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Vertex detector concept for a SuperB factory ☆

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Abstract

The two existing asymmetric operating B-factories, PEP-II and KEKB, have achieved very high luminosities at the level of $10^{34}\,cm^{-2}\,s^{-1}$ producing impressive physics results. A SuperB factory capable of producing luminosities in excess of $10^{36}\,cm^{-2}\,s^{-1}$, will permit a program of precision measurements sensitive to New Physics (NP) beyond the Standard Model (SM), complementarily to the LHC experiments. Here we present the conceptual design of the vertex detector, focusing on the physics requirements for time-dependent analysis, according to different configurations for the energy asymmetry of the beams and of the radius of the innermost vertex detector layer. The possibility to reduce the radial dimension of the beam-pipe, down to $\simeq 1\,cm$, allows to measure the first hit of the tracks very close to the interaction point, by adding a layer-0 to the present BABAR five-layer vertex detector configuration. Vertexing requirements for physics will be discussed, considering different technology solutions for the layer-0 sensors, such as striplet, MAPS and hybrid pixel detectors.

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Keywords: Vertex detector; SuperB factory; MAPS

1. Introduction

The two existing asymmetric B Factories, PEP-II and KEKB, started their operations in 1999 and since then, their design peak luminosities have been exceeded, reaching values above $10^{34}\ cm^{-2}\,s^{-1}$. The measurement of $\sin 2\beta$ has become a program of precision measurement, while extraction of the other two angles of the Unitarity Triangle α and γ has been more challenging. However, the consistency of the CKM mechanism, which explains flavor mixing in the SM, requires more data to be definitely tested. We currently have very intriguing results in the time dependent analysis of the decay channels via penguing loops, where $b \to s\bar{s}s$ and $b \to s\bar{d}d$. Most of them are not accessible at the LHC experiments because of the presence of neutral particles, which require a clean environment to be correctly reconstructed. A SuperB factory, capable of producing luminosities above $10^{36}\,cm^{-2}\,s^{-1}$, would definitely test the consistency of the CKM mechanism, checking the possibility of NP beyond the SM. Data samples of the order of $50\,ab^{-1}$ are necessary to reduce the experimental error below the theoretical one for the most sensitive analyses [1,2]. The possibility to have polarized beams will allow precision measurements sensitive to NP in τ sector [3,4]. In addition, lepton flavor violation in τ decays, as well as charm and initial state radiation physics, are important parts of the scientific program of a SuperB factory [1].

An initial proposal of the SuperB factory project, with similar final focusing and damping rings to the International Linear Collider (ILC) can be found in Ref. [2]. The accelerator design changed significantly from the initial proposal, finally adopting a multipass colliding storage ring design but still exploiting the small beams emittances

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($\varepsilon_x \simeq 0.8$ nm rad, $\varepsilon_y \simeq 2$ pm rad) to obtain high luminosity ($>10^{36}\,\text{cm}^{-2}\,\text{s}^{-1}$). The beam currents are below the present PEP-II/KEKB ones with an estimated power consumption below 35 MW [5].

The vertexing requirements for time-dependent analyses are very demanding since the accelerator design suggests a reduced energy asymmetry of the beams. Further improvements on the vertex resolution would help also to distinguish between signal and background events.

2. Vertex detector concept

The SuperB interaction region design is characterized by the small size of the transversal section of the beams, at the level of few μm for σ_x, and tens of nm for σ_y. Therefore it will be possible to reduce the radial dimension of the beam-pipe tube, to $\simeq 1$ cm, while preventing the beams to scatter into the beam-pipe material within the detector coverage angle. The total amount of radial material of the berillium beam-pipe, which includes a few μm of gold foil, and a water cooling channel, has been estimated to be about $0.5\% X_0$. For the proposed value for the center of mass boost, $\beta\gamma = 0.28$ (7 GeV e^- beam against a 4 GeV e^+ beam), the average B vertex separation along the z coordinate, $\langle \Delta z \rangle \simeq \beta\gamma c\tau_B = 125\,\mu\text{m}$, is reduced almost by a half with respect to the BABAR experiment, where $\beta\gamma = 0.55$.

In order to maintain a suitable resolution on Δt for time-dependent analyses, the proper time difference between the two B decays, it is necessary to improve the vertex resolution with respect to the current BABAR performances: typically 50–60 μm in z for exclusively reconstructed modes and 100–150 μm for inclusively reconstructed modes. The vertex precision requirements for physics, have been achieved in the BABAR experiment, thanks to the performances of the silicon vertex tracker (SVT), a five-layer double-sided silicon detector [6].

The configuration of the SuperB interaction region allows to measure the first hit of the tracks near the production vertex, by adding a vertex detector layer (layer-0) very close to the beam-pipe and keeping the BABAR SVT layout for the outer layers. This six-layer vertex detector solution would improve significantly the track parameter determination, matching the more demanding requirements on the vertex resolution, while maintaining the stand-alone tracking capabilities for low momentum particles.

Various options are under consideration for the layer-0 sensors, such as striplet [7], CMOS monolythic active pixel sensors (MAPS) [8–10] and hybrid pixel detectors [11]. The choice has to take into account the physics requirements for the vertex resolution, depending on the pitch and the amount of material of the sensors. In addition, to assure optimal performance for track reconstruction, the sensor occupancy has to be maintained under the level of a few percent, imposing further requirements on the sensor segmentation and on the front-end electronics. Radiation hardness should also be taken into account, although it is expected not to be particularly demanding compared to LHC detector specifications. Background studies are ongoing to determine the hit rate in the detector region and particularly in layer-0. Therefore, at this stage it is only possible to draw a conceptual design.

The optimal choice for layer-0 sensors is represented by the CMOS MAPS detectors, with full in-pixel signal processing implemented at the pixel level. In this case, the high segmentation of the detector ($\simeq 50 \times 50\,\mu\text{m}^2$ pixel area) and the small amount of the sensor material budget ($\simeq 50$ μm thick silicon sensor, $0.05\% X_0$), provide optimal performance both in terms of occupancy and multiple scattering. A low material budget support structure has been considered to assure the required mechanical stiffness of the detector. It will host also the cooling system which is necessary to drain the heat generated by the present power dissipation of the chips, not yet optimized for low power consumption. Support structure is placed at a larger radius with respect to layer-0, with an expected amount af radial material of about 0.2–$0.3\% X_0$, dominated by the cooling system material. A hit resolution of the order of 10–15 μm is expected to be achievable with MAPS detectors. However this solution still requires some R&D even if important results have been achieved so far [8–10].

Another viable solution is represented by striplet detectors described in more detail in Ref. [7]. In this case, using small standard high resistivity silicon detectors with short strips on both sides, it is possible to reduce the occupancy by geometrically reducing the single strip area. This solution still offers a reasonably low sensor material budget ($\simeq$ 200–300 μm silicon thickness, 0.2–$0.3\% X_0$) and a hit resolution of about 10 μm. The amount of radial material of the support structure in this case is expected to be comparable with the previous solution. The detector occupancy is instead an issue to be considered, which requires detailed background simulation studies. On the other hand this solution does not require significant R&D.

The hybrid pixel solution, while assuring a low occupancy of the detector and being an established technology, has the drawback of a larger amount of material due to the overlap of the sensor and the readout electronics. In this case, the total amount of sensor material is estimated to be exceeding $2\% X_0$ [11], degrading the track parameter reconstruction, especially for low momentum particles. The readout pitch should be optimized with respect to the solution proposed in Ref. [11] ($50 \times 400\,\mu\text{m}^2$), in order to achieve a better single ϕ hit resolution while keeping a hit resolution of about 10–15 μm on z hit.

3. Vertexing studies

In order to simulate the resolution on the B decay vertices and on Δt for different layer-0 configurations, we have used the TRACKERR simulation program [12], which reproduces the detector response according to analytical parameterizations. In this study, we have reconstructed exclusively the $B \to \pi^+\pi^-$ decay mode, and evaluated the other B decay vertex using the charged tracks

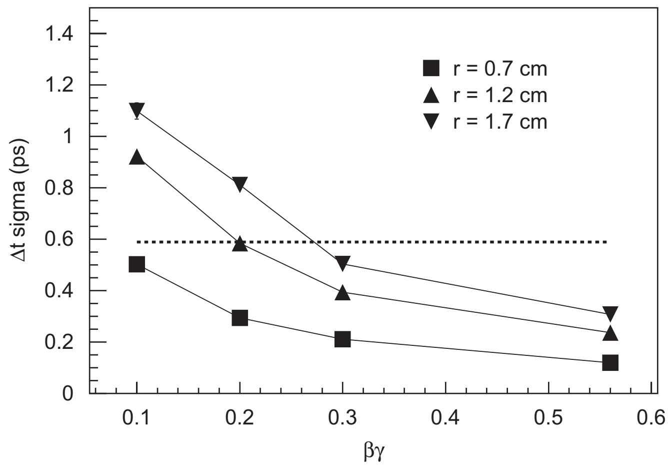

Fig. 1. Δt resolution as a function of the $\beta\gamma$ boost value of the center of mass rest frame adding a MAPS layer-0 at different radii. The resolution on the single hit (z and ϕ) was assumed to be 5 μm for layer-0 in the 0.7 cm radius configuration and 10 μm in the other cases. The dashed line represents the BABAR reference value according to the fast simulation.

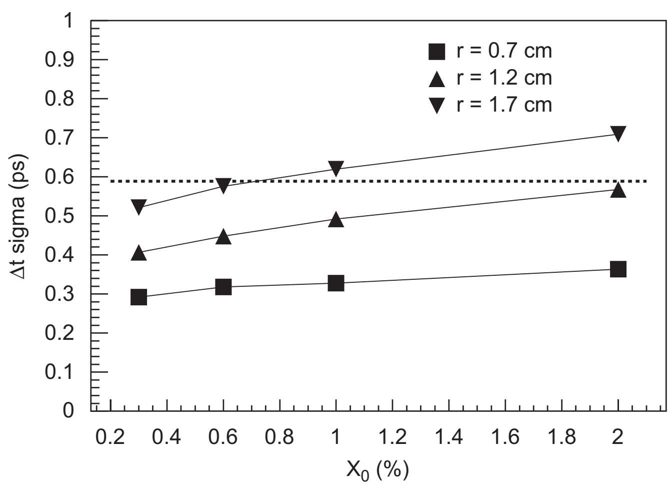

Fig. 2. Δt resolution for the nominal center of mass boost of $\beta\gamma = 0.28$ as a function of the amount of radial material (in $X_0\%$) before the first hit measurement, for different layer-0 radii: 0.7 cm (□), 1.2 cm (△) and 1.7 cm ▽). The resolution on the single hit (z and ϕ) was assumed to be 5 μm for the layer-0 in the 0.7 cm radius configuration and 10 μm in the other cases. The dashed line represents the BABAR reference value according to the fast simulation.

of the rest of event after rejecting long-lived particles and tracks not compatible with the candidate vertex. Fig. 1 shows the resolution on Δt for different layer-0 radii, as a function of the $\beta\gamma$ value of the center of mass boost. The dashed line represents the BABAR reference value (0.6 ps) using the nominal value of the boost, $\beta\gamma = 0.55$, according to the fast simulation. The different layer-0 radii considered are: 0.7 cm (□), 1.2 cm (△) and 1.7 cm (▽). The amount of material of the sensor is consistent with the MAPS solution ($\simeq 0.05\% X_0$), while the beam-pipe radiation length changes in the range 0.4–0.6% X_0 for the three different configurations, accounting for the possibility to reduce radial material, when reducing the beam-pipe radius.

Fig. 2 shows the resolution on Δt as a function of the amount of material before the first hit measurement accounting for the radial material budget differences among the layer-0 proposed solutions. According to these studies it is possible to evaluate the feasibility of different solutions for layer-0, in terms of radial distance and of amount of material before the first hit measurement of the tracks. For the proposed value of the boost $\beta\gamma = 0.28$, and for a layer-0 radius of 1.2 cm, the total radial material before the first hit measurement has to be kept below $2\% X_0$. While this constraint is supposed to be easily met with MAPS and striplet, it could be marginal for hybrid pixels detectors.

4. Conclusions

The SuperB factory project has an enormous discovery potential for NP beyond the SM, complementarily to LHC experiments. The accelerator requirements suggest a center of mass boost of $\beta\gamma = 0.28$, about a half of the present BaBar experiment boost value. In order to achieve a suitable resolution on Δt for time-dependent measurements (0.6 ps according to fast simulation), the requirements on vertexing performances are more demanding with respect to the BABAR experiment. A conceptual design of the SuperB vertex detector based on the BABAR SVT layout, with an additional innermost layer-0, has been considered. For a layer-0 radius of 1.2 cm and $\beta\gamma = 0.28$, the radial material budget before the first hit measurement of the tracks has to be kept below $2\% X_0$. Striplet and MAPS detectors seem to be the optimal choice in terms of sensor material and of intrinsic detector resolution. The impact of the machine background on the performances of the track reconstruction has not be considered here, since it requires more detailed simulations which are ongoing.

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