BABAR Note # **SVTREQ**
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Preliminary Draft

BABAR SVT Mechanical Systems Design Requirements

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Abstract

The physics goals and a general overview of the Silicon Vertex Tracker (SVT) for the *BABAR* experiment are presented, followed by a detailed list of the essential and functional requirements for the mechanical systems.

Contents

I Introduction

This document describes the requirements for the *BaBar* Silicon Vertex Tracker (SVT) mechanical structure. The document begins with a general introduction to the SVT, including its primary physics goals, the constraints imposed by PEP-II, and an overview of the SVT geometry and its expected performance. In the second section, the essential and functional requirements for the SVT mechanical systems are described. The essential requirements are driven by the physics goals and accelerator constraints, while the functional requirements are derived from the essential requirements and from good engineering practice.

A detailed description of the mechanical support and assembly procedures for the SVT can be found in the companion document, "*BaBar* SVT Mechanical Systems and Assembly Procedures." For a more general description of the SVT detector and the *BaBar* physics program the reader is referred to the *BaBar* Technical Design Report[1].

I-A The SVT and its Physics Goals

The major motivation for building *BaBar* is to find and precisely measure *CP* violation in the decays of neutral B mesons. To this end, the time interval between the two B-meson decays must be measured for each event by reconstructing the two primary B decay vertices to an accuracy which is better than one-half of their average separation. At PEP-II, with $\beta\gamma = 0.56$, the average separation between two B decay vertices is 250 μm along the boost $(+z)$ direction. The primary B decay vertices must therefore be measured to accuracy of $80\,\mu$m or better. Without vertex information, no useful CP asymmetry measurment can be obtained on the $\Upsilon(4S)$, so measurement of primary decay vertices in B decays is the main task of the vertex detector. Secondary vertex measurement is also important for B reconstruction, and the vertex detector dominates in the determination of track angles. In addition, the vertex detector provides complete stand-alone tracking; this is particularly important for the reconstruction of the many particles with low transverse momenta ($p_t < 100\,\mathrm{MeV}/c$) which cannot be reconstructed in the drift chamber. Due to this capability, the *BaBar* vertex detector is known as the silicon vertex tracker (SVT).

I-B SVT Detector Geometry

The coverage of the SVT extends to within 350 (520) mrad of the beamline in the forward (backward) direction. The SVT has five layers of double-sided silicon microstrip detectors, with the strips oriented orthogonally to provide 5 measurements each in z and ϕ. The detectors are built on n-type, 4 inch diameter silicon wafers that are 300 μm thick. On the junction side p^+ strips are employed, and on the ohmic side n^+ strips are employed with p^+ blocking strips in between. Floating strips are foreseen in between the readout strips in some layers, in order to increase capacitive charge sharing and improve position resolution.

The silicon detectors and the associated readout electronics are assembled into mechanical units called detector modules. Each module contains several silicon detectors glued to low-mass Kevlar beams, referred to as ribs. The ribs are attached to electronic circuits at each end called hybrids. A ceramic substrate for the hybrid provides precise mechanical mounting surfaces and is the heat sink for the electronics. Flexible fanout circuits bring the signals from the silicon strips to the inputs of the readout IC's, which are mounted on both sides of the hybrids. See Figure 1 for a conceptual drawing of a layer 3 detector module.

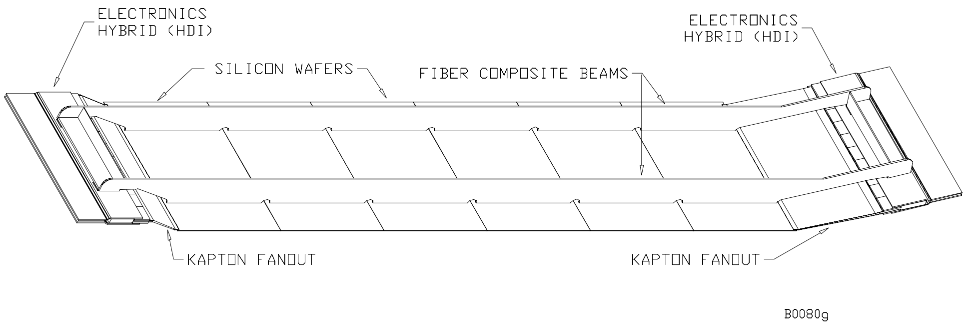

Figure 1: Detector module from Layer 3, consisting of six silicon detectors wirebonded together and read out at each end.

Each of the three inner layers has six detector modules, arrayed azimuthally around the beam pipe, while layers 4 and 5 consist of 16 and 18 detector modules, respectively. The inner 3 layers of detector modules are traditional barrel-style structures, while the outer detector modules employ a novel arch structure in which the detectors are electrically connected across an angle. The bends in the arch modules minimize the area of silicon required to cover the solid angle and also avoid very large track incident angles. Layers 4 and 5 are further divided into "a" and "b" modules, where layers 4a and 5a are situated at slightly smaller radii than layers 4b and 5b, respectively. The azimuthal overlap between the "a" and "b" type modules ensures full efficiency. In the inner three layers a pin-wheel type arrangement is used to provide overlap.

In all five layers of the SVT the detector modules are oriented with the z-strips closest to the beampipe, and the support ribs on the top side (away from the IP). Detector modules in layers 1 and 2 are glued together to form "sextants"; this is the only case where the ribs are glued to the z-side fanout, which extends the full length of the detector module. For layers 1-3, the p-side of the detectors is used for the z-strips (positive polarity signals), while in layers 4-5 the n-side is used for the z-strips (negative polarity signals).

In layers 4 and 5, two z-strips may be connected to a single readout channel. This is necessary due to lack of space to mount additional readout IC's. This results in a ganging ambiguity which must be handled in the event reconstruction, and it also increases the capacitive load seen by the front-end preampflier. The ϕ-strips are daisy-chained between detectors, resulting in total strip lengths of up to 26 cm and a maximum capacitance of 35 pF.

A side view of the detector is shown in Figure 2, and an end view is shown in Figure 3. The parameters of the SVT detector are summarized below in Table 1. The intrinsic resolution is calculated at 90° track incidence assuming $S/N = 20 : 1$. The z-ganging numbers represent the percentage of readout channels connected to more than one readout strip.

The detector modules are mounted to carbon-fiber support cones located in the forward and backward directions. The support cones are kinematically mounted from the B1 magnets using gimbals. The detector module is fixed in position with two screws on each end attaching the readout hybrids to cooling rings on the support cones, with pins to provide the alignment. This mount must provide both good mechanical stability and good thermal contact in order to cool the readout IC's. The support cones are split to allow the vertex detector to be mounted on the B1 magnets by clam-shelling the pieces together.

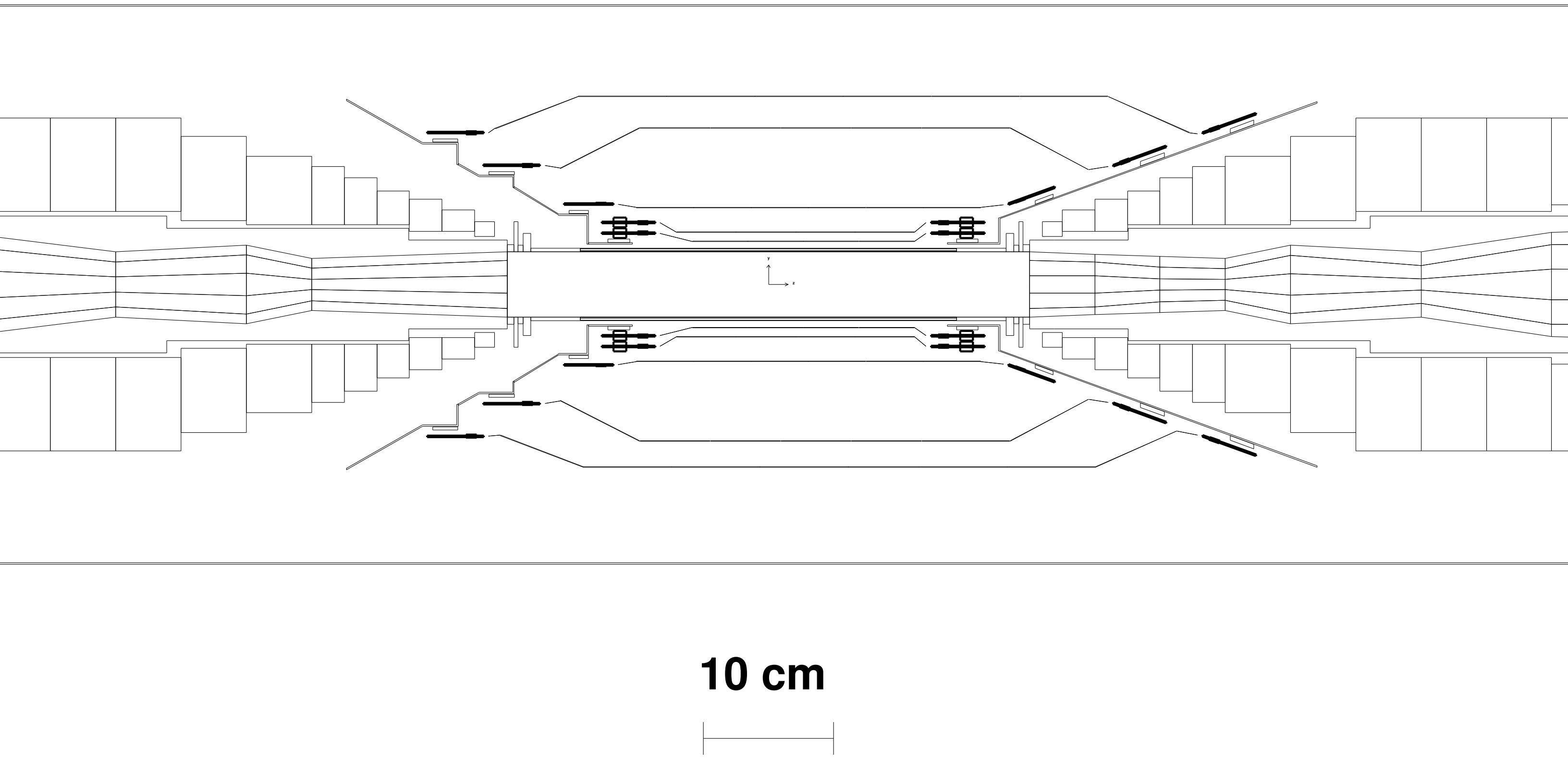

Figure 2: Side view of the SVT in a plane containing the beam axis. The beampipe, B1 magnets, and SVT support structure is also shown.

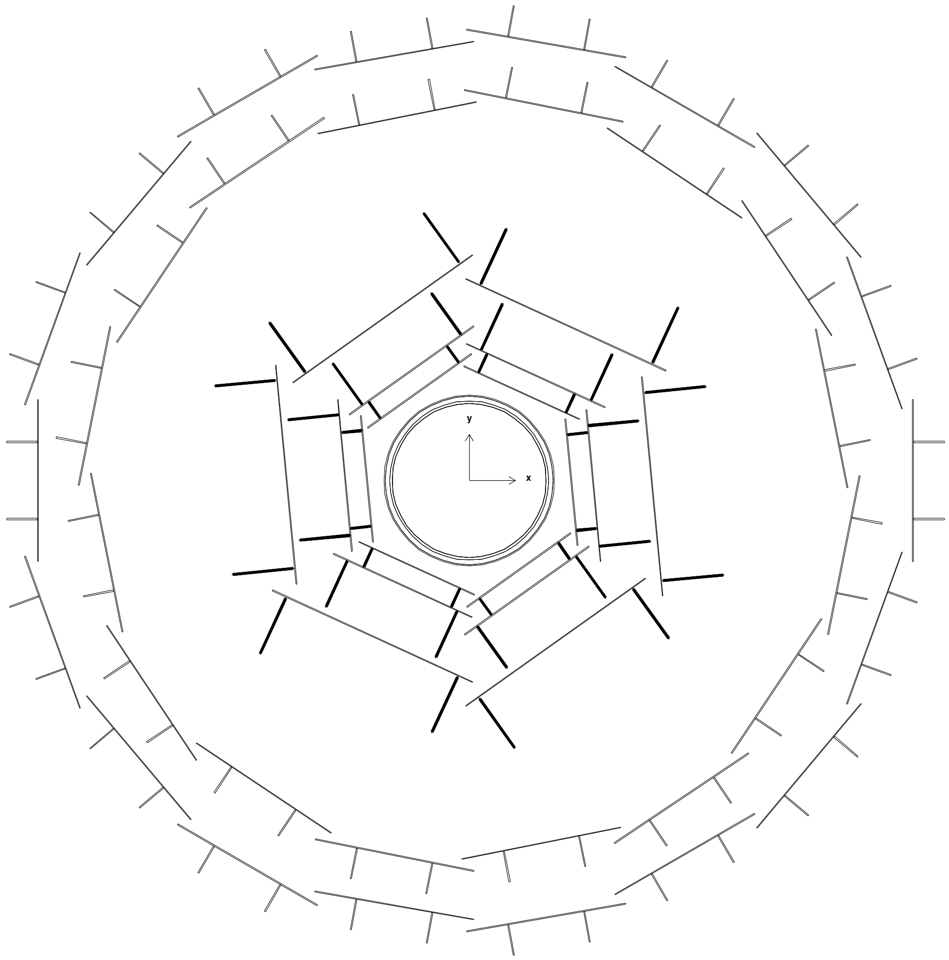

Figure 3: Cross-sectional view of the SVT in a plane perpendicular to the beam axis.

Quantity	Layer 1	Layer 2	Layer 3	Layer 4a	Layer 4b	Layer 5a	Layer 5b
Radius (mm)	32	40	54	124	127	140	144
Wafers/Module	4	4	6	7	7	8	8
Modules/Layer	6	6	6	8	8	9	9
R.O. Sections/Module	4	4	4	4		4	
ICs/R.O. Section	7	7	10	5		5	
Strip Length, b/f (mm):							
ϕ	82	88	127	230/189	230/203	270/257	270/270
z	40	48	70	42–51	42–51	42–51	42–51
z Ganging (f/b):				34%/67%	48%/67%	88%/98%	98%/98%
Readout pitch (μm):							
ϕ	50	55	55	80–100		80–100	
z	100	100	100	210		210	
Floating Strips:							
ϕ	—	—	—	1		1	
z	1	1	1	1		1	
Intrinsic Resolution(μm):							
ϕ	10	10	10	10–12		10–12	
z	12	12	12	25		25	

Table 1: Parameters of the SVT detector layout.

The stiffness of the overall structure is provided by a very low mass space frame, constructed of carbon-fiber tubes, connecting the forward and backward support cones. The motivation for this space frame stems mainly from the possible relative motion of the two B1 magnets during the assembly procedure. Cooling water, power, and signal lines are routed along the support cones to points outside the active region where manifolds for the cooling water and drivers for the electronics are located.

The design has a total of 340 silicon detectors of six different types. The total silicon area in the SVT is about $1\,\mathrm{m}^2$, and the number of readout channels is $\sim$150,000.

I-C Accelerator Constraints

The support structure design and configuration of the SVT is largely dictated by the location and size of machine components near the interaction point. Permanent dipole magnets (B1 magnets) are located on either side of the IP at $\pm 20\,\mathrm{cm}$. They are necessary to separate the electron and positron beams to avoid parasitic crossings of the closely spaced bunches. The B1 magnets occupy the region below 17.2° (300 mr). In order to minimize the mass inside the active tracking volume and maximize the detector acceptance, it is desirable to confine all of the mechanical support and electronics to a compact region surrounding the B1 stayclear. In the forward direction, this requires that electronics, cooling, cabling, and support be confined in a volume approximatley one centimeter thick around the B1 magnet. In the backward direction, SVT coverage is limited to within 30° of the beam pipe in order to leave room for some machine components, such as the plumbing and vacuum bellows for the water-cooled beryllium beampipe.

A further constraint on the SVT is imposed by the PEP-II support tube, which is a tube of radius 20 cm used to maintain the alignment of the B1 and Q1 magnets. The central part of the support tube is a thin carbon-fiber structure, while the outer sections are stainless steel. The SVT must be supported inside the support tube and therefore cannot be mounted from the drift chamber endplates. We have chosen to support the SVT from the B1 magnets rather than from the beampipe. Since the SVT must be installed with both B1 magnets in place, it is designed to split in half in order to be clam-shelled around the beam pipe.

The assembly and alignment of the beam pipe, B1 magnets, Q1 magnets, and SVT inside the support tube will take place in a staging area away from the interaction hall. The entire assembly will then be transported and installed in the interaction hall. This procedure is reversed in order to gain access to the SVT for repair.

I-D SVT Detector Performance

In this section, we present the SVT performance in order to set the scale for the required precision of the mechanical systems. The intrinsic position resolution of the silicon strips is described, followed by the track parameter resolutions and the resulting reconstructed vertex resolution for B decays to CP eigenstates and to tagging B's. By combining the latter two quantities in quadrature we obtain the error on Δz, which contributes directly to the error on the CP asymmetry measurement.

I-D-1 Intrinsic Resolution

The intrinsic point resolution in the inner layers at normal incidence is $\sim 10\,\mu$m in ϕ (employing $50\,\mu$m readout pitch) and $\sim 12\,\mu$m in z (employing $100\,\mu$m pitch with one floating strip). A larger pitch in z eliminates the need to gang different z strips to the same electronics readout channel and provides good resolution for tracks at small crossing angles, as shown in Figure 4(a). The simulation used for Figure 4 includes Landau fluctuations in energy loss, diffusion, channel-to-channel gain variations (5%), and noise. The results are in good agreement with experimental data on the energy loss in silicon, and with experimental measurements of position resolution made in a test beam with prototype *BABAR* silicon detectors.

The upper curve in Figure 4(a) shows that for a $200\,\mu$m readout pitch with one floating strip, the resolution is about $25\,\mu$m at normal incidence. This configuration is used for the z strips in layers 4 and 5, and gives more than adequate resolution for the determination of the track polar angle, while minimizing the amount of ganging. For the ϕ strips we employ $100\,\mu$m pitch in the outer layers with 1 floating strip.

The effect of the readout scheme on point resolution is also shown as a function of track incident angles in Figure 4(b). The resolution for a TOT readout scheme is quite similar to the ideal analog readout. Digital readout, which provides hit/no-hit information only, shows much poorer resolution in comparison.

In addition to the advantage of improved resolution, analog readout may be useful for background rejection of non-MIP signals, for pattern recognition techniques which correlate pulse height with angle, and for correction of the time-walk which will affect the time-stamp information generated by the readout chip.

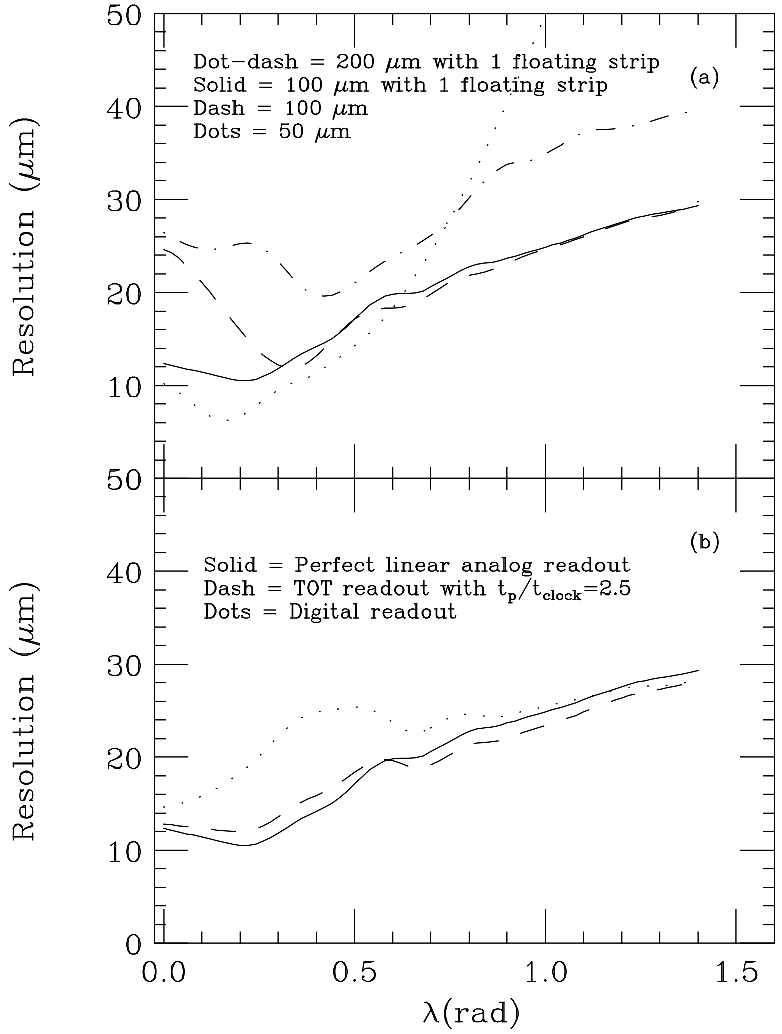

Figure 4: (a) Intrinsic resolution for a 300 μm-thick silicon detector as a function of the dip angle for various strip configurations, assuming perfect analog readout. (b) Same as as (a), assuming 100 μm readout pitch and one floating strip, for various readout techniques.

Mode	$\sigma_n(\mu\text{m})$	$\sigma_w(\mu\text{m})$	f_n (%)	rms
$\pi^+\pi^-$	27.5 ± 0.4	85.8 ± 3	84.0 ± 0.4	36.8 ± 0.6
ΨK_s	42.1 ± 0.7	168 ± 7	88.0 ± 0.2	57 ± 1.0
D^+D^-	46.5 ± 0.6	159 ± 10	94.0 ± 0.1	53.3 ± 0.8

Table 2: A two-Gaussian fit to the z vertex resolution for various CP eigenstates; σ_n and σ_w are the rms of the narrow and wide Gaussians, respectively, and f_n is the fraction of the area contained in the narrow Gaussian. The rms is the weighted sum of σ_n and σ_w.

I-D-2 Track Parameter Resolution

The track parameter resolutions were calculated using an analytical technique based on the method of Billoir [4] which can be applied to arbitrary detector geometries in the program TRACKERR [6]. Figure 5 shows the resolutions for the track impact parameter along the beam (σ_z) and in the plane perpendicular to the beam (σ_{xy}) for various momenta. The resolution is dominated by multiple scattering and not by the intrinsic position resolution of the silicon detectors, except for the highest momentum tracks from B decays.

If for some reason Layer 1 is not usable, the tracking resolution is degraded by about 20% (for a 1 GeV/c track); thus, layer 2 is an effective backup in case of a failure in layer 1.

The resolution on layers 4 and 5 does not significantly affect any of the track parameters, and the choice of the readout pitch in the outer layers is determined by other considerations (i.e. noise, occupancy, and detector design considerations).

I-D-3 Vertex Resolution

The z vertex resolution has been calculated using a parameterized Monte Carlo simulation for three B decay modes: $B^0 \to \pi^+\pi^-$, $B^0 \to J/\psi K_S^0$, and $B^0 \to D^+D^-$. For each decay, the distribution of the difference between the reconstructed and generated B^0 vertex positions in the z direction is fit with a sum of two Gaussian functions. The results are shown in Table 2. In all cases, the expected rms resolution (obtained by taking the weighted sum of σ_n and σ_w) is better than the 80 μm required for CP violation studies.

The z vertex resolution for the tagging B has also been studied with both parameterized and GEANT-based Monte Carlo simulations. The resolution depends upon which type of tag one employs. For direct leptons, we find $\sigma_n \approx 60\,\mu$m, while for kaon tags, $\sigma_n \approx 75\,\mu$m, with about 70–80% of the tags contained in the narrow Gaussian.

Good vertex resolution in the plane perpendicular to the beam pipe is also important. This information will help in associating tracks from B and D decays to the correct secondary or tertiary vertices, thus reducing combinatorial backgrounds. Figure 6(a) shows the distribution in the xy plane of the distance between two D vertices in the decay $B^0 \to D^+D^-$. The distribution is fit to a function of the form $A \cdot xe^{-x/\lambda}$ and yields a value of $\lambda = 276\,\mu$m. For comparison, the expected resolution on the separation between the two D decay points in the x-y plane is plotted in Figure 6(b) for the decay $D \to K\pi\pi$. The rms resolution is about 125 μm.

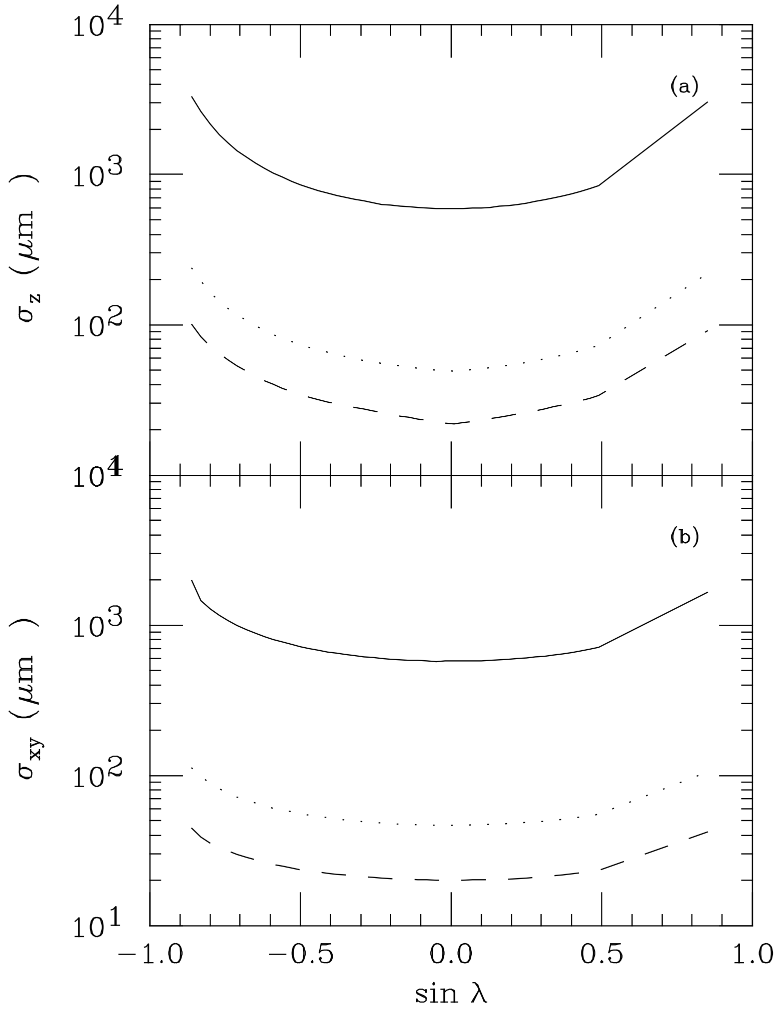

Figure 5: (a) Impact parameter resolution along the beam (σ_z) and (b) in the plane perpendicular to the beam (σ_{xy}) vs. dip angle for three different momenta: 100 MeV/c (solid line), 1.0 GeV/c (dotted line), and 3.0 GeV/c (dashed line).

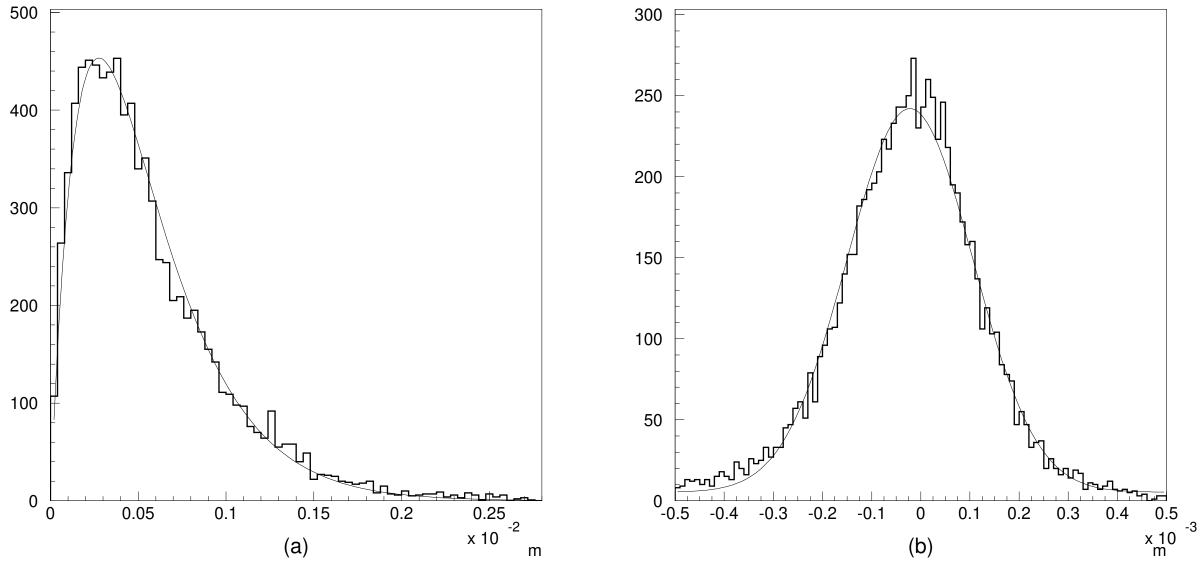

Figure 6: (a) Separation between D vertices in the xy plane. (b) Resolution on the separation between the D vertices in the x-y plane. Note the different scales on the abscissa.

II Requirements

The requirements are divided into two major categories: (A) essential requirements derived from physics goals and from practical considerations of the PEP-II/*BABAR* environment, and (B) functional requirements derived from the essential requirements and from good engineering practice. The second category is further broken down by subcomponent.

II-A Essential Requirements for the SVT Mechanical System

1. **Resolution**

   The most important function of the SVT is the determination of the B decay positions, especially along the beam direction. This measurement is used to extract CP asymmetries; the error on the measured asymmetry increases by less than 10% if the separation between the B vertices (Δz) is measured with a resolution of approximately one half the mean separation, which is 250 μm at PEP-II [7]. This translates into a requirement on single B vertex resolution of 80 μm which is readily achieved with silicon strip detectors.

   This requirement is derived for CP eigenstates which suffer from little or no background contamination. For modes which do have significant background, such as $B \rightarrow \rho\pi$, better vertex resolution will benefit the measurement due to suppression of backgrounds from light quark production, which have an average Δz of zero with a width due to finite vertex resolution.

   We can also benefit from additional precision over the stated requirement of 80 μm on Δz with improved pattern recognition and secondary vertex reconstruction capabilities. Therefore, our aim is to achieve the best precision practical given the physical constraints of the accelerator. In particular, the beampipe outer radius of 2.8 cm imposes a minimum distance from the IP of 3.3 cm for the first measurement. The multiple scattering in the beam pipe and in the silicon itself also sets a lower limit on the useful intrinsic resolution, corresponding to a point resolution of about 10–15 μm for measurements made close to the IP.

In addition to providing impact parameter information, the vertex detector dominates in the determination of the track production angles. The angle measurements should be good enough that they do not significantly contribute to the experimental uncertainty in the measurements of track impact parameters or the invariant mass of combinations of tracks. This requirement is met with a point resolution of 30–40 μm in the outer layers [5], and imposes no requirements on the inner layers beyond those already discussed.

2. **Acceptance**

   The measurement of CP asymmetries in B^0 decays depends upon the reconstruction of final states with very small branching fractions, and consequently it is very important to maximize acceptance and efficiency. The coverage of the SVT must be as complete as technically feasible, given the location of the B1 magnets below 17.2° (300 mr) with respect to the beam line in both the forward and backward directions.

   The active tracking volume is defined to be the region greater than 350 mr from the beamline in the forward $+z$ direction and greater than 520 mr from the beamline in the backward direction. The SVT readout and mechanical support occupies the region from 300 – 350 mr in the forward region. In the backward region, additional space is allowed for beampipe bellows and the plumbing and manifolds required for the water-cooled beryllium beampipe. Putting these services in the backwards direction maximizes the active tracking volume in the forward direction. In the $\Upsilon(4S)$ center-of-mass, the active tracking volume is $-0.95 < \cos\theta_{cm} < 0.83$; acceptance in the forward direction is the limiting factor.

3. **Material**

   There should be as little material as possible within the active tracking volume, as defined above. Special attention must be paid to minimizing the amount of material between the IP and the first measurement in order to reduce multiple scattering. The beam pipe itself contributes $0.006X_0$ at normal incidence. Material located beyond the inner layers does not significantly degrade the measurement of track impact parameters, but does affect the performance of the overall tracking system and leads to increased photon conversions in the active region.

4. **Efficiency**

   In order to maximize the total number of reconstructed B decays with useful vertex information, the SVT single point efficiency must be very high for tracks at all angles and momenta. This is especially true for the inner layers, since the impact parameter resolution is dominated by the precision of the measurement closest to the IP.

5. **Reliability and Redundancy**

   The SVT is mounted inside a support tube of radius 20 cm, which also supports and aligns the machine elements closest to the IP. Access to the SVT is not possible without a major shutdown involving removal of the support tube from the detector. The reliability requirements for the SVT are therefore more stringent than usual for such a device, with implications for engineering design at all levels.

As additional insurance against failure modes, the detector layout must provide redundant measurements wherever possible, especially for the first hit which determines the impact parameter resolution. The detector monitoring and interlock system must serve as a safeguard against catastrophic failure in the event of a component malfunction or a simple human error.

6. **Radiation Tolerance**

   The functionality of the SVT must not be compromised by exposure to the expected radiation levels. As described in Chapter 12 of the TDR[1], the expected dose in the innermost layer of the SVT averages about 33 krad/yr. The radiation is highly nonuniform in azimuth, peaking in the bend plane of the accelerator with a local maximum of up to 240 krad/yr over a small region covering approximately 6° in azimuth. At the location of the front-end electronics for Layer 1 the maximum dose is 110 krad/yr, with an average value of 47 krad/yr. Detectors, front-end electronics and all mechanical structures are specified to be able to withstand at least 10 times the annual radiation dose.

7. **RF Shielding**

   The front-end electronics must tolerate or be shielded from RF noise generated by the accelerator. Large RF power losses are expected at PEP-II with frequencies in the range from 10^5 to 10^6 Hz, due primarily to the beam structure which includes a 5% ion clearing gap. This matches the frequency range at which the readout IC pre-amplifier gain peaks. It is difficult to predict whether this will pose an operational problem, and bench tests which simulate the PEP-II environment are not easy to carry out. For this reason we require an RF shield which is hermetic in the region of the IP. The RF shield extends between the beampipe and the first layer of the SVT and surrounds the spaceframe. The SVT cables are brought out inside the shield.

8. **Accelerator Constraints**

   The SVT must be designed to be compatible with the PEP-II machine components. It must respect the stayclear established for the beampipe and B1 magnets, must assemble in two halves around the B1 magnets, and must tolerate the anticipated relative motion of the B1 magnets during transport.

II-B Derived Functional Requirements

These requirements follow from the essential requirements, taking existing constraints into account and following good engineering practices.

II-B-1 Detectors

1. **Efficiency**

   Each silicon wafer must have a total strip leakage current which is less than 100 nA/cm^2, i.e. a detector which measures 5 cm by 5 cm must have a total strip leakage current less than 2.5 μA. Including the guard ring current, the total leakage current must be less than 15 μA.

Futhermore, the total leakage current should be stable to $\pm$ 20% over a period of one hour after bias voltage has been applied for two hours.

The average strip efficiency is required to be $> 99\%$, where the average is taken over each of the six types of silicon wafers individually. The minimum efficiency for a single wafer is specified to be 97% for the strips on each side of the wafer. A good strip is defined to be one which has:

- Leakage current $< 1\mu A/cm^2$, i.e. a strip 5 cm long with 100 μm pitch has I $<$ 50 nA.
- Isolation resistance (to nearest neighbor) $>$ 200 MΩ
- Current across the AC coupling capacitor $<$ 1 nA at 20V.
- AC coupling capacitor breakdown voltage $>$ 80 V (measured on a test structure).

2. **Mechanical Tolerances**

   The detector thickness is specified to be $300\pm30\mu$m. The lithography must have a precision of $\pm2\mu$m.

3. **Radiation Tolerance**

   The strip leakage current must not increase by more than 1 $\mu A/cm^2$ after 1 MRad gamma irradiation with a Cobalt 60 source, and the interstrip capacitance must not increase by more than 20%. Measurements of prototype detectors show that we can expect approximately 0.7 $\mu A/cm^2$/MRad.

   Radiation dose is highly non-uniform in azimuth at PEP-II, with pronounced peaks in the bend plane of the machine. Th average annual dose in layer 1 is 33 kRad, while the worst case layer 1 detector module sees an average annual dose of 82 kRad, peaking to 240 kRad in a very localized region. Ten times the expected average annual dose for the worst case layer 1 detector module results in an increase in the leakage current of approximately 70 nA on the longest (ϕ) strips. When added in quadrature with the expected intrinsic noise of the pre-amplifier, this will result in a net increase in the noise of approximately 10%.

II-B-2 Fanouts

1. **Efficiency** Each fanout will be tested to measure electrical continuity and test for shorts. An acceptable fanout is one with zero shorts and at most 3 broken traces. This translates into an efficiency of better than 99.5% for the fanout type with the smallest number of connections.

2. **Mechanical Tolerance and Stability**

   The lithography on the fanouts must have a precision of $\pm2\mu$m. The tolerance on the edges of the fanouts after cutting is $\pm100\mu$m.

   The mechanical dimensions of the fanouts must be very stable in order to avoid stressing the wirebonds. Coefficient of thermal expansion for the polyimide substrate should be matched to that of silicon if possible. In fact the CTE for polyimides are very low, typically less than $1\times10^{-}5/^\circ$C for Upilex, while the CTE for silicon is 2.5 $\times10^{-3}/^\circ$C. This should not be a problem because the layer of glue between the Upilex and the silicon will allow for some small relative motion, and we expect the temperature to be constant to better than $\pm1^\circ$ C.

	Type I	Type II	Type III
Width (mm)	46.80	66.30	33.80
Length (mm)	41.20	38.00	43.51
Thickness(mm)	1.2	1.2	1.2
Quantity	24	12	68

Table 3: Dimensions and quantities of the HDI layouts.

Absorption of water should be as low as possible and hygroscopic expansion should be less than 0.1% at 90% humidity. This requirement is met by the Upilex-S substrate chosen for BaBar.

3. **Radiation Tolerance**

   The fanouts must withstand at least 10 times the worst case annual radiation dose without losing their mechanical stability. Upilex is able to withstand several Mrad of ionizing radiation with negligible degradation of mechanical integrity.

II-B-3 Hybrids

1. **Mechanical Dimensions and Precision**

   The SVT hybrid consists of two separately manufactured items along with the readout IC's and discrete components. One is the high density interconnect (HDI), which is a electrical circuit on a ceramic substrate. The other component is the tail, a long multi-layer kapton cable which brings signals from the readout IC out along the support cone to a place where a transition to conventional cable can be made.

   The HDI's function is to provide the physical support, cooling and electrical interconnections for the readout IC's, and the connections to other components. The silicon detectors are mounted via the support ribs to the HDIs, which in turn are mounted to the support/cooling cones. The positioning tolerance of the detectors determines the dimensional tolerances of the HDIs. Also, the size of the HDIs is extremely constrained by the small gap between the B1 magnet stay clear at 300 mrad and the active tracking volume at 350 mrad. The need to run electrical connections for the inner layers out under the HDIs of the outer layers imposes additional mechanical constraints.

   To accomodate these mechanical requirements, there will be three different HDI layouts, as summarized in Table 3. All of the circuits are double-sided in order to read out both the ϕ and the z strips of one half detector module. The quantity listed does not include spares.

   Type I, which is used for layers 1 and 2, will have 7 chips per side. Type II, used for layer 3, has 10 chips per side, and Type III which is used for layers 4 and 5, will have 5 chips per side.

   The mechanical tolerances for the hybrid are as follows:

   - Planarity tolerance in the stay-clear regions for the contact with support feet: 12.5 μm
   - Accuracy of the cuts of holes for feet: $\pm$ 50 μm

- Accuracy in the cut of substrate: $\pm$ 100 μm.
- Accuracy in IC positioning: ± 25 μm.
- Stay-clear region on front of HDI for gluing the fanout, minimum length: 4.5 mm.
- Stay-clear regions on the four corners of the HDI for mechanical tools accessing: at least 2.5 x 0.5 mm^2.
- Connectors to the tail: Berg connectors glued or soldered on the HDI.
- Total thickness, including external mounted components: no more than 7.4 mm.

2. **Thermal Requirements for the HDI**

   The power dissipated on the HDI will be in the range 3.8 - 7.6 W, while the maximum operating temperature of the chip is 40° C. For this reason the HDI substrate must have high thermal conductivity and a good thermal contact with the cooling system.

   FEA calculations[10] and laboratory measurements have been carried out, with consistent results. They show that an AlN substrate with a thickness of 1.2 mm provides sufficient thermal conductivity to meet the requirement on the chip operating temperature.

II-B-4 Detector Modules

1. **Alignment and Placement Accuracy**

   The SVT alignment can be viewed as a set of nested coordinate systems. At the lowest level are the relative positions of wafers within the detector module coordinate system. Next are the relative positions of detector modules with respect to one another in the local SVT coordinate system. Finally, the SVT considered as a rigid body is positioned in the global BaBar coordinate system. Additional discussion of the SVT alignment can be found in [9].

   We quote two different types of tolerances: placement accuracy, the precision with which the parts must be put together, and survey accuracy, the precision with which the locations of parts must be measured during assembly.

   The quoted requirements are derived from the spatial resolutions that the SVT must provide, which are on the order of 10 μm, and from the requirement that the survey with tracks must converge in a reasonable time. The survey with tracks must provide the required precision of a few μm, such that the alignment errors, when added in quadrature with the position resolution, make a negligible contribution.

   - The relative placement of the wafers within a module should be within $\pm 10\,\mu$m in each of the two coordinates in the plane of the module, and optically surveyed to ± 3 μm.
   - Planarity of the wafers within a detector module should be good to $30\,\mu$m maximum planar displacement over the module length; survey should be accurate to $\pm 10\,\mu$m.
   - Precision on the placement of the wedge detector should be $\pm 25\,\mu$m and surveyed to $\pm 10\,\mu$m.
   - Precision of the placement of the wafer with respect to the mounting bushings in the hybrid should be $\pm 50\,\mu$m.

- The detector module placement accuracy on the support cones relative to other detector modules should be on the order of $100\,\mu$m in the azimuthal direction and optically surveyed to within $25\,\mu$m.

The wafer placement accuracy and survey is readily achieved using standard techniques previously developed. In particular, the wafers within a detector half-module are glued end-to-end and must be accurately positioned to facilitate wire-bonding on a $50\,\mu$m pitch. Larger displacements are to be expected at the boundary between detector half-modules, but can be accurately surveyed. The detector module placement is achieved with positioning pins in the cooling rings that mate to alignment holes and slots on the hybrid bushings. The alignment holes have an accuracy of better than 10μm. Along the z direction, the alignment pins can move in slots which allow for up to 500μm of motion longitudinally. However, this motion is limited to $\pm175\mu$m by the tolerances on the holes in the bushings for the permanent screws. The survey is accomplished *in situ* as detector modules are mounted, using alignment crosses on the silicon wafers to measure their relative positions module to module, as well as alignment pins at the large ends of the support cone to locate the detector module relative to the support structure.

2. **Quality Control**

   Wirebonding between wafers, from wafers to fanout, and from fanouts to readout IC's is an enormous task for the SVT, with approximately 570,000 bonds in total. The reliability of these bonds must be extremely good such that fewer than 1% of the approximately 150,000 readout channels has wrong or bad bonds. With an average of approximately 4 bonds per readout channel this corresponds to a failure rate of less than 0.25% per bond.

3. **Mechanical Rigidity and Stability**

   Some deflection with gravity is acceptable, so long as it is predictable and stable. Finite element analysis [11] shows that the inner detector modules have a maximum deflection due to gravity of 3.5 μm for the longest (layer 3) module. This is quite acceptable compared to the thickness of the silicon wafers of $300\pm30\mu$m and the associated error on the determination of the charge centroid in the direction perpendicular to the wafer surface. For the layer 5, the maximum deflection is calculated to be 25 μm which is also acceptable. The natural frequencies for the layer 3 detector modules are quite high, with the first mode at 310 Hz (torsional). For the layer 5 module, the first mode is at 120 Hz which should not pose a problem in the SVT environment.

   Stability of the positions should be such that resurvey with tracks is rarely required. This leads to the requirement that the relative positions of the various wafers be stable to the $5\,\mu$m level over long periods of time (months or more). The relative positions of detector modules should also be stable at the $5\,\mu$m level over long periods.

II-B-5 Mechanical Support Structure

1. **Mechancial Tolerances** There are no stringent requirements on the placement of the SVT detector on the beampipe derived from essential physics requirements, because the SVT position in the BaBar global coordinate system is given by six numbers that are readily determined using tracks.

The nominal gap between the SVT support structure and the accelerator components varies from 3.7 mm to several cm. This gap, together with the kinematic mount between the B1s and the support cones, allows for some motion between the B1 magnets without stressing the silicon detectors. To preserve this gap as close to possible at its nominal value everywhere, our goal is to position the SVT with an accuracy of $100\,\mu$m about the beampipe and B1 magnets.

2. **Mechanical Rigidity and Stability**

   The position of the entire detector structure with respect to the IR and the drift chamber can be determined with tracks sufficiently well that variations on the order of an hour can be tracked. However, much longer time constants are desirable.

3. **Assembly Requirements** The SVT mechanical support structure must be designed so that it can be separated into two halves which clam-shell around the beampipe and B1 magnets.

II-B-6 Cooling

A stable operating temperature is important to ensure mechanical stability. The temperature in the support tube environment will be dominated by the B1 magnets, which have much greater thermal mass than the SVT. The temperature of the B1 magnets must be stable to within $\pm 0.5°$C in order to maintain sufficient uniformity in the magnetic field; this requirement on B1 temperature stability is more stringent than the requirements of the SVT. A good neighbor policy is in effect, which requires that each system maintain temperature stability and remove its own heat. This applies to the B1 magnets, which are water cooled to remove the heat generated by synchrotron radiation hitting the masks inside, and to the SVT, which employs water cooling to remove the heat generated by its frontend electronics.

In addition, it is desirable to maintain the silicon at 20°C. Heating of the silicon results in increased leakage current; a doubling occurs for every 7°C in temperature rise.

1. **Thermal Requirements**

   The temperature of the SVT must be controlled to within $\pm 1°$ C to guarantee mechanical stability. The temperature will be measured using thermistors located on each HDI and mounted in various locations on the space frame. To achieve this requirement on stability, the inlet temperature of the cooling water in the SVT cooling system must be controlled to to better than 1° C.

   The heat generated by the readout ICs will be less than or equal to 3 mW per channel, or 0.38 W per IC (averaged over time and depending slightly upon the rate at which triggers are issued). The total power which must be removed from the front-end electronics is approximately 200 W per end. In order to have a reasonable safety margin, the water cooling system is designed to meet a requirement of 300 W per end with a total maximum temperature rise per cooling circuit of less than $3\circ$ C (output temperature - input temperature).

   The hottest point on the detector, close to the readout IC's, should not exceed 40° C, and 30° is a desirable operating temperature. The inlet water temperature will be regulated so that the ICs are operating in the desirable range. It is desirable to maintain the average temperature of the system very close to the ambient temperature of approximately 20°C. The cooling system must be interlocked with the power so that it is not possible to power the front-end IC's when the cooling system is shutdown. The power system is also interlocked with the temperature monitors.

2. Reliability

   The cooling system must be leak-tight. All joints must be pressure-tested to 15 psi gauge pressure and helium vacuum tested as well. Insulated metal plumbing should be used, and all joints must be either brazed or high-pressure Swage-Lock type fittings.

   It is desirable to run the entire cooling circuit at sub-atmospheric pressure so that any leaks will suck air into the cooling system rather than leaking water onto the detector.

II-B-7 Detector Monitoring

There are four main areas of detector monitoring: radiation, position, temperature and humidity monitoring. The schedule for the design of all the SVT detector monitoring sytems is later than that for the mechanical systems, due to shorter lead time to procure the monitoring components and the fact that it is not directly coupled to the detector module assembly and testing. These requirements are described in more detail in [12].

Radiation Monitoring

The radiation-monitoring system should be operational at all times when beams are present in the accelerator and the SVT is installed. The primary requirement of the radiation monitor system is to protect SVT components from radiation damage by early detection of increasing radiation levels and triggering of the PEP-II beam abort system as well as interlocking of the SVT high-voltage system. The radiation monitors will also provide real-time monitoring of slowly-varying radiation levels in the interaction region for accelerator diagnostics and tuning.

Because of the limited space available near the beampipe, the primary mechanical requirement for the radiation monitors is that they should be compact enough to fit into the agreed envelope which has been reserved near the small end of the support cones. The space reserved on each end is an annulus of rectangular cross section around the beampipe, 3.6 mm in radius by 20 mm along z. All of the signals for the radiation monitors must exit on two kapton tails per end, which are reserved for detector monitoring signals.

Position Monitoring

The primary requirement of the position monitoring system is to monitor the relative motions between the B1 magnets and the SVT, in order to ensure that no load is applied to the SVT. This system should be operational during mounting and unmounting of the SVT on the B1 magnets, during transport of the support tube from the assembly lab to the detector hall, during installation and removal of the support tube from the detector, and when the support tube is inside the detector.

The maximum relative motion allowed at the forward cone end is an angular motion of 2.25°, changing the large-end gap from the nominal 9.81 mm to 0 mm, while the small-end gap changes from the nominal 3.67 mm to 2.68 mm. The maximum deflection due to gravity loading of the support tube during installation is 1.5–2.4 mm, depending on the support tube design. A deflection of 2.0 mm causes a 0.06 degree rotation of both cones with respect to the B1 magnets, resulting in a 0.28 mm motion at the large end of the cones.

The required sensitivity for the position monitoring system is to measure the expected deflections with 5–10% accuracy and measure gaps where contact can be made with an accuracy of at least 1% of the full range of motion.

The alignment requirement for physics analysis is that misalignments not contribute significantly to the overall spatial resolution of approximately 10 microns. Although alignment constants will be determined with charged tracks, the position monitoring system should provide realtime measurements of changes in the relative positions of the SVT and the B1 magnets to aid in the design and implementation of alignment algorithms.

The position monitors must fit in the region at the large end of the support cones. In the forward direction, they must not occupy a significant fraction of the nominal 1 cm gap between the support cone and the B1 magnet. The available space beyond the end of the support cone is about 1 cm. There is much more available space in the backward region. The signal lines from the position monitors and other monitoring systems must occupy no more space than that allocated to two HDI's per end.

Temperature Monitoring

Temperatures must be monitored at three types of locations in the vicinity of the SVT: the HDI's, the mechanical structure, and the radiation monitors. The temperatures of the HDI's must be monitored to provide a signal for a fail-safe interlock on the power supplies for the front-end electronics. The front-end electronics generates about 3 mW per channel, or about 500 W total for the 150,000 readout channels. The electronics is actively cooled with water, and should be shut down if for any reason the temperature rises significantly above the normal operating range. There will be one resistive temperature monitor per HDI provided for this purpose.

Stability of the detector components at the 5 micron level requires a stable operating temperature. Therefore, the temperature of the mechanical structure (away from the HDI's) should be monitored. Preliminary calculations for the thermal expansion of the entire structure predict on the order of $0.5\,\mu$m/$^\circ$C over the length of the active region of the detector. If the temperature inside the support tube is maintained at $\pm 1^\circ$C, thermal expansion will not be a problem. To meet this requirement, the temperature should be measured to an accuracy of a fraction of a degree.

The photodiodes that will be used for monitoring radiation levels will experience an increase in leakage current with integrated radiation dose. The leakage current is temperature dependent. In order to maintain sensitivity at the level of 10% of nominal background levels after an integrated dose of 100 kRad, photodiode temperature changes must be monitored with a precision of 0.1°C. The requirement on the accuracy with which the absolute temperature is measured over the longterm (months) is not as stringent because the fractional change in leakage current depends only on the change in temperature. A longterm accuracy of $0.5 \circ$C should be sufficient. However, the accuracy over the time between calibrations (when the leakage current and temperature are measured with no beam in the machine) must be 0.1°C, the same as the precision requirement.

Humidity Monitoring

The primary requirement for the humidity monitors is that they must monitor the relative humidity and, together with the temperature monitors, allow a determination of whether there is sufficient moisture in the environment and a low enough ambient temperature near the SVT detectors and electronics for condensation to occur. If the ambient temperature approaches the dew-point, action must be taken to either increase the purge rate with dry nitrogen, raise the temperature, or both.

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