NEXT GENERATION B-FACTORIES

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Abstract

The KEKB and PEP-II B factories have achieved world record luminosities while doubling or tripling their original design luminosities. The demand now from the physics community is for Super B Factories with orders of magnitude higher luminosities than those achieved by the present generation of machines. The next-generation B factories, which aim to push back the luminosity frontier in the search for physics beyond the Standard Model, are reviewed in this report.

INTRODUCTION

PEP-II and KEKB

PEP-II [1] and KEKB [2] have operated the world's highest luminosity e^+e^- colliders with stored beam currents greater than 1 A. In addition to record luminosities, the two projects have made several other important technical achievements:

- Establishment of technology of key components, such as RF, vacuum and beam monitors, to handle multi-ampere beam currents.
- Operation with crossing angle, and crab cavities (KEKB).
- Proof that IR configuration with permanent magnets (PEP-II) / superconducting magnets (KEKB) works.
- Detector backgrounds at manageable level with continuous (trickle-charge) injection scheme.
- Demonstration of effectiveness of solenoids against electron clouds.
- Benchmarks for simulations made and further understanding of beam dynamics obtained.

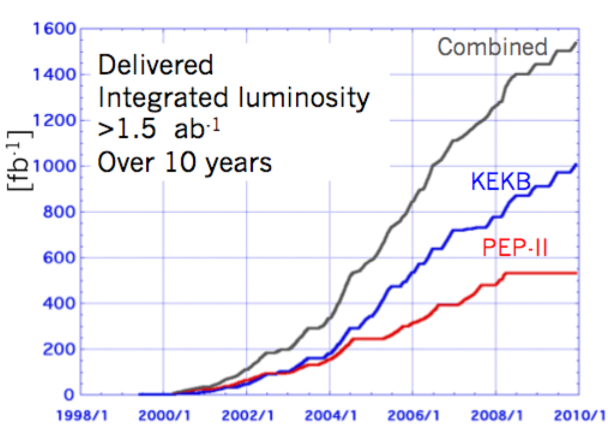

Figure 1: What we, PEP-II and KEKB, have achieved.

Next Generation B-factories

As seen in Fig. 1, PEP-II and KEKB have delivered a combined integrated luminosity of over 1.5 ab^{-1} in the course of approximately 10 years. The physics community has now set a target of 50 (75 for SuperB) ab^{-1} for the exploration of new physics. At a luminosity of 2×10^{34} cm^{-2} s^{-1} (near the KEKB peak) this would take 167 years, assuming 1.5×10^7 seconds/year of running time. This points to the need for much higher luminosity machines, the next-generation B Factories, of which there are two projects being planned: SuperB and SuperKEKB. These projects aim to increase the peak luminosity by a factor of 40-50 from the world record peak luminosity that KEKB currently holds. The targets of the next-generation B Factories are indicated in Fig. 2, where the peak luminosity trends over the past 40 years of several e^+e^- colliders are plotted.

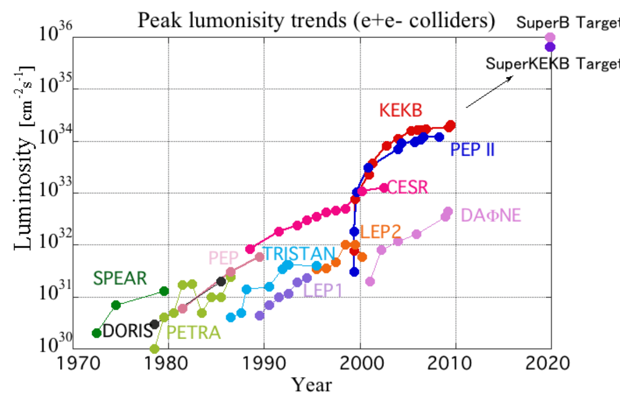

Figure 2: Peak luminosity trends in the last 40 years.

Strategies for Higher Luminosity

Design work has been going on for a while for both SuperB and SuperKEKB. Information is being exchanged between the two groups, learning from each other and improving the designs. The designs and parameters are not yet finalized, so numbers presented here are still somewhat preliminary.

Three main parameters determining luminosity are the beam currents, the beta function at the Interaction Point (IP), β_y^*, and the vertical beam-beam parameter, ξ_y. The initial design approaches were extrapolations of the PEP-II and KEKB designs, with higher beam currents, higher ξ_y, somewhat reduced β_y^*, shorter bunch lengths to reduce the hour-glass effect, and, at least for SuperKEKB, crab crossing for effective head-on collisions. Higher currents lead to large power consumption, and shorter bunch lengths face challenges from HOM heating as well as bunch lengthening due to coherent synchrotron radiation. An alternative approach, first proposed by P. Raimondi for the SuperB project, uses low-emittance beams, colliding with a very small spot size, to achieve higher luminosities at more modest beam currents [3].

Both projects are currently using designs based on the use of low-emittance beams. The current status of the designs for the two projects will be reviewed individually, and then compared.

SUPERB PROJECT

SuperB Layout and Parameters

The SuperB project has the goal of constructing a very high luminosity (1×10^{36} $cm^{-2}s^{-1}$) asymmetric e^+e^- flavor factory with a possible location on or near the campus of the University of Rome at Tor Vergata, or at the site of the INFN Frascati National Lab. Figure 3 shows the SuperB layout at the Frascati site [4].

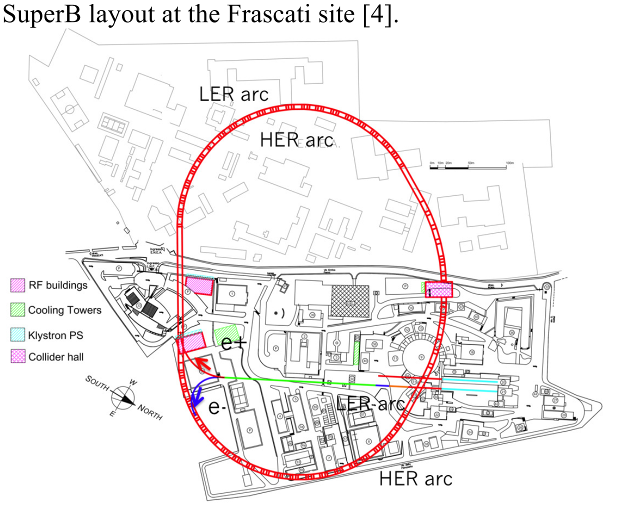

Figure 3: SuperB ring at INFN Frascati National Lab. site.

The SuperB design aims for the following features [5]:

- Very high luminosity (~10^{36})
- Flexible parameter choices
- High reliability
- Longitudinally polarized beam (e^-) at the IP (>80%)
- Ability to collide at charm threshold ($E_{c.m}$=3.8 GeV)
- Flexible lattice.

The baseline design that satisfies the design luminosity (except in tau-charm mode) is discussed here. The baseline parameter set is compared with SuperKEKB in the final section.

Collision Scheme with Large Piwinski Angle and Crab Waist

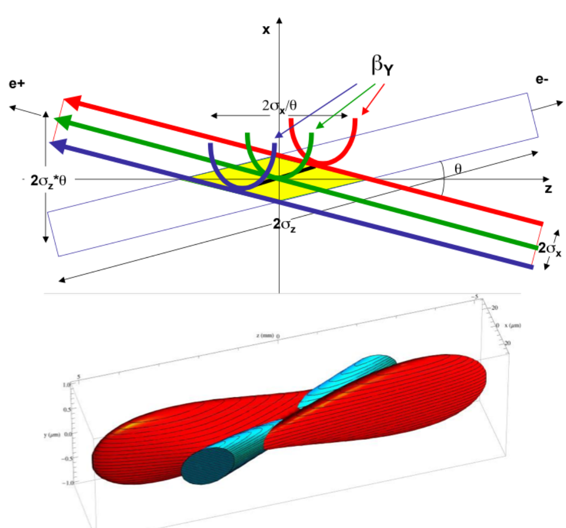

Figure 4: Crab waist scheme.

The collision scheme with large Piwinski angle with crab waist is shown in Fig. 4. All particles from both beams collide in the minimum β_y region, giving both a geometric luminosity gain and suppression of X-Y betatron and synchro-betatron resonances as observed in a beam-beam simulation shown in Fig.5 [6].

Tests have been carried out at DAϕNE which show that colliding with a large Piwinski angle and crab waist works well. The crab waist sextupoles have been of great importance in increasing the collider luminosity, and are used in regular operations.

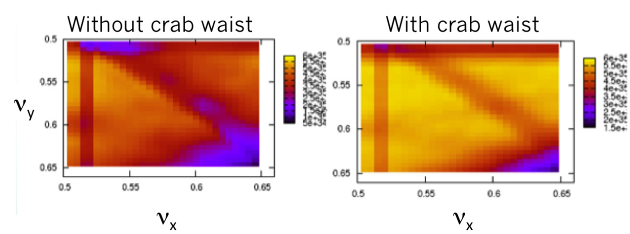

Figure 5: Illustration of suppression of X-Y betatron resonance by crab waist. (Note: simulation is for SuperKEKB.)

Polarized LER (e-)

The physics program for SuperB has set a requirement of 60-85% polarization in one of the beams to enable τ *CP* and *T* violation studies, measure the τ *g*-2, and improve sensitivity to lepton flavor-violating decays [7]. In principle, either beam could be polarized. Spin rotators are needed on either side of the IP because longitudinal polarization is needed at the IP, while the axis of polarization of the beam in the bends should be vertical. It was decided to polarize the LER because the spin rotators are easier to accommodate there, and the spin depolarization time in the LER is longer than in the HER. SLAC has a long and rich experience with polarized electrons guns, so the LER will become the (polarized) electron ring and the HER the positron ring. The depolarization time of the beam depends on the energy. The energy of the LER is chosen to be 4.18 GeV to minimize the rate of depolarization. It is estimated that with continuous injection at 90% polarization, and a beam lifetime of 3.5 minutes at high luminosity, a steady-state polarization of 75-80% is achievable [8].

Interaction Region (IR)

The interaction region design has to accommodate the machine needs as well as the detector requirements, which leads to the following set of requirements:

- Final focus elements as close to the IP as possible
- As small a detector beam pipe as backgrounds allow
- As thin as possible detector beam pipe
- Adequate beam-stay-clear for the machine (low emittance beams helps here)
- Synchrotron radiation backgrounds under control
- Adequate solid angle acceptance for the detector
- Twin bore IR quadrupoles.

Figure 6 shows the SuperB IR. The crossing angle in the baseline design is ± 33 mrad, with the innermost quadrupoles being permanent magnets, and the next outer set of quadrupoles (QD0 and QF1) being superconducting, with a warm-bore cryostat. For the innermost superconducting quadrupoles, QD0, a twin-bore design is under development; a super-ferric design is also under study as an alternative, using Permendur yokes surrounded by superconducting coils [9].

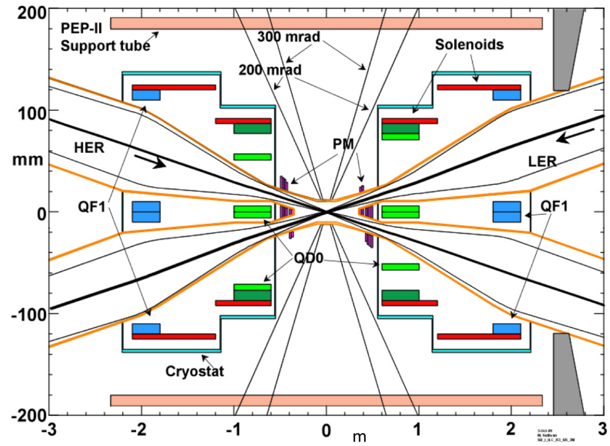

Figure 6: Schematic view of SuperB IR.

Status

As of March 2010, the lattice and design parameter optimization is continuing, with attention being paid to beam dynamics issues such as intra-beam scattering, fast-ion instability, emittance diffusion, beam-beam effects, and feedback.

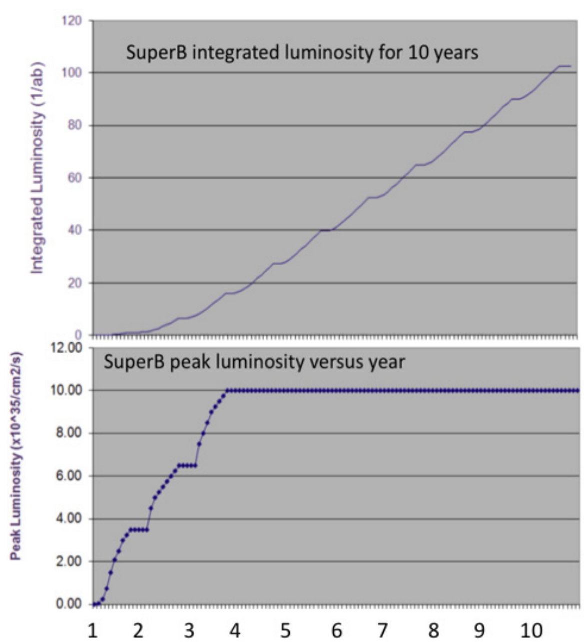

Figure 7: SuperB luminosity projection plotted against number of years from start of commissioning.

Component and lattice tolerances with corrections are being studied, and work on polarization is progressing with studies of beam-beam depolarization, work on simplifying the polarized gun, and on methods for spin measurements.

The luminosity is projected to reach 1×10^{36} cm^{-2} s^{-1} within about 4 years from commissioning, as shown in Fig. 7, with a goal of reaching 75 ab^{-1} in 5 years of full running.

SUPERKEKB PROJECT

Parameters

The KEKB B-Factory will be upgraded to SuperKEKB, using the same tunnel as KEKB. The upgrade is based on the "nano-beam" scheme, which was first proposed for the Super B factory in Italy:

- Squeeze β_y* as small as possible: 0.27 (0.41) mm in LER (HER)
- Assume beam-beam parameter of 0.09, which has already been achieved at KEKB
- Change beam energies from 3.5 & 8 GeV (KEKB) to 4 & 7 GeV to achieve longer Touschek lifetime and mitigate the effect of intra-beam scattering in LER (also helps lower emittance in the HER)
- Reuse KEKB components as much as possible.

The major items to be upgraded are:

- New antechamber beam pipes for both rings.
- Al (Cu) beam pipes for LER (HER)
- Mitigation techniques electron cloud suppression
- New IR optics
- New superconducting/permanent magnets around IP
- Optimization of the IR compensation solenoid
- Additional normal magnets to reduce emittance
- Replace dipoles & change wiggler layout for LER
- New HER arc lattice
- New power supplies for more precise magnet setting
- Rearrangement of existing ARES cavities with additional power sources
- Positron damping ring and new positron target
- New RF gun for electrons with reduced emittance.

Lattice

To achieve low emittance with minimal change to the lattice, the SuperKEKB LER dipole magnets will be lengthened to 4 m, from the 0.89 m used at KEKB. In addition, the wiggler period will be shortened. In the HER, the number of cells in a quarter-arc section is increased from 6.5 to 8.5 to make the horizontal dispersion smaller in order to reduce the emittance, replacing the main dipole magnets of 5.9 m with ones 3.8 m long. Solutions which preserve the number of HER arc cells are also being studied. The use of a crab waist scheme has been studied for SuperKEKB. So far, a solution with sufficient dynamic aperture has not been found, so crab waist is not currently in the baseline design.

IR Design

The IR of SuperKEKB employs a crossing angle of ±41.5 mrad. The large crossing angle helps to separate the two beams quickly and to fit the final focus quadrupole magnets closer to the IP for achieving a small β_y^*. Like the SuperB IR, it is composed of a combination of superconducting and permanent magnets, but with separated superconducting magnets forming the innermost quadrupoles rather than permanent magnets. The schematic layout is shown in Fig. 8. The solenoid field of the Belle-II detector is fully compensated with compensation solenoids on each side of the IP. The superconducting quadrupole and solenoid magnets on each side of the IP are contained in a common cryostat. These magnets surround a warm bore vacuum chamber connected to the cryostats via bellows.

The leakage fields of the superconducting magnets are cancelled by correction windings on the opposite beam pipes, as shown in Fig. 9. In recent studies of beam dynamics it was found that the fringe fields of the compensation solenoids increase the vertical beam emittance. To reduce this effect, the compensation solenoids are segmented into small coil pieces to produce a slow gradient of the solenoid fringe field along the Belle-II axis, as shown in Fig. 10. The optimization of the IR magnets and field configuration is under way.

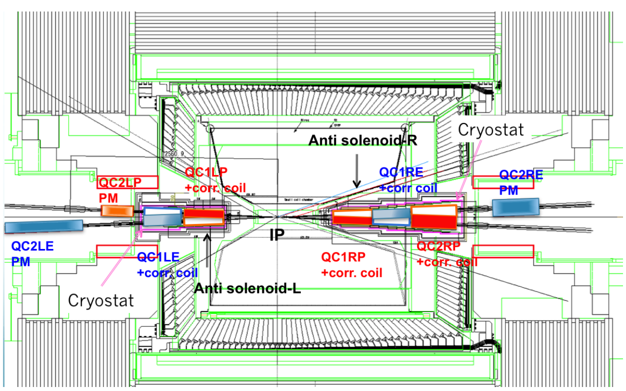

Figure 8: SuperKEKB IR. The permanent magnets (QC2LP, QC2LE and QC2RE) are located further from the IP than the superconducting magnets.

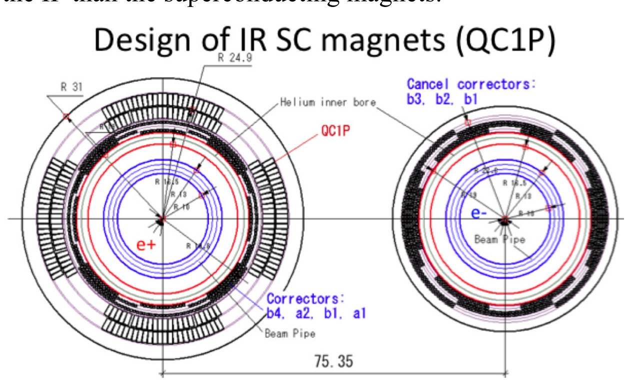

Figure 9: Design of superconducting IR quadrupole for the LER, with the leakage field cancelled by correction coils wound on the HER beam pipe.

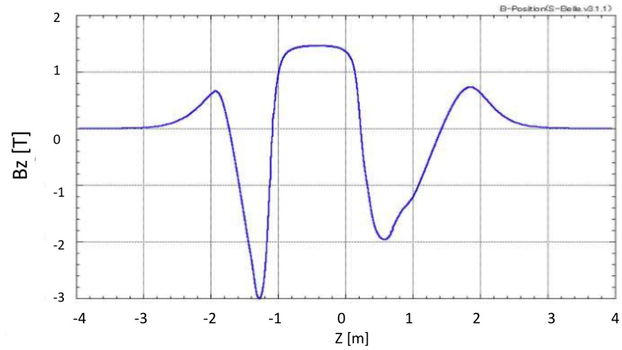

Figure 10: Solenoid field profile along the Belle-II axis.

Damping Ring

The injected beam must have very low emittance to fit within the dynamic aperture of the main rings. We have decided to construct a damping ring for positrons and a low emittance RF-gun for electrons. The damping ring employs a FODO cell with alternating dipole magnets, where one of the two dipoles in each cell is reversed [10]. The damping ring parameters are summarized in Table 1.

Table 1: Damping Ring Parameters

Energy	1.1	GeV
# of bunch trains, # of bunches/train	2, 2	
Circumference	135.50207	m
Max. Stored current	70.8	mA
Horizontal damping time	10.87	ms
Injected-beam emittance	1700	nm
Emittance at extraction	42.5 / 3.15	nm
Energy spread	0.055	%
Momentum compaction factor	0.0141	

Vacuum

Even with the nano-beam scheme, the beam currents will be doubled from KEKB, which poses a challenge to the vacuum components from higher-order mode (HOM) heating and synchrotron radiation (SR) power.

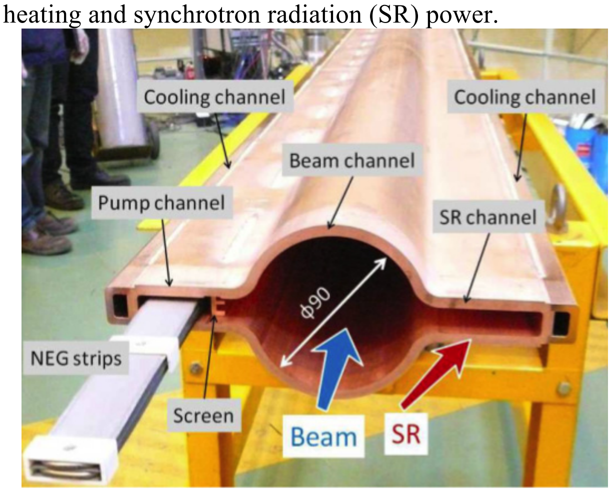

Figure 11: Antechamber for the LER arc-sections.

The vacuum ducts in both rings will be replaced with an antechamber type, shown in Fig. 11. Antechambers help to keep SR power at a manageable level in the HER. It also, in combination with TiN coating, reduces the build-up of electron clouds in the LER, as demonstrated at PEP-II. Electron cloud mitigation techniques are continually under study; clearing solenoids were shown at PEP-II and KEKB to reduce the electron cloud density in drift sections, and grooved surfaces and clearing electrodes have also been found to be effective in electron cloud suppression in dipole fields [11].

Status

A decision to change strategy from a high-current scheme to the nano-beam scheme was made. Design work is making steady progress in that direction, with much of the high-current R&D remaining applicable. The luminosity projection for SuperKEKB is shown in Fig. 12. Assuming commissioning starts in mid-2014, the integrated luminosity would reach 50 ab^{-1} in 2020-2021.

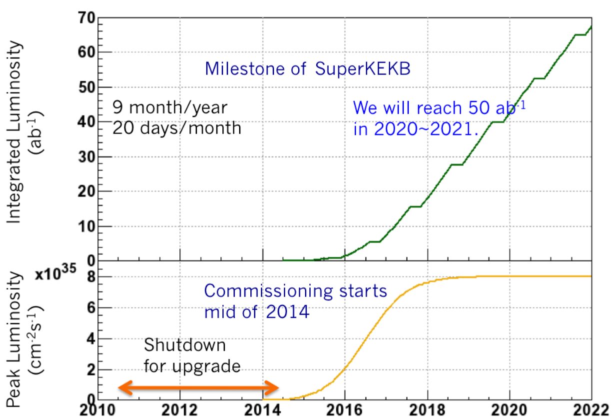

Figure 12: SuperKEKB luminosity projection.

COMPARISON AND SUMMARY

The operation of PEP-II and KEKB has provided an important base of technological experience for the designs of the Super B Factories: ampere-range beam current operations, crossing angle collisions, electron cloud mitigation techniques, and many other items. The designs of SuperB and SuperKEKB have converged somewhat from different starting points, but the projects still retain individual differences. The derivation of the two projects' design elements from the foundation of experience gained by PEP-II and KEKB is shown schematically in Fig. 13.

The basic machine parameters for SuperB and SuperKEKB are summarized in Table 2. The different circumferences are determined by site constraints. Both machines have smaller energy differences between the rings (and hence smaller boost) than PEP-II and KEKB to minimize intra-beam scattering and emittance, with further constraints in the case of SuperB arising from polarization. The use of crab-waist focusing and more aggressive emittance targets allows SuperB to run with somewhat lower beam currents.

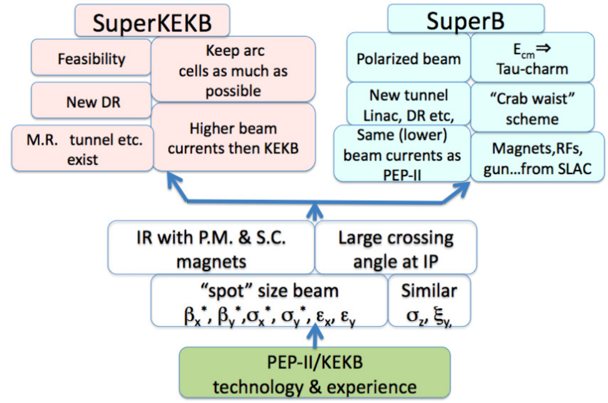

Figure 13: Main features of SuperB and SuperKEKB, and their derivation from PEP-II/KEKB experience base.

Table 2: SuperB and SuperKEKB Parameters.

		SuperB (Baseline)		SuperKEKB	
Parameter	units	HER (e+)	LER (e-)	HER (e-)	LER (e+)
Circumference	m	1258.4		3016.3	
Energy	GeV	6.7	4.18	7	4
X angle (full)	mrad	66		83	
β_x at IP	cm	2.6	3.2	2.4	3.2
β_y at IP	cm	0.0252	0.0206	0.041	0.027
ε_x	nm	2.0	2.41	2.4	3.1
Emittance ratio	%	0.25	0.25	0.35	0.40
σ_z (full)	mm	5	5	5	6
I	mA	1892	2410	2620	3600
σ_x at IP	μm	7.211	8.782	7.75	10.2
σ_y at IP	μm	0.035	0.035	0.059	0.059
ξ_x		0.0021	0.0033	0.0028	0.0028
ξ_y		0.0978	0.0978	0.0875	0.09
Luminosity	cm^{-2} s^{-1}	1x10^{36}		0.8x10^{36}	

Physics requires the next generation of B factories to achieve 40-50 times the present peak luminosity. SuperB and SuperKEKB are in advanced stages of design to meet these goals. The two machine groups are trading notes in an open manner, and both groups are making steady progress toward the success of the next-generation B-Factories.

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