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# BaBar Silicon Vertex Tracker: Status and Prospects

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## Abstract

The BaBar Silicon Vertex Tracker (SVT) has been efficiently operated for six years since the start of data taking in 1999. Due to higher than expected background levels some unforeseen effects have appeared. We discuss: a shift in the pedestal for the channels of the AToM readout chips that are most exposed to radiation; an anomalous increase in the bias leakage current for the modules in the outer layers. Estimates of future radiation doses and occupancies are shown together with the extrapolated detector performance and lifetime, in light of the new observations.

*Key words:* Silicon detector, radiation damage, charge accumulation
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**The *BaBar* Silicon Vertex Tracker** The *BaBar* experiment [1] at the PEP-II $e^+e^-$ storage ring is designed to primarily measure CP violation in the $B\overline{B}$ system and to perform precision measurements of the CKM quark mixing matrix. The asymmetric beams provide a center-of-mass energy of 10.58 GeV, near the $\Upsilon(4S)$ resonance, with a net boost that gives a measurable separation of the decays of the two $B$ meson daughter particles of the $\Upsilon(4S)$. The *BaBar* Silicon Vertex Tracker (SVT) [2,3] is the sub-detector that is nearest to the $e^+e^-$ interaction point. Its primary purpose is the precise determination of the track parameters of charged particles to allow the reconstruction of vertices with a resolution that is sufficient to disentangle the two $B$ decays. The SVT has achieved a beam (z) axis vertex resolution of $80\mu$m which is well below the average separation along the beam axis of the two $B$ mesons, $280\mu$m. For charged particles with transverse momentum too low to reach the other detector elements ($p_T < 120\mathrm{MeV}/c$), pions from $D^{*\pm}$ for example, the SVT provides the sole reconstruction information.

The SVT is a concentric five layer silicon microstrip detector comprised of over 150 000 channels on 340 double-sided, AC-coupled silicon wafers. The layers range in radius from the beam axis from 3.2 to 14 cm. Each wafer has one side instrumented with strips oriented perpendicular to the beam axis ('z-strips') and the other side instrumented with strips parallel to the beam axis ('$\phi$-strips'). The silicon strips are read using a custom-designed integrated circuit known as the AToM chip [4]. Each AToM chip is capable of simultaneous acquisition, digitization, and sparsified readout of 128 channels. The linear analog section consists of a charge sensitive preamplifier, followed by a shaper. The output signal is compared to a programmable threshold producing a logic pulse whose width (Time over Threshold, ToT) is approximately proportional to the logarithm of the collected charge. The logic pulse is digitized at 15 MHz and stored in a latency buffer. Upon a Level-1 trigger signal, the AToM chip searches a one $\mu$s window in the buffer for the first hit. For channels with a hit, the ToT and hit time in the buffer is transmitted to the data acquisition system.

**Performance** The SVT hit efficiency, measured using reference tracks traversing the active area, averages at 97%. (This is calculated excluding five currently unresponsive readout sections.) The efficiency for reconstructing low momentum particles is 75% for momenta above 100 MeV and 90% for momentum above 200 MeV. The hit resolution is measured using high-momentum tracks in two-prong events. For tracks that are incident perpendicular to the silicon modules, the hit resolution is between 10 and $15\mu$m for the inner three layers and between 30 and $40\mu$m for the outer two layers. With this, the SVT achieves its design goal of an average vertex resolution better than $80\mu$m in $z$, depending on the reconstruction channel, for a fully reconstructed $B$ decay. The resolution of the separation of the vertices of the two $B$ mesons from the $\Upsilon(4S)$ is $190\mu$m.

**Radiation Damage Studies** By October 2005, the PEP-II storage ring has delivered more than $300\mathrm{fb}^{-1}$ and achieved an instantaneous luminosity in excess of $1 \times 10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ (over three times the design value). However the radiation backgrounds have also been higher than foreseen. The total radiation dose over the full lifetime of *BaBar* was not expected to exceed 2 Mrad, but certain parts of the detector have already accumulated a 3 Mrad dose. The inner layers naturally absorb the most dose and, due to the design of the interaction region, the radiation is concentrated in a 1-cm wide band in the horizontal direction. Away from the horizontal band, the radiation levels are up to a factor of 10 lower at the same radius.

Given that *BaBar* is expected to continue recording data through 2008 with ever-increasing luminosities, extensive radiation studies have been performed to determine the lifetime of the SVT [5]. However, despite these extensive tests, some unexpected radiation-related effects were observed in the installed detector; we will discuss: a shift in the pedestal for some channels in the AToM readout chips; an anomalous increase of the bias leakage current for the modules of the outer layers. Fortunately, the SVT is designed with sufficient flexibility that we are able to overcome these effects with essentially no loss in detector efficiency.

**Pedestal Shift** After an accumulated dose of about 1 Mrad, we observe an increase in the pedestal of the signal into the comparator in the

AToM, requiring an increased threshold level in order to keep the noise occupancy at a reasonably low level. The pedestal increase was first observed in the readout channels exposed to the highest amount of radiation, but other channels soon followed as their accumulated dose reached about 1 Mrad. This is illustrated in Fig. 1, which shows the measured pedestal versus the radiation dose in the most irradiated channels. The readout channels in the AToM chip are geometrically offset in azimuth with respect to the silicon strips, allowing us to determine that it is the most irradiated readout channel, not silicon strip, that is affected first. From this we conclude that the radiation damage is in the AToM chip itself.

The pedestal continues to rise until an additional 400 krad of dose has been accumulated, after which it starts to fall back to its original value. The pedestals peak at half the dynamic range of the threshold DAC, corresponding to roughly 1 fC. This effect is qualitatively understood to be caused by an asymmetry in the comparator circuitry, which causes a net offset with accumulated dose. After sufficient irradiation the balance slowly gets restored. Radiation tests [6] with a narrow electron beam reproduced the pedestal shift. Operationally the noise is kept under control by increasing the threshold used in the readout. However this can only be set on a chip-by-chip basis, leading to an inefficiency for small charges in channels where the pedestal has not yet increased. A procedure has been devised that selects the optimal threshold for each chip by balancing the inefficiencies from the noise occupancy and the minimum charge requirement. The thresholds need to be re-optimized bimonthly, especially as new modules reach a 1-Mrad radiation dose.

ANOMALOUS BIAS CURRENT INCREASE A second effect has occurred more recently. In March 2004, the leakage currents in several modules in the fourth layer suddenly started to increase from a few $\mu$A to hundreds of $\mu$A over a period of three months. At such a high current level, the occupancy increases significantly due to noise, resulting in a loss in hit efficiency. In the same period no significant leakage current increase was observed in any of the inner layers, which receive higher radiation levels, and thus this increase could not be caused by radiation damage to the bulk silicon. The leakage current only increased during time periods with both radiation and a fully biased detector. If either of the two conditions were not satisfied, the leakage current dropped at roughly the same rate as it had been increasing.

This curious effect is believed to be caused by static charge accumulation. Ions are produced in the gap between layer four and five by radiation; they build up on the $SiO_2$ passivation layer on the p-side of layer four. The accumulated charge increases the field at the edge of the $p^+$-implant junction, eventually causing junction breakdown manifested as the increased leakage current. The effect of accumulated charge has been qualitatively understood in simulations and in lab tests with ionized air and an external electric field. Only layer four is affected due to its particular configuration of p- and n-sides with respect to the other layers. The effect was not observed before because in the past the SVT was normally unbiased for about 10 minutes every hour in order to refill the storage ring, during which times the accumulated static charge could dissipate. In March 2004, PEP-II began injecting continuously and the SVT now remains biased for many hours at a time.

The rate of increase in leakage current depends on the voltage difference between the outer side of layer four and the inner side of layer five, originally 40 V. We modified the reference voltages of the power supplies to reduce this voltage difference to 0 V, this allowed the leakage current to drop with no adverse effect on SVT performance. We also increased the humidity of the air surrounding the detector to about 8% in order to facilitate charge dissipation. As a result of these modifications, we have successfully remedied the high leakage currents, which are now all below 50 $\mu$A.

EXPECTED PERFORMANCE As stated above, radiation levels have been higher than anticipated. As PEP-II increases the instantaneous luminosity even further, this poses a potential problem for the SVT. The expected noise levels as a function of radiation dose are shown in Fig. 2. The degradation of the front-end electronics dominates. The signal-to-noise ratio, $S/N$, takes into account the loss in signal from the charge collection efficiency and gain losses. At a dose of 5 Mrad, a $S/N$ of 10 is reached, at which point studies show a serious impact on detector performance.

The accumulated and expected radiation dose to the SVT modules in the horizontal plane is shown in Figure 3. The dose predictions are based on measured dose rates parameterized as a function of beam currents and luminosity together with the predicted future beam currents and luminosity. The beam currents are predicted to double, while the luminosity should triple. By 2007 the first modules are predicted to reach the performance-degradation limit of 5 Mrad. However, the dose away from the horizontal plane is much lower: by 2008 only (5–10)% of the readout channels in the two inner layers are expected to be significantly affected by radiation damage.

We expect that some parts of the SVT will become inoperable as the radiation dose reaches 5 Mrad, and so detailed studies have been performed to quantify the possible impact on physics analysis. In a set of realistic to pessimistic scenarios in which up to 10% of the inner layers are disabled, we find a loss in reconstruction efficiency of (2–4)% for $B^0 \to J/\psi\, K^0_S$ decays with no significant impact on the mass or vertex resolution. The most significant loss observed is a (2–10)% drop in reconstruction efficiency for slow pions from $D^*$ decays. However, the loss in efficiency is acceptable and leaving the damaged modules in place should have little impact on physics. Thus, since it is not worth the added risk and downtime to replace the modules, we plan to leave the SVT unchanged through 2008.

Conclusion The SVT has had excellent performance during the past six years and has been an essential part of the *BABAR* experiment. A few unforeseen problems have arisen, but due to the flexibility of the system, they have been remedied without loss in performance. Extensive radiation studies have shown that the future increase in luminosity, and hence radiation dose, will result in (5–10)% of the inner-layer readout channels exceeding a newly established radiation budget of 5 Mrad. This radiation dose limit is significantly higher than the original design requirement of 2 Mrad. However, the physics impact has been evaluated to be negligible, and we therefore expect the SVT to perform well through to the conclusion of the experiment. Work supported in part by the U.S. Department of Energy under contract number DE-AC02-76SF00515.

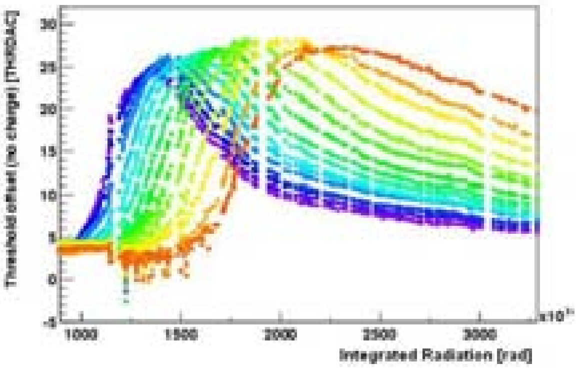

Fig. 1. (color online) Each line represents a group of eight readout channels. The ordinate, Integrated Radiation, is the average dose received by the most-irradiated channels. The pedestal is averaged over each group and plotted versus the Integrated Radiation. One THRDAC count corresponds to a charge of 0.05 fC.

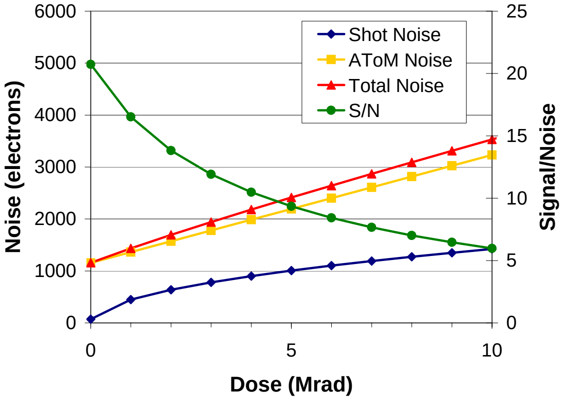

Fig. 2. (color online) Individual noise components and total predicted noise versus radiation dose. Also shown is the signal-to-noise ratio that takes efficiency losses into account.

## References

[1] B. Aubert, et al., *Nucl. Instrum. Meth.* **A479**, pp. 1–116, 2002.

[2] "The *BABAR* Technical Design Report," SLAC-R-95-457, March 1995.

[3] D. Barbieri, et al., *Nuovo Cimento*, **A112**, pp. 113–130, 1999.

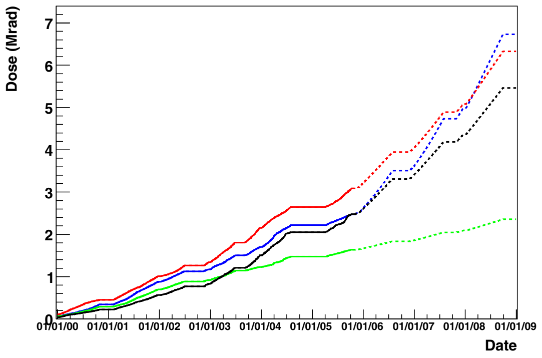

Fig. 3. (color online) Measured (solid lines) and predicted (dashed lines) radiation doses in four locations in the horizontal plane as a function of time. The predictions are based on predicted beam currents and luminosity.

[4] V. Re, et al., *Nucl. Instrum. Meth.* **A409**, pp. 354–359, 1998.

[5] V. Re, et al., “Performance, Radiation Damage and Future Plans of the *BABAR* Silicon Vertex Tracker,” 2003 Nuclear Science Symposium Proceedings, vol. 2, pp. 1048–1051, 2004.

[6] S. Bettarini, et al.,“Study of the Radiation Hardness of Irradiated AToM Front-End Chips of the BaBar Silicon Vertex Tracker,” presented at the 2004 Nuclear Science Symposium, Rome, Italy, 2004.