NEW DEVELOPMENTS IN SUPER B-FACTORIES

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Abstract

A Super Flavor Factory, an asymmetric energy e^+e^- collider with a luminosity of order 10^{36} cm^{-2}s^{-1}, can provide a sensitive probe of new physics in the flavor sector of the Standard Model. The success of the PEP-II and KEKB asymmetric colliders [1,2] in producing luminosity above 10^{34} cm^{-2}s^{-1} has taught us about the accelerator physics of asymmetric e^+e^- colliders in a new parameter regime. Furthermore, the success of the SLAC Linear Collider and FFTB [3], and the subsequent work on the ILC [4] allow a new Super-Flavor collider to also incorporate linear collider techniques. This paper describes the parameters of an asymmetric Flavor-Factory collider at a luminosity of order 10^{36} cm^{-2}s^{-1}at the Υ(4S) resonance and 10^{35} cm^{-2}s^{-1} at the τ production threshold. Such a collider would produce an integrated luminosity of about 14,000 fb^{-1} (14 ab^{-1}) in a running year (10^7 sec) at the Υ(4S) resonance. In the following only the parameters relative to the Υ(4S) resonance will be shown, the ones relative to the lower energy operations are still under study.

INTRODUCTION

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 (~95%).

The present B-Factories have proven that their design concepts are valid:

1) Colliders with asymmetric energies work well
2) BeamBeam energy transparency conditions are weak
3) Interaction regions with two energies can work
4) IR backgrounds can be handled successfully
5) High current RF systems can be operated (3x1.8 A)
6) Beam-beam parameters reach 0.06 up to 0.09
7) Continuous injection is done in production
8) The electron cloud effect (ECI) can be managed
9) Bunch-by-bunch feedbacks at the 4nsec spacing work well.

Lessons learned from SLC and subsequent linear collider studies (for ILC) and experiments (FFTB, ATF, ATF2) have also shown new successful concepts:

1) Small horizontal and vertical emittances can be produced in a damping ring with a short damping time
2) Very small beam spot sizes and beta functions can be achieved at the interaction region

All of the above techniques can be incorporated in the design of a future Super-Flavor Factory (SuperB) collider.

THE CRAB WAIST COLLISION SCHEME

The design is based on a new collision scheme, that we call a “crab waist”. This new scheme will allow SuperB to reach a luminosity of the order of 10^{36} cm^{-2}s^{-1} by overcoming some of the issues that have plagued earlier super e+e. collider designs, such as very high beam currents and very short bunches. In this section we will review the crab waist concept and address key issues related to high luminosity colliders, such as luminosity with a crossing angle, beam lifetime and injection, backgrounds, beam emittances and stability, polarization, power and costs.

In high luminosity colliders, one of the key requirements is very short bunches, since this allows a decreased β_y at the IP, thereby increasing the luminosity. However, β_y cannot be made much smaller than the bunch length without incurring an “hourglass” effect. Moreover, high luminosity requires small vertical emittance, together with large horizontal beam size and horizontal emittance, to minimize the beam-beam effect. It is, unfortunately, very difficult to shorten the bunch length σ_z in a ring.

This problem can be overcome with the recently proposed crab waist scheme [5] for beam-beam collisions, which can substantially increase luminosity without having to decrease the bunch length, since it combines several potentially advantageous ideas.

The first idea is the use of a large Piwinski angle: for collisions at a crossing angle θ, the luminosity L, the horizontal ξ_x and the vertical ξ_y tune shifts scale according to [6]:

$$\mathcal{L} = \frac{\gamma^+ \xi_y N^+ f_c}{2\, r_e\, \beta_y}\left(1+\frac{\sigma_y}{\sigma_x}\right) \propto \frac{N^+\,\xi_y}{\beta_y}$$

$$\xi_y = \frac{r_e N^-}{2\pi\gamma^+}\frac{\beta_y}{\sigma_y\left(\sigma_x\sqrt{1+\varphi^2}+\sigma_y\right)} \propto \frac{N^-\sqrt{\beta_y}}{\sigma_y\sigma_z\theta}$$

$$\xi_x = \frac{r_e N^-}{2\pi\gamma^+}\frac{\beta_x}{\sigma_x^2\left[(1+\varphi^2)+\frac{\sigma_y}{\sigma_x}\sqrt{1+\varphi^2}\right]} \propto \frac{N^-\beta_x}{(\sigma_z\theta)^2}$$

The idea of colliding with a large Piwinski angle is not new (see for example [7]). It has been also proposed for the LHC upgrade [8], to increase the bunch length and the crossing angle. In such a case, if it were possible to increase N in proportion to $\sigma_x\theta$, the vertical tune shift ξ_y would indeed remain constant, while the luminosity would grow proportional to $\sigma_z\theta$. Moreover, the horizontal tune shift ξ_x drops like $1/(\sigma_z\theta)^2$ so that for very large Piwinsky angle the beam-beam interaction can be considered, in some sense, one-dimensional, since the horizontal footprint in the tune plane shrinks. However, as distinct from [8], in the crab waist scheme described here, the Piwinski angle is increased by decreasing the horizontal beam size and increasing the crossing angle. In this way, the luminosity is increased, and the horizontal tune shift due to the crossing angle decreases. The most important effect is that the overlap area of colliding bunches is reduced, as it is proportional to σ_x/θ. Thus, if the vertical β-function β_y can be made comparable to the overlap area size:

$$\beta_y \sim \sigma_x, \quad \theta \ll \sigma_z,$$

Several advantages are gained:

- small spot size at the IP, i.e., higher luminosity
- reduction of the vertical tune shift
- suppression of vertical synchrobetatron resonances [9]

There are additional advantages in such a collision scheme: there is no need to decrease the bunch length to increase the luminosity, as proposed in standard upgrade plans for B and Φ-Factories [10–12]. This will certainly ease the problems of HOM heating, coherent synchrotron radiation of short bunches, excessive power consumption, etc... Moreover the problem of parasitic collisions (PC) is automatically solved by the higher crossing angle and smaller horizontal beam size, which makes the beam separation at the PC large in terms of σ_x.

However, a large Piwinski angle itself introduces new beam-beam resonances and may strongly limit the maximum achievable tune shifts (see for example [13]). This is where the crab waist innovation is required. The crab waist transformation boosts the luminosity, mainly by suppression of betatron (and synchro-betatron) resonances that usually arise (in collisions without the crab waist) through vertical motion modulation by horizontal beam oscillations [14]. A sketch of the crab waist scheme is shown in Fig.1.

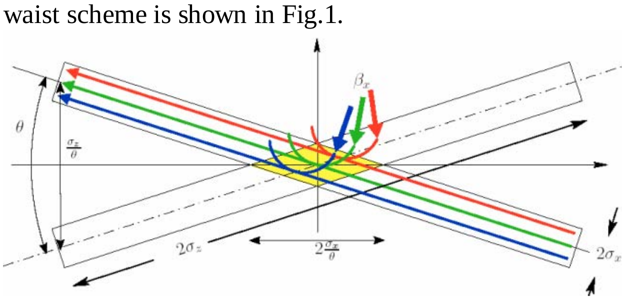

Figure 1 Large Piwinsky angle and crab waist scheme. The collision area is shown in yellow

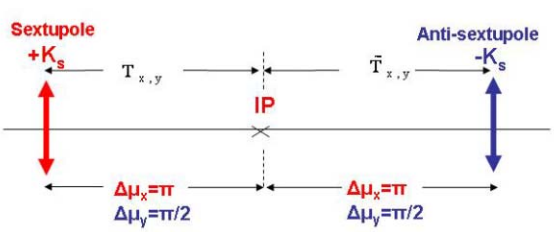

Figure 2 Crab waist correction by sextupole lenses

The crab waist correction scheme can easily be realized in practice with two sextupoles magnets in phase with the IP in the x plane and at π/2 in the y plane, on both sides of the IP, as shown in Fig. 2.

LUMINOSITY

For very flat beams, luminosity can be written as:

$$L = \frac{\gamma}{2er_e}\frac{I\xi_y}{\beta_y}$$

where I is the beam current, γ is the Lorentz factor, ξ_y the vertical tune shift, β_y is the vertical beta at the Interaction Point.

2. Synchrotron radiation power: Power dissipation is related to the beam current I and to the energy loss per turn U_o via:

$$P = I\, U_o.$$

All colliders aim to maximize L while keeping P as small as possible. The SuperB design is based on a "large Piwinski angle" and crab waist scheme as described above. This allows us to lower β_y to 0.2mm and increase ξ_y to 0.2. These values should be compared with the present KEKB parameters of β_y = 6 mm and ξ_y = 0.06. The SuperB parameters result in a luminosity about two orders of magnitude larger than that achieved at KEKB, with beam currents and power consumption essentially unchanged.

3. Detector backgrounds: Maintaining beam power as low as possible is important to minimize backgrounds, which scale with the beam currents. The interaction region (IR) design also plays a fundamental role. The combination of large crossing angle and small beam sizes, emittances and beam angular divergences at the IP in the SuperB design is very effective in further decreasing the absolute background levels with respect to the current B Factories. These same factors also relax design requirements for the IR. Luminosity-related backgrounds must, of course, be taken into account, and can impose serious shielding requirements.

4. Beam lifetime: In the current e^+e^- factories, beam lifetime is determined mainly by ring characteristics such as vacuum quality, dynamic aperture, etc. In SuperB, beam lifetime is instead almost entirely dominated by the luminosity itself: radiative Bhabhas limit the lifetime to a few minutes for both rings. All other contributions are much smaller, except for the Touschek lifetime of the low energy beam, which causes a worsening by about a factor 1.3. Given the short beam lifetime, the injection system must be able to provide particles at a rate about 10 times larger than those for the present factories.

5. Beam emittance: The horizontal emittance ε_x is determined mainly by the ring lattice optics; the vertical emittance ε_y is dominated by ring imperfections, which must be tightly controlled to reach the design value. The current factories, and most of the other e^+e^- colliders, have achieved vertical/horizontal emittance ratios similar to the SuperB design. However, the absolute values for SuperB are much smaller; they are similar to those at the test damping ring for the ILC project, the ATF [15]. Thus, tolerances, stability levels and tuning constraints are also

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tighter than those for the current factories. Instead, they are very similar to those for the ATF and the design values for the ILC Damping Rings, which will produce beams very similar to those of SuperB.

6. Polarization: SuperB can provide collisions with longitudinally polarized electrons by using a polarized electron gun and spin rotators in the ring. Polarized positrons could be provided as well, but further study is required to evaluate whether the additional physics benefit outweighs the added complexity.

A vigorous R&D program is being pursued by the ILC community to provide a polarized positron source. Production rates required by SuperB are 100 times less demanding than those for the ILC, so such a source could be feasible by the time SuperB is funded.

7. Cost: In the conventional Super B Factory designs, the cost is dominated by the requirements for dealing with higher currents and shorter bunches: for example, substantial additions to the RF system, engineering design for larger HOM power due to shorter bunches, and the cooling and vacuum challenges posed by larger synchrotron radiation power. Most of these problems do not exist in the SuperB design; the absolute cost of SuperB is therefore very similar to the present machines. In addition, the SuperB design allows the reuse of a great deal of PEP-II hardware, resulting in substantial savings for the project, even at a new site.

SUPERB PARAMETERS

The IP and ring parameters have been optimized based on several constraints. The most significant are:

- maintaining wall plug power, beam currents, bunch lengths, and RF requirements comparable to present B-Factories;
- planning for the reuse as much as possible of the PEP-II hardware;
- requiring ring parameters as close as possible to those already achieved in the B-Factories, or under study for the ILC Damping Ring or achieved at the ATF ILC-DR test facility [15];
- simplifying the IR design as much as possible. In particular, reduce the synchrotron radiation in the IR, reduce the HOM power and increase the beam stay-clear. In addition, eliminate the effects of the parasitic beam crossings;
- relaxing as much as possible the requirements on the beam demagnification at the IP;
- designing the Final Focus system to follow as closely as possible already tested systems, and integrating the system as much as possible into the ring design.

Columns 1,2 of Table 1 show a parameter set that closely matches these criteria.

Many of the nominal SuperB design parameters could, in principle, be pushed further to increase performance. This provides an excellent upgrade path after experience is gained with the nominal design. The upgrade parameters are based on the following assumptions:

- beam currents could be raised to the levels that PEP-II should deliver in 2008;
- vertical emittance at high current could be reduced to the ATF values;
- the lattice supports a further reduction in β_x and β_y;
- beam-beam effects are still far from saturating the luminosity.

In principle, the design supports these improvements, so a luminosity higher than nominal may well be feasible. In addition, it should be pointed out that, since the nominal design parameters are not pushed to maximum values, there is flexibility in obtaining the design luminosity by relaxing certain parameters, if they prove more difficult to achieve, and pushing others. Columns 3,4 and 5,6 of Table 1 show two potential upgrade paths.

Table 1. SuperB Parameters list

PARAMETER	LER	HER	LER	HER	LER	HER
Particle type	e+	e-	e+	e-	e+	e-
Energy (GeV)	4	7	4	7	4	7
Luminosity x 10^{36}	1,0		2,4		3,4	
Circumference (m)	2250	2250	2250	2250	2250	2250
Revolution frequency (MHz)	0,13	0,13	0,13	0,13	0,13	0,13
Eff. long. polarization (%)	0	80	0	80	0	80
RF frequency (MHz)	476	476	476	476	476	476
Harmonic number	3570	3570	3570	3570	3570	3570
Momentum spread	8,4E-04	9,0E-04	1,0E-03	1,0E-03	1,0E-03	1,0E-03
Momentum compaction	1,8E-04	3,0E-04	1,8E-04	3,0E-04	1,8E-04	3,0E-04
Rf Voltage (MV)	6	18	6	18	7,5	18
Energy loss/turn (MeV)	1,9	3,3	2,3	4,1	2,3	4,1
Number of bunches	1733	1733	3466	3466	3466	3466
Particles per bunch x10^{10}	6,16	3,52	5,34	2,94	6,16	3,52
Beam current (A)	2,28	1,30	3,95	2,17	4,55	2,60
Beta y* (mm)	0,30	0,30	0,20	0,20	0,20	0,20
Beta x* (mm)	20	20	20	20	20	20
Emit y (pmr)	4	4	2	2	2	2
Emit x (nmr)	1,6	1,6	0,8	0,8	0,8	0,8
Sigma y* (microns)	0,035	0,035	0,020	0,020	0,020	0,020
Sigma x* (microns)	5,657	5,657	4,000	4,000	4,000	4,000
Bunch length (mm)	6	6	6	6	6	6
Full Crossing angle (mrad)	34	34	34	34	34	34
Wigglers (#)	4	2	4	4	4	4
Damping time trans/long(ms	32/16	32/16	25/12.5	25/12.5	25/12.5	25/12.5
Luminosity lifetime (min)	10,4	5,9	7,4	4,1	6,1	3,5
Touschek lifetime (min)	5,5	38	2,9	19	2,3	15
Effective beam lifetime (min)	3,6	5,1	2,1	3,4	1,7	2,8
Injection rate pps (100%)	4,9E+11	2,0E+11	1,5E+12	5,0E+11	2,1E+12	7,2E+11
Tune shift y (from formula)	.17	.17	0.16	0.16	0.02	0.02
Tune shift x (from formula)	0.004	0.004	0.007	0.007	0.009	0.009
RF Power (MW)	17		35		44	

RING AND INTERACTION REGION LATTICE

A detailed description of the lattice is presented in [16].

The Main ring lattice is composed by 6 arcs and two insertions, one for the Final Focus, and one for the Injection and tunes trombone etc. The straight sections in between the arcs are also suitable for installing 10m long wigglers. The basic arc cell, with a phase advance μ_x=0.5, μ_y=0.2, provides a much smaller emittance with respect to the TME cell adopted for the ILC damping ring, allowing a very compact ring, despite the need of very small emittances. The ring optical functions are shown in Figure 3.

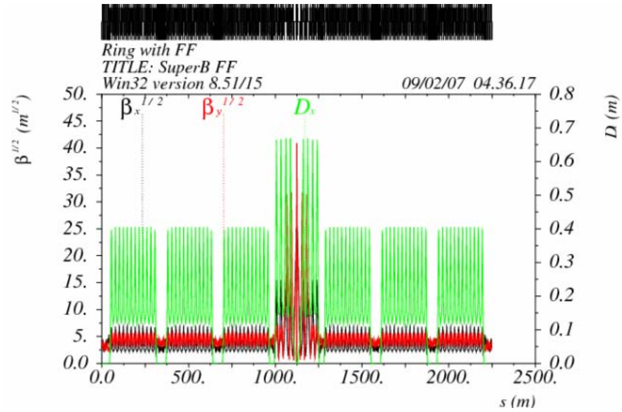

Figure 3 SuperB Optical Functions

The Interaction Region is being designed to leave about the same longitudinal free space as that presently used by *BABAR* but with superconducting quadrupole doublets as close to the IR as possible [17].

Recent work at Brookhaven National Laboratory on precision conductor placement of superconductors in large-bore low-field magnets has led to quadrupoles in successful use in the interaction regions for the HERA collider in Germany [18]. A minor redesign of these magnets will work well for the SuperB.

A design of the Final Focus, similar to the NLC/ILC ones, has been performed for the IP parameters in Table 1. The total FF length is about 2*150 m and the final doublet is at 0.3 m from the IP. The Final Focus is inserted in one of the straight sections of the ring. It also has to be noted that the Final Focus produce a net bend angle of about 43 degrees, roughly 2/3 of the one produced by one of the 6 ring arcs. The optical functions in the incoming half of the FF region are shown in Fig. 4.

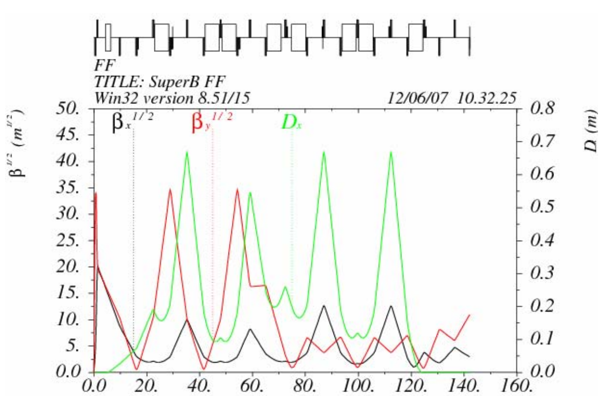

Figure 4 Optical functions in half Final Focus region.

The need for a finite crossing angle at the IP greatly simplifies the IR design, since the two beams are now naturally separated at the parasitic collisions. An expanded view of a preliminary IR layout is shown in Fig. 5. The LER radiative Bhabhas trajectories for several energies are also shown.

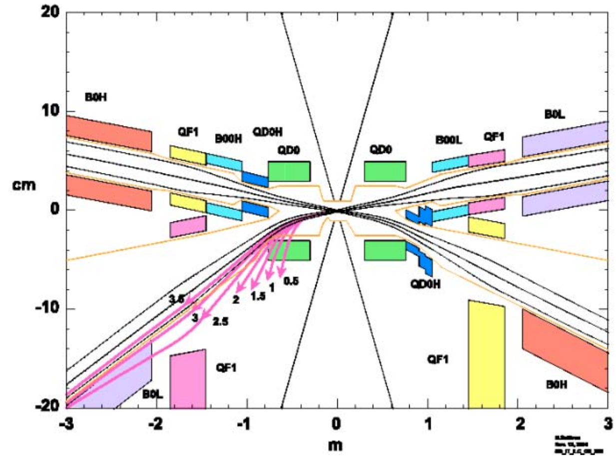

Figure 5 Plan view of a possible IR layout.

INJECTOR CONCEPT AND PARAMETERS

The injector for the Super Flavor Collider will make up for lost particles with the finite beam lifetime in the damping rings and the losses from collisions. The injector will be similar to the SLAC injector delivering about 10^{10} electrons or positrons per pulse at about 50 Hz each. The present scheme requires a 7GeV Linac to accelerate the electrons up to the nominal HER energy. A positron converter will be installed in the Linac at about 3GeV. The remaining 4GeV Linac will accelerate the positron up to the nominal LER energy. If the positron emittance results too large to allow an efficient continuous injection, a 1GeV damping ring will be necessary as well.

POWER REQUIREMENTS

The power required by a collider is the sum of a site base and the accelerator operation. The damping ring power (about 12 to 30 MW) to replace the synchrotron radiation loss will be the dominant factor in this Super-F Factory. About 6MW are needed to power up the rings magnets and 5MW for the injection system. Overall power consumption will range between 25MW up to 50MW for the ultimate parameters. Better estimates and optimizations are under study.

SYNERGY WITH ILC

There are significant similarities between the SuperB storage rings and the ILC damping rings [19]. Beam energies and beam sizes are similar. The ILC damping rings have a circumference three times larger than the SuperB rings (because of the need to store a long train of bunches with bunch spacing sufficiently large to allow injection and extraction of individual bunches); the nominal bunch charge is smaller in the ILC damping rings than in the SuperB storage rings, leading to a lower average current. Nevertheless, one may expect the overall beam dynamics in the two facilities to be in comparable regimes. A similar lattice design is used in both cases, the main difference being a reduction in circumference and

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the insertion of an interaction region in the case of SuperB.

The ILC damping rings and the SuperB storage rings will face similar demands on beam quality and stability: the SuperB rings for direct production of luminosity, and the ILC damping rings for reliable tuning and operation of the downstream systems, to ensure efficient luminosity production from the extracted beams.

The interaction regions have very similar characteristics with flat beams and overall geometries. The ratio of IP beta functions are similar (10-30 mm horizontally and 0.1-0.5 mm vertically). The collimation schemes are comparable. The chromatic correction of the final doublets using sextupoles is very similar and almost identical to the one tested in the FFTB experiment.

Other significant issues common to both the SuperB rings and the ILC damping rings include:

- alignment of the magnets, including orbit and coupling corrections, with the precision needed to produce vertical emittances of a few pm on a routine basis;
- reduction of magnet vibration to a minimum, to ensure beam orbit stability at the level of a few microns;
- optimization of lattice design and tuning to ensure sufficient dynamic aperture for good injection efficiency (for both SuperB and the ILC damping rings) and lifetime (particularly for the SuperB LER);
- bunch-by-bunch feedbacks to keep the beam instabilities and beam-beam collisions under control;
- control of beam instabilities, including electron cloud and ion effects.

These are all active areas of research and development for the ILC damping rings. In general, the similarity of the proposed operating regimes for the ILC damping rings and the SuperB storage rings presents an opportunity for a well-coordinated program of activities that could yield much greater benefits than would be achieved by separate, independent research and development programs.

DESIGN PROGRESS

The parameter optimization is continuously going on and we hope to further reduce the criticality of several machine constraints. In addition more careful studies are needed to make sure that the current constraints are valid.

The present scheme seems very promising but, given the rapid evolution of the concepts, it might still have some weak points that can jeopardize it. In addition new ideas and breakthroughs could also further change and improve the design.

It has also to be pointed out that with the present scheme the SuperB luminosity performance is a weak function with respect to the total length of the ring. The present length (about 2.2 Km) provides the best performances so far, but if there are strong constrains in terms of space and costs, it could be reduced together with a re-optimization of the other parameters.

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