

THE *SUPERB* ACCELERATOR: OVERVIEW AND LATTICE STUDIES

M.E. Biagini, INFN-Laboratori Nazionali di Frascati, Frascati, Italy
on behalf of the *SuperB* Accelerator Team*

Abstract

SuperB [1] aims at the construction of a very high luminosity ($10^{36} \text{ cm}^{-2} \text{ s}^{-1}$) asymmetric e^+e^- Flavour Factory, with possible location at the campus of the University of Rome Tor Vergata, near the INFN Frascati National Laboratory. In this paper the basic principles of the design and details on the lattice are given.

INTRODUCTION

Attempts to design a Super B-Factory date to 2001. The initial approach at SLAC and KEK had much in common: they were extrapolations of the very successful B-Factory designs, with increased bunch charge, more bunches, and crab cavities to correct for the crossing angle at the Interaction Point (IP). These proposed designs reached luminosities of 5 to $7 \times 10^{35} \text{ cm}^{-2} \text{ s}^{-1}$ but had wall plug power of the order of 100 MW. This daunting power consumption was a motivation to adapt linear collider concepts from SLC and ILC to the regime of high luminosity storage ring colliders. Among the possible schemes were a two arcs SLC-like layout and a 2 Linacs (ILC-like) layout.

The implementation of a new colliding scheme [2] with the combination of “large Piwinski angle”, low β_y^* , ultra low emittances and “*crab waist*” transformation opened new possibilities with the return to the usual two rings layout. This allowed for the design of a *SuperB* Factory with a target luminosity two orders of magnitude higher than presently achieved, 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 the most recent *SuperB* design an electron beam (7 GeV, HER) and a positron beam (4 GeV, LER) are stored in two low-emittance damping rings similar to those designed for an International Linear Collider (ILC) or the next generation light source. An ILC style Interaction Region (IR) is included in the rings to produce sub-millimeter vertical beta functions at the collision point. A large crossing angle (± 24 mrad) is used at the IP to allow better beam separation. A “*crab waist*” scheme is used to reduce the hourglass effect and restore peak luminosity. Beam currents of the order of 1.9 A can produce a luminosity of $10^{36}/\text{cm}^2/\text{s}$ with upgrade

*M.E. Biagini, M. Boscolo, R. Boni, A. Drago, S. Guiducci, M. Preger, P. Raimondi, S. Tomassini, C. Vaccarezza, M. Zobov (INFN/LNF, Italy), Y. Cai, A. Fisher, S. Heifets, A. Novokhatski, M.T. Pivi, J. Seeman, M. Sullivan, U. Wienands (SLAC, US), K. Ohmi, Y. Ohnishi (KEK, Japan), I. Koop, S. Nikitin, E. Levichev, P. Piminov, D. Shatilov (BINP, Russia), A. Wolski (Liverpool University, UK), M. Venturini (LBNL, US), S. Bettoni (CERN, Switzerland), E. Paoloni, G. Marchiori (Pisa University, Italy), A. Variola (LAL/Orsay, France)

possibilities. Such a collider would produce an integrated luminosity of about $10,000 \text{ fb}^{-1}$ (10 ab^{-1}) in a running year (10^7 sec) at the Y(4S) resonance. A longitudinally polarized electron beam in the HER, with injection of a transversely polarized electron beam and a spin rotator section, will allow for producing polarized τ leptons, opening an entirely new realm of exploration in lepton flavour physics.

A Conceptual Design Report (CDR) [3] was issued in May 2007, with about 200 pages dedicated to the accelerator design. This report discusses site requirements, “*crab waist*” compensation, parameters optimization in order to save power, IP quadrupole design, Touschek backgrounds, spin rotator scheme, and project costs. As many as 320 scientists from 85 Institutions, spread in 15 countries, have signed the CDR. The contribution to the accelerator design, about 200 pages, came from machine experts from LNF (Italy), SLAC (US), KEKB (Japan), BINP (Russia), BLNL (US) and Cockcroft (UK).

In order to evaluate the proposal, an International Review Committee (IRC) has been established in 2007, chaired by J. Dainton (Daresbury, UK). In November 2007 and April 2008 two IRC meetings were organized for the presentation of the various aspects of the proposal. The final report is due on May 2008. A presentation to the CERN Strategy Group before any formal approval and funding model definition is foreseen for fall 2008, a Technical Design Report (TDR) will be then issued on the time scale of 1.5 years.

A possible location of *SuperB* at Tor Vergata University near Rome, - in synergy with the FEL SPARX project to be built on the same grounds, - is shown in Figure 1.

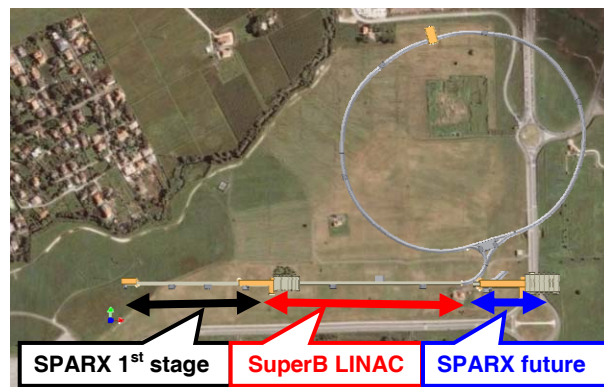


Figure 1: Possible *SuperB* location at Tor Vergata University with a ring circumference of 1800 m and an injector located adjacent to the future SPARX FEL.

BASIC CONCEPTS

B-Factories (PEP-II and KEKB) reached very high luminosity ($>10^{34} \text{ s}^{-1} \text{ cm}^{-2}$), but to increase luminosity of about two orders of magnitude borderline parameters are needed, such as:

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

However this may result in a difficult and costly operation. On the contrary *SuperB* exploits an alternative approach, with a new IP scheme:

- small beams (ILC-DR like);
- large Piwinsky angle and “*crab waist*” transformation;
- currents comparable to present Factories.

New collision scheme

The novel collision scheme uses frozen variables in parameter space to ascend to a new luminosity scale, by effectively exchanging the roles of the longitudinal and transverse dimensions. The design is based on collision with a “large Piwinsky angle” and small beam sizes, plus the so-called “*crab waist*” transformation. In the new scheme, the Piwinsky angle ϕ :

$$\phi = \frac{\sigma_z}{\sigma_x} \tan \frac{\theta}{2} \approx \frac{\sigma_z}{\sigma_x} \frac{\theta}{2}$$

(σ_x being the horizontal rms bunch size, σ_z the rms bunch length and θ the horizontal crossing 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 β_y^* can be made comparable to the overlap area size, several advantages are gained, as small spot size at the IP, i.e. higher luminosity, a reduction of the vertical tune shift, and suppression of vertical synchro-betatron resonances. 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 larger in terms of σ_x .

However, a large Piwinsky angle itself introduces new beam-beam resonances and may strongly limit the maximum achievable tune shifts. This is where the “*crab waist*” innovation is required, boosting the luminosity mainly by suppression of betatron and synchro-betatron resonances, through vertical motion modulation by horizontal beam oscillations. “*Crab waist*” sextupoles near the IR introduce a left-right longitudinal waist position variation in each beam allowing a vertical beta function which is much smaller than the bunch lengths. The “*crab waist*” transformation can easily be realized

with two sextupole magnets on both sides of the IP, in phase with the IP in the x plane and at $\pi/2$ in the y plane.

This scheme is being firstly tested at the upgraded DAΦNE Φ-Factory in Frascati, with very encouraging results so far [4]. The details on the scheme features and principles can be found in [5]. Figure 2 shows the left-right *crab waist* compensation at the IP. Figure 3 shows the beam cross sections at the IP with unequal emittances but equal beam-beam tune shifts without and with the crab sextupole transformation.

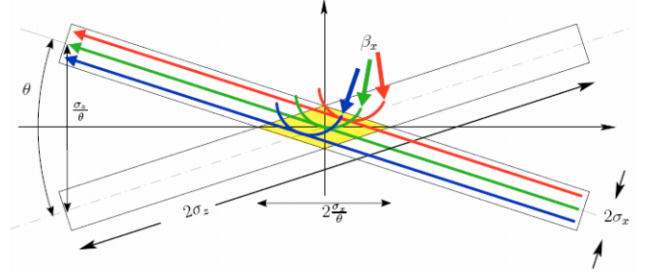


Figure 2: Interaction region showing two beams crossing at a large angle with the *crab waist* to improve the beam-beam interaction.

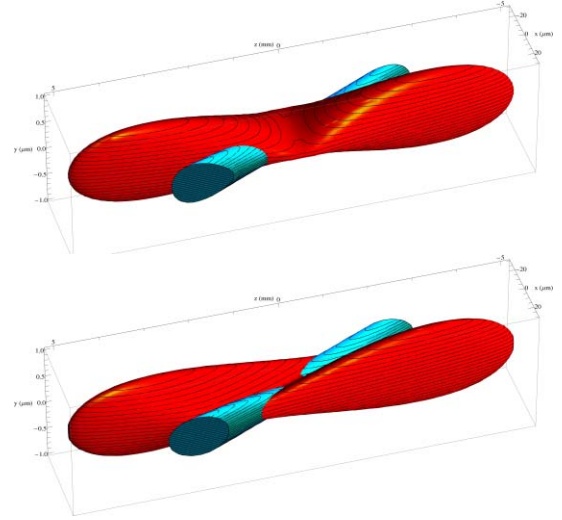


Figure 3: Beam distributions at IP. Top: *crab waist* sextupoles OFF, bottom: crab sextupoles ON.

TRANSPARENCY CONDITIONS

In order to have equal tune shifts for the two beams, asymmetric B-Factories operate at unbalanced beam currents, with a current ratio inverse to the energy ratio. For *SuperB*, with an energy ratio of 4/7 and a large crossing angle, new conditions for having equal tune shifts are possible. LER (+) and HER (-) beams can have different emittances and β^* but equal currents:

$$\xi^+ = \xi^- \Leftrightarrow \frac{\beta_y^+}{\beta_y^-} = \frac{E^+}{E^-} \quad (1)$$

Then, in order to have equal vertical beam sizes at IP, the LER and HER vertical and horizontal emittances must be:

$$\epsilon_y^+ = \frac{E^-}{E^+} \epsilon_y^-, \quad \epsilon_x^+ = \frac{E^-}{E^+} \epsilon_x^- \quad (2)$$

with the horizontal beam sizes in the inverse ratio with the beam energies. Thus, the LER beam sees a shorter interaction region, in a ratio 4/7, with respect to the HER beam. This allows for further β_y^* reduction, a larger emittance, increased the Touschek lifetime, and reduced injection rates. Table 1 summarizes *SuperB* beam parameters for the three operational scenarios, nominal, upgrade and ultimate with increasing peak luminosity.

Table 1: *SuperB* main parameters

Parameter (LER/HER)	Nominal	Upgrade	Ultimate
Energy (GeV)	4/7	4/7	4/7
Luminosity (cm ⁻² s ⁻¹)	1x10 ³⁶	2x10 ³⁶	4x10 ³⁶
C (m)	1800	1800	1800
N. of bunches	1251	1251	2502
F _{RF} (MHz)	476	476	476
N. part/bunch	5.5x10 ¹⁰	5.5x10 ¹⁰	6.8x10 ¹⁰
I _{beam} (A)	1.85/1.85	1.85/1.85	3.7/3.7
β_x^* (mm)	35/20	35/20	35/20
β_y^* (mm)	0.22/0.39	0.16/0.27	0.16/0.27
ϵ_x^* (nm rad)	2.8/1.6	1.4/0.8	1.4/0.8
ϵ_y^* (pm rad)	7/4	3.5/2	3.5/2
σ_x^* (μm)	10/5.7	7/4	7/4
σ_y^* (μm)	0.039	0.023	0.023
σ_z (mm)	5./4.3	5./4.3	5./4.3
θ_{cross} (mr)	48	48	48
α_c (x10 ⁻⁴)	3.2/3.8	3.2/3.8	3.2/3.8
$\tau_{x,y}/\tau_s$ (ms)	40/20	28/14	28/14
x-tune shift	0.004/0.003	0.006/0.003	0.006/0.003
y-tune shift	0.15	0.20	0.20
RF power (MW)	17	24	50

SUPER-B FACTORY LAYOUT

The two rings each have four arcs and two long straight sections. One straight is for the IR, the other is for diagnostics, RF and injection. The two rings will be crossing in only one IR at a horizontal angle of about 50 mrad and will have ultra low-emittances, similar to those of the ILC Damping Rings [6]. Beam currents will be lower than 2 A per beam, a number close to the achieved currents in the present e⁺e⁻ Factories. The Final Focus

(FF) section design is similar to that designed for FFTB/ILC.

RINGS LATTICE

The lattice design is based on the reuse of all PEP-II magnetic elements, vacuum system and RF system (for a total RF power of 17 MW, lower than the PEP-II one). The overall length, including the spin rotator sections, will be about 1.8 Km.

After the CDR completion, the work on the lattice design has continued in order to decrease power consumption and costs, optimize the “*crab waist*” compensation by sextupoles and the FF design. The updated lattice presents a larger horizontal phase advance μ_x in the arc cell, with consequent smaller intrinsic emittance, so that for the nominal phase operation it will not be necessary the insertion of wigglers to reach the emittances and damping times needed. Without wigglers damping times increase by 30% but the RF power decreases, with a net operational costs saving. Beam-beam simulations (see for example in [3], page 211) have studied the degree to which an increase in the damping time affects the luminosity and beam-beam induced tails: an increase by a factor of 2.5 does not lead to any substantial luminosity degradation. In the new lattice the longitudinal damping times are of the order of 20 msec in both rings, about 1.3 times larger than the CDR values but still below the threshold of beam tail growth. Space in the lattice has been provided in each ring for the installation of two wigglers, 40 m long, for the achievement of the emittance and damping times for the upgrade parameters.

LER and HER lattices are very similar: The arcs have an alternating sequence of two different cells: a $\mu_x = \pi$ cell, that provides the best dynamic aperture, and a $\mu_x = 0.72$ cell that has a much smaller intrinsic emittance and provides a phase slippage for the sextupoles pairs, in such a way that one arc corrects all the phases of the chromaticity. As a consequence, the chromatic functions W_x and W_y are lower than 20 and the second order dispersion is almost zero everywhere except in the IR. With this arrangement, the number of arcs can be reduced to 4, with two 40 m long “empty” wiggler sections for the upgrade scenario. With 14 cells in each arc a horizontal emittance of 1.6 nm in HER and 2.8 nm in LER are obtained, the LER lattice having still room for further reduction. The 2 different phase arc cells for HER (top) and LER (bottom) are shown in Fig. 4.

The ring circumference was also shortened, better fitting the proposed construction site. Background studies have continued after the CDR, in synergy with the detector experts, in order to optimize the collimators set for backgrounds reduction and the design of the Final Focus.

Several spin rotation schemes for the e⁻ beam in HER have been studied to provide longitudinal polarization at the IP, and implementation into the lattice is in progress.

Dynamic aperture and working point optimization for both rings is in progress (see in [7]).

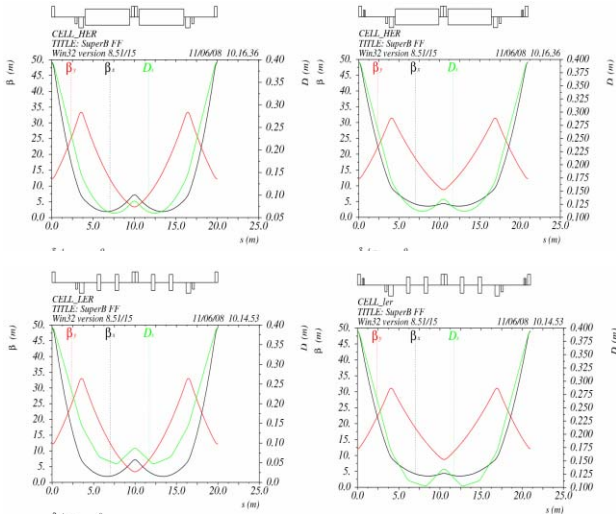


Figure 4: HER (top) and LER (bottom) arc cells:
 $\mu_x = 0.72$ (left), $\mu_x = 0.5$ (right).

Figure 5 shows the optical functions for the LER ring (HER's being very similar). The spin rotator sections are not included.

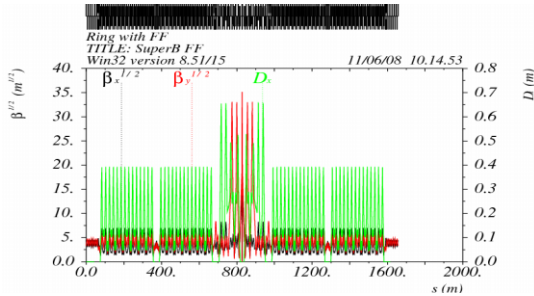


Figure 5: LER optical functions.

INTERACTION REGION

The IR layout (see Figure 6) was designed to leave about the same longitudinal free space for the detector as that presently used by BABAR or BELLE, but with superconducting quadrupole doublets QD0/QF1 as close to the IR as possible.

The Final Focus is based on an ILC/FFTB-like design and complies with all the requirements in terms of high order aberrations correction, needs to be slightly modified for LER to take care of energy asymmetry.

The final doublets must provide a pure quadrupole field on each of the two beams to avoid high background rates in the detector. Because of the small separation of LER and HER beams the influence of each winding on the other one is not negligible and, for the same space limitation, a multi-layer configuration is not suitable to compensate the high order multipoles. A novel helical-type superconducting design has been then studied [8] to

compensate the fringe field of one beam line quadrupole onto the other one.

The choice for a finite crossing angle at the IP greatly simplifies the IR design, naturally separating the beams at the parasitic collisions. The beams enter the IP nearly straight to minimize synchrotron radiation and lost particle backgrounds, and are bent more while exiting the IR to avoid parasitic collisions and the resulting beam-beam effects. Half IR optical functions ($\sqrt{\beta}$) are shown in Fig. 7.

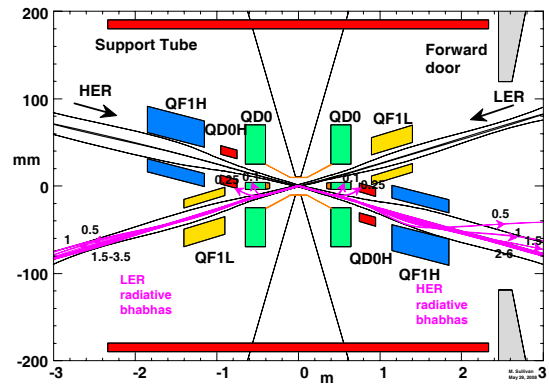


Figure 6: Near IP Interaction Region for two asymmetric beams.

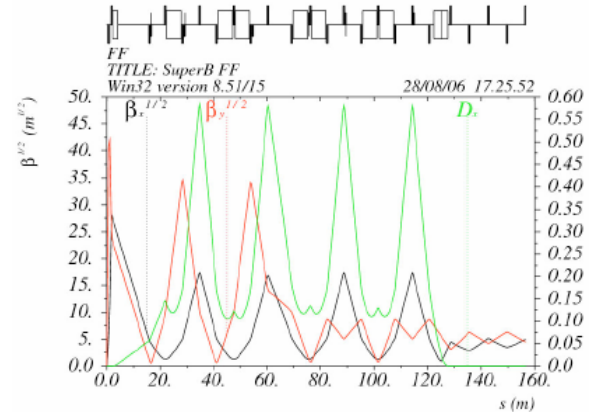


Figure 7: Optical functions in half IR ($\sqrt{\beta}$).
 IP is at $s=0$, crab sextupole at $s = 140$.

POLARIZATION

Polarization of one beam is included in *SuperB*:

- either energy beam could be the polarized one
- the LER would be less expensive, the HER easier

Longitudinal polarization times and short beam lifetimes indicate a need to inject vertically polarized electrons. There are several possible IP spin rotators: solenoids look better at present, since vertical bends will give unwanted vertical emittance growth.

The expected longitudinal polarization at the IP is about 87% (injected beam) \times 97% (ring) = 85% (effective).

Several spin rotation schemes for the e^- beam in HER have been studied (see for example in [9]) to provide longitudinal polarization at the IP.

POWER REQUIREMENTS

The power required for this collider is the sum of power for the magnets, RF system, cooling water, controls, and the accelerator operation. The present estimates indicate about 17 MW is needed for the nominal case. These values do not include the campus power requirements or that of the particle physics detector. There are upgrade possibilities for this collider to 2 to 4 times the design luminosity that will require more power. Due to the advantages of the very low emittances and the *crab waist* collision scheme, the power requirements are significantly lower than those of the present B-Factory colliders.

CONCLUSIONS

SuperB is a new machine that can exploit novel very promising design approaches:

- large Piwinski angle scheme will allow for peak luminosity of the order of $10^{36} \text{ cm}^{-2} \text{ s}^{-1}$, well beyond the current state-of-the-art, without a significant increase in beam currents or shorter bunch lengths;
- “*crab waist*” sextupoles will be used for suppression of dangerous resonances;
- the low beam currents design presents reduced detector and background problems, and affordable operating costs;
- a polarized electron beam can produce polarized τ leptons, opening an entirely new realm of exploration in lepton flavor physics.

SuperB studies are already proving useful to the accelerator and particle physics communities. The principle of operation is being tested at DAΦNE.

The baseline lattice, based on the reuse of all PEP-II hardware, fits in the Tor Vergata University campus site, near Frascati.

A CDR is being reviewed by an International Review Committee, chaired by J. Dainton (UK). A Technical Design Report will be prepared to be ready by beginning of 2010.

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