Future e⁺e⁻ Flavour Factories: accelerator challenges

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Operation of the B-Factories (PEP-II and KEKB) has been very successful, both having exceeded their design peak and integrated luminosity and provided a huge amount of good data to the experiments. Proposal for upgrades, in order to achieve about two order of magnitude larger luminosity, are in progress in Japan, with Super-KEKB, and in Europe, with SuperB. Very high beam intensity, very short bunch length and low Interaction Point β -functions are the key points of the Japanese design, very challenging for the hardware components (RF, vacuum). On the other hand SuperB exploits a new collision scheme, namely large Piwinski angle and "crab waist", which will allow for reaching a luminosity two order of magnitude larger without increasing beam currents and decreasing bunch lengths. In this talk the present status of the two projects will be briefly reviewed.

I. INTRODUCTION

Presently operating B-Factories (PEP-II and KEKB) have exceeded their design goals, both in peak and integrated luminosity. PEP-II [1], running from mid-1999 to April 2008, has reached 4 times the design peak luminosity, delivering to the BaBar experiment an integrated luminosity larger than 557 fb⁻¹ (see Fig. 1, left plot). KEKB [2] also started operation in 1999 and reached a peak luminosity 60% higher than the design value, delivering about 820 fb^{-1} (up to April 2008) to Belle (see Fig. 1, right plot). In Table I the performances reached at the end of April 2008 are summarized. Very good performances and high operation reliability represent a big success for all the Factories, and upgrade of an order of magnitude or more in luminosity is desirable for investigation on particle physics beyond the Standard Model.

TABLE I: B-Factories performances (April 2008).

	PEP-II	KEKB
Energy (GeV)	3.1x9	3.5x8
Design peak L $(\times 10^{33} \text{cm}^{-2} \text{s}^{-1})$	3	10
Achieved peak L ($\times 10^{33}$ cm ⁻² s ⁻¹)	12	17
Design int. $L/day (pb^{-1})$	130	600
Achieved int. $L/day (pb^{-1})$	911	1231
Achieved total int. L (fb^{-1})	557.4	824

The construction and operation of multi-bunch e⁺e⁻ colliders have brought about many advances in accelerator physics in the area of high currents, complex interaction regions, high beam-beam tune shifts, high power RF systems, controlled beam instabilities, rapid injection rates, and reliable uptimes (about 95%). The present B-Factories have proven that their design concepts are valid, since asymmetric energies work well, the beam-beam energy transparency conditions are weak, high currents can be stored and the electron cloud instability (ECI) can be managed. On the detector-machine side the Interaction Regions

(IR) backgrounds can be handled successfully and IR with two energies can work. Moreover unprecedented values of beam-beam parameters have been reached (0.06 up to 0.09), and continuous injection in production has helped increasing the integrated luminosity. However a step forward is needed in order to increase luminosity by one or even two order of magnitude.

II. TWO APPROACHES

To increase Luminosity of about two orders of magnitude, with the same philosophy of the present B-Factories, borderline parameters are needed such as those chosen by the Super-KEKB project, that is:

- very high currents;
- smaller β_y^* ;
- smaller damping times;
- very short bunches;
- crab cavities for head-on collision;
- higher power.

To squeeze the vertical beam size, so increasing Luminosity, the vertical β_y^* at the Interaction Point (IP) must be decreased: this is efficient only if at the same time the bunch length is shortened to about the β_y^* value, otherwise particles in the head and tail of the bunch will see a larger β_y^* (hourglass effect). However shorter bunches require an increase of RF voltage with consequent costs increase. This approach is then difficult in terms of operational costs because of the large RF power needed, the higher backgrounds, and High Order Modes (HOM) heating.

The SuperB project exploits an alternative approach, with a new collision scheme [3]:

- very small beams (ILC-Damping Rings like);
- large Piwinski angle and "crab waist";

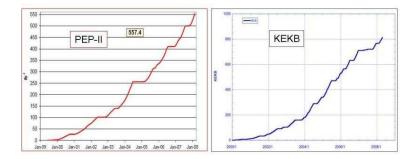


FIG. 1: Integrated luminosity for PEP-II (left) and KEKB (right) at end of April 2008.

• currents comparable to present Factories.

This configuration moves the difficulties to the realization and maintenance of extremely focused beams. Remarkably, SuperB would produce this very large improvement in luminosity with circulating currents and wall plug power similar to those of the current B-Factories.

Both approaches require status-of-the-art technology, but the operation of SuperB would probably be easier.

III. KEKB AND SUPER-KEKB

Since 2004 a major upgrade of KEKB has been studied, and has been described in a Letter of Intent [5]. A layout of the machine is in Fig. 2.

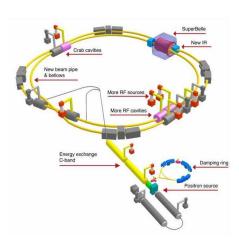


FIG. 2: Layout of Super-KEKB.

What are the challenges of the Super-KEKB design is straightforward when looking at the simplified luminosity formula below:

$$L \approx \frac{\gamma_{\pm}}{2er_e} \frac{I_{\pm}\xi_{\pm y}}{\beta_y^*} \tag{1}$$

The key parameters are of course the beam currents, beam-beam tune shifts and the β_y^* . To reach a luminosity of $8 \times 10^{35} \text{cm}^{-2} \text{s}^{-1}$ (a factor of 47 higher than the achieved one) stored currents need to increase from the values achieved in LER and HER (1.7 A x 1.4 A) to 9.4 A x 4.1 A (a factor 5.5 and 2.9 respectively). The beam-beam parameter should go from the achieved 0.059 to 0.24 (a factor of 4 increase), while the β_{y}^{*} needs to be squeezed down from 6.5 mm and 5.9 mm to 3 mm, with a simultaneous shortening of the bunch length to 3 mm. According to beam-beam simulations this can be done if a specific luminosity per number of bunches larger than $22\times10^{30}{\rm cm^{-2}s^{-1}}$ A⁻² with the crab cavities is achieved (a factor of 2 larger than the present one at least), and high specific luminosity at high currents(9.4 A at LER) can be kept. Moreover 5000 bunches need to be stored, no ECI should arise and the bunch-by-bunch feedback system should work without any problem.

To get the Super-KEKB design parameters the ARES copper cavities need to be upgraded with higher energy storage ratio to support higher currents. Superconducting cavities need to be upgraded too, in order to absorb more HOM power up to 50 kW. The beam pipes and all vacuum components will be replaced with higher-current-proof design. Compatibility with SuperB design has also been explored: the arc cell lattice of the KEKB LER can be modified to decrease the emittance to 12 nm by weakening the magnetic field of the dipoles. Lower emittance can be reached if the dipoles are replaced. There is no need for changing other components, like beam pipes or geometry, but of course the IR must be rebuilt. The KEKB HER emittance is not reduced, but unequal emittance may be fine for operation.

A. Crab Cavity Operation at KEKB

Two crab cavities, one per ring, have been installed in KEKB last year. The expected increment in peak luminosity, given by the strong-strong beam-beam simulations, was about a factor of 2. However, as it can be seen in Fig. 3, where the specific luminosity is plotted as a function of the product of beam currents with and without crab cavities, a very high specific luminosity is reached at low currents, dropping down faster than without crab cavities for high beam currents. Studies are in progress to understand the causes of this behaviour which prevents increasing luminosity at high currents.

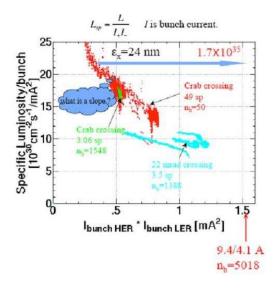


FIG. 3: Specific luminosity vs product of currents for different operation scenarios.

B. Super-KEKB Summary

A high current scheme approach will allow to get a luminosity for KEKB upgrade from 5 to 8 $\times 10^{35} {\rm cm}^{-2} {\rm s}^{-1}$. In case needed, a smaller emittance of 12 nm in LER can be feasible without hardware changes, and about 2 nm are achievable if the bends are replaced. The design of the new vacuum system, needed to deal with the very high stored currents, is almost completed except for the IR chamber. In the IR design there are still things to be fixed, especially the cure of synchrotron radiation fans on the beam pipes. The injection complex needs also to be upgraded.

IV. SUPERB

SuperB aims at the construction of an asymmetric e⁺e⁻ Flavour Factory with very high peak (10³⁶cm⁻²s⁻¹) and integrated luminosity (75 ab⁻¹ in 5 years), with possible location at the campus of the University of Rome Tor Vergata, near the INFN Frascati National Laboratory (Italy). Since 2005 several Workshops have been held to prepare the Physics case,

the BaBar detector upgrade and the design of the accelerator. Many schemes have been studied, from an ILC-like layout to a SLC-like one. Finally, an innovative idea for collisions, supported by beam-beam simulations, has shown the possibility to have the usual two rings scheme. The new design is based on the "large Piwinski angle and crab waist" collision scheme which will allow to reach unprecedented luminosity with low beam currents and reduced background at affordable operating costs. The so called "crab waist" transformation, by means of a couple of sextupole magnets for each ring, will add a bonus for the suppression of synchro-betatron resonances arising from the large collision angle. A polarized electron beam will allow for producing polarized τ leptons, opening an entirely new realm of exploration in lepton flavor physics. The principle of operation of this scheme is presently under test at the DA Φ NE Frascati Φ -Factory.

In its final layout the accelerator consists of two rings of different energy (4 x 7 GeV) colliding in one IR at a large horizontal angle. Spin rotator sections in the HER will provide helicity of a polarized electron beam. A Conceptual Design Report (CDR) [4], was issued in May 2007, with about 200 pages dedicated to the accelerator design.

A. A New Idea for Luminosity Increase

The key point of the SuperB design is to focus more the beams at IP and have a large crossing angle: this translates into having a large Piwinski angle.

In summary, the design is based on:

- large Piwinski angle;
- "crab waist" scheme (with no RF cavities but sextupoles);
- very small β_y^* at IP;
- small collision area;
- small power consumption.

Due to the smaller collision area, it is possible to get lower β_y^* values without shortening the bunch length. Moreover, due to the large crossing angle, there will be fewer or no parasitic crossings. Two sextupoles per ring, in phase with the IP in x and at 90 degrees in y, will suppress the dangerous betatron and synchrobetatron resonances, and all particles in each beam will collide at the minimum β_y^* region (waist) with a net luminosity gain (see Fig. 4 for the beam distributions without (top) and with (bottom) "crab waist" transformation). As a result a higher luminosity will be possible, with same currents and bunch length as in the present B-Factories, this means that:

• beam instabilities are less severe;

- HOM heating is manageable;
- there will be no coherent synchrotron radiation (CSR) from short bunches;
- stored currents small will be smaller (less than 2 A per beam);
- power consumption will be much lower;
- background rates will be lower.

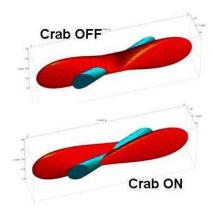


FIG. 4: Beam cross sections at the IP without (top) and with (bottom) "crab waist" transformation.

The SuperB, as described in the Conceptual Design Report, is the result of an international collaboration between experts from BINP, Cockcroft Institute, INFN, KEKB, LAL/Orsay, SLAC. The design is flexible but challenging and the synergy with the ILC Damping Rings, which helped in focusing key issues, will be important for addressing some of the topics (low emittance tuning, ECI remediation, etc...). No wigglers will be needed to reach the design emittances and damping times. The design is based on recycling all PEP-II hardware: dipoles, quadrupoles, sextupoles, RF system, and possibly vacuum system, allowing to reduce costs. Background studies have been carried out in synergy with the detector experts, in order to optimize the collimators set for backgrounds reduction. The design of the Final Focus has been optimized in terms of chromatic corrections and luminosity performances. The large crossing angle geometry allows for having two separate QD0 for HER and LER: since the mechanical constraints are too tight for a conventional septum magnet, a novel concept to compensate the cross-talk among the two QD0's core and fringe fields has been studied [6]. Longitudinal polarization for the electron beam will also be included. with the possibility to run at lower energy (τ) with a loss of a factor of 10 in luminosity. The layout of one ring is shown in Fig. 5, while the possible location on the Tor Vergata University campus is shown in Fig. 6. In Table II is a comparison of SuperB and Super-KEKB main parameters.

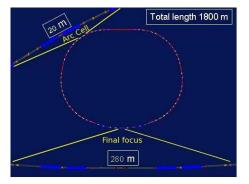


FIG. 5: Layout of one SuperB ring.

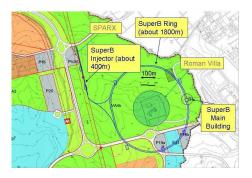


FIG. 6: Sketch of the SuperB accelerator on the Tor Vergata campus.

B. SuperB Summary

SuperB has very ambitious goals in terms of peak and integrated luminosity, supported by a new collision scheme and confirmed by beam-beam simulations. The initial design meets the goals requested by the experimenters. The test on this scheme is in progress at DA Φ NE and encouraging results have been achieved at the moment. The work on the accelerator is continuing to focus on possible issues. The next step will be to form a team to complete a Technical Design Report by 2010.

V. CONCLUSIONS

Operation of present B-Factories has been very successful and an upgrade of is desirable and feasible. KEKB and PEP-II experience was highly positive and instructive, but going to higher luminosities is much more challenging: the "brute force" approach seems hard to pursue and new ideas need to be tested. Solutions to problems can come from the collaboration between international laboratories, as it is done for the ILC.

Two different approaches are being considered for Super-KEKB and SuperB, with different challenges. Super-KEKB is the natural continuation of KEKB,

Parameter Units SuperB Super-KEKB Energy GeV4x73.5x8 $\times 10^{36} \text{cm}^{-2} \text{s}^{-1}$ Luminosity 1 to 2 0.5 to 0.81.9x1.9Beam currents Α 9.4x4.10.223. mm β_r^* 20. cm3.5x2.Crossing angle (full) mrad 48. 30. to 0. RF power (AC line) MW17. to 25. 80. to 90. Tune shifts 0.0004/0.20.27/0.3(x/y)

TABLE II: Comparison of SuperB to Super-KEKB.

studies are advanced and it is waiting for funding. SuperB exploits new concepts in colliding beams physics, allowing for the collection of a larger data sample. The test of the novel collision scheme is in progress and

the first results of the upgraded DA Φ NE are very encouraging and important for the very high luminosity regime required by future Flavour Physics studies.

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- [2] K. Oide et al, "Compensation of the Crossing Angle with Crab Cavities at KEKB", Proc. of Particle Accelerators Conference, Albuquerque, June 2007.
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- [5] "Super-KEKB Letter of Intent (LoI)", KEK Report 04-4, 2004.
- [6] S. Bettoni, E. Paoloni, P. Raimondi, "Design of the QD0 for SuperB IR", ICFA Workshop on e⁺e⁻ Factories, April 2008, Novosibirsk (Russia).