# Measurement of Two Particle Resolution in Silicon Drift Detectors. [1]

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*Abstract*

A study resolving two hits in a 45x45 mm rectangular n-type Silicon Drift Detector is presented as a function of drift field using a pulsed Nd:Yag laser. The data are analyzed under the assumption of the general form of a Gaussian distribution in two variables (including correlations). The two hit resolving power degrades with drift distance. As the two electron clouds approach each other their correlation coefficients are shown to increase and be anti-correlated. Arguments for optimal two hit resolution versus drift field are presented. A simple method to determine whether electron cloud distributions arise from multiple overlapping hits or single hits is demonstrated. Practical implications for analyzing data from high occupancy experiments such as STAR at the RHIC collider are discussed.

## I. Introduction

A Silicon Drift Detector (SDD) is a charged particle position measuring device with a position resolution on the order of 10 $\mu$m in each coordinate[1, 2, 3]. A charged particle crossing the detector leaves a trail of electron-hole pairs within a tube of $< 1$ $\mu$m along its path whose center of gravity shifts slightly due to $\delta$ electrons and fluctuations in energy loss[4]. Holes are immediately absorbed by the cathodes on the surface of the detector. Electrons converge to the middle of the bulk and drift at a constant speed under the influence of an applied uniform electric field toward low capacitance anodes located near the edge of the silicon wafer. One coordinate of the particle position is determined from the drift time while charge division between anodes gives the other coordinate.

Future experiments will take place in high luminosity machines such as the Large Hadron Collider (LHC), and the STAR-SVT experiment at the Relativistic Heavy Ion Collider (RHIC) where large occupancies per detector are expected (35-100 hits per 6x6 cm silicon wafer). Silicon detectors are expected to track charged particles close to the collision for primary and secondary vertex reconstruction, momentum measurements, and to resolve near by tracks to enhance the Bose-Einstein measuring capabilities and resonance reconstruction ability of detectors. Silicon drift detectors have pixel like readout with relatively few readout channels (compared to pixel detectors) making them attractive to work with in a heavy ion environment. The ability of these drift detectors to resolve close hits is important to study.

The goal of this present work is to to study the two track resolution of SDD's, in all orientations of the drift and anode coordinates, with respect to the drift velocity, and drift distance. Previous works have only investigated orientations (often simulated) where both hits are along the drift direction and collected on one anode[2, 5, 6]. The general form of a Gaussian distribution in two variables (including correlations) is assumed while fitting the distributions of the two charge depositions. Using this general fitting form is argued to greatly increase the two hit resolution of SDD's when both hits are parallel to the anodes. It is shown that there exists an optimal drift field to maximize the SDD's two track resolution. Measurements are compared to the theoretical response of the detectors.

## II. Background

The measurements were made using a STAR-1 4.5 cm x 4.5 cm rectangular, 300 $\mu$m thick, one-way drift Silicon Drift detector (SDD) having 178 anodes at 250 $\mu$m pitch and 332 cathodes at 120 $\mu$m pitch. They were made out of 3" diameter 8 k$\Omega$·cm N-type NTD Silicon wafers with (111) crystal orientation. The operation of this type of detector has been described in detail elsewhere[7].

A minimum ionizing particle deposits about 24000 electrons which are efficeintly collected by the SDD as seen in fig. 1a. These electrons are constrained to the center of the silicon wafer while they drift towards the anodes subject to diffusion and coulomb self-repulsion producing an approximately gaussian spread in carrier density[8]. The longer the cloud drifts the more it spreads and the lower is its amplitude as seen in fig. 1b. The change in cloud width with drift distance seen in fig. 1c implies a change in two hit resolving power with distance.

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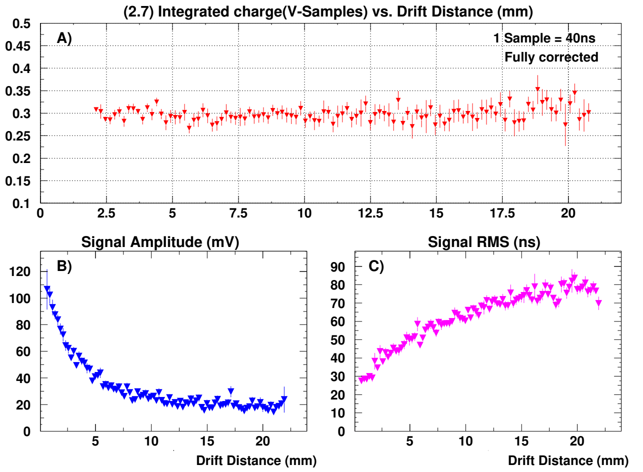


Fig. 1 Measured hit characteristics of a MIP on a STAR 2.7 SDD. The change in hit width with distance in c) changes the two hit resolution with distance.

The natural variable to study two hit resolution issues is

$$\kappa = \Delta r / \sigma_r \tag{1}$$

where $\Delta r$ is the measured separation between the two hits (either in units of time or length) and $\sigma_r$ is the width of an individual hit (the gaussian sigma in this case). One's two hit resolving power is strongly correlated to $\kappa$ (large $\kappa$ means good two hit resolving power). In the following discussion we assume both hits are caused by a minimum ionizing particle (MIP). Looking at the problem in two dimensions has more information than one dimension as seen in fig. 2. The one dimensional projections (anodes and drift time) hide information as reflected in their reduced $\kappa$ compared to the 2D figure. In the projections in fig. 2 when $\kappa = 3$ two hits are distinguishable by eye with two well resolved peaks separated by a valley (the equivalent Rayleigh criteria). When $\kappa = 2$ in the projections in fig. 2, the two hits merge into one and can only be distinguished from one another via a deconvolution based on a knowledge of the shape of each hit (not always know in advance since one hit might arise from a particle of several MIP). In principle with deconvolutions in the absence of noise and with infinite sampling one's double track resolution is of the order of one's single hit resolution. In fig. 3 the sum of two gaussian shaped hits separated by $\kappa = 2$ is barely distinguishable from a single gaussian. In the presence of 4mV noise (true for the STAR-SVT) and a digitization bucket of 40ns the two are indistinguishable without prior knowledge of the expected shape of each hit. Also shown in fig. 3b, c, and d is the measured shape of a hit left by a MIP using the STAR-SVT electronics. We sample only a few points on the hit and in the anode projection essentially only 3-4 anodes have distinguishable signal/noise (S/N) on them.

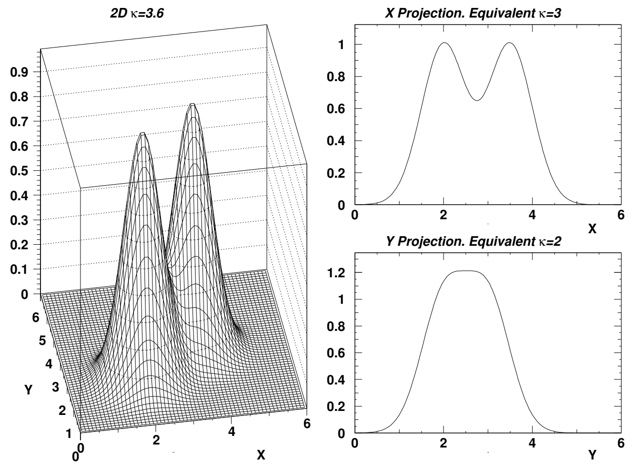


Fig. 2 Simulated profile of two hit resolving power as a function of $\kappa$ in 2D on the left and the corresponding projections on the right. X and Y are arbitray labels for axis in the same units.

A one dimensional gaussian has 3 free parameters (2 if one constrains the width to a known value) and one would have trouble fitting the data in the anode direction to determine the position and amplitude of the hit (0-1 degrees of freedom in the fit). This difficulty only gets compounded when two hits are close to each other. The solution is to fit the hit under the assumption of a two dimensional gaussian. In general a two dimensional gaussian including correlations has 6 free parameters:

$$z = Aexp\left(-\frac{1}{2}\frac{1}{1-\rho^2}\left(\frac{(x-x_0)^2}{\sigma_x^2}+\frac{(t-t_0)^2}{\sigma_t^2}-\frac{2\rho xt}{\sigma_x\sigma_t}\right)\right) \tag{2}$$

where z is the probability function, A is the amplitude, x and t are the anodes and drift time buckets coordinates, $x_0$ and $t_0$ are the position of the peak in anode and drift time coordinates, $\sigma_x$ and $\sigma_t$ are the widths of the distribution, and $\rho$ is the correlation coefficient[9]. The complete hit in fig. 3b has over 25 pixels with good S/N or degrees of freedom, which is large compared to 6 free parameters in the fit. In fig. 4 any distortions to the

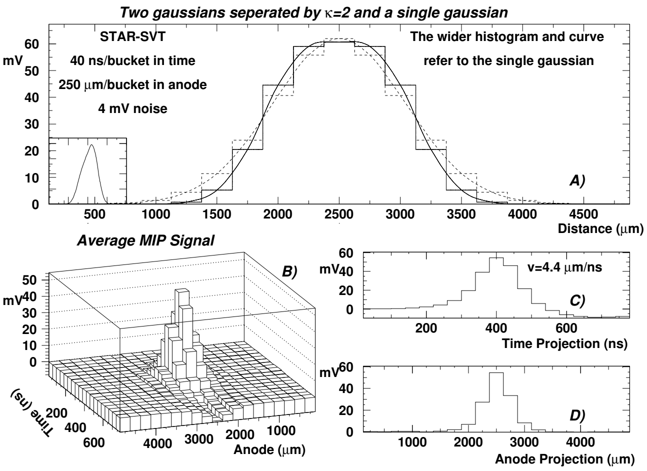


Fig. 3 In a) two simulated gaussians separated by $\kappa = 2$ are barely distinguishable from a single gaussian especially in the presence of 4mV noise. If one hit has half the amplitude of the other the resulting waveform is nongaussian and will be distinguishable as seen in the inset in a). Figure b) shows a measured typical MIP hit on a SDD. Figures c) and d) are projections of b) in the time and anode direction. Finite sampling of the hit in STAR-SVT complicates fitting. The undershoot in the time direction arises from the bipolar PASA response.

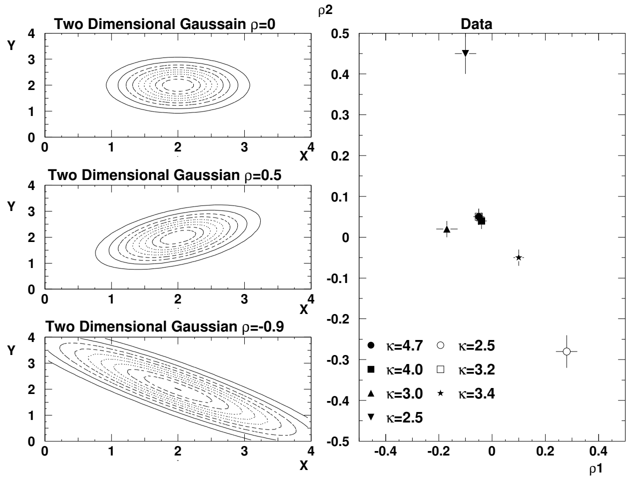


Fig. 4 On the left is the simulated shape of a gaussian with different correlation coefficients ($\rho$) but identical widths. X and Y are arbitary labels for axis in the same units and the contours shows areas of equal amplitude. On the right are measured values of the correlation coefficients for two hits for different values of $\kappa$. As $\kappa$ decreases the $\rho$'s of each hit increase and are anti-correlated

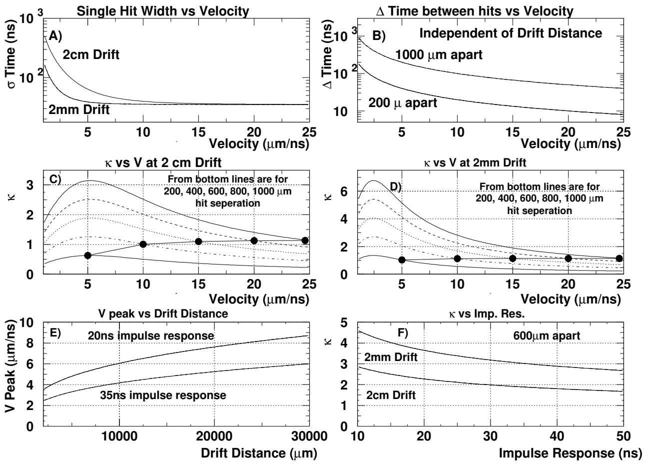


Fig. 5 These plots show the predicted SDD's two hit resolving power in the drift direction (or $\kappa$) is a function of drift velocity, drift distance, sampling rate, and the PASA impulse response. The lines connected by dots in c) and d) are the 40ns sampling limit. The curves in c) and d) bend over due to the finite impulse response of a PASA. In e) optimal velocity to maximize the SDD's two hit resolution is a function of drift distance. In f) lowering the impulse response of the PASA improves $\kappa$.

shape of a expected gaussian hit can be determined by the value of $\rho$. In practice one can ignore the correlation coefficient since in SDD's we are primarily interested in the mean position and integrated charge of a hit rather than its shape.

The measured separation between two hits, a constant separation apart, remains constant in both the drift and anode direction with increasing drift distance, but the width of a hit increases proportional to the the square root of the drift distance. Thus in SDD's two hit resolving power (or $\kappa$) gets worse with increasing drift distance. With increasing velocity the measured separation in time between two hits a constant separation apart decreases inversely with increasing velocity. In the anode direction the measured separation is constant with increasing velocity. However, the width of each hit decreases with increasing velocity since we drift for shorter periods of time:

$$\sigma = \sqrt{2Dt} = \sqrt{2Dx_0/\nu} \qquad (anode\ direction) \tag{3}$$

where D is the diffusion constant, and $\nu$ is the velocity. In the drift direction one divides the above equation by $\nu$ to get the width. Hence $\kappa$ in both the drift and anode directions is

$$\kappa = \frac{\Delta x \nu^{\frac{1}{2}}}{\sqrt{2Dx_0}} \tag{4}$$

where $\Delta x$ is the distance the two hits are apart. Thus $\kappa$ increases with increasing velocity and the SDD's two hit resolving power increases with increasing velocity as seen in fig. 5.

The front end electronics (preamp plus shaper or PASA) have a finite impulse response (25-35ns depending on which PASA one uses) causing a lower limit on the measured width. As one increases the velocity at a fixed drift distance one will reach this limit and then while the measured separation in time between two hits keeps decreasing with increasing velocity the measured hit width remains constant and $\kappa$ decreases as seen in fig. 5c. In the anode direction there are no impulse response considerations, however, there is a lower limit on the hit width caused by the self-repulsion of all the electrons in the hit. This limit is much lower than the impulse response (about a factor of 5). Further, since the anode pitch is $250\mu$m the smallest width (rms) we can measure is $250/\sqrt{12}$, still lower than the impulse response for most practically achievable velocities, thus $\kappa$ increases with velocity in the anode direction as seen in fig.6b. An optimal velocity is thus constrained by drift direction considerations as seen in fig. 5 and fig. 6. In fig.6c the optimal velocity is consistently smaller in the anode direction than the drift direction due to the absence of the PASA impulse response. As the drift distance increases the optimal velocity to run at increases since it takes longer to reach the impulse response width of the PASA. A practical velocity to operate at is one that maximizes $\kappa$ for the longest drift distance since this is where one has the lowest $\kappa$. Then even though $\kappa$ is not optimal at shorter drifts and one loses optimal two hit resolving power at shorter drift distances (fig. 5e) the overall worst separation one can resolve gets better. Optimizing for short drifts implies running at low velocities which lowers the measured signal on each anode for long drift since the hits diffuses more thus decreasing one's S/N and increasing errors on extracted fit parameters.

We sample the signal at a finite rate (40ns in drift and $250\mu$m in anode in the STAR-SVT). A practical limit on the two hit resolving power is when both hits are separated by less than one's sampling rate as well as $\kappa > 1$. If $\kappa \ll 1$ in the above situation one could in principle still resolve the hits. This is rarely true with SDD's. Hence in the anode direction a lower limit on the two hit separation is $250\mu$m and in the drift direction the lower limit is when two hits are separated by less than 40ns which varies with velocity and is independent of drift distance on an SDD. Note that

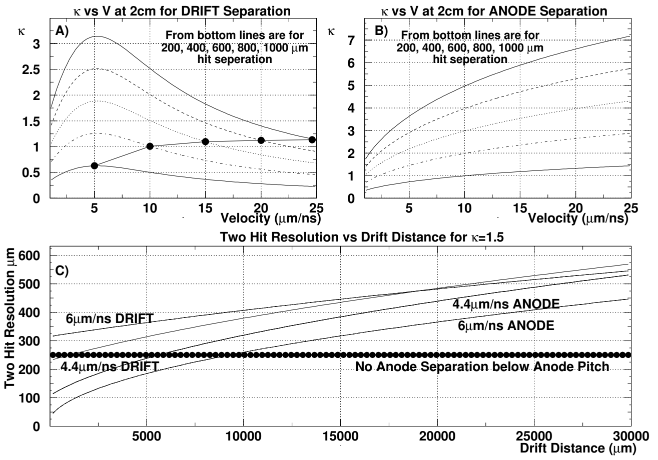


Fig. 6 Figures a) and b) show the two hit resolving power, or $\kappa$, in both the drift and anode direction. Figure c) shows how the two hit resolving power varies with drift distance for two drift velocities. As seen increasing the drift velocity does not lead to large improvements.

in general two hits will rarely be positioned parallel to the anodes or drift direction but at some angle relative to the two. The SDD's true two hit resolving power is thus between the two curves in fig. 6c. One should note that there are no noise considerations in this analysis which will in general reduce the resolving power by increasing the errors on extracted fit parameters. Errors on extracted fit parameters will generally be larger in the anode direction than the drift direction as the separation between two hits approaches the anode pitch due to finite sampling considerations thus shifting the anode curves in fig. 6c upwards for practical applications. Further it is assumed in fig. 6 that one can resolve hits separated by $\kappa = 1.5$. The curves scale linearly with $\kappa$ should one want to change this limit.

In summary due to the finite impulse response of the PASA in the drift direction there is an optimal velocity to operate the detector. In the anode direction the optimal velocity to operate is as fast as possible (without causing breakdowns or sparks on the detector). In the drift direction there is a trade off in two hit resolving power and velocity depending on drift distance and operating the detector at the velocity to maximize $\kappa$ for long drifts is best. Lowering the PASA impulse response improves the overall two hit resolving power of the detector. Lowering the readout pitch of the anodes and the digitization sampling in time is also important if one goes very high in velocity but in the anode direction can lead to a lower S/N. The phase space to operate the detector is defined by drift velocity, drift distances, PASA impulse response, sampling rate, and noise.

## III. Experimental Procedure

Measurements were carried out at The Ohio State University Silicon Detector Test Laboratory. Charged particle events were simulated via photoionization using a Nd:YAG laser of wavelength 1.064 $\mu$m, just above the band edge where silicon becomes transparent. The laser pulse duration was 8 ns. The laser light was carried by two optical fibers to a 20X microscope objective where a precision screw controlled the distance between the two fibers. When the light is focussed on the surface of the detector the spot size and distance between the laser spots is $1/20$ th that of the corresponding quantities before the microscope objective. The precision screw was calibrated by shining white light thought the two optical fibers and looking at the spots against the background of a silicon drift detector. The cathode lines on the detector are spaced $135\mu$m apart and were used to calibrate the precision screw to an estimated $\pm 20\mu$m. The size of the laser spot on the surface was about 20 $\mu$m which does not introduce significant additional uncertainty in the drift position since it is smaller than the natural charge cloud spread due to coulomb self-repulsion and diffusion ($\approx 100 - 200\mu$m at typical drift fields and drift distances) and it does not affect the mean of the drift cloud position. The laser light also triggers a photodiode of 500ps jitter which defines the start time. In this set up the impulse response of the PASA electrons is 35ns though in the STAR-SVT it is 25ns. Seven neighboring anodes all having nearly identical gain are read out through oscilloscopes to a computer. For each configuration 200 events were stored for further analysis. We sample at 5ns intervals compared to the STAR-SVT which samples at 40ns. Since the smallest separation we consider in this study is 300 $\mu$m at $\nu = 4.2\mu m/ns$ this does not impact the validity of our conclusions for STAR. The laser amplitude was attenuated to deposit the same amount of energy as 1-2 times a minimum ionizing particle. However, the laser has 20% pulse to pulse amplitude fluctuations. Further, the ratio of the two spot intensities was observed to vary event by event perhaps since the pulse splitting method is sensitive to speckle effects[2]. While measuring the separation between two hits is relatively insensitive to amplitude fluctuations (as verified from the correlation matrix of fit parameters) if $\kappa < 2$ this poses a problem for the deconvolution and will increase the errors on the fit parameters. Three drift fields ($\nu = \mu E$, $\mu$ is mobility, E is electric field) corresponding to velocities of 2.8 $\mu$m/ns, 4.2 $\mu$m/ns, and 6.0 $\mu$m/ns were used in all orientations of the two hits with respect to the anode and drift coordinates. The data were corrected for changes in temperature. Changes in temperature change the carrier concentration, the thermal average velocity of electrons, and including all scattering mechanisms at room temperature[10, 11] $\mu \propto T^{-2.4}$ or the velocity decreases by 1% for each Kelvin increase in temperature near room temperature.

## IV. Data and Results

For each configuration we fit the data under the assumption of eqn. 2. The 200 events in each configuration were used to estimate errors and off-diagonal elements in the error matrix due to the finite PASA response were estimated via arguments presented in [5]. Little change in extracted fit parameters or errors was observed when ignoring off diagonal elements in the error matrix.

A typical set of waveforms is seen in fig. 7. As seen in fig.7a, b, and c the value of $\kappa$ decreases gradually for longer drifts for a fixed separation between two hits and a fixed

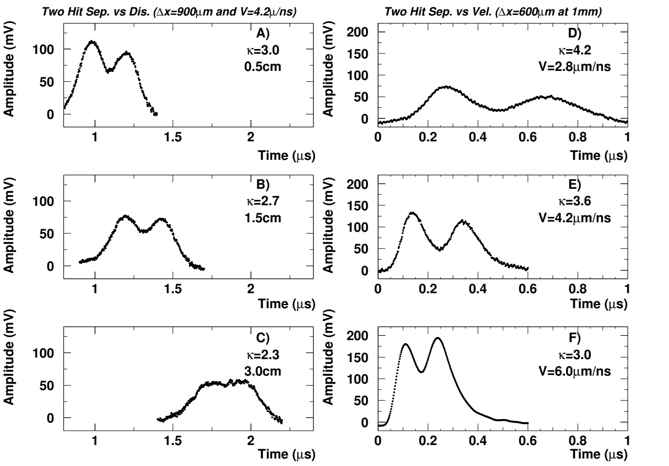


Fig. 7 Figures a, b, and c shows two hits on one anode on a SDD as a function of drift distance for a fixed separation and constant velocity. Figures d, e, f show two hits on one anode as a function of velocity for a fixed separation and drift distance. The STAR-SVT PASA has a smaller impulse response than the PASA used in these measurements leading to a better $\kappa$ overall.

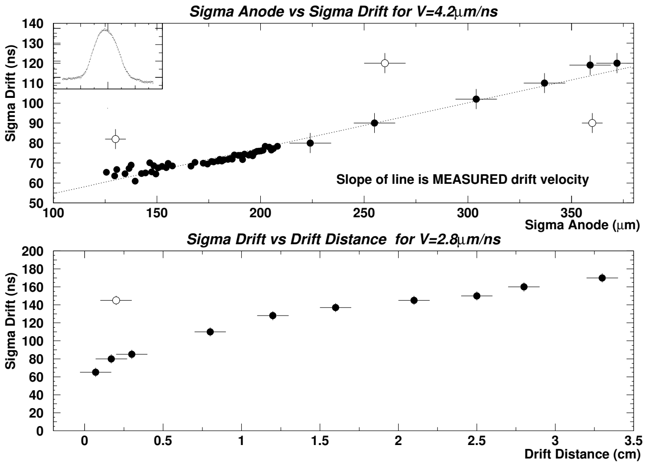


Fig. 8 The top figure plots the drift and anode waveform RMS against each other (solid circles). The open circles ($\kappa < 2$) are easily identifiable as multiple hits. Multiple hit identification is less obvious with information only in the time direction (see inset). The bottom plot shows another method of identifying multiple hits which becomes important when two hits lie on a 45 degree angle in anode-time phase space (when both are converted to similar units) or MIP hits masquerade as two hits. The open circle is for a multiple hit and the closed are for single hits.

velocity consistent with fig. 6c. The values of $\kappa$ are consistent with those from fig.5c and d. Resolving two hits 900$\mu$m apart is easy on an SDD. One can do better by increasing $\kappa$ in fig. 7c by increasing the velocity to about 6$\mu$m/ns as seen in fig 5e either by increasing the drift field or dramatically lowering the temperature. Further, increasing the velocity increases the signal on each measured point (larger S/N) since the cloud spread less as seen in fig 7d, e, and f. At a drift distance of 1mm the optimal velocity is below 2.8$\mu$m/ns thus $\kappa$ decreases with increasing velocity in these pictures. However, at 2.0$\mu$m/ns the signal in fig. 7c would have a significantly lower $\kappa$. It is interesting to note that in fig. 7d, e, and f the width of the second peak in time is wider than that of the first. This is since the width of a hit rapidly increases at short drift distances as seen in fig. 1. This makes it difficult to define a $\kappa$ and the average of the two widths was taken in the definition.

Fitting via deconvolution is necessary when $\kappa < 2$ as seen in fig. 3a. Demonstrations of what the theoretical errors should be in a deconvolution where the hit widths are known can be found in the literature[5, 6]. Other methods, notable maximum entropy which tries to reconstruct an image which is as smooth as consistent with the data give similar results. As mentioned before and seen in fig. 3 when $\kappa < 2$ it is first necessary to determine whether one has a cluster formed from one hit or two and then proceed with the deconvolution. In fig. 8 a simple method for determining whether a cluster arises from one or two hits is presented. By plotting the hit width in the anode direction against the hit width in the drift direction one can determine whether electron cloud distributions arise from multiple overlapping hits or a single hit (see fig. 8). This is an efficient filter before applying CPU intensive double hit cluster algorithms and fitting routines. The slope of the resulting line is the velocity above 60ns (nonlinearities occur below this due to the PASA impulse response). Unless two hits are lying at a 45 degree angle in anode-time phase space (when both are converted to similar units) if one plots them on a anode width versus time width plot they should stand away from the linear line given by the velocity of the single hits. Even if they do lie on a 45 degree angle plotting the widths of the signals in both direction versus drift distance and comparing them to those for single hits can resolve multiple hits as seen in fig. 8. This also allows one to separate MIP hits masquerading as two hits with $\kappa < 2$. In practice one uses both of the above methods.

In fig. 9 extracted fit parameters when $\kappa > 2$ are presented. The $\chi^2$ per degree of freedom for fits is around one so quoted errors are meaningful. As seen at large drift distance one can only reconstruct widely separated hits in agreement with fig. 5 and fig. 6. As expected when both hits are parallel to the anodes one has better two hit resolution. Errors for data taken at 6$\mu$m/ns are consistently higher than those at lower velocities at short drift distances in agreement with fig. 6c. Errors are always smaller than 10%. Deconvolutions used when $\kappa < 2$ usually result in larger errors.

As two hits get close to one another it is observed that the charge clouds of 24000 electrons each generates in the SDD appear to interact with each other. As the two electron clouds approach each other their correlation coefficients (eqn.2) are shown to increase and be anti-correlated indicating their interaction with one another as seen in fig. 4. As the clouds generated by MIP's get close to each other one might expect the clouds to repel each other. While there is evidence for this in the data for hits parallel to the anodes along the drift direction the data are inconclusive (perhaps due to velocity ambiguities). This has implications for the accuracy as opposed to precision of measurements of two close hits on an SDD though only at the 10% level for $\kappa < 2.2$ if the anode data is reliable.

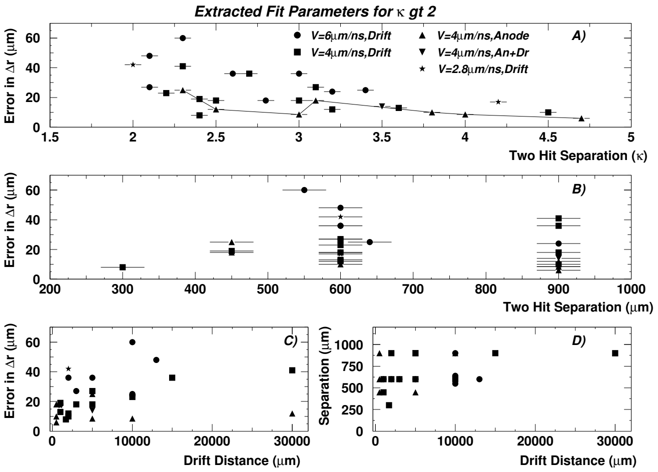


Fig. 9 Figures a, b, and c show fit errors on the separation between two hits as a function of $\kappa$, drift separation and drift distance. Note the errors are never larger than $10\%$. Errors for two hits along the anode are generally smaller than those along drift. Errors are larger at $\nu = 6\mu m/ns$ than at $\nu = 4.2\mu m/ns$.

## V. Discussion

The information that a cluster is comprised of two hits can be important, even while not knowing to great accuracy or precision the exact separation of two hits, SDD's are usually built around a collision vertex in high energy physics and sit in magnetic fields. The magnetic fields bend tracks apart as they leave the collision center making them easier to resolve further away. Known unresolved multiparticle clusters can be assigned to more than one track candidate helping solve ambiguities in detectors positioned further away. The overall two hit resolution of the detector is thus useful down to about $\kappa = 1$ (use fig. 6c to convert this to a distance).

The pulse undershoot becomes important when a 10 MIP particle is followed shortly by a 1 MIP particle in the drift direction. As seen in fig. 3b the STAR-SVT has a bipolar PASA and the 1 MIP hit would get swallowed in the tail of the 10 MIP hit. This is a rare occurrence and most interesting physics signatures involve two similar MIP hits close together (Bose-Einstein correlations or resonance decay biproducts). In principle since the PASA response function is known the undershoot can be removed before further analysis is attemped on hits.

The two hit resolution of the SDD varies across the detector and is dependant on many factors (drift velocity, drift distances, PASA impulse response, sampling rate, and noise). Optimizing the two hit resolution at longest drifts increases the overall two hit resolution of the detector but degrades the best achievable two hit resolutions at short drift. This optimization implies running at around 6$\mu$m/ns for a 3cm drift SDD at STAR. It should be mentioned that running slower increases the dead time of the detector.

## VI. Conclusions

Silicon Drift Detectors are shown to have good two track resolution without deconvolutions at 600 $\mu$m separation in either the anode or drift directions at drift distances less than 3cm and thus will be a useful tool at the LHC and RHIC colliders. At shorter drift distances two hits can be resolved down to 400$\mu$m at $\kappa > 2$. The two hit resolution is better when both hits are parallel to the anodes. For waveform separations of $\kappa = 1$ to $\kappa = 2$ the detector can identify double hits down to 300$\mu$m but with poor resolution. A SDD's velocity should be carefully optimized due to electronic constraints to maximize two hit resolution.

## VII. Acknowledgements

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