COLLIDERS FOR B-FACTORIES
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Abstract
Both SuperB and SuperKEKB projects have been approved and are being constructed based on the achievements of PEP-II and KEKB. The new B-factories are aiming at \( \sim 10^{36} \text{cm}^{-2} \text{s}^{-1} \) by squeezing the vertical beam sizes to 40-60 nanometer at the interaction point with relatively modest beam currents. In this paper, recent progress on design and construction status of both projects will be presented.

INTRODUCTION
The PEP-II and KEKB B-Factories, which are \( e^+e^- \) energy-asymmetric double-ring colliders, have been successfully operated until their run ends. They have achieved the world’s highest luminosities: 1.21 (PEP-II) and 2.11 (KEKB) \( \times 10^{34} \text{cm}^{-2} \text{s}^{-1} \). The integrated luminosity combined in both factories has amounted to over 1.5 ab\(^{-1}\) resulting fruitful outputs by the BaBar and Belle experiments such as proofs of the Kobayashi-Maskawa theory and some hints for new physics beyond the Standard Model. Then, boosting the luminosity of B-factories to \( \sim 10^{36} \text{cm}^{-2} \text{s}^{-1} \) at \( \Upsilon (4S) \) is strongly required to integrate 50-75 ab\(^{-1}\) for further investigations.

The two projects reported at IPAC10[1], SuperB[2] and SuperKEKB[3], have been approved and a new generation of B-factories has kicked off. Both colliders are constructed by utilizing experiences and resources of the precedent B-factories as much as possible. This paper reports design and construction status of the two projects.

DESIGN CONCEPT
As it is well-known, the luminosity is expressed as
\[
L = \frac{\gamma_{\pm}}{2e r_e} \left( 1 + \frac{\sigma_y'}{\sigma_z'} \right) \left( \frac{I_e \xi_y}{\beta_y' \beta_z'} \right) \left( \frac{R_L}{R_{\xi_y}} \right),
\]
when the beam sizes and beta functions of both beams are equal at the interaction point (IP). The parameters \( R_L \) and \( R_{\xi_y} \) are reduction factors for the luminosity and the vertical beam-beam tune-shift parameter, respectively, due to the crossing angle and the hourglass effect. Higher beam current \( (I) \), larger vertical beam-beam parameter \( (\xi_y) \) and smaller \( \beta_y' \) are to be pursued for higher luminosity.

From the practical viewpoint, lower beam currents are preferable for hardware feasibility and also for reducing the running cost which is strongly demanded. It is not realistic to expect much higher \( \xi_y \) than those ever achieved in real colliders. Thus, extremely small \( \beta_y' \) is required in order to increase the luminosity to a large extent. For this purpose, a large Piwinski angle \( (\phi_{\text{Piw}} = \theta_x \sigma_z' / \sigma_z') \) and “Crab Waist” (CW) scheme is proposed for SuperB[4]. The design of SuperKEKB is also based on large \( \phi_{\text{Piw}} \) after having changed from the high current and crab crossing scheme.

In the case of collision with large \( \phi_{\text{Piw}} \), beams with sufficiently small \( \sigma_z' \) collide at a large horizontal crossing angle as shown in Fig. 1. The longitudinal size of the overlap region is decreased to \( \sigma_z / \phi_{\text{Piw}} \), therefore \( \beta_{y'} \) can be squeezed to \( \sim \sigma_z / \phi_{\text{Piw}} \) which is much smaller than \( \sigma_z \), avoiding the hourglass effect. For sufficiently small \( \sigma_z \), both low horizontal emittance \( \varepsilon_y \) and low \( \beta_{y'} \) are required.

It is concerned that the luminosity may be degraded by large \( \phi_{\text{Piw}} \) due to enhancement of \( x-y \) coupling and/or synchrotron-betatron resonances. In order to mitigate these adverse effects, the CW scheme has been innovated and has worked successfully in a test at DAΦNE. In this scheme, the vertical waist positions of beam particles with any horizontal offsets can always be matched on the central orbit of the counter-rotating beam by using the CW sextupoles as shown in Fig. 1.

On the other hand, even the CW sextupoles are connected with the \( I \) or \( -I \) transformer, their nonlinearities influence the dynamic aperture[2, 5], thus careful consideration should be necessary. Different selections have been made: SuperB has adopted the CW scheme, but SuperKEKB does not use it as the baseline design.

Machine parameters of SuperB and SuperKEKB are listed in Table 1. There are main common features as follows:

- Low \( \beta_y' \): 200~300 \( \mu \text{m} \).
- Low \( \beta_{y''} \): 25~32 mm.
- Large Piwinski angles: \( \sim 20 \).
- Low emittances and flat beams: 2~5 nm (horizontal), 5~12 pm (vertical), and 0.25~0.28% coupling.

Note that the horizontal emittances are increased by...
Table 1: Machine Parameters of SuperB and SuperKEKB. The parameters of SuperB are based on the latest design report [2]. Values in parentheses denote parameters without intra-beam scattering.

<table>
<thead>
<tr>
<th></th>
<th>SuperB LER (e-)</th>
<th>HER (e+)</th>
<th>SuperKEKB LER (e+)</th>
<th>HER (e-)</th>
<th>units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam energy</td>
<td>$E$</td>
<td>4.18</td>
<td>6.7</td>
<td>4</td>
<td>7.007</td>
</tr>
<tr>
<td>Circumference</td>
<td>$C$</td>
<td>1258.4</td>
<td></td>
<td>3016.3</td>
<td></td>
</tr>
<tr>
<td>Half crossing angle</td>
<td>$\theta_x$</td>
<td>33</td>
<td></td>
<td>41.5</td>
<td></td>
</tr>
<tr>
<td>Piwinski angle</td>
<td>$\phi_{\text{Piw}}$</td>
<td>18.60</td>
<td>22.88</td>
<td>24.6</td>
<td>19.3</td>
</tr>
<tr>
<td>Horizontal emittance</td>
<td>$\varepsilon_x$</td>
<td>2.46 (1.82)</td>
<td>2.0 (1.97)</td>
<td>3.2 (1.9)</td>
<td>4.6 (4.4)</td>
</tr>
<tr>
<td>Vertical emittance</td>
<td>$\varepsilon_y$</td>
<td>6.15</td>
<td>5.0</td>
<td>8.64</td>
<td>11.5</td>
</tr>
<tr>
<td>Coupling</td>
<td>$\sigma_z/\sigma_y$</td>
<td>0.25</td>
<td>0.25</td>
<td>0.27</td>
<td>0.28</td>
</tr>
<tr>
<td>Beta function at IP</td>
<td>$\beta_z/\beta_y$</td>
<td>32 / 0.205</td>
<td>26 / 0.253</td>
<td>32 / 0.27</td>
<td>25 / 0.30</td>
</tr>
<tr>
<td>Horizontal beam size</td>
<td>$\sigma_z$</td>
<td>8.872</td>
<td>7.211</td>
<td>10.1</td>
<td>10.7</td>
</tr>
<tr>
<td>Vertical beam size</td>
<td>$\sigma_y$</td>
<td>36</td>
<td>36</td>
<td>48</td>
<td>62</td>
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<tr>
<td>Betatron tune</td>
<td>$\nu_x/\nu_y$</td>
<td>42.575/18.595</td>
<td>40.575/17.595</td>
<td>44.530/44.570</td>
<td>45.530/45.570</td>
</tr>
<tr>
<td>Momentum compaction</td>
<td>$\alpha_p$</td>
<td>4.05</td>
<td>4.36</td>
<td>3.25</td>
<td>4.55</td>
</tr>
<tr>
<td>Energy spread</td>
<td>$\sigma_z$</td>
<td>7.34</td>
<td>6.43</td>
<td>8.14(7.96)</td>
<td>6.49(6.34)</td>
</tr>
<tr>
<td>Natural chromaticity</td>
<td>$(x)/y$</td>
<td>-137 / -449</td>
<td>-134 / -447</td>
<td>-107 / -785</td>
<td>-168 / -1131</td>
</tr>
<tr>
<td>Beam current</td>
<td>$I$</td>
<td>2.447</td>
<td>1.892</td>
<td>3.60</td>
<td>2.60</td>
</tr>
<tr>
<td>Number of bunches</td>
<td>$n_b$</td>
<td>978</td>
<td></td>
<td>2500</td>
<td></td>
</tr>
<tr>
<td>Particles / bunch</td>
<td>$N$</td>
<td>6.56</td>
<td>5.08</td>
<td>9.04</td>
<td>6.53</td>
</tr>
<tr>
<td>Energy loss/turn</td>
<td>$U_0$</td>
<td>0.865</td>
<td>2.11</td>
<td>1.87</td>
<td>2.45</td>
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<tr>
<td>Long. damping time</td>
<td>$\tau_z$</td>
<td>20.3</td>
<td>13.4</td>
<td>21.6</td>
<td>29.0</td>
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<tr>
<td>RF frequency</td>
<td>$f_{RF}$</td>
<td>476.</td>
<td></td>
<td>508.9</td>
<td></td>
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<tr>
<td>Synchrotron tune</td>
<td>$\nu_s$</td>
<td>-0.0129</td>
<td>-0.0135</td>
<td>-0.0247</td>
<td>-0.0280</td>
</tr>
<tr>
<td>Bunch length</td>
<td>$\sigma_z$</td>
<td>5.0 (4.29)</td>
<td>5.0 (4.69)</td>
<td>6.0 (5.0)</td>
<td>5.0 (4.9)</td>
</tr>
<tr>
<td>Beam-beam parameter</td>
<td>$\xi_x/\xi_y$</td>
<td>0.0033/0.097</td>
<td>0.0021/0.097</td>
<td>0.0028/0.088</td>
<td>0.0012/0.081</td>
</tr>
<tr>
<td>Total beam lifetime</td>
<td>$\tau_{\text{beam}}$</td>
<td>269</td>
<td>254</td>
<td>346</td>
<td>332</td>
</tr>
<tr>
<td>Luminosity</td>
<td>$L$</td>
<td>$10 \times 10^{35}$</td>
<td></td>
<td>$8 \times 10^{35}$</td>
<td></td>
</tr>
<tr>
<td>Integrated luminosity</td>
<td>$\int L$</td>
<td>75</td>
<td></td>
<td>50</td>
<td></td>
</tr>
</tbody>
</table>

30-70% due to the intra-beam scattering.

- Small $\sigma^*_z$: 40-60 nm.
- Modest beam currents: 1.9-3.6 A.
- Modest bunch lengths: 5-6 mm.
- Modest vertical beam-beam parameters: 0.09-0.10. The horizontal beam-beam parameters are very small, which may help the vertical beam-beam performance.
- Smaller energy asymmetries than PEP-II and KEKB. These values are still acceptable for physics experiments.
- Short beam lifetimes: 250-350 sec. Thus powerful injectors are necessary.
- Minimize construction and running costs.

Each project will be individually reviewed in the following sections.

**SUPERB**

**Status**

The SuperB project has been approved by the Italian Research Minister as part of the Italian National Research Plan, with a 5 years construction budget. The construction site has been recently selected in the campus of the Tor Vergata Rome II University, 5 km away from the IFNF Frascati National Lab. The international "Cabbibo Laboratory" will be newly constituted and will host the SuperB project [6].

**Parameters and Lattice**

The SuperB collider whose target luminosity is $10^{36}$ cm$^{-2}$s$^{-1}$ has own characteristics as [7]:

- Longitudinally polarized electron beam in the LER.
- Wide ranges of flexibility for machine parameters.
- Beside the baseline design, two options, lower emittance.

Figure 2: SuperB rings in the Tor Vergata University site.

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The arcs of both rings have conceptually the same structure which consists of short and long cells as shown in Fig. 3. The arc dipoles in the LER are shorter (bending radius about 3 times smaller) than those in the HER. Sextupoles are paired with the $-I$ transformer to cancel their major nonlinearities.

In the final focus section, large chromaticities arising from final focus quadrupoles are locally corrected by $-I$ sextupole pairs in both planes as shown in Fig. 4. The CW sextupoles are placed at the ends of the local chromaticity correction sections. The spin rotators are placed only in the LER. The CW scheme demands for particular care in designing the chromaticity correction in the final focus section.

The final focus quadrupoles are a set of permanent (PM) and superconducting (QD0, QF1) magnets with warm bore cryostats. The permanent magnets are installed so that their front pole faces are at 30 (38) cm from the IP in the LER (HER). There are two types of QD0; super-ferric design with vanadium permendur yoke and air-core design. Additional vanadium permendur quadrupoles are installed only for the HER in both cases. Advanced design of air-core dual quadrupoles whose axes are parallel to the beam orbit is being developed [11]. A prototype is being constructed and will be tested soon.

Practical solutions of collimation against Touschek particle losses have been found. Four horizontal collimators are placed near the peaks of the horizontal dispersion in the final focus sections. The reduction of Touschek lifetime by this collimation is estimated to be from 7.8 (40) to 6.6 (33.2) min in the LER (HER)[12].

Tolerances for the vibrations have been comprehensively estimated, including ground motion, motion sensitivity of machine components and performance of beam feedback system. Ground vibration measurements of the Tor Vergata site have shown very good stabilities[13]. The measured values of the vertical displacement (20-40, 20-30, 20-30 nm) are much smaller than the required values (300, 300, 500 nm rms for the IP, final focus quadrupoles, and arc quadrupoles respectively). It is noted that the vibration sensitivity is greatly reduced for coherent motion of the IR components in a common cryostat. Similar robustness for the coherent motion is also pointed out at SuperKEKB.

### Table 2: Two Options

<table>
<thead>
<tr>
<th>Low emittance</th>
<th>High current</th>
</tr>
</thead>
<tbody>
<tr>
<td>LER</td>
<td>HER</td>
</tr>
<tr>
<td>εₓ</td>
<td>1.23</td>
</tr>
<tr>
<td>εᵧ</td>
<td>3.075</td>
</tr>
<tr>
<td>βᵧ</td>
<td>0.145</td>
</tr>
<tr>
<td>I</td>
<td>1.888</td>
</tr>
<tr>
<td>nₒ</td>
<td>978</td>
</tr>
<tr>
<td>ξᵧ</td>
<td>0.0892</td>
</tr>
</tbody>
</table>

**Units**: nm for ε, pm for εᵧ, mm for βᵧ, A for I.
**Injector and Others**

The injector complex has been updated for high efficiency of positron production and top-up injection of polarized electrons. The present design features are: one damping ring only for positrons, positron production at low energy (0.6 GeV) and polarized electron gun[14]. Many works are making progress on beam dynamic issues such as e-cloud instability. Low Emittance Tuning (LET) procedures[15], intra-beam scattering[16]. R&D works are also going on as longitudinal and transverse bunch-by-bunch feedbacks and luminosity IP feedback.

**SUPERKEKB**

**Parameters and Lattice**

KEKB is upgraded to SuperKEKB based on the scheme with large Piwinski angle, which is called the Nano-Beam scheme. Compared with KEKB, three key parameters are: beam currents are doubled, $\varepsilon_y$'s are same, and $\beta_y$'s are reduced by a factor of 1/20, resulting 40 times higher luminosity.

The beam energies are changed from 3.5 to 4 GeV for the LER and from 8 to 7 GeV for the HER. For the LER, the higher energy is necessary to suppress emittance growth due to the intra-beam scattering and also to make Touschek lifetime longer. For the HER, the lower energy is better to reduce $\varepsilon_x$ and the synchrotron radiation power.

SuperKEKB is constructed in the KEKB tunnel. The required values of beam optical parameters such as $\varepsilon_x$ will be achieved by reusing the components of KEKB as much as possible:

- Preserve the present arcs in the HER because $\varepsilon_x$ can be decreased to an acceptable level by utilizing the tunability of the 2.5π cell as shown in Fig. 7. Then, the magnets, vacuum chambers and beam position monitors etc. can be reused.
- Replace dipoles to longer ones (from 0.89 to 4.2 m), reusing other main magnets in the LER arc sections.
- Final focus sections (~300 m) are fully reconstructed in both ring. Like SuperB, the local chromaticity correction sections with $-I'$ sextupole pairs for both vertical and horizontal planes are installed in both rings as shown in Fig. 8.
- Wiggler sections only in the LER at KEKB are modified to shorten the wiggler period to half. One third of LER wigglers are reused in the HER.

**IR Design**

All of final focus quadrupoles are superconducting magnets which are placed on axis of the beam orbits as shown in Fig. 9 [17]. Each quadrupole has four correctors of horizontal and vertical dipoles, skew quadrupole, and octupole windings as shown in Fig. 10. Except two innermost quadrupoles, iron yokes are used in order to eliminate non-linear leakage fields which significantly decrease dynamic apertures of the counter-rotating beams[18, 19]. Cannel correctors of 6-, 8-, 10-, 12-poles are wound on the HER beam pipes against the leakage fields of the LER innermost quadrupoles (QC1RP, QC1LP). The detector solenoid field is cancelled with compensation solenoids so that the integrated field on each side of the IP is to be zero, and is also canceled at the center of each final quadrupole as small as possible.

As well as sextupoles, octupole correctors of the final quadrupoles and skew sextupoles installed in the rings are used to optimize the dynamic aperture. Because solutions with sufficient dynamic aperture have not yet found, the CW scheme is not used as the baseline lattice. If a good solution is found, the CW sextupoles will be installed afterward in the other straight section than that of the final focus.

Beam background simulation and design of machine detector interface are in progress[20, 21].

**Construction**

A budget was announced for the high performance upgrade program of KEKB over the three years starting in Figure 7: HER 2.5π unit cell with noninterleaved $-I'$ sextupole pairs (left) and its tunability (right). It is possible to decrease $\varepsilon_x$ to 5.2 nm only by adjusting quadrupoles, and to 4.4 nm with wigglers.

Figure 8: Final focus optics of the LER (top) and layout of both rings in the final focus section (bottom). The beam lines are fitted into the existing tunnel.
Japanese fiscal year of 2010 and KEKB operation ended in June 2010. Subsequently SuperKEKB was approved in JFY2011 budget in Dec. 2010. The construction of SuperKEKB has now started and mass fabrication of magnets, beam pipes, etc is going on.

Beam pipes of the LER arc section are replaced with TiN-coated aluminum-alloy pipes with antechambers. In the HER arc section, present copper beam pipes are reused with antechamber are used in both rings. Clearing electrodes in the wiggler sections, groove surfaces in dipoles, and solenoid windings in drift spaces are adopted in the LER to suppress electron cloud instabilities[22].

The construction schedule including a new positron damping ring and upgrade of the injector linac[23] are summarized in Fig. 11. The commissioning of SuperKEKB rings will start in the second half of JFY2014.

**SUMMARY**

Both SuperB and SuperKEKB projects have been approved and a new generation of B-factories has started. To realize the luminosity of \( \sim 10^{36} \text{cm}^{-2}\text{s}^{-1} \), many other works not mentioned here are also steadily in progress. Both projects will push the luminosity frontier with competition and collaboration.

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