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W. Ashmanskas et al.
For the CDF Collaboration

Fermi National Accelerator Laboratory
P.O. Box 500, Batavia, Illinois 60510

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IL NUOVO CIMENTO

The CDF Silicon Vertex Tracker: online precision tracking of the CDF Silicon Vertex Detector

W. Ashmanskas(1), A. Bardi(2), M. Bari(3), S. Belforte(2),J. Berryhill(1), M. Bogdan(1), A. Cerri(2), A.G. Clark(4), G. Chlachidze(5), R. Condorelli(2), R. Culbertson(1), M. Dell'Orso(2), S. Donati(2)(*), H.J. Frisch(1), S. Galeotti(2), P. Giannetti(2), V. Glagolev(5), A. Leger(4) E. Meschi(2), F. Morsani(2), T. Nakaya(1), G. Punzi(2), L. Ristori(2), H. Sanders(1) A. Semenov(5), G. Signorelli(2), M. Shochet(1), T. Speer(4), F. Spinella(2), P. Wilson(1), X. Wu(4) and A.M. Zanetti(3)

(1) *University of Chicago, USA*
(2) *University and Scuola Normale Superiore and INFN Pisa, Italy*
(3) *INFN Trieste, Italy*
(4) *University of Geneve, Switzerland*
(5) *Joint Institute for Nuclear Research, Dubna, Russia*

Summary. — The Silicon Vertex Tracker is the CDF online tracker which will reconstruct 2D tracks using hit positions measured by the Silicon Vertex Detector and Central Outer Chamber tracks found by the eXtremely Fast Tracker. The precision measurement of the track impact parameter will allow triggering on events containing B hadrons. This will allow the investigation of several important problems in B physics, like CP violation and B_s mixing, and to search for new heavy particles decaying to $b\bar{b}$.

1. – Introduction

The precision measurement of track impact parameter is crucial for B physics at a hadron collider. In the past experiments this information was available only after the offline reconstruction of data. The Silicon Vertex Tracker (SVT) [1] is presently being built for the CDFII [2] detector operation for the Tevatron run II (to begin in the year 2000). The SVT will work in the level 2 of CDF trigger chain and will refine the level 1 track processor (XFT) information, which uses data from the central drift chamber COT, by combining it with the Silicon Vertex Detector (SVXII) hits.

(*) Corresponding author

Since the SVT has to complete track reconstruction within 10 μsec, the design of the device has exploited parallelization of the various tasks (reconstruction of the hit coordinates from the strip pulse heights, pattern recognition and final precision track fitting). The architecture of the SVT is data driven and many functions overlap in the internal processor pipeline. Specification requires 30 MHz operation for each module with an asinchronous data transfer rate of 630 Mbit/s on custom data paths.

2. – SVT tracking strategy

The SVT separates the phases of pattern recognition and track fitting into two pipelined stages. Pattern recognition is performed by the Associative Memory system, which identifies low resolution track candidates called roads. The roads found by the Associative Memory and the full resolution hits corresponding to them are passed to the Track Fitters which calculate track parameters. This is done using a linearized fitting algorithm implemented in hardware.

2·1. *Pattern recognition.* – A track which traverses a multi-layer detector, produces a certain pattern of hits on each detector layer. Since detector resolution is finite, one could imagine to subdivide each detector layer in a finite number of elements with size comparable to resolution and to identify a track with the list of fired elements. Hit patterns corresponding to candidate tracks are stored in a memory, the Associtive Memory, and are continuosly compared in parallel to the data coming from the detector: a track candidate is found when all the hits corresponding to it are in the data [3], [4] . To reduce the size of the needed memory, pattern recognition is performed by the Associative Memory with a limited spatial resolution, for this purpose the Silicon Vertex Detector layers are segmented into 250 μm wide superstrips, while the actual strip pitch is $\sim$ 60 μm.

The Associative Memory functions are implemented in a full custom VLSI chip with 0.7 μm technology. Each chip can store 128 patterns of 6 words (layers) of 12 bits. Operation of the chip has been tested up to 40 MHz, with the SVT specification being 30 MHz.

2·2. *Track fitting.* – Track fitting is the problem of estimating the parameters of the candidate tracks found in the phase of pattern recognition by the Associative Memory. The SVT reconstructs tracks projected on the plane transverse to the beam axis and measures transverse momentum, azimuthal angle and impact parameter (p_t, ϕ, d). Track parameters are expressed as scalar products:

$$p_i = \vec{f_i} \cdot \vec{x} + q_i \tag{1a}$$

where p_i is one of the track parameters and $\vec{x}$ is the array containing hit positions and track curvature and azimuthal angle. Within each 30^o SVX wedge the parameters $\vec{f_i}$ and q_i are constants. Since variations of track parameters are small within a road, it is possible to expand p_i around a position x_0 in the hit space (typically the lower road edge). The following algorithm can thus be used:

$$p_i = \vec{f_i} \cdot (\vec{x}_0 + \vec{d}) + q_i \tag{2a}$$

$$p_{0i} + \delta p_i = (\vec{f_i} \cdot \vec{x}_0 + q_i) + \vec{f_i} \cdot \vec{d} \tag{2b}$$

where $p_{0i} = \vec{f}_i \cdot \vec{x}_0 + q_i$ and $\delta p_i = \vec{f}_i \cdot \vec{d}$. The advantage of this algorithm is that the p_{0i} can be precalculated and stored in a look-up-table reducing the computational load required by eq. 1. Since $\vec{d}$ varies within the road edges (∼250 μm wide), a lower number of bits is necessary to have the full hit resolution.

SVT performance has been tested reconstructing real CDF run I data using a bit-level simulation program of the device and it has been proven that track parameters are measured with offline quality resolution: $\sigma_{p_t} = 0.003 \cdot p_t^2$, $\sigma_\phi = 1$ mrad and $\sigma_d = 35$ μm (at $p_t = 2$ GeV/c).

3. – SVT architecture

The Silicon Vertex Detector is divided into 6 barrels along the z direction and each barrel in 12 wedges (sectors), each covering 30^o in azimuthal angle. To maximize speed the SVT architecture resembles the SVX geometry. The SVT is made of 12 identical systems and each system processes data only from one SVX wedge. All the systems run in parallel. The main functional blocks of each system are: Hit Finder, Associative Memory system, Hit Buffer and Track Fitter.

3·1. *Hit Finder*. – The Hit Finder receives sparsified and digitized pulse heights from the SVX front end electronics via optical G-links. Optical signals are converted to electrical at 53 MHz. The Hit Finder board sincronizes data coming from the G-links, subtracts pedestals and suppresses hot channels. Cluster centroids are found calculating the charge center of gravity. Since the number of silicon channels is very large, 3 Hit Finders are necessary for one 30^o sector. Data output from the 3 Hit Finders corresponding to one sector are sent to a board called Merger which merges them with the XFT track information. The Hit Finder has been successfully prototyped and tested at the specified speed of 30 MHz.

3·2. *Associative Memory system*. – The Associative Memory system receives the silicon hits found by the Hit Finder and the XFT tracks, merged into one single stream by the Merger, and performs pattern recognition. The AM system is made of one control board (the Associative Memory Sequencer) and two Associative Memory boards. The AM system performs its function "on-the-fly" during detector readout and results are available shortly after the end of the input phase.

The Sequencer board interfaces the AM system to the rest of SVT and provides the proper operational codes to the Associative Memory boards through a custom P3 backplane. The AM board has two operating modes: "VME mode" and "Running Mode". VME mode is used to load patterns into the AM chip and for diagnostics and the board operates on an internal (slow) clock ignoring signals from the P3 backplane. In Running Mode the AM board is controlled and receives the clock from the AM Sequencer through the P3 bus.

Each AM board holds 128 AM chips: in running mode the board distributes the data and the opcodes to the chips and queues patterns output by the chips to the P3 bus. To this purpose two tree-like structures have been created, one for input and one for output, with the 128 chips at the bottom [5].

3·3. *Hit Buffer*. – The Hit Buffer receives silicon hits and XFT tracks from the Merger and the roads from the AM Sequencer. Data from the Merger are received first, while the board is in "Write Mode". Data are sorted according to their superstrip number and stored in a structured database, called Hit List Memory, where each road number can then be used as a key to access lists of hits [6]. There is one Hit List for each superstrip and all these lists are filled as hits are received in input. The Hit Buffer has two operation modes: “Write Mode” and “Read Mode”. In Write Mode the hits are organised in the Hit List Memory, in Read Mode the roads found by the AM system are used to access the Hit List Memory and retrieve all and only the hits corresponding to the roads found in the current event. The road and all the corresponding hits retrieved from the Hit List Memory make the road-info packet. The road-info packet is sent to the Track Fitter board which performs the full resolution fit of the track.

3˙4. *Track Fitter*. – The main function of the Track Fitter is the calculation of the track parameters (p_t, ϕ, d) and the track χ^2. The linearized algorithm described in section **2**˙2 has been implemented in hardware using currently available FPGA.

4. – Error handling

Data flow through the SVT with a uniform protocol. The system is data-driven, there is no handshake other than the data flow: each block starts to process data as soon as it receives them and outputs results as soon as they are ready. This protocol offers a great flexibility to the system but debugging and monitoring is complicated. To monitor data flow, SVT boards are equipped with circular spy buffers where input and output data are continuosly copied. These buffers can be frozen and read from VME with no interruption of the normal data flow. There is one Spy Control board in each crate to control the freezing of the spy buffers. All the spy buffers in one crate are frozen simultaneously. One Spy Control board is the master and can take the decision to freeze all the spy buffers in all crates.

Error conditions, such as FiFo full, parity error or invalid data are continuosly monitored by each board. As a consequence of error conditions the Spy Buffers can be frozen and read through the VME interface. The occurrence of error condition is recorded setting error flags in the VME register of the single board and propagated in the data stream setting appropriate bits in the End Event word.

5. – Physics triggers with the SVT

During run I (1993-1996) B triggers of the CDF experiment were limited to the leptonic modes. Now the precision measurement of impact paramaters from the SVT allows to exploit more efficiently the huge Tevatron $b\bar{b}$ cross section ($\sim$100 μb) and to design new triggers much better tuned on the geometry of B events. We have studied a trigger to select the all hadronic decay $B_d^0 \rightarrow \pi^+\pi^-$ [7] which is of fundamental importance in the study of CP violation in the Standard Model. The trigger selects two stiff ($p_t > 2$GeV/c) opposite charge XFT tracks at level 1, with some separation in the azimuthal angle ($\delta\phi < 135^o$) in order to remove back-to-back pairs produced in dijet events. The trigger requires two SVT tracks with impact parameter greater than 100 μm and a positive decay length of the two track vertex at level 2. We have performed a simulation of the trigger using a detailed simulator of the SVT to reconstruct real CDF data from run I and the extrapolation to run II configuration shows that run II trigger rates are well within DAQ bandwidth. The expected signal yield is of the order of 15,000 events in 2 fb^{-1}, assuming a branching ratio for $B_d^0 \rightarrow \pi^+\pi^-$ of 10^{-5}.

Further studies have shown that with very small modifications of the cuts, the trigger is effective also in the selection of multibody decay channels useful to measure the B_s^0

mixing. The channels are $\mathrm{B}_s^0 \to D_s^- \pi^+$, $\mathrm{B}_s^0 \to D_s^- \pi^+ \pi^- \pi^+$, with the D_s^- fully reconstructed through the hadronic decays $\mathrm{D}_s^- \to \phi\pi^-$ and $\mathrm{D}_s^- \to K^{*0} K^-$. The estimated signal yield is 25,000 B_s^0 decays in 2 fb^{-1} [8]. Work is in progress to understand how to perform the CP violation and the B_s^0 mixing measurements from the collected data.

More recent studies have shown how to optimize the $\mathrm{B}_d^0 \to \pi^+\pi^-$ trigger to select $Z^0 \to b\bar{b}$ events. A low statistics $Z^0 \to b\bar{b}$ signal has been observed at CDF in run I data [9]. A high statistics $Z^0 \to b\bar{b}$ would be extremely useful in run II to improve the b-jet energy calibration and consequently the resolution on the mesurement of top mass. Moreover, the $Z^0 \to b\bar{b}$ trigger would also increase CDF sensitivity to new heavy particles decaying to $b\bar{b}$.

6. – Conclusion

The new CDF Silicon Vertex Tracker has been completely designed and simulated. Most components have been successfully prototyped and tested and are running into production. The expectation is to have all the system ready for installation in the year 2000 for the Tevatron run II data taking. Physics studies are in progress to investigate how to use this new powerful tool to attack many fundamental problems, like CP violation in the b sector, B_s^0 mixing and the search for new physics.

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