
- a computer-controlled x-y stage to precisely position the detector under the laser beam

Figure 2 shows the experimental setup. The infrared pulse from the

Figure 2. Experimental setup used at Pittsburgh for SDC tests.

laser is brought to the focussing optics via light fibers which help define the eventual size of the focussed spot on the detector and which, in groups of fibers, can be used to simulate multi-particle hits on the detector. The anode signals are then put through low-noise preamplifiers and gaussian shapers ($\sigma = 27$ ns). The gaussian signals are finally digitized and stored onto disk by the digitizer-PC system for further analysis.

IV) Position versus Time measurements

Figure 3 shows pulse shapes from their respective gaussian shapers (negative pulses) of four adjacent anodes from incident laser pulses.

Figure 3. Digitizer readout of four adjacent anodes with laser pulses incident on the silicon drift detector. Note that pulses are negative.

Three pulses are seen in each anode corresponding to three optical fibers which guided the laser light to positions 4.71mm, 5.64mm, and 13.4mm along the drift direction of the silicon drift detector. Although each light pulse was focused onto the detector to a 5 micron spot, charge is seen to leak into adjacent anodes (Anodes are 250 microns apart.) showing the lateral size of the electron cloud for each pulse to be of order > 250 microns. Note that the intensities of the laser pulses were adjusted to simulate as closely as possible the charge produced by minimum ionizing particles, i.e. about 25,000 electrons. A drift field of 300 V/cm was used for the measurement, resulting in a drift velocity for the electrons of 3.57 mm/microsecond. Using data like this, we produced the drift time versus laser beam position (along drift-field) plot shown in Figure 4.

Figure 4. Drift time versus position for two different field settings, 170 V/cm--star, and 230 V/cm--cross.

Plots are shown for two different drift fields, 170 V/cm and 230 V/cm. The plots are seen to be quite linear throughout the measured ranges, resulting in a position error for a particular time on the order of 10 microns. We have also examined position readout in the anode direction using charge division between anodes and get a similar results for that coordinate. These results agree with previous measurements and are close to theoretical expectations (see Ref. 2).

V) Two-track resolution measurements

In the high particle density environment of RHIC, the ability of an SDC to resolve close hits in space is crucial for good track reconstruction efficiency. This ability is particularly important for two-boson interferometry studies where close hits are most sensitive to

the interference effect³. Thus one of our highest priorities has been to measure the two-hit resolution of our 1 X 1.8 cm² SDC and compare our measurements with theoretical predictions for these devices. Gatti et al.⁴ have made two-hit resolution predictions for SDC's.

Our two-hit measurements will be briefly described here. These results have been published and thus a more detailed account of our measurements can be obtained elsewhere¹. We simulated two particle hits using 8 ns pulses of 1064 nm light from a Nd:Yag laser which was split into two pulses using two light fibers. These fibers illuminated a microscope objective which was used to focus the light pulses to 20 micron spots on the SDC. The separation between the fibers at the microscope was adjustable using a precision set screw. The anode signal was preamplified and shaped ($\sigma=27$ ns) and fed into a 50 Mhz 7-bit digitizer. The digitized anode signal was then stored in an 8088-based computer and analysed off-line. Four adjacent anodes were instrumented in this way. The off-line analysis consisted of fitting two Gaussians to the two-hit anode signals and comparing the fitted positions of the peaks with the known positions of the light fibers having been set with the precision set screw mentioned above. Figure 5 shows a comparison between our measured two-hit spacing errors (points) and that predicted by Gatti et al. (curve). Plotted in this figure is the two-hit spacing error relative to the σ of the individual pulse width versus the relative pulse separation.

Figure 5. The measured spacing reconstruction uncertainty normalized to the single Gaussian waveform sigma versus the spacing normalized to the same. The prediction of Gatti et al. is shown as the curve.

Measured points are shown for one to four times minimum ionizing (simulated by varying the laser pulse intensity). All measured points are seen to fall near or below the predicted error except for the one-minimum-ionizing point below $2\text{-}\sigma$ separation, which is twice the predicted error. In terms of actual positions, Gatti et al. predict position errors of about 25 microns or less at 500 micron separation (i.e. $2\text{-}\sigma$) or greater which we also measure except for our 500 micron separation point which gives a 50 micron error. As discussed in Ref. 1, this could be due to sampling errors.

VI) Magnetic Field Measurements

Because these detectors might find applications as particle trackers in the magnet fields of spectrometers (as in the STAR experiment) it is important to study the effects of magnetic fields on the operation of silicon drift chambers. Since no measurements of this kind existed, we decided to perform a series of measurements with our prototype detector in a 1 Tesla magnet that exists at the University of Pittsburgh. A range of magnetic fields were used from .1 T to 1 T, the direction of the field always being perpendicular to the surface of the detector to see the maximum effect on the drifting electrons. Figure 6 shows a calculation of

$B_y = 0.88 \text{ T}, \quad E = 531.0 \text{ V/cm}, \quad u = .148$
 $x_0 = 5.288 \text{ mm}, \quad dx = -0.58 \text{ mm}, \quad T = 0.788 \text{ usec}$

Figure 6. Simulation of the path deviation of electrons in a 0.8 T field for a particle hit at 5.2 mm from the anodes. A deflection of about 2 anodes is seen.

Figure 7. Tan(θ) vs. B-field measured on our prototype drift chamber. The drift field was 531 V/cm.

how the path of the electrons in a drift chamber is modified by a 0.8 T field for a laser pulse (or particle) incident at 5.2 mm from the anodes. The deflected path, deflected by an angle $\theta=6.4$ deg. from the no-field case, is a straight line that is offset by 0.58 mm at the readout anodes, i.e. about a two anode deflection. For this calculation a drift field of 531 V/cm and electron mobility in silicon of 0.14 meter/(V-sec) were used. We have measured tan(θ) versus B-field for a range of fields and get the results shown in Figure 7.

The Hall mobility, μ_H , is given by the ratio tan(θ)/B and is expected to be close in value to the electron mobility, μ . We used measurements like those shown in Figure 7 to obtain the Hall mobility versus B for several different drift fields. The results are shown in Figure 8.

Figure 8. Hall mobility versus B-field and drift field. circle--185 V/cm, star--295 V/cm, cross--531 V/cm. Note that B-field is perpendicular to the surface of the drift detector.

In Figure 8, three different drift fields are shown, 185 V/cm, 295 V/cm, and 531 V/cm. Within the error bars, μ_H seems independent of the applied B-field, though it does depend on the drift field--the larger the drift field, the smaller μ_H . The Hall mobility for electrons for high-resistivity silicon has been previously measured using the Hall effect at room temperature (300K) to be 0.145 meter/(V-s)⁵. This is seen in Figure 8 to be close to what we measure using the method described above. Our dependence on drift voltage is thought to be caused by heating of the drift chamber by the implanted resistive divider at the higher drift voltages, since it is found in the literature that μ_H has a strong temperature dependence⁶. In our next series of measurements, we plan to monitor the temperature of the silicon drift chamber to study this dependence. As a comparison to the Hall mobility, we have also measured the electron mobility, μ , as a function of B-field and drift field, as shown in Figure 9.

Figure 9. Electron mobility versus B-field and drift field. circle--185 V/cm, star--295 V/cm, cross--531 V/cm.

The electron mobility has been extracted from information like that obtained in Figure 4, i.e. from the drift velocity and applied drift field. The electron mobility is also seen to be independent of B-field but strongly dependent on drift field. A quantity which is often defined is the Hall factor which is the ratio μ_H/μ . This is plotted in Figure 10 versus B-field for a drift field of 295 V/cm.

Figure 10. Hall factor versus B-field for a drift field of 295 V/cm. The crosses represent laser pulses that simulate a minimum ionizing particle, and the stars represent three times minimum ionizing.

The Hall factor is seen to be about 1.2 for this drift voltage, which is close to a theoretical prediction made by Long at room temperature (300K). Note that this ratio is not very sensitive to the intensity of the laser pulse (see figure caption).

VII) Design of STAR Detectors

In the Summer of 1991 Pittsburgh and BNL (Rehak) designed a 4 X 4 cm² prototype SDC for the OASIS detector, the design of which was taken over by STAR when OASIS was cancelled as mentioned above. The design of the electrode and guard-ring layout was done by G. Vilkelis of Pittsburgh working at BNL under the supervision of P. Rehak on a SUN-based CAD system. The anode region has been designed by Rehak and incorporates two transistors in a Darlington pair configuration directly integrated on half of the anodes for a first stage of low-noise amplification. Figure 11 shows a schematic representation of the STAR1 prototype.

Figure 11. Schematic representation of the STAR1 prototype

Note that the active area of the detector is trapezoidal in shape with a lower width of 4.5 cm, an upper width of 3.5 cm, and height of 4

cm. This shape is determined by the requirement that the voltage at the (negative) high voltage end must be given a finite distance to drop to ground to avoid unwanted surface currents and sparking. The "useful active area" is defined as the rectangle 3.5 cm wide and 4 cm high---anodes in this width will be instrumented. The readout anode pitch is 250 microns resulting in 140 anodes being read out per detector. The detector thickness is 250 microns. As mentioned above, only half of the anodes have the implanted Darlington-pairs. This is to insure that if the higher-risk-of-production Darlington-pair anodes fail, the prototype can still be used in the more conventional preamplifier readout mode. Although the rest of the prototype design was finished by August 1991 the anode region design (with Darlington pairs) was more problematic. Near the beginning of February 1992, the problems with the anode region design were solved and a mask of the detector layout was made by an outside vendor. The first STAR1 detectors were fabricated in August 1992. These have been wire-bonded to PC-boards which Rama Jayanti helped to design.

Two new prototypes are also being designed and fabricated for later evaluation. The STAR2 prototype is somewhat larger than the STAR1 in size and also has the feature of being read out as two half-detectors as seen in Figure 12. This has two main advantages: increased read-out speed due to smaller drift distances and lower applied drift voltages.

Figure 12. Schematic representation of the STAR2 prototype

The disadvantage is seen to be twice as many read-out channels. The second new prototype is also similar to STAR1 but is made with p-type silicon doping instead of the n-type now being used. The main advantages of this design are that p-type silicon is much cheaper and more plentiful than the high-resistivity n-type used for STAR1 and may be more resistant to radiation damage. The main disadvantage seems to be the lower mobility of holes (which are the majority charge carriers in p-type) making the read-out times three times longer than n-type. Gintas Vilkelis has been responsible for designing the masks for the p-type detector. Both new detector prototypes should be available for testing by the beginning of 1993.

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