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Double particle resolution in STAR silicon drift detectors

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Abstract

The inner tracking detector of the STAR experiment at the BNL Relativistic Heavy Ion Collider will consist of a three layer barrel structure of 216 silicon drift detectors. Calculations of the two–hit resolution achievable for these detectors are presented in this article. The effects on two–hit resolution of the electronic's response function, frequency of signal digitization and noise level are discussed.

I. Introduction

The Silicon Vertex Tracker (SVT) improves considerably the momentum resolution, main interaction vertex position resolution and secondary vertex resolution for the STAR experiment [1]. The ability of SVT detectors to resolve nearby hits is important for two–particle correlation measurements and studies of short–lived particles. The SVT consists of 216 bidirectional Silicon Drift Detectors (SDD) with a maximum drift distance of 30 mm. Detailed description of the SDD design is presented in [2].

Electrons created by the ionizing particle in the SDDs, drift towards collecting anodes. The drift time of the electrons gives the distance between anodes and the crossing point of the particle. Diffusion and mutual electrostatic repulsion cause the drifting electron cloud to spread out. As a result, the arrival time of electrons at the anode has an approximately Gaussian distribution [3] with the width depending on the amplitude and drift time. The number of electrons created in the SDD by a minimum ionizing particle is about 25000. This allows us to determine the location in the drift direction of the center of gravity of the whole electron cloud with a precision of a few micrometers [4].

In this paper we show what resolution one can expect from the SVT detectors for close hits. We use a method developed in [5] to calculate the errors in amplitudes and drift coordinates of two hits with signals overlapping at the preamplifier–shaper output.

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II. Method

Our goal is to determine the amplitudes $Q_{1,2}$ and centroids $T_{1,2}$ of two superimposed pulses using a set of N experimental samples s_i. The method of maximum likelihood [5] is used for estimation of parameters and their variances. According to the maximum likelihood method the values of the parameters are determined by minimization of the functional:

$$-\frac{1}{2}\sum_i^N\sum_i^N(s_i-q_i)g_{ik}(s_k-q_k) = -\frac{1}{2}\mathbf{X}\mathbf{g}\mathbf{X}^t, \quad (1)$$

where g_{ik} are the elements of the inverse covariance matrix of the measurement errors, s_i are the experimental samples, q_i are the values of the fitting function at the time t_i, and $\mathbf{X}$ is the vector of deviations between samples and fitting curve.

The fitting function q(t,A), where $\mathbf{A} = (Q_1, Q_2, T_1, T_2)$, is linearized by linear expansion around starting values of $\mathbf{A}_0$. The expression for the linear expansion of q_i is:

$$q_i = q_{i0} + \sum_{j=1}^{4}\left(\frac{\partial q_{i0}}{\partial A_j}\right)\Delta A_j.$$

The matrix equation for the values of $\Delta\mathbf{A}$, which minimize (1), is

$$\mathbf{\Gamma}\Delta\mathbf{A} = \mathbf{N},$$

where

$$\Gamma_{jl} = \sum_i^N\sum_k^N g_{ik}\frac{\partial q_{i0}}{\partial A_j}\frac{\partial q_{k0}}{\partial A_l}$$

and

$$N_j = \sum_k^N\sum_i^N g_{ik}\frac{\partial q_{i0}}{\partial A_j}(s_k - q_{k0}) = \sum_k^N B_{jk}x_k,$$

where $B_{jk} = \sum_i^N g_{ik}\frac{\partial q_{i0}}{\partial A_j}$. This expression can be rewritten as:

$$\Delta\mathbf{A} = \mathbf{\Gamma}^{-1}\mathbf{N} = \mathbf{\Gamma}^{-1}\mathbf{B}\mathbf{X} = \mathbf{T}\mathbf{X},$$

where $\mathbf{T} = \mathbf{\Gamma}^{-1}\mathbf{B}$.

The covariance matrix M of variables $\Delta\mathbf{A}$ is given by [6]

$$\mathbf{M} = \mathbf{T}\mathbf{g}^{-1}\mathbf{T}^t = \mathbf{\Gamma}^{-1}\mathbf{B}\mathbf{g}^{-1}\mathbf{B}^t(\mathbf{\Gamma}^{-1})^t.$$

In our case $\mathbf{B}\mathbf{g}^{-1}\mathbf{B}^t = \mathbf{\Gamma}$, as shown in [5], and the equation for M becomes:

$$\mathbf{M} = \mathbf{\Gamma}^{-1}.$$

III. Fitting Function and Noise Covariance Matrix

For simplicity, following [5], we take the Gaussian response function with the width σ_f for the preamplifier–shaper

$$W(t) = \frac{1}{\sqrt{2\pi}\sigma_f}\exp(\frac{-t^2}{2\sigma_f^2}).$$

This function transforms a Gaussian input signal of an electron cloud with σ_{cloud} to a Gaussian output signal with $\sigma^2 = \sigma_f^2 + \sigma_{cloud}^2$.

The fitting function for two–hits is

$$q_i = \frac{Q_1}{\sqrt{2\pi}\sigma_1}\exp(\frac{-(t_i-T_1)^2}{2\sigma_1^2}) + \frac{Q_2}{\sqrt{2\pi}\sigma_2}\exp(\frac{-(t_i-T_2)^2}{2\sigma_2^2}),$$

where σ_1 and σ_2 are the values of a known function $\sigma = \sigma(Q,T)$ in the points (Q_1,T_1) and (Q_2,T_2). In the real experiment the function $\sigma = \sigma(Q,T)$ could be obtained from calibration data. For these calculations a "calibration" was done as follows: signal width for different drift times and amplitudes was simulated by a "slow SDD signal simulator" [7] and approximated by the polynomial expression:

$$\sigma(Q,T) = \sqrt{P_m(Q) \times P_m(T)},$$

where m is the polynomial order. Good approximation was achieved for m=3. The output signal widths simulated for hits with amplitudes 12500e ($\frac{1}{2}MIP$) and 125000e ($5MIP$) and $\sigma_f = 20ns$ are shown in fig.1.

The following noise sources are taken into account: anode leakage current shot noise, series equivalent voltage noise of the input amplifier, and Poisson fluctuations in the pulse shape. The noise covariance at the output, from [5], is:

$$K_{out}(t_i,t_k) = K_{ik} = \frac{\nu q^2}{2\sqrt{\pi}\sigma_f}\exp(-\frac{(t_i-t_k)^2}{4\sigma_f^2}) +$$
$$\frac{C^2 e_n^2}{8\sqrt{\pi}\sigma_f^3}(1-\frac{(t_i-t_k)^2}{2\sigma_f^2})\exp(-\frac{(t_i-t_k)^2}{4\sigma_f^2}) +$$
$$\frac{q^2}{2\sqrt{\pi}\sigma_f} f_{in}(\frac{t_i+t_k}{2})\exp(-\frac{(t_i-t_k)^2}{4\sigma_f^2}).$$

where q is the value of the electron charge. The first term is the contribution of the shot noise of the anode leakage current $I = \nu q$. The second term is the contribution of the series noise, where C is the total input capacitance and e_n^2 is the physical spectral density of the amplifier series noise. The third term is the contribution of the Poisson fluctuations with the input signal waveform $f_{in}(t)$.

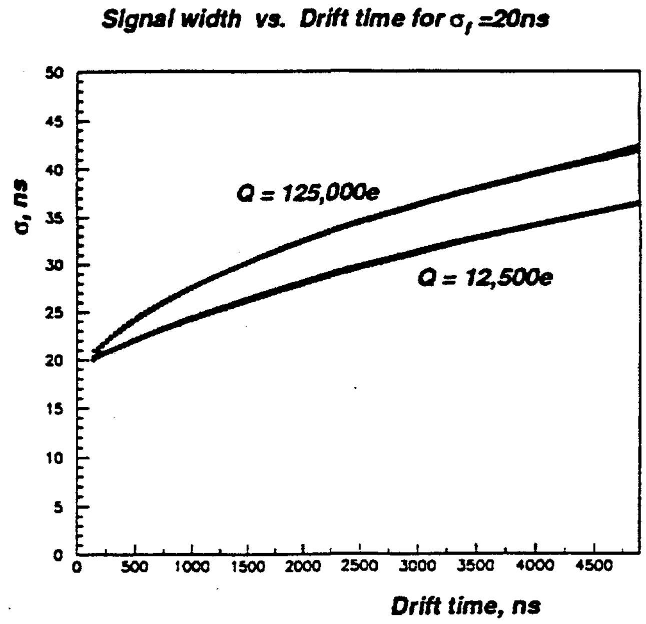

Fig. 1 Approximation of the signal width by polynomial expression for amplitudes 0.5 MIP and 5 MIP.

IV. Constants Used in Calculations

The most important parameters of the front end electronics for two–hit resolution are: noise level, response function width and sampling frequency. Two versions of preamplifier–shapers with the width (FWHM) of response functions of 52 ns and 97 ns and a noise level less than 400e for both designs have been developed for the SVT. The following values have been used in calculations: equivalent noise charge (ENC) of the series noise = 400e, $\sigma_f = 20ns$ and $40ns$. The sampling frequency for the SVT is 26.77 MHz. Calculations with different frequencies were performed to show how resolution depends on sampling frequency.

Results of SDD prototype tests show that we can expect the anode leakage currents to be in the range of 1 – 10 nA. In calculations, $I = 5nA$ has been used. The ENC of this current is equal to 33e for $\sigma_f = 20ns$ and 47e for $\sigma_f = 40ns$. The electron drift velocity in the STAR SDDs is 6.43 $mm/\mu s$. This value gives a maximum drift time of $T_{max} = 4.7\mu s$ for the drift distance of 30 mm.

V. Results

The criterion for successful resolution of two hits is a value of errors in reconstructed amplitudes and times. Usually, if errors are larger than 20 – 30 %, pulses are consider to be unresolved. To determine at which minimum distance two hits could be resolved the standard deviations of amplitudes and times are calculated as a function of the spacing between hits normalized to the signal width.

Contributions of the leakage current shot noise and Poisson noise are an order of magnitude less than the series noise of the input preamplifier. Moreover, the behavior of the resolution in the presense of, for example, the shot noise or series noise only, is very similar. The standard deviations in amplitude and time determination due to series noise or shot noise only are shown in fig.2 for the case of 25000e in each pulse and ENC=400e . As is seen from fig.2, our calculations are in a good agreement with results obtained in [5]. Hits could be resolved at distances $\simeq 1.5\sigma$. This corresponds to $300\mu m$ separation for hits drifting from the middle of the detector.

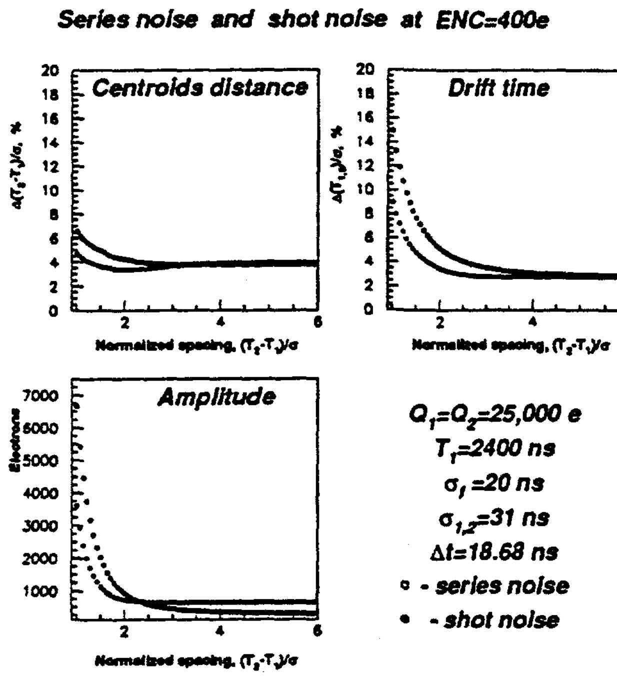

Fig. 2 Comparison of series noise and leakage current shot noise with the ENC=400e.

The amplitude and time resolution as a function of sampling frequency is shown in fig.3 for 1σ, 1.5σ, 2σ spacing between hits and for frequencies in the 25–67 MHz range. The resolution is rather insensitive to the sampling frequency when the distance between hits is about 2σ or more. Only when the distance is less than or equal to 1.5σ and the frequency is lower than 28 MHz does resolution deteriorate.

The amplitude and coordinate resolution as a function of drift distance is shown in fig.4 and fig.5 for two–hit separations of: 0.5, 0.75 and 1.0 mm. For minimum ionizing particles coordinate resolution is less than 20 μm and amplitude resolution is about 1000e for the whole drift length.

VI. Summary

Double hit resolution for the STAR SDD has been calculated using the method proposed in [5]. Presented results show:

– two hits could be resolved at the distance of 300 μm;

– coordinate resolution of the order of 15–20 μm could be

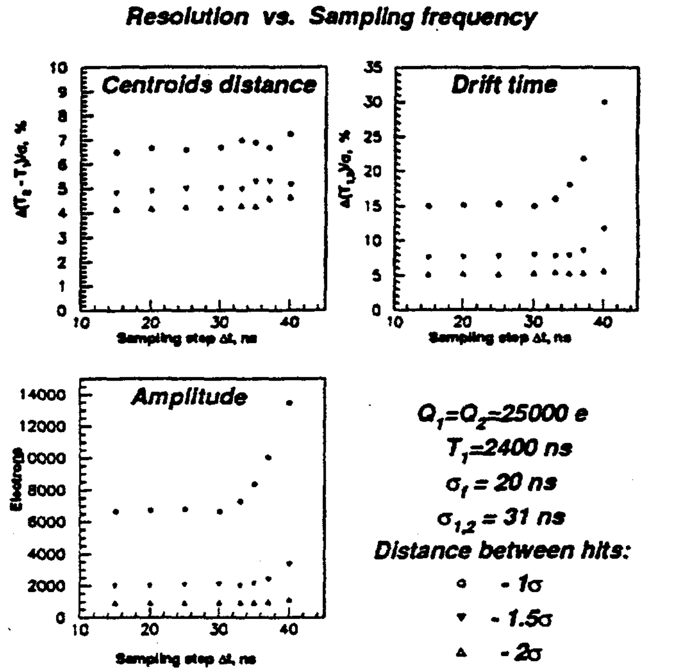

Fig. 3 Resolution as a function of sampling frequency for two-hit separations of 1σ, 1.5σ, 2σ.

obtained for minimum ionizing particles;

– expected amplitude resolution is about 1000e.

VII. Acknowledgments

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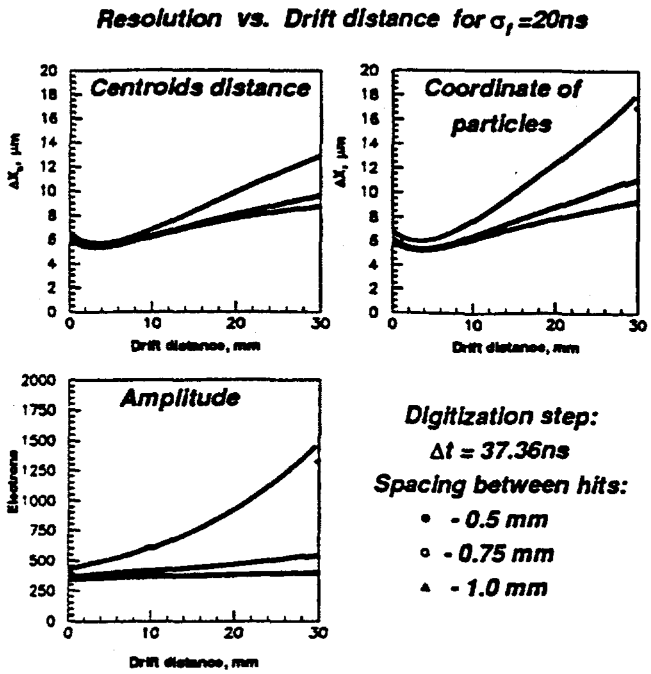

Fig. 4 The amplitude and coordinate resolution for $\sigma_f = 20ns$ for two-hit separations of 0.5 mm – black dots; 0.75 mm – open dots; 1.0 mm – triangles.

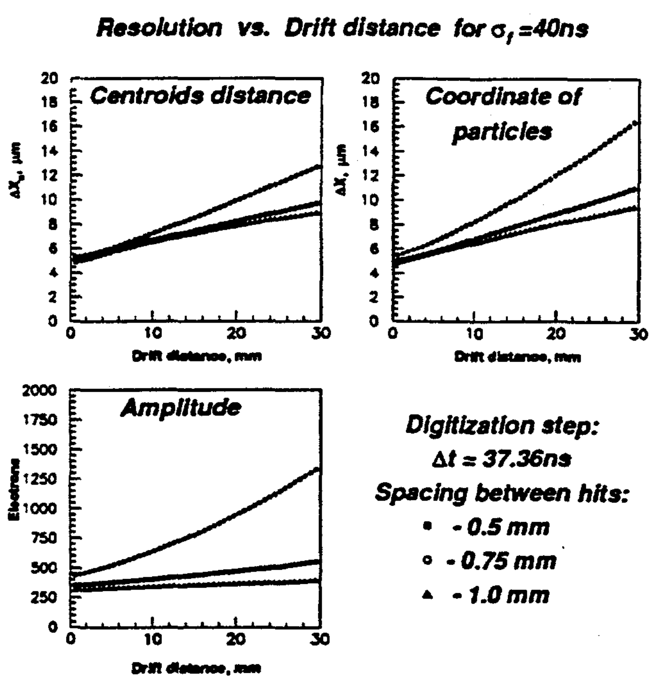

Fig. 5 The amplitude and coordinate resolution for $\sigma_f = 40ns$. The same two-hit separation as in fig.4.