SLAC-PUB-10722
September 2004

Performance, radiation damage, and future plans of the BaBar Silicon Vertex Tracker

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Abstract

The *BABAR* Silicon Vertex Tracker has been in operation for four years at the PEP-II electron-positron storage ring. During this time the SVT modules have accumulated a radiation dose up to 2 Mrad. We study the degradation in the performance of the SVT due to this accumulated dose which is highly non uniform across the device and also within the individual silicon detectors. To extrapolate the performance of the device to the future we study separately the effect of the irradiation on silicon detectors, front end integrated circuits and on a complete detector module under controlled radiation conditions, using a ^{60}Co source and a 0.9 GeV e^- beam. We compare the results to the data from the SVT. In particular we show the dependence of the charge collection efficiency on the radiation dose even when a small stripe of the module is irradiated up to space charge sign inversion. Since the modules that are located in the plane of the beams will suffer significant radiation damage, we will describe our plans for their replacement in 2005 and for the operation of the SVT through the lifetime of the *BABAR* experiment.

Submitted to IEEE Transaction on Nuclear Physics

Work supported by Department of Energy contract DE-AC02-76SF00515

Manuscript received November 23, 2003; revised March 1, 2004.

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I. Introduction

The Silicon Vertex Tracker (SVT) is the central vertexing device of the *BABAR* detector [1] which is installed on the PEP-II storage ring at SLAC. The PEP-II machine collides head-to-head positrons and electrons with asymmetric energies, respectively 3.1 GeV and 9.0 GeV. The primary goal of the *BABAR* experiment [2] is the measurement of the time dependent violating asymmetries in the decay of the neutral B mesons. The $B^0\overline{B^0}$ mesons produced from the $\Upsilon(4S)$ resonance evolve together coherently and decay with an average z-separation $\Delta z \simeq 260$ μm due to the boost of the center of mass with $\beta\gamma \simeq 0.56$. The proper time difference $\Delta t = \Delta z/\beta\gamma c$ is determined using the SVT information and is the fundamental ingredient of such a measurement.

II. Design

A. Physics Requirements

The main design goal of the SVT is to reconstruct the z-separation of the decay vertices of the B mesons. A resolution better than 190 μm is required such that the precision on the CP asymmetry measurement is reduced by only 10% with respect to perfect resolution. The SVT also provides standalone tracking for charged particles that do not reach the main tracking chamber.

B. Detector Layout

The SVT sensors are made of 300 μm thick double sided silicon AC coupled detectors with strip pitch varying from 50 to 210 μm [3]. The resistivity of the n bulk varies from 6 to 30 KΩcm. The silicon detectors are assembled in modules which consist of several silicon detectors glued head to head and fanout circuits for carrying the strip signals to the front-end electronics, on hybrid circuits, at the end of the modules. The modules are assembled in five layers with radii varying from 3.3 to 14.6 cm. Layer 1, 2, 3 are made of 6 modules each, layer 4, 5 consist of up to 18 modules. The modules in layers 4 and 5 are arch-shaped in order to maximize the angular coverage minimizing the track angle of incidence with respect to the detector surface.

C. Readout Electronics

A custom designed chip, the AToM chip [4], is used to read out the strips. It is based on a radiation hard 0.8 μm CMOS process developed at Honeywell, and is capable of signal digitization by means of the time-over-threshold (ToT) algorithm. A minimum ionizing particle passing trough the silicon sensor generates a signal of about 24,000 electrons distributed in a cluster of two or more strips, while the measured electronics noise (at construction time) is 700-1500 ENC (equivalent noise charge) per strip, depending on the layer and the readout view.

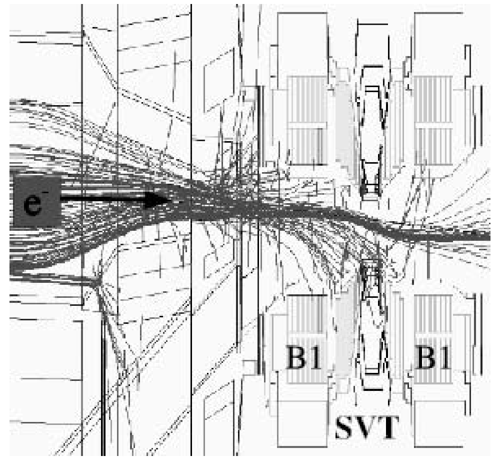

Fig. 1. Simulation of the background in the SVT; the red lines represent the 9.0 GeV electrons, the SVT and the B1 magnets are also indicated

III. Radiation Damage

A. Radiation Environment

The interaction region of the PEP-II storage ring is designed to have permanent bending magnets (called B1) 20 cm away from the interaction point in order to collide the beams with zero crossing angle. The particles of the beams can lose energy along the ring due to coulomb scattering or bremsstrahlung emission of a hard photon. If they lose enough energy they are over-bent by the B1 magnets and directly hit the SVT or the material in front of it (1). The resulting radiation is mainly concentrated in the bending plane. This is the main source of accumulated dose for the SVT.

B. Radiation Monitoring

The radiation dose accumulated by the SVT is monitored by a set of 12 reverse biased silicon p-i-n diodes, 1cm x 1cm area, 300 μm thick, located between the beam pipe and the front-end electronics of the innermost layer. The measured radiation in the bending plane of the beams is about 10 times higher than the average, which corresponds to a peak dose of 50-100 mrad/s in a 1 cm wide stripe on the silicon detectors of layer 1. The maximum accumulated radiation foreseen at construction time was about 250 krad/year while the SVT has already integrated, in the worst cases, almost 2Mrad in four years.

C. Irradiation tests

The accumulated dose affects the performance of both the silicon detectors and the front end electronics. In order to understand quantitatively the limits of operability of the detector in this environment we have performed a set of studies of signal/noise degradation and efficiency reduction on irradiated detectors. We have also compared those analyses to the data from the installed detector.

D. Radiation Damage in the Silicon Detectors

The most relevant effect in the silicon detectors is the displacement of atoms in the crystalline structure of the bulk. This results in a change of the effective dopant concentration and the electrical properties of the detector. To study these effects we have irradiated silicon detectors with electrons in the energy range 0.9 to 3 GeV at SLAC and Elettra(Trieste) up to a maximum dose of 5Mrad (equivalent to $1.5 \times 10^{13} 1 MeV\ n/cm^2$). The detectors have been irradiated at SLAC with direct electron beams and with electrons scattered by a copper target to reproduce the electromagnetic showers generated by the accelerator elements. At Elettra the irradiation was spatially non uniform to simulate the azimuthal dependence of the PEP-II radiation background. The measured increase [5] of the detector reverse current is about $2\mu A/cm^2/\mathrm{Mrad}$ (at 27^oC) which is consistent with the values measured on the installed detectors. The shift in the full depletion voltage is determined from the measurement of the capacitance of a diode test structure as a function of the voltage applied and is consistent with the NIEL [7] scaling hypothesis. The Space Charge Sign Inversion (SCSI) occurred around 3Mrad. The measurement of the electrical properties of the detectors (contribution to the current from the edge zones of the detector, inter-strip capacitance, insulation between the p-strips at low bias voltages) indicate that the detector can be operated after SCSI.

E. Charge Collection Efficiency

1) Damage mechanism: The defects in the crystalline structure generate energy levels between the valence and conduction band. These energy levels act as traps for the electrons and holes generated in the space charge region. The trapped carriers are released on a time scale larger than the integration time of the front-end electronics of the inner layers (200 ns) and thus they do not contribute to the signal formation. The trapping probability ($1/\tau$) is expected to increase linearly with the fluence of ionizing particles (ϕ) with a coefficient (γ) such that: $1/\tau = \gamma \times \phi$. γ has been measured [6] in the range $\gamma = 5 \times 10^{-16} cm^2 ns^{-1}/n$. Given the sensitivity of our method (5%) and a typical signal formation time of 10 ns we expect to measure a reduction of the CCE around an equivalent fluence $\phi = 10^{13} 1 MeV\ n/cm^2$.

2) Irradiation: We have irradiated a complete SVT module consisting of silicon detector and front end electronic circuits with the 0.9 GeV electron beam of Elettra (Trieste) up to a maximum dose of 5.5 Mrad (equivalent to $1.6 \times 10^{13} 1 MeV\ n/cm^2$). The detector was irradiated in a narrow stripe of width 1.44 mm (the detector is 4 cm wide) in order to simulate the non uniform radiation generated in the *BABAR* experiment. The front end electronics were not irradiated in order to disentangle this effect from the degradation of the ATOM chip. The irradiation was performed in four steps and after every step the charge collection efficiency was measured.

3) Determination of the CCE: To determine the CCE we illuminate the silicon detector with a 1060 nm light-emitting-diode focused on a 0.5 mm diameter spot. The 50ns long light pulse penetrates trough the silicon wafer and generates e-h pairs in the bulk by photoelectric effect. The power of the LED is chosen to be in a linear response range such that the amount of nonequilibrium e-h pairs generated in the space charge region is proportional to the LED supply current I_{LED}. Let i be the channel index on one of the two sides and let $T(i)$ be the threshold of channel i corresponding to a charge signal generated by the LED light. $T(i)$ can be determined by means of a threshold scan and is proportional to the collected charge. By varying the LED power we modulate the amount of charge generated in the detector volume and we can measure the slope $S(i)$ of the corresponding threshold variation as a function of I_{LED}. It can be shown that the sum of the ratio $S(i)/G(i)$ on all the illuminated channels is $\sum(S(i)/G(i)) = B \times CCE \times D$ where $G(i)$ is the measured gain of the channel i, D is a conversion factor, CCE is the charge collection efficiency and B accounts for the nonuniformity of the light intensity across the illuminated strips. By comparing the sum before and after the irradiation we can determine the change in the charge collection efficiency $(\sum S(i)/G(i)^{after})/(\sum S(i)/G(i)^{pre}) = (CCE^{after}/CCE^{pre})$. The ratio of CCE is measured on a 30x30 grid on the detector and is shown in Fig. 2. The most damaged region of the detector reaches space charge sign inversion in the sensitive volume after about 3Mrad. In this zone the detector could be locally not fully depleted and that will lead to a reduction of the CCE. To verify that the measurement is not sensitive to this effect, we measure the charge collection efficiency as a function of the applied voltage and we verify that the CCE reaches the saturation to the maximal value at a bias voltage of 60V, smaller than the operational voltage used in this test (70V). Since the SVT power supplies are capable of providing a voltage up to 80 Volts we do not expect any problem to fully deplete the detectors up to 5.5 Mrad integrated dose. To evaluate the systematic error we estimated the effects of the alignment of the detector with respect to the diode support structure to be less than 0.2% and we verified that the measurement is stable in time to the 1% level.

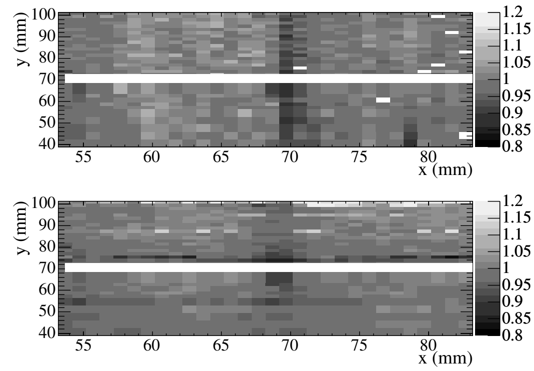

Fig. 2. Map of CCE ratio (gray scale) after/before irradiation for signals measured from strips on the n-side (upper plot) and on the p-side (lower plot) over a grid of 30×30 spots of $0.5 \times 0.5 mm^2$ area.

4) Results: In the central part of the irradiated zone we observe a reduction of the charge collection efficiency of $6\% \pm 4\%$.

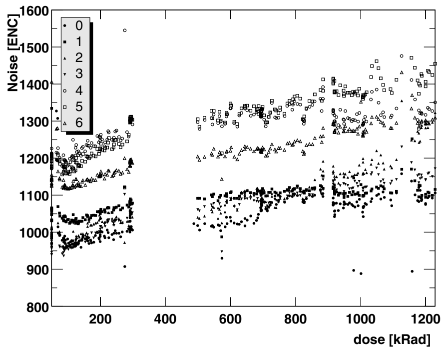

Fig. 3. Noise level measured on SVT detectors as a function of the accumulated dose (different markers correspond to different chips)

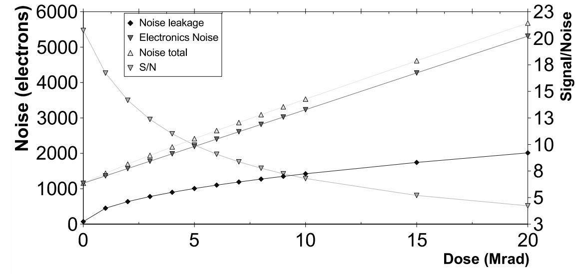

Fig. 4. Predicted noise level and signal/noise ratio as a function of the integrated dose

The zones in Fig. 2 with reduced CCE outside the irradiated region correspond to electronics channels damaged by external factors.

F. Radiation Damage in the Front End Electronics

1) ATOM chip irradiation with ^{60}Co: The dominant damaging mechanism to the front end chips is the creation of defects in the interface between the silicon and the silicon oxide. This leads to an increase of the noise, a reduction of the gain in the analog part of the chip, and possible failures of the digital part. To study these effects one hybrid circuit loaded with ATOM chips has been irradiated at LBL with a ^{60}Co source up to a maximum dose of 5 Mrad. In order to irradiate uniformly all the elements, the gamma rays were thermalized by means of an aluminum/lead box. The chips were powered and clocked during the irradiation since, in a working environment, the chips are always powered, and irradiation without power is known to have very different effect from irradiation of powered devices. The irradiation was performed in several steps and after each step the analog parameters of the chip (noise, gain, threshold) were measured. Load capacitances of various values were bonded on a few channels of the chip to simulate the detector strips. The chips didn't show any digital failures, however we we observed an increase of the noise and a decrease of the gain. The noise σ_n was parameterized with a linear dependence on the capacitative load $\sigma_n = \alpha + \beta \times C_{load}$. The measured increase of the α and β coefficients was 59 enc/Mrad and 6.8 enc/pF/Mrad, respectively, and the gain decreased by 2.8%/Mrad. The values measured in reference irradiations tests qualitatively agree with the increase of noise (Fig. 3) and decrease of gain observed in the installed front end chips .

G. Signal/Noise degradation

The signal/noise ratio for a single readout strip (S/N) is the figure of merit for the operability of the detector and at the time of installation was about 20. The total noise level can be estimated as the sum of the contributions from the leakage current (shot noise) and the electronics noise of the chip itself. The gain and the charge collection efficiency reduction affect the magnitude of the signal. All those effects can be estimated using the measurements presented in this work. After 5Mrad of accumulated dose the S/N ratio is reduced down to our operability limit 10, mainly because of the increase of the front-end chips noise (Fig. 4).

This limit is somewhat conservative in the sense that is based on the S/N for the worst case of the detector which represents only 10% (the bending plane) of the inner layers.

IV. Future plans

It has been shown that the radiation damage in the silicon detectors and the front-end electronics of the SVT is mainly concentrated on the modules that intersect the bending plane of the beams. These modules represent $\frac{1}{3}$ of the inner layers of the SVT and are foreseen to reach the 5 Mrad dose limit by 2005. In order to maintain the full azimuthal angle coverage we plan to replace the damaged modules with spare ones during the 2005 shutdown. The mechanical supports of SVT and the B1 magnets have to be extracted from the *BABAR* detector and disassembled in order to allow access to the SVT. Replacing the innermost modules requires extraction of all the modules from the SVT carbon fiber frame and assembling them together again. This operation requires stopping the experiment for at least four months.

We have recently found that during this process it will be possible to modify the support structure of the SVT to allow the rotation of the device around the beam axis. The SVT is supported on the beam pipe by so-called "gimbal rings". These rings allow the z movement on one end of the beam pipe and the azimuthal degree of freedom on the other end. Those rings can be modified to also allow the rotation with an unlocking and locking mechanism. The rotation would only require extracting the structure from the *BABAR* detector but would not require disassembling the SVT from the beam pipe.

A rotation of $\pm 60^o$ can move the damaged modules out of the bending plane of the beams and bring fresh modules were the radiation is concentrated, while maintaining the same detector geometry. A combination of module replacement and rotation will allow us to reach the end of the experiment with less than 5Mrad integrated dose in the worst case.

V. Conclusion

We have reviewed the radiation damage to Silicon Vertex Tracker of the *BABAR* detector and presented the results from the irradiation tests in controlled conditions on silicon detectors and front end chips. From these tests we conclude that the silicon detectors will continue to function after type inversion, the charge collection efficiency will not be significantly reduced up to 5.5Mrad and the degradation of the signal/noise of the SVT will be dominated by the increase of the noise of the front end electronics. The results presented allow to predict the evolution of the signal/noise ratio as a function of the integrated dose and to establish a lifetime estimate of about 5 Mrad. In addition the replacement of the most damaged modules will allow us to reach the end of the experiment with an efficient vertex detector.

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