



## THE CDF ONLINE SILICON VERTEX TRACKER

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The Silicon Vertex Tracker (SVT) is the new trigger processor which reconstructs 2-D tracks with high speed and accuracy at the level 2 trigger of the CDFII experiment. SVT allows tagging events with secondary vertices and therefore enhances the CDFII B-physics capability. SVT has been fully assembled and operational since the beginning of Tevatron RunII in April 2001. In this paper we briefly review the SVT design and physics motivation and then describe its performance during the early phase of CDF RunII.

## 1 Introduction

The Collider Detector at Fermilab (CDF) is a general purpose detector for the study of high energy  $p\bar{p}$  interactions produced at the Tevatron Collider. CDF completed its first period of data taking (RunI) in 1996. The Teva-

tron has recently completed major upgrades to achieve higher energy (from 800 to 990  $GeV$  per beam) and instantaneous luminosity (from  $2 \times 10^{31}$  to  $10^{32} \text{ cm}^{-2}\text{s}^{-1}$ ). CDF has been upgraded to cope with the reduced bunch spacing condition (from 3.5  $\mu\text{s}$  to 396  $\text{ns}$  and then further down to 132  $\text{ns}$  during the phase “b” of RunII), with the higher number of interactions per bunch crossing, and to extend its physics reach.<sup>1</sup>

The detector upgrades relevant for this paper are the tracker and the trigger. The new silicon vertex detector (SVXII and Layer00)<sup>2,3</sup> covers the region from 1.5 to 10  $\text{cm}$  from the beamline and about 2 units in pseudorapidity. SVXII is made of 5 layers of double-sided ( $r - \phi$  and  $r - z$  readout) microstrip sensors arranged in a 12-fold azimuthal geometry and segmented in 6 longitudinal barrels (3 mechanical units, each read out at both ends) along the beam line (CDF  $z$ -axis). Layer00 is made of one layer of radiation hard silicon microstrips ( $r - \phi$  readout) placed just outside the beam pipe ( $r = 1.5 \text{ cm}$ ). The trigger is completely new and consists of three levels. Its challenging task is to reduce the 5  $MHz$  level 1 input rate down to a level 3 output rate of 50  $Hz$  for data storage and analysis. Levels 1 and 2 are completely hardware implemented while level 3 is software implemented and runs on a PC farm. The most relevant level 1 device is the eXtremely Fast Track finder processor (XFT)<sup>4</sup> which reconstructs 2-D tracks (in the  $r - \phi$  plane, transverse to the beam line) in the central drift chamber (COT). The SVT is part of the level 2 trigger. It receives the list of COT tracks ( $P_t$  and  $\phi$  coordinates) from the XFT processor and the digitized pulse heights on the silicon layers ( $\sim 10^5$  channels) and reconstructs tracks with offline-like quality. The expected resolution for SVT tracks is:  $\delta\phi \simeq 1 \text{ mrad}$ ,  $\delta P_t \simeq 0.003 \cdot P_t^2 \text{ GeV}/c$ ,  $\delta d \simeq 35 \mu\text{m}$  ( $d$  is the track impact parameter i.e. the distance of closest approach of the particle trajectory helix to the  $z$ -axis of the CDF reference system). By providing a precision measurement of the impact parameter SVT allows triggering on events containing long lived particles. B-hadrons in particular have a decay length of the order of 500  $\mu\text{m}$  and tracks which come out of the B decay vertices have an impact parameter on average greater than 100  $\mu\text{m}$ . This novel feature, available for the first time at a hadron collider experiment, greatly enriches the CDF B physics program. In particular it provides access to rare purely hadronic B decays like  $B^0 \rightarrow \pi\pi$  and  $B_s \rightarrow D_s\pi \rightarrow \text{hadrons}$ , which are extremely interesting respectively for CP violation and  $B_s$  mixing.

## 2 The SVT working principle

The SVT has a very short time to perform its task (on average  $\sim 20 \mu\text{s}$  per event) to keep up with the 50  $KHz$  level 1 accept rate. In order to speed up

operations SVT has a parallelized design: it is made of 12 identical azimuthal slices (“wedges”) which work in parallel. Also tracks are reconstructed in 2-D only (stereo info from SVXII is dropped) and only with  $P_t$  above  $2 \text{ GeV}/c$ .

Track reconstruction is performed in two steps: in the pattern recognition step candidate tracks (“roads”) are searched among a list of precalculated low resolution patterns; in the subsequent track fitting step the full resolution fit of the hit coordinates found within the roads is performed using a linearized algorithm. The pattern recognition step is performed in a completely parallel way by the Associative Memory system which uses full custom VLSI chips (AMchips).<sup>5</sup> The AM system compares the SVT input data with the set of precalculated patterns. A pattern is defined as a combination of five bins (“SuperStrips”): four SuperStrips correspond to the position coordinates of the particle trajectory on four silicon layers which can be chosen among the five SVXII layers and Layer00, the fifth SuperStrip corresponds to the azimuthal angle of the particle trajectory at a distance  $r = 12 \text{ cm}$  from the beam line (this distance was found to maximize average pattern coverage). The output of the AM system is the list of patterns (“roads”) for which at least one hit has been found on each SuperStrip. Each SVT wedge uses  $\sim 32K$  patterns which cover more than 95% of the phase space for  $P_t \geq 2 \text{ GeV}/c$ . Simulation studies have shown that SVT performance is optimized (in terms of processing time and final resolution) by choosing a SuperStrip size of about  $250 \mu\text{m}$  on the silicon layers and  $5^\circ$  for the  $\phi$  angle measured by XFT. The track fitting method is based on linear approximations and principal component analysis.<sup>6</sup> The analytical relationship between the track parameters and the 6 measured hit coordinates (hit positions on 4 silicon layers, curvature and azimuthal angle of XFT track) can be expressed in terms of 6 equations:

$$P_j = P_j(\mathbf{x}) = \mathbf{F}_j \cdot \mathbf{x} + Q_j \quad (1)$$

where,  $\mathbf{x}$  is the vector of hit coordinates and  $\mathbf{P} = (P_1, P_2, \dots, P_6) = (d, c, \phi, \chi_1, \chi_2, \chi_3)$  is a vector consisting of: the impact parameter ( $d$ ), the curvature ( $c$ ), the azimuthal angle ( $\phi$ ) at the point of closest approach to the  $z$ -axis, and three independent constraints ( $\chi_1, \chi_2$  and  $\chi_3$ ) which all real tracks must satisfy within detector resolution effects.  $\mathbf{F}_j$  and  $Q_j$  are constants which depend only on the detector geometry and on the magnetic field.

Once pattern recognition has been performed, each track candidate is confined within a road and hit coordinates can be referred to the SuperStrips edge ( $\mathbf{x}_0$ ); equation 1 becomes:

$$P_{0j} + \delta P_j = \mathbf{F}_j \cdot (\mathbf{x}_0 + \delta \mathbf{x}) + Q_j \quad (2)$$

where,  $P_{0j} = \mathbf{F}_j \cdot \mathbf{x}_0 + Q_j$  is a constant which depends on the road, while  $\delta P_j$

is the correction which depends on the precise hit positions inside the road. The  $P_{0j}$  coefficients which correspond to the track lying exactly on the road edge, are calculated in advance and stored in RAMs. Therefore the track fitting task reduces to a fast computation of simple scalar products (done by FPGA chips):

$$\delta P_j = \mathbf{F}_j \cdot \delta \mathbf{x}. \quad (3)$$

The output list of high precision tracks is sent to the global level 2 processor for the final trigger decision.

SVT is made by over one hundred VME boards housed in 8 crates.<sup>7</sup> The installation has been completed and the system has been fully operational since the beginning of 2001. In the following section we report on the performance achieved by the system in the early phase of RunII.

### 3 SVT performance

The first evidence that SVT finds good tracks is the plot of the correlation between the impact parameter  $d$  and the azimuthal angle  $\phi$  in a sample of candidate tracks (figure 1, *left*). If the position of the interaction vertex in the transverse plane is  $(x_0, y_0)$ , displaced from the nominal one  $(0, 0)$ , the relationship between  $d$  and  $\phi$  for primary tracks is:

$$d = -x_0 \sin(\phi) + y_0 \cos(\phi). \quad (4)$$

A fit of the  $d - \phi$  scatter plot measures the  $(x_0, y_0)$  coordinates with an accuracy of few microns. A beam displacement of few millimetres is the present typical running condition for CDF. This is a potential problem because unphysical large impact parameters erroneously affect the level 2 trigger decision. In practice the problem has been solved in the following way: a process running on one of the SVT VME crate controllers performs the fit of the  $d - \phi$  correlation of the SVT tracks independently for tracks in each one of the six SVXII  $z$ -barrels. The beam offset is subtracted online:

$$d' = d + x_0 \sin(\phi) - y_0 \cos(\phi) \quad (5)$$

and physical impact parameters (measured with respect to the actual beam position) are actually output by the SVT. Figure 1 illustrates the effect of beam offset subtraction (*left*) and the online  $d'$  distribution (*right*). The gaussian shape and the width of the  $d'$  distribution originate from the convolution of the actual transverse beam profile with the impact parameter (i.p.) resolution. A gaussian fit gives  $\sigma \simeq 69 \mu m$ .

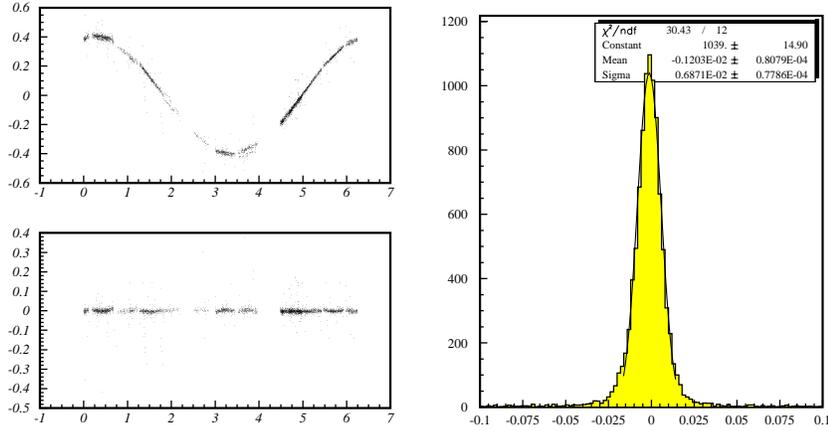


Figure 1. *Left:*  $d - \phi$  correlation for SVT tracks before (*top*) and after (*bottom*) correcting for the beam offset. The measured beam position in the transverse plane is  $x_0 = 0.0995$  cm and  $y_0 = -0.3895$  cm with a precision of  $\simeq 3$   $\mu$ m. The regions without points around  $\phi = 2.2$  and  $\phi = 4.2$  rad are due to missing SVXII wedges. The scale on the  $x$  axes is radians, the scale on the  $y$  axes is cm. *Right:* Distribution of the online impact parameter (in cm) corrected for the beam offset.

A big effort has been put in understanding the various factors contributing to the impact parameter resolution with the aim of possibly improving it. In fact, as the resolution degrades the trigger rate increases and the background contamination in the data samples selected by impact parameter cuts is larger.

The potentially most relevant contribution to the impact parameter resolution arises from the  $z$ -tilt of the beam with respect to the detector. The effect of a  $z$ -misalignment ( $m_x = \delta x / \delta z$ ,  $m_y = \delta y / \delta z$ ) shows up as a residual  $\phi$  modulation in the impact parameter after correcting it for the beam offset:

$$d' = -m_x z_0 \sin(\phi) + m_y z_0 \cos(\phi) \quad (6)$$

where  $z_0$  is the  $z$ -coordinate of the point of closest approach of the particle trajectory to the  $z$ -axis. Since SVT does not measure  $z_0$ , a beam tilt along  $z$  results in an irreducible widening of the impact parameter distribution. In order to make this spread small compared to the natural beam width, SVT requires the detectors and the beam line to be all parallel within 100  $\mu$ rad. Assembly of the SVXII barrels met (even exceeded) this specification,<sup>3</sup> the  $z$ -alignment of the beam orbit is unfortunately more challenging. During the April-October 2001 data taking the beam slope was found to be significantly large:  $m_x \simeq 600$   $\mu$ rad,  $m_y \simeq 150$   $\mu$ rad, well beyond the SVT specification.

The effect of the  $z$ -misalignment on the impact parameter distribution was estimated using data of a special run taken with an approximately null beam tilt. A gaussian fit to the online impact parameter distribution gives  $\sigma \simeq 59 \mu m$ .

In addition to the beam tilt, there are two more major contributions to the impact parameter resolution. One is the relative misalignment of the SVXII wedges. This can be easily corrected by performing the beam offset fit and subtraction independently in each wedge. The size of this correction to i.p. resolution is approximately  $6 \mu m$ . The second major contribution to i.p. resolution is a consequence of the linear approximation used in the SVT track fitting method, which assumes a first order power expansion centred on the nominal beam position. Since during the April-October 2001 data taking the beam was very far from its nominal position ( $\sim 4mm$  away) the effect of non linearity was significantly large: it degrades i.p. resolution by approximately  $5 \mu m$ . This effect can be corrected in two steps: first the fit constants in equation 2 are recalculated centred on the measured beam position; second, the beam position fit is done on each wedge separately using a linear  $d-\phi$  relationship. With these corrections applied the impact parameter distribution was found to have a gaussian shape with a sigma of  $48 \mu m$  in a run taken with the beam aligned in  $z$ .<sup>a</sup> All these corrections can be implemented in the SVT and applied online. But the best SVT performance relies on the accelerator capability to provide an aligned beam.

Using a sample of events in which at least two good ( $\chi^2 < 10$ ) SVT tracks were found we have been able to calculate the true beam transverse size ( $\sigma_B$ ). The result of this study (described in detail in reference <sup>6</sup>) for the run with negligible beam tilt is  $\sigma_B = 33 \pm 1 \mu m$ . Deconvolving this beam width from the above  $48 \mu m$  we obtain  $\sigma_d \simeq 35 \mu m$  for the SVT i.p. resolution, in agreement with the design value.

In October 2001 the first trigger tests using SVT have been done. A level 2 trigger was implemented requiring at least 2 SVT tracks with  $\chi^2 < 25$ ,  $P_t > 2 \text{ GeV}/c$ ,  $|d| < 50 \mu m$  and a level 1 prerequisite of at least 2 XFT tracks. Figure 2 (*left*) shows the distribution of the second largest impact parameter in the event. Using this data (corresponding to  $\simeq 15 \text{ nb}^{-1}$  of integrated luminosity) a small signal of  $D^0 \rightarrow K\pi$  was reconstructed (figure 2, *right*).<sup>6</sup>

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<sup>a</sup>Additional lower order corrections can be applied: like correcting for a residual non linearity in  $d$  and  $\phi$ , and for the misalignment of silicon layers within a wedge. However their implementation in the online is less straightforward because it requires reprogramming some SVT boards and adjusting the SVT map which describes the detector geometry. It has been found that these additional corrections reduce the sigma of the impact parameter distribution from  $48$  to  $45 \mu m$ .

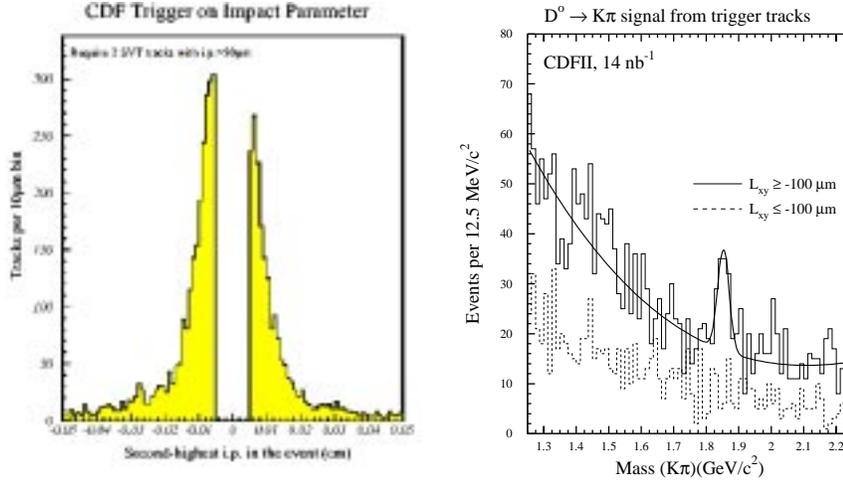


Figure 2. Plots done with data selected by the level 2 trigger requests described in the main text. *Left*: Impact parameter of the track with the second-highest impact parameter in each event. *Right*: Invariant mass distribution for track pairs assuming the two tracks to be  $\pi$  and  $K$ , and applying cuts optimized to select a  $D^0 \rightarrow K\pi$  signal.

## 4 Conclusions

The SVT is the new level 2 trigger processor dedicated to the reconstruction of tracks within the tracking chamber and the silicon vertex detector of the CDFII experiment. The device has been thoroughly tested during the early phase of RunII data taking (April-October 2001). The performance is already close to design.

## References

1. J. Spalding, *Run-II upgrades and physics prospects*, these proceedings.
2. S. D'Auria, *Commissioning and Operation of the CDF Silicon Detector*, these proceedings.
3. F. Palmonari, *The CDF-II Silicon Tracking System*, these proceedings.
4. C. Ciobanu *et al*, IEEE Trans. Nucl. Sci. **46**, 933-939 (1999).
5. S.R. Amendolia *et al*, IEEE Trans. Nucl. Sci. **39**, 795-797 (1992).
6. W. Ashmanskas *et al*, *Performance of the CDF Online Silicon Vertex Tracker* to be published in IEEE Trans. Nucl. Sci. (2001).
7. S. Donati *et al*, *Nuovo Cimento* **112A n.11**, 1239-1243 (1999).