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# $e^+$ $e^-$ Factory Developments

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The impressive performance of current (KEKB) and recent (PEP-II) B-Factory colliders has increased interest in developing even higher luminosity B-factories. Two new designs are being developed (SuperKEKB and SuperB). Both designs plan to deliver a luminosity in the range of $1\times10^{36}$ $cm^{-2}s^{-1}$, nearly 100 times the present B-factory level. Achieving this high luminosity requires high-current beams and short bunch lengths and/or a new way of colliding the beams. The SuperB design employs a crabbed magnetic waist with a large crossing angle and the SuperKEKB design is looking at crab cavities with high-current beams and/or a travelling focus. I describe the designs being studied to achieve the high luminosity needed for the next generation of B-Factories.

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## Introduction

In the field of accelerator-based high-energy physics there are two important machine parameters: the beam energy and the collision luminosity. Throughout the history of the field accelerators have been built that generally try to increase both of these numbers. It is important to increase the luminosity as one increases the beam energy since many interactions of interest have cross-sections that decrease (usually as $1/E_{cm}^2$) as the center-of-mass energy ($E_{cm}$) increases. Clearly, increasing the $E_{cm}$ by increasing the beam energy opens up new areas of study since the higher $E_{cm}$ can form new, heavier states of matter. There is another avenue for extending the scope of the field and that is to construct an accelerator that is optimized for maximum luminosity while colliding at a lower $E_{cm}$. Usually these accelerators operate at an $E_{cm}$ equal to a resonance mass in order to enhance the cross-section and hence increase the effective luminosity. These factories, so far, have been $e^+e^-$ colliders that have specialized in heavy quark production. These high-luminosity machines generate enormous datasets that are essentially clean of background processes which allows for the careful study of rare decay channels of the heavy flavor quarks. If the rate from a particular channel is either too low or too high when compared to the expected value from the Standard Model, new physics in the form of a new heavy-mass particle (much higher than the $E_{cm}$ of the produced event) can be the answer. Of course, cross-checks must be performed before any announcement of new physics can be made and this is achieved through predictions based on the new physics for other rare decay channels. This method of exploration can lead to measurements of decay rates that are sensitive to new physics on a much higher energy level than the $E_{cm}$ of the factory and in fact these accelerators are an important compliment to the accelerators designed or working at the energy frontier.

## Present $e^+e^-$ factories

This paper will concentrate on new developments for higher luminosity B-factories. However, we need to mention the other factories that are in operation and are being proposed. Figure 1 shows a plot of all $e^+e^-$ colliders with beam energy displayed on the horizontal axis and luminosity on the vertical axis [1]. The high luminosity factories are roughly in the upper middle part of this plot. The

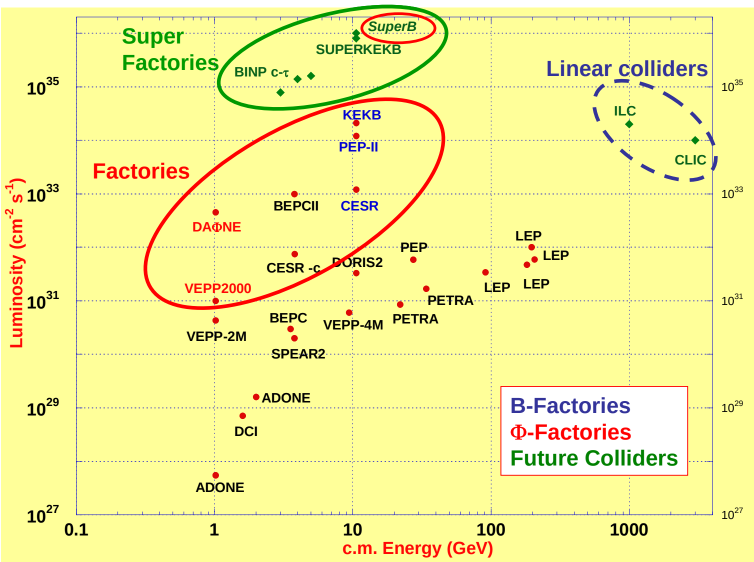


Figure 1. A plot of e+e- colliders. The present (red circle) and future (green circle) factories have the highest luminosity at more modest beam energies.

factories that are in operation are: DAFNE [2] in Frascati, Italy, running on the Φ resonance ($E_{cm}$=1 GeV), BEPCII [3] in Beijing, China, running in the Tau-charm region ($E_{cm}$ =3-4 GeV), and KEKB [4] in Tsukuba, Japan, running on the Upsilon 4S resonance ($E_{cm}$=10.6 GeV). PEP-II [5] a B-factory located at SLAC, USA also ran on the Upsilon 4S before turning off on 2007.

## Future $e^+e^-$ factories

There is a proposal for a new $e^+e^-$ factory based in BINP in Novosibirsk that would run in the Tau-charm energy range [6]. The two most recent B-factories, KEKB and PEP-II are the highest luminosity accelerators to date with KEKB holding the world record at over $2\times10^{34}$ $cm^{-2}s^{-1}$ through the use of crab cavities. PEP-II is a close second at $1.2\times10^{34}$. Both values are 10 times higher than any previous accelerator. These two accelerators together have delivered over 1.5 $ab^{-1}$ or over $2\times10^9$ B mesons to the respective detectors. These large datasets have allowed the two experimental groups to push the limits of the Standard Model farther than ever before. Both groups are still sifting through their respective datasets looking for new physics.

The success of the two B-factories has spurred an effort to design a super B-factory, one with 100 times more luminosity ($1\times10^{36}$ $cm^{-2}s^{-1}$) than present day accelerators. Two groups are presently working on super B designs. KEK has a SuperKEKB [7] design and INFN in Italy together with a group at SLAC are working on a design called SuperB [8, 9].

## The luminosity equation

Equation 1 is a typical luminosity formula for colliding beams. One can see from the equation that there are five general parameters controlling the luminosity of an accelerator. For a factory the beam energy is set by the physics and hence is not a variable for luminosity.

$$L = 2.17\times10^{34}\frac{n\xi_y E I_b}{\beta_y^*} \qquad (1)$$

n = number of beam bunches
$\xi_y$ = vertical beam-beam parameter
E = beam energy (GeV)
$I_b$ = bunch current (A)
$\beta_y^*$ = IP vertical beta (cm)

The present B-factories used a large increase in the number of beam bunches (from 10-20 bunches to well over 1000 bunches) to get the increase in luminosity they had above previous accelerators. The bunch current and other parameters were either modest or similar when compared to previous machines. Now that we have increased the number of bunches it is difficult to get any dramatic further increase in luminosity from that parameter. One way to increase the luminosity by a factor of 100 is to get factors of 2-3 from every available parameter. Increasing the bunch current, lowering the $\beta_y^*$, doubling or tripling the number of bunches and doubling the beam-beam parameter one can get a factor of 100. Another way is to change how the beams collide by making the collision with a crossing angle but not significantly shorten the beam bunches. This allows for a large increase in luminosity through a dramatic decrease in $\beta_y^*$ (a factor of 30-50). Table 1 shows the machine parameters for the different options mentioned above. The super PEP (or PEP-III) design was an initial attempt to use high-current beams and short beam bunches to make a high luminosity B-factory. We found out that high-current beams with short beam bunches generate significantly high levels of High-Order Mode (HOM) power at very high frequencies. During PEP-II running, we experienced several cases where shortening the beam bunch as little as 10% caused unexpected heating issues in vacuum components. So the high-current design was abandoned in favor of the SuperB design (see below). The KEKB design is a more modest version of the Super PEP design. However, it still has rather high total beam currents as well as quite short (~3 mm) beam bunches. The design also uses crab cavities to rotate the beam bunches into an essentially head-on collision. The inherent effect of beam bunch lengthening as a function of bunch current can be offset by introducing a travelling magnetic focus at the IP. This idea uses sextupoles placed close to the crabbing cavities to change the z position of the focal point at the IP as a function of the z position of the beam particle in the bunch.

***Table 1. Machine parameters for various Super B-factory designs***

| Parameter | Units | Super PEP | Super KEKB | SuperB |
|---|---|---|---|---|
| Luminosity | $cm^{-2}s^{-1}$ | $1\times10^{36}$ | $5\times10^{35}$ | $1\times10^{36}$ |
| Energies | GeV | 8/3.5 | 8/3.5 | 7/4 |
| Bunch I | mA | 1.5/3.3 | 0.8/1.9 | 1.6 |
| bunch num | | 6900 | 5018 | 1740 |
| Total I | A | 10/23 | 4.1/9.4 | 2.7/2.7 |
| $\beta_y^*$ | mm | 1.8 | 6/3 | 0.37/0.21 |
| $\xi_y$ | | 0.11 | 0.3/0.5 | 0.09/0.09 |
| Crossing | mrad | 15 | 30 to 0 | 60 |

## A New Beam Collision

The SuperB design on the far right of Table 1 uses the new way of colliding beams mentioned above. The beam currents, the number of bunches, and the tune shifts are all similar to present day B-factories. The main difference is the much smaller $\beta_y^*$ (~30 times smaller). In addition, by crabbing the magnetic waist at the IP one gets another factor of about three. The crabbing of the waist is done by introducing sextupoles at an exact phase from the IP to produce a z change in the focal point at the IP as a function of the x position of the beam particle.

The new collision scheme combines several ideas. The first is a large crossing angle at the Interaction Point (IP) (greater than 20 mrad). The second is to maintain longer beam bunches (~5 mm). This keeps the beam-beam parameter in the range of present machines and reduces HOM heating effects. The third is to have very low-emittance beams (very similar to present day light source storage rings). The above conditions then allow for a very small $\beta_y^*$ (~0.3 mm) which is the primary gain in luminosity. The large crossing angle with the long beam bunches generate synchro-betatron coupling which can limit the luminosity gain but by incorporating a crabbed magnetic waist at the IP the strength of the coupling resonances is greatly reduced which opens up space in the tune plane and increases the luminosity by a factor of 2-3.

The DAFNE accelerator team at Frascati redesigned their collision point and adopted as many of the above conditions as they could to test this new collision scheme. The emittance of a running accelerator is fairly well defined and generally is very difficult to change. However, the crossing angle was increased, the $\beta_y^*$ was decreased and the sextupoles used to crab the magnetic waist were installed. The predicted increase in luminosity was about a factor of three,



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a spectacular improvement for an accelerator that has been operating for over 10 years. Figure 2 shows the luminosity increase from the test. The luminosity is well over 2 times the previous best running. The Frascati team believe they will get a further luminosity increase after fixing and/or improving some "standard" problems. The figure also shows the effect of turning off the crab magnetic waist optics (the black points)[10].

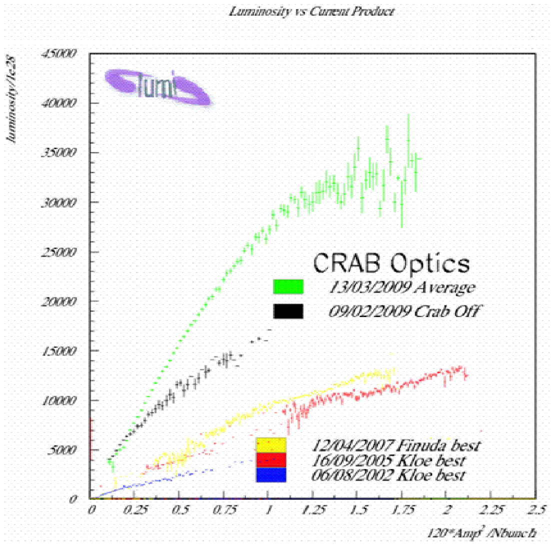


Figure 2. Plot of the luminosity of the DAFNE machine. The black plot is with the crab optics off and the green plot is with the crab optics on. Both plots show a significant increase in luminosity from the previous running cycles (yellow, blue and red)

## The SuperB Interaction Region

The Interaction Region (IR) design is one of the more complicated aspects of a Super B-factory. For the SuperB design, because of the very small $\beta^*$ values, one must get the final focusing elements as close as possible to the IP to keep the beta function maximums reasonable and thereby control the chromaticity from these elements. In addition, the beams can not share any magnetic elements. The required large crossing angle would require one or both of the beams to be considerably off-axis in any shared focusing magnetic element. This would generate a large bending of the beam trajectory together with a large amount of synchrotron radiation for the off-axis beam. In addition, any bending of outgoing beams generate unacceptably high detector backgrounds from radiative bhabhas. This background is especially high because it increases as a function of the luminosity of the accelerator. Figure 3 shows a layout of the SuperB interaction region design. The design uses two pairs of superconducting quadrupoles laid side-by-side to produce the final focus elements of the two beams. These quadrupoles are wound in such a way that the external field of the neighbouring quadrupole is cancelled. In front of the cryostat that holds these magnets is a set of permanent magnet slices that produce a quadrupole field for the Low-Energy Beam (LEB) which has a lower $\beta_y^*$ than the High-Energy Beam (HEB) [11,12].

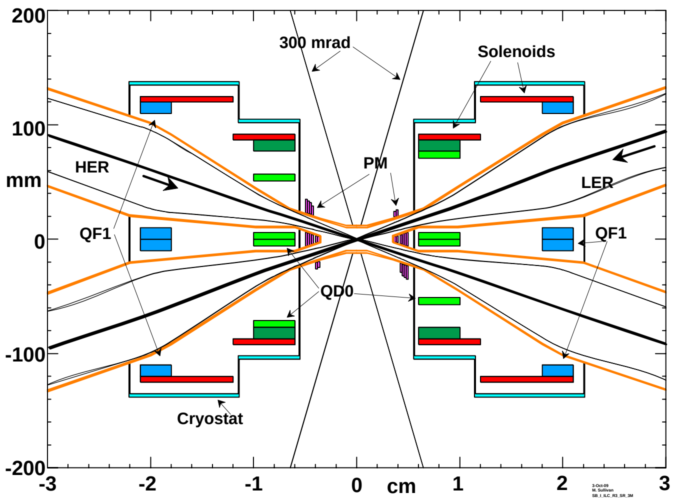


Figure 3. Layout of the SuperB interaction region. Please note the exaggerated vertical scale.

The cryostat design calls for a warm bore as there are many watts of synchrotron radiation (SR) power striking the inside walls of the cryostats from the last upstream bending magnets.

The central beam pipe is composed of a thin layer (~1 mm) of Be with a 4 um coating of Au on the inside surface to block scattered SR photons from penetrating the pipe and striking the detector. The design acceptance of the detector goes down to two cones with an angle of 300 mrad with respect to the center axis of the beams and detector.

The final focus accelerator magnetic elements are entirely contained inside the detector magnetic field. These magnets must be shielded from the detector field and we use compensating super-conducting solenoids to cancel the total integrated detector magnetic field. We do this by cancelling the field at the two sets of quadrupole pairs and then overcompensating the detector field between the quadrupole pairs in order to cancel the integral of the center field between the cryostats that is not directly cancelled.

The high luminosity of the SuperB design actually sets the lifetime of the beams to about 10 minutes. The overall lifetime due to Touschek scattering, Inter-Beam Scattering, and beam-gas scattering and the luminosity bring the beam lifetime down to about 5 minutes. With this small lifetime it is actually possible to inject polarized electrons and they will stay polarized as long as the depolarization lifetime is long compared to the beam lifetime. If the beam energy is away from depolarizing resonances the superB design can produce a polarized electron beam by this technique through the use of a polarized electron gun. Spin rotators are used to convert the transversely polarized beam to a longitudinally polarized beam at the IP.

## Summary

The success of the present day B-factories has raised interest in developing much higher luminosity B-Factories with a luminosity of about $1\times10^{36}$ $cm^{-2}s^{-1}$. Two majors design efforts are ongoing; one in Japan called SuperKEKB and another in Italy called SuperB. The SuperKEKB design, until recently, was concentrating on a scheme to increase the beam currents, lower the $\beta_y^*$, increase the beam-beam tune shifts and shorten the beam bunch in order to achieve the large increase in luminosity. The Italian design employs a novel way of colliding the beams that needs very low emittance beams and a very small $\beta_y^*$ value. The added effect of crabbing the magnetic waist reduces the synchro-betatron coupling resonances resulting in a gain in beam stability as well as an increase in luminosity. This approach does not require beam currents any higher than that of present machines and the tune shifts, though high, are near the range of present machines. Just recently the KEK design has shifted focus and is looking at ways to incorporate the Italian collision scheme into their design.

## Conclusions

A high luminosity B-Factory (or Factories) is a strong compliment to the energy frontier machines. In fact, the mass reach for new physics through the study of very rare decays from these super B-factories can be as high as 20 TeV for certain models [13]. Super B-factories as well as other high luminosity factories (DAFNE and BEPCII) can and will be able to search extensively for dark matter candidates.

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