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The Inchworm System: A Dynamical Positioning Device for the SVX

S. Lai, S. Pashapour, M. Riveline, P. Sinervo, W. Trischuk
University of Toronto

Abstract

An inchworm system has been designed to ensure that the SVX can be aligned and maintained parallel to the proton-antiproton collision beam to a precision of 100 μradians. The motivation behind SVX alignment is discussed, and an overview of the inchworm system is presented. The operation of the inchworms on October 28, 2001 to align the SVX is described. The operation of the inchworm system resulted in a decrease of the misalignment from -0.78 mradians to 0.16 mradians in the x (horizontal) direction and from 0.35 mradians to -0.14 mradians in the y (vertical) direction. The location of the SVX centre was also placed closer to the collision beam line, changing from -4.4 mm in y to -2.4 mm and from 1.8 mm in x to 0.8 mm.

1 Aligning the SVX: Physics Motivation

One of the physics goals of CDF in Run II of the Tevatron is to access B meson decays with fully hadronic final states. Using such decays will enable measurements of branching ratios of B decays that either have remained unobserved or have not yet been studied. Furthermore, these hadronic B meson decays can impose constraints on the CKM matrix and provide measurements of CP Violation parameters. Of particular interest are measurements of $\sin 2\alpha$ using $B^0 \to \pi^+\pi^-$ and $\sin 2\gamma$ using $B_s^0 \to K^\pm\pi^\mp$ and $B_s^0 \to \rho K_s$.

In Run I, CDF was able to select B events in offline analysis using the Silicon Vertex Detector (SVX). However, this capacity was limited to B candidates collected with leptonic triggers. To access hadronic B decays, the events must be selected in real time with a trigger to acquire sufficient statistics. Because B hadrons have an average decay length of $\sim 500\mu$m, hadronic decays can be accessed by triggering on secondary vertices. To provide this functionality, the Silicon Vertex Trigger (SVT) has been designed to trigger on track impact parameters at Level 2 [1].

For the SVT to operate effectively, the SVX must be aligned parallel to the beam. Misalignment causes angular deviations that result in primary vertices appearing as secondary vertices and vice-versa. This causes high mistag rates, lower efficiency, and saturation of the available DAQ bandwidth. These deviations can be corrected in offline tagging, but such corrections cannot be made for trigger level tagging of B decays. This is because no z-vertex information is available in the trigger for these events. Though the Tevatron accelerator can steer the beam to align with the SVX, steering adjustments as small as 0.5 mradians potentially result in high beam losses [2].

Adverse effects also arise from a position offset of the SVX centre away from the collision beam line. A position offset of the SVX results in one side of the SVX being situated closer to the beam pipe than the other side. This results in a higher rate of radiation damage for the Layer 00 (L00) side that is closer to the beam pipe, and a small reduction in the SVT efficiency. Thus, both angular alignment and positioning about the nominal collision beam line of the SVX are crucial to achieve measurements using hadronic B decays.

The inchworm system has been designed to position the SVX so that it can be kept parallel to the collision beam to within 100 μradians. The inchworm system is also able to centre the SVX relative to the beam so that the position offset of the SVX is minimized.

The sections that follow will give an overview of the inchworm system and its design, followed by a discussion of the inchworm motor kinematics and how the SVX motion is inferred from the movement of the inchworm motors. A summary will then be given of the use of the inchworm system to align the SVX with the collision beam on October 28, 2001.

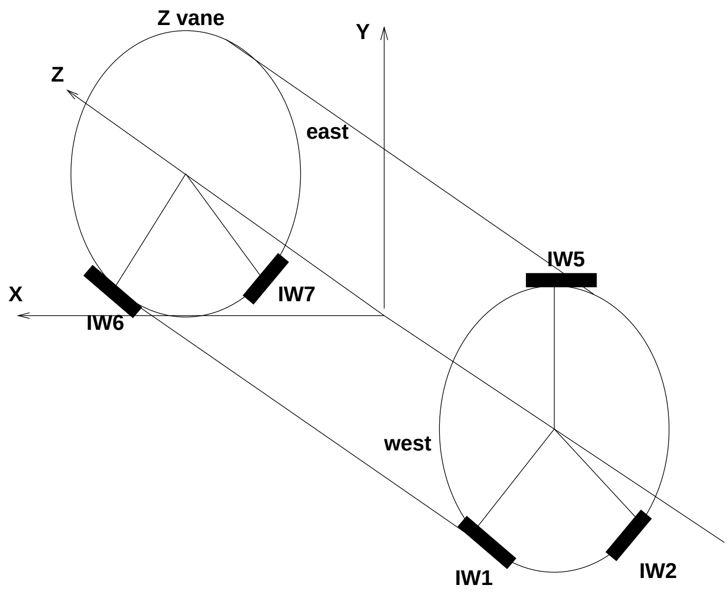

Figure 1: Inchworm motor deployment on the Silicon Vertex Detector.

2 The Inchworm System: An Overview

The inchworm system is composed of 5 motors that mount the SVX to the Central Outer Tracker (COT). Four of these motors are placed at 45 degree angles to the vertical at the bottom corners of the SVX, supporting the SVX weight. One more is placed on the top of the west end, ensuring that the SVX remains in an upright, non-rotated position. At the top of the east end, a "z-vane" constrains the motion along the beam axis (z-axis). A diagram of inchworm motor deployment on the SVX is shown in Figure 1. Each inchworm motor has the ability to adjust the SVX position by executing steps in a particular direction along the inchworm axis. In conjunction, they are able to translate and rotate the SVX along the CDF x-axis and y-axis.

A drawing of an inchworm motor is shown in Figure 2. The motors operate using piezoelectric drive cells that expand and contract under varying amounts of voltage. There are four piezoelectric cells on each motor, two expanding along the inchworm axis to enable translations (jack cells), and two expanding perpendicular to the inchworm axis to enable the unclamping of the inchworm as it makes its steps (clamp cells). By applying voltage to the piezocells in succession, the motor will extend (step up) or contract (step down) along the inchworm axis. Each step is approximately 15 μm in length and the total travel range of an inchworm motor is about 1.5 cm.

The inchworms have two sensors that provide monitoring capabilities. A potentiometer mounted between the top and bottom plates of the inchworm motors (see Figure 2) yields a voltage reading that depends linearly on the displacement of the inchworm motor. Therefore, the potentiometer enables us to determine how far the

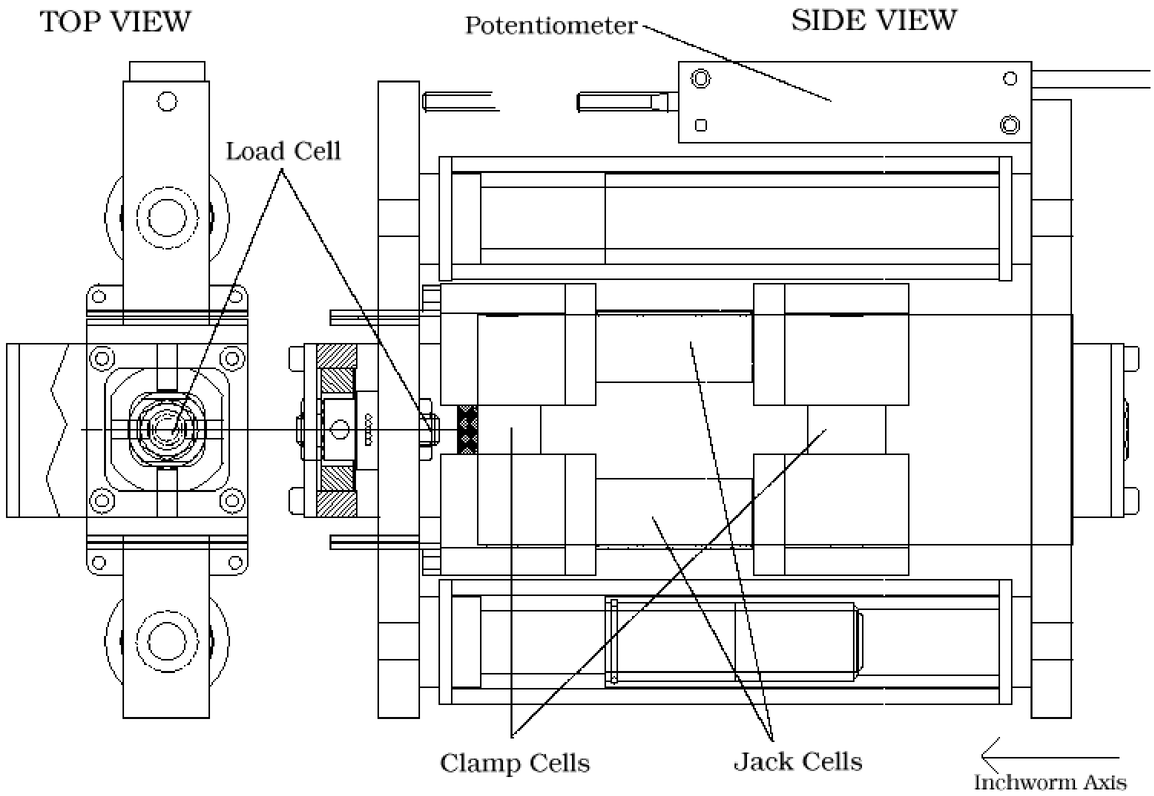

Figure 2: An engineering drawing of an inchworm motor from the top and side views. Shown are the clamp and jack piezoelectric cells, the potentiometer, and the load cell, and the direction of the inchworm axis.

inchworm has traveled in the inchworm frame of reference, enabling a calculation of the SVX displacement. A load cell is also placed on the inchworm motors to give readings of the static compressional force that each inchworm motor experiences.

The inchworm system was originally designed to support and position a detector weighing 65 kg. However, the SVX turned out to weigh 110 kg prior to cabling, with the cables adding another 70 kg in effective load due to the free weight of the cables and tension forces that they exert on the SVX space frame. This increases the load on the inchworm motors. An effective load of 180 kg yields an average load on each inchworm of 63 kg while the motors were designed originally to operate in the 23 kg range [3]. This is a serious concern, because the step sizes of the motors decrease significantly under increasing loads. A plot of step size as a function of load appears in Figure 3. Notice that at 37 kg, the inchworm motors fail to step as the step size approaches zero. In addition, tests on the inchworm motors under static conditions have shown that the inchworms can each support 50 kg without slipping, but a load of 60 kg may cause such slipping to occur.

Because of the large weight of the SVX, 3 additional springs were placed on each end between the bottom of the SVX frame and the COT inner cylinder, assisting the inchworm motors in supporting the SVX. Each of these springs has a spring constant of 1 kg/mm, so their ability to offload the inchworm is dependent on the SVX position. With the addition of these springs, the load on each motor is within 32 to 38 kg, where the motors have the ability to step. The inchworms themselves have springs installed adjacent to the motors, each with spring constants of 0.2 kg/mm to provide additional support. These springs also introduce a further dependency of stepping ability on the displacement of the inchworm motors. This effect however, has already been taken into account in the result shown in Figure 3.

The inchworm system was installed on the SVX and tested extensively in March 2001 and was shown to be able to support and position the SVX without difficulty, but this was prior to the installation of the SVX cables.

It should also be noted that during one of the tests, a spark was observed on one of the motors. The cause of this spark has been investigated and is believed to be caused by either an insulation failure between the piezo-cell leads and the body of the inchworm motor, or a short circuit on the high voltage boards. This caused considerable concern, since any spark during the operation of the inchworm system could ignite the flammable gas in the COT in the event of leakage. As a result, various precautions were taken. The first was a decision that the inchworm motors would only be operated with the COT purged of the flammable gas. Secondly, the inchworm motors were to be operated with someone in the collision hall able to see the motors. Such a person could advise the operator to abort the stepping of the motors immediately in the event of a spark. A third measure was the covering of the inchworm electronic terminal boards with insulating dope, so that no discharge between high voltage leads could occur. Finally, the high voltage circuitry was modified, with higher value resistors placed in series with the high voltage, limiting the current applied to the motors in the event of a short circuit.

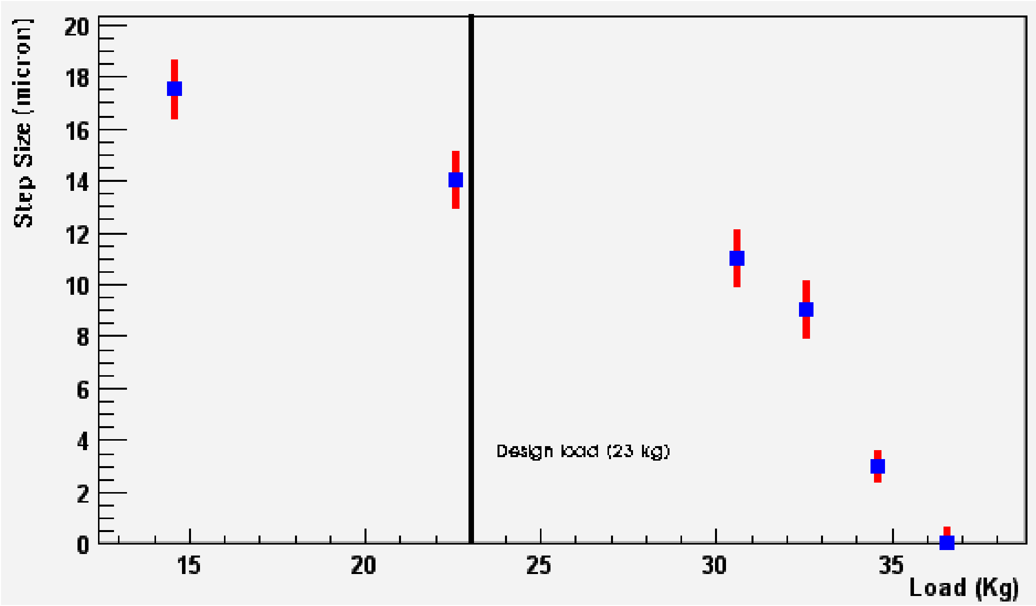

Figure 3: Inchworm step size as a function of load. The original design load was 23 kg for each motor, but the actual load each motor supports is between 32 and 38 kg.

3 Inchworm Motor Kinematics

Because the inchworm axes are not parallel to the CDF axes, the impact of inchworm steps must be converted to changes in the orientation of the SVX. Such an interpretation allows us to use potentiometer position readings to infer the displacement of the SVX due to inchworm motions.

The coordinated use of several motors allows us to displace the SVX along the CDF x-axis and y-axis. By moving the motors on one end, while leaving the motors on the other end stationary, the SVX can be rotated to correct for angular deviations of the SVX with respect to the collision beam.

For a vertical motion on a particular end of the SVX, both inchworm motors at the base are extended or contracted by the same amount. In this case, the bottom plate of the motors remains stationary, and the upper plate will move in the "up" or "down" direction, depending on the desired SVX motion. The SVX displacement is approximately equal to $\sqrt{2}\Delta L$ in the limit that ΔL is much smaller than the length of the inchworm motor. Here, ΔL is the total integrated displacement of each of the two stepping inchworm motors. A diagram of a positive ΔY motion of the SVX west end is shown in Figure 4, which is accomplished by the displacement of inchworms 1 and 2 both in the upward direction. The small displacement approximation yields $\Delta Y = \sqrt{2}\Delta L$. There is no horizontal displacement of the SVX, since the horizontal components of inchworm motion cancel.

A horizontal motion of the SVX is accomplished in much the same way, with both

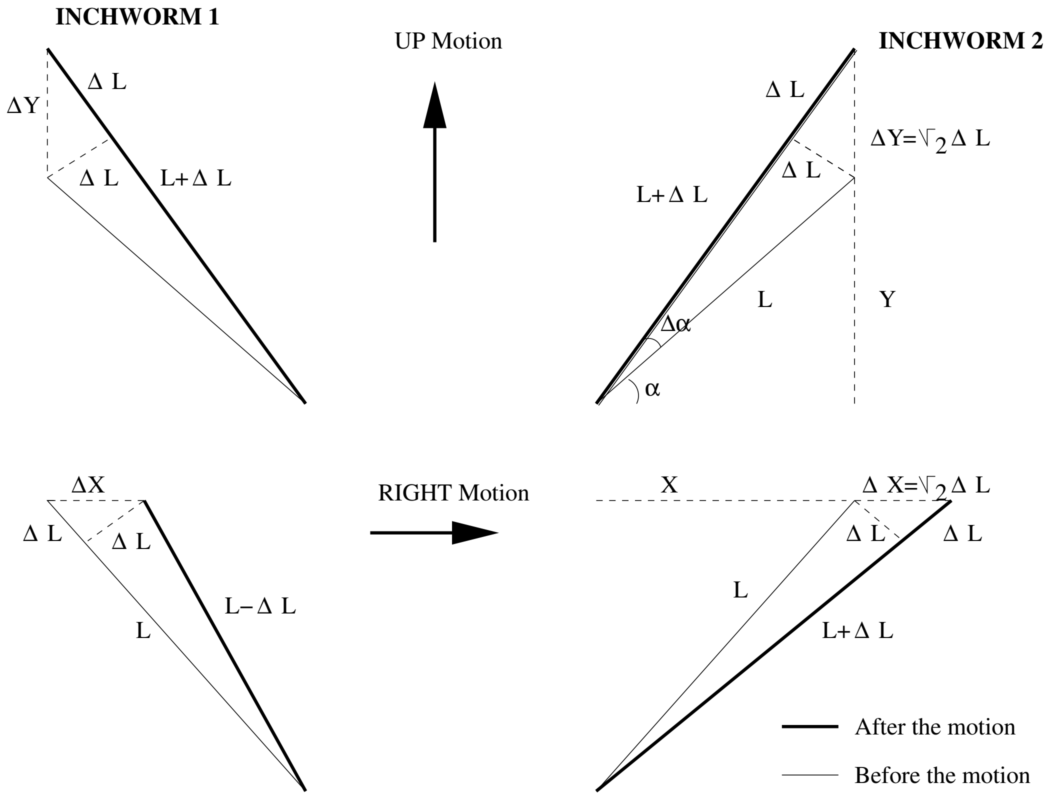

Figure 4: Examples of SVX west end motion in the upward and rightward directions due to displacements in inchworms 1 and 2. These results for ΔY and ΔX are valid in the limit $\Delta L << L$ and $\Delta\alpha << \alpha$.

inchworm motors stepping simultaneously. However in this case, one motor must expand, while the other motor on the same end must contract. This ensures that the vertical displacements due to the motors cancel, while the horizontal motions are given by $\Delta X = \sqrt{2}\Delta L$ in the small displacement limit. A diagram of a negative ΔX motion on the SVX west end is shown in Figure 4, accomplished by the "downward" motion of inchworm 1 and "upward" motion of inchworm 2. A horizontal motion can introduce a small angle rotation of the SVX, causing undesired torques on the SVX frame. This can be mitigated by moving inchworm 5 by the same amount and in the same direction as the expected displacement of the SVX. This ensures that the SVX does not rotate during horizontal translations.

In practice, one can never ensure that the displacements of the two inchworm motors along their axes are exactly the same size. Typically, these displacements will differ by up to $\sim 100\mu$m, and may introduce an additional displacement. We treat this case as two separate motions, one motion in the desired direction, and a residual motion perpendicular to the desired displacement. As an example, if inchworm 1 steps 400 μm upwards and inchworm 2 steps 500 μm upwards, then the SVX motion is a superposition of a pure upward motion of 450 μm and a southward motion of 50 μm. The SVX motion in the west end is then $\Delta Y = \sqrt{2} \times 450$ μm and $\Delta X = -\sqrt{2} \times 50$ μm.

These are the relations that enable us to predict the SVX motion from the observed displacements of the inchworm motors.

4 Inchworm Operation: October 28/01

A scheduled six-week shutdown of the Tevatron commenced on October 8, 2001. With charged track data, it was determined that the SVX was misaligned with respect to the Tevatron orbit [2]. The misalignment was 0.35 mradians in y, equivalent to the west end lower than the east end by 1.1 mm. In the x-direction, the misalignment was -0.78 mradians, with the west end further north than the east by 2.5 mm. Such a misalignment would cause large beam losses if the Tevatron were to attempt aligning the beam parallel to the SVX. In addition, a substantial offset of the SVX was also detected. The centre of the SVX was 4.4 mm low in the y-direction, and 1.8 mm further north than the beam in the x-direction.

We used the inchworm system to modify the SVX position with respect to the beam. A step sequence was planned to optimally position the SVX. The first step was to move the SVX west end toward the south (Tevatron centre) by 2.5 mm, eliminating the misalignment in x and reducing the x offset by 1.2 mm so that the SVX centre was 600 μm away from the beam in x. Once this was accomplished, the SVX west end would be moved upwards by 1.1 mm, eliminating the misalignment in y and reducing the y offset by 500 μm, leaving the centre of the SVX 3.9 mm too low. Then the west and east ends would be moved in turn by displacements of $\sim$500μm each.

However, due to the large weight of the SVX, the inchworm motors were near the

Motor	Placement	Load Before Relief (kg)	Load After Relief (kg)	Load After Operation(kg)
1	NorthWest	32.2	28.3	40.1
2	SouthWest	35.1	30.5	42.0
5	WestTop	0.5	0.5	-1.3
6	NorthEast	35	26.3	35.4
7	SouthEast	broken	broken	broken

Table 1: Inchworm motor loads before and after relieving the loads prior to operation are shown along with the loads immediately following inchworm operation. Note that inchworm 7 does not have load monitoring capability due to a damaged load cell.

maximum carrying capacity under dynamic operation. Table 1 shows the load on each inchworm motor, as given by the respective load cells before operation of the inchworm motors on October 28.

Because the motors were close to the dynamic threshold, any movement in the upward direction would be minimal, since the step sizes of the motors would approach zero in a short amount of time. Since there would be an upward motion of inchworm 2 (SW) already loaded at 35.1 kg to move the west end towards the north, and in the upward direction, this motor would approach its dynamic limit in a displacement of a few hundred microns. This is due mainly to the 3 additional springs, each with $k_{spring} = 1$ kg/mm supporting the SVX on each end, implying that a displacement of 0.5 mm upward would cause increases of $\sim$1 kg on each inchworm.

To reduce the strain on the inchworm motors, a lever system was used, with the fulcrum placed on the SVX frame, balanced by the SVX weight on one side and bricks placed in a bucket on the other side. This reduced the load on each inchworm by $\sim$ 5 kg, bringing the maximum load on any inchworm to 30.5 kg (inchworm 2). The loads on all motors after relieving the load are also listed in Table 1. This lever system increased the dynamic range of the motors, enabling us to safely operate the inchworm motors through the full range of motion. In addition to the inchworm potentiometers, dial indicators and the Rasnik system [4] were used to confirm the SVX movement.

Once the setup was satisfactory, we proceeded to use the inchworm motors to align the SVX. Table 2 lists the planned movements and the resulting movements of the SVX. No sparking was observed during these series of motions.

With these motions, the new position of the SVX was calculated. The misalignment in x went from -0.78 mradians (2.5 mm) to 0.16 mradians (480 μm), with the west end tilted slightly toward the south. The misalignment in y went from 0.35 mradians (1.1 mm) to -0.14 mradians (420 μm), with the west end now higher than the east end. The location of the SVX centre was raised to -2.4 mm in y from -4.4 mm, and was translated to 0.8 mm in x from 1.8 mm. The SVX was now within a range where the accelerator could steer the beam parallel to the detector without

Step	Purpose	Motion(mm)	Motion(mm)	Motion(mm)	Δy(mm)	Δx(mm)
1	Move West 2.5[S]	IW1: -1.74	IW2: 1.82	IW5: -2.23	0.06	-2.40
2	Move West 1.6[up]	IW1: 1.22	IW2: 1.25		1.73	-0.03[S]
3	Move East 1.0[up]	IW6: 0.68	IW7: 0.48		0.81	0.14
4	Move West 0.5[up]	IW1: 0.55	IW2: 0.48		0.72	0.05
5	Move East 0.5[up]	IW6: 0.31	IW7: 0.37		0.47	-0.03
6	Move West 0.2[up]	IW1: 0.13	IW2: 0.15		0.20	-0.02
7	Move East 0.3[N]	IW6: 0.18	IW7: -0.28		-0.06	0.32
	Total West				2.68	-2.40
	Total East				1.22	0.43

Table 2: Movements by inchworm motors on October 28, 2001.

experiencing high losses, and the offset was reduced by half. The overall change in SVX position appears in Table 3 along with the independent measurements of SVX displacement from the Rasnik system and track fitting algorithms [5].

We expect that the improvement of the SVX position with respect to the beam will improve the SVT efficiency, while any further corrections can be made by the Tevatron with minimal losses in luminosity. In addition, the lifetime of L00 will be increased, since the top portion is now placed 2.0 mm further from the collision beam.

After the SVX positioning on October 28, the inchworm system continued to be monitored for changes in load and position. No slippage has been observed by the potentiometers, and this has been confirmed by the Rasnik system. In addition, the maximum load on any inchworm is 42 kg, and tests have shown that loads of this magnitude will not cause the inchworm motors to slip from their current position. The loads on each motor after the operation of the inchworm system are shown in Table 1.

5 Conclusions

The inchworm system was designed to dynamically align the SVX. After extensive testing and mock-up of the SVX space frame, it has been installed on the SVX. Because of the misalignment of the SVX and collision beam, the inchworm system was used to improve the SVX position.

Reading	Inchworm	Rasnik	Track Fitting
West x-motion (mm)	-2.40	-2.28	
West y-motion (mm)	2.68	2.35	
East x-motion (mm)	0.43	0.36	
East y-motion (mm)	1.22	1.20	
ΔX (mm)	-0.99	-0.96	-0.85
ΔY (mm)	1.95	1.78	1.75
$\Delta X'$ (mrad)	0.94	0.88	1.04
$\Delta Y'$ (mrad)	-0.49	-0.38	-0.49

Table 3: Shown are inchworm potentiometer, Rasnik system, and track fitting measurements of the motion of each end and the change in the SVX centre and angular alignment before and after the move. Note that these are not the offset and misalignment numbers for the SVX with respect to the beam.

With this adjustment of the SVX positioning, the misalignment and offset of the SVX with respect to the beam has been considerably reduced. We expect this will prolong the lifetime of L00 and increase the SVT efficiency, allowing reliable triggering on secondary vertices, giving CDF the ability to accumulate a large hadronic B-meson sample. Furthermore, the accelerator should be able to correct for any further alignment, since the adjustment needed will not result in high beam losses.

Continued monitoring of inchworm feedback systems is necessary to ensure that no slippage occurs and any changes to loads are detected. Barring any slippage of the inchworms or adverse displacements of the collision beam, the SVX is now positioned such that secondary vertex triggering can be fully utilized.

References

[1] S. Belforte *et al.*, Silicon Vertex Tracker TDR, CDF Note 3108, 1995.

[2] R. Culbertson, A. Foland *et al.*, Beam Steering Tests, CDF Note 5733, 2001.

[3] We will use kg to describe forces on the inchworm motors. To convert to units of newtons, multiply the force given in kg by the value of $g = 9.8$ m/s^2.

[4] D. Goldstein, D. Saltzberg, CDF Rasnik webpage, http://www-cdf.fnal.gov/internal/upgrades/rasnik/main.html

[5] R. Culbertson *et al.*, CDF Alignment webpage, http://www-cdf.fnal.gov/internal/upgrades/align/news.html