THE SUPERB PROJECT*

Tadeusz Lesiak

The Henryk Niewodniczański Institute of Nuclear Physics
Polish Academy of Sciences
Radzikowskiego 152, 31-342 Kraków, Poland
and
Tadeusz Kościuszko Cracow University of Technology
Warszawska 24, 31-155 Kraków, Poland

(Received November 11, 2011)

The SuperB is a new generation flavour factory. This paper comprises a review of the project, covering the highlights of the broad physics programme and the conceptual design of the accelerator and detector.

DOI:10.5506/APhysPolB.43.679
PACS numbers: 14.40.Nd, 14.40.Pq, 14.60.Fg, 14.40.Lb

1. Introduction

The primordial goal of the SuperB project [1] is the continuation and extension of the extremely successful physics programme of so-called B-factories, *i.e.*, the accelerators PEP-II [2] and KEKB [3] together with the respective detectors BaBar [4] and Belle [5]. These two high-luminosity, asymmetric energy e^+e^- colliders collected over the last decade huge amount of data (1.6 ab^{-1}). Endowed with these data, the collaborations BaBar and Belle provided the evidence for the CP violation in the b quark sector and tested the unitarity of the Cabibbo–Kobayashi–Maskawa (CKM) matrix [6] with the precision of the order of few percent. Last but not least, the evidence of the D^0–$\overline{D}^0$ mixing was given, together with observation of several new hadrons and a substantial progress in the studies of τ lepton decays.

SuperB is a e^+e^- collider to be built with the ability of operation with a high luminosity at energies from open charm threshold (corresponding to the mass of the $\psi(3770)$ meson) to above the $\Upsilon(5S)$ resonance. The accelerator's site is on the campus of "Tor Vergata" University of Rome. The principal

* Presented at the Conference "Strangeness in Quark Matter 2011", Kraków, Poland, September 18–24, 2011.

aim of the SuperB is to collect 75 ab^{-1} of data at the $\Upsilon(4S)$ resonance which would correspond to the world largest samples of B, D and τ pairs. Moreover, large data samples will be collected at other Υ resonances. A similar project is pursued at KEK (Japan). It is based on the upgrade of the KEKB/Belle facility to SuperKEKB/Belle-II [7] with the goal to collect 50 ab^{-1} of data. To compare with the latter, the SuperB offers not only the perspective of recording a bigger data sample, but also two unique features: a longitudinal polarization of the electron beam (80%) and the possibility of running with a high-luminosity at the $\psi(3770)$ resonance. This feature allows for use quantum correlations between pairs of D–$\overline{D}$ mesons in full analogy with the case of B–$\overline{B}$ pairs at the $\Upsilon(4S)$.

This paper is organized as follows. The basic physics motivation for the SuperB project is presented in Sec. 2. The next two sections discuss issues related to the accelerator and detector.

2. Physics potential of the SuperB

2.1. B-physics

Studies of B mesons produced via $e^+e^- \to \Upsilon(4S) \to B\overline{B}$, based on the SuperB data sample of 75 ab^{-1}, are expected to improve the precision of the determination of the apex and angles of the unitarity triangle (UT) by an order of magnitude [8] (*cf.* Table I). In particular, it would be possible to perform inclusive measurements of the CKM elements $|V_{cb}|$ and $|V_{ub}|$ with the precision of 1% (5%), respectively [9]. Such an impressive progress in the experimental precision could potentially reveal inconsistencies of the CKM paradigm in the Standard Model (SM) leading to the evidence for New Physics (NP). The effects of the latter will be also searched directly with

TABLE I

Uncertainties of the unitarity triangle (UT) parameters obtained from the Standard Model fit based on the experimental and theoretical input available today (left) and expected for the SuperB (right) [8].

UT parameter	Current value	Precision expected at SuperB (50 ab^{-1})
$\overline{\rho}$	0.163 ± 0.028	± 0.0028
$\overline{\eta}$	0.344 ± 0.016	± 0.0024
α	$(92.7 \pm 4.2)^0$	$\pm 0.45^0$
β	$(22.2 \pm 0.9)^0$	$\pm 0.17^0$
γ	$(64.6 \pm 4.2)^0$	$\pm 0.38^0$

great sensitivity in studies of time-dependent CP asymmetries resulting from heavy particles contributing to loops in the respective topologies. The golden channels are penguin dominated transitions $b \to s$ and $b \to d$, while the $b \to c\bar{c}s$ is used as the most important reference among tree level processes.

The SuperB will also offer the possibility to measure the set of observables related to several rare decays of B mesons that are sensitive to different NP scenarios [8, 10] (*cf.* Table II). The fulfillment of this programme could potentially allow to pinpoint the nature of New Physics. All these observables are related to decay channels with neutral particles (in particular neutrinos) in the final state. The possibilities of reconstruction of such decays are extremely limited for the LHC experiments.

TABLE II

Experimental sensitivities of observables related to direct searches for the New Physic in rare decays of B mesons. More details can be found in [11, 12, 13].

Mode	Precision	
	Current	Expected (75 ab^{-1})
$\mathcal{B}(B \to X_s\gamma)$	7%	3%
$\mathcal{A}_{\mathrm{CP}}(B \to X_s\gamma)$	0.037	0.004–0.005
$\mathcal{B}(B \to \tau^+\nu_\tau)$	30%	(3–4)%
$\mathcal{B}(B \to \mu^+\nu_\mu)$	not measured	(5–6)%
$\mathcal{B}(B \to X_s l^+ l^-)$	23%	(4–6)%
$\mathcal{A}_{\mathrm{FB}}(B \to X_s l^+ l^-)$	not measured	(4–6)%
$\mathcal{B}(B \to K\nu\bar{\nu})$	not measured	(16–20)%
$\mathcal{S}(B \to K^0_{\mathrm{S}}\pi^0\gamma)$	0.24	0.02–0.03

The SuperB is also expected to contribute significantly to the studies of B_s mesons, produced in pairs at the center-of-energies corresponding to the $\Upsilon(5S)$ resonance. The particular attention will be paid to the penguin dominated decays involving neutral particles in the final state like *e.g.* $B_s \to J/\psi\eta^{(\prime)}$, $B_s \to D^{(*)}\phi$, $B_s \to J/\psi K^0_{\mathrm{S}}$, $B_s \to \pi^0 K^0_{\mathrm{S}}$, $B_s \to \phi\eta^{(\prime)}$ and $B_s \to \gamma\gamma$. More details about the B_s physics at the SuperB can be found in [9].

2.2. τ physics

The physics programme in the sector of the τ lepton would encompass searches for lepton-flavour-violating (LFV) decays, experimental investigations on CP violation and measurements of the τ electric dipole moment (EDM), as well as of the anomalous magnetic moment $g - 2$.

Searches for LFV decays constitute one of the most clean and powerful tools to discover New Physics and to elucidate its nature. The lepton-flavour-violating effects are considered to scale quadratically with the lepton mass, that together with a large number of decays which can be studied, clearly favours the τ. The branching fractions for LFV decays of charged leptons are negligibly small in the SM, *e.g.*, $\mathcal{B}(B \to l\gamma) < 10^{-54}$ and $\mathcal{B}(B \to lll) < 10^{-14}$, $(l = e, \mu)$. They are predicted, however, to be significantly enhanced in many NP models, especially in supersymmetric extensions of the Standard Model. In particular, the branching fraction $\tau \to l\gamma$ is then expected at the level 10^{-9} [14] which matches with the sensitivity of the SuperB. Other interesting classes of LFV decays are $\tau \to lP^0$, $(P^0 = \pi^0, \eta^{(\prime)}, K^0_{\rm S})$, $\tau \to lS^0$, $(S^0 = f^0)$, $\tau \to lV^0$, $(V^0 = \rho^0, K^{*0}\phi, \omega)$ and $\tau \to lll$. The SuperB will be able to uniquely explore the lepton-flavour-violating transitions between the third and first or second generations. The results of these studies will be complementary with the MEG experiment [15] which will search for the decay $\mu \to e\gamma$ with great sensitivity.

The effects of CP violation have not been observed yet in charged lepton decays. In the Standard Model they are predicted to be vanishingly small, *e.g.*, the CP asymmetry of the decay $\tau^\pm \to K^0_{\rm S}\pi^\pm\nu_\tau$ is calculated to be of the order of 10^{-12} [16]. Observable CP-violating effects are expected in R-parity violating supersymmetric models [17] and in specific non-SUSY multi-Higgs models [18]. The first search for CP violation in τ decay has been performed by the CLEO Collaboration [19]. A tau-charge-dependent asymmetry of the angular distribution of the hadronic system produced in the decay $\tau \to K^0_{\rm S}\pi\nu_\tau$ has been studied. The mean value of the optimal asymmetry observable $\langle\xi\rangle = (-2.0 \pm 1.8) \times 10^{-3}$ was obtained. It was estimated [9] that the SuperB with the data sample of 75 ab^{-1} would reach an experimental sensitivity of the order of 2.4×10^{-5} for that variable.

The τ EDM could influence both the angular distributions and the polarization of the taus produced in e^+e^- annihilation. The polarization of the electron beam allows for construction of observables that unambiguously discriminate between the contribution due to the τ EDM and other effects. Moreover, in the presence of the polarized electron beam, these variables can be reconstructed from the angular distribution of the products of a single τ decay [20]. For the SuperB with 75 ab^{-1} it was estimated [9] that the upper limit sensitivity for the real part of the τ electric dipole moment is $\Re\,|(d^\gamma_\tau)| \leq 7.2 \times 10^{-20} e\,\mathrm{cm}$. Using similar techniques and the same data sample, the SuperB can also measure both real and imaginary parts of the $g-2$ form factor of the τ lepton with a resolution of the order 10^{-6} [21].

2.3. Charm physics

One of the unique features of the SuperB project is the possibility of collecting data at the charm threshold. The run at the center-of-mass energy corresponding to the $\psi(3770)$ is foreseen with the luminosity of the order 10^{35} cm^{-2} s^{-1}. After a few months of running, the data sample of 0.5 ab^{-1} is expected. For such events, tagging those in which one D meson is identified, the other D can be studied with very small background contamination. The $D\overline{D}$ are also produced in the state of quantum entanglement (as $B\overline{B}$ pairs at the $\Upsilon(4S)$). The availability of quantum-correlated D decays allows independent measurement of strong phases like $\delta_{K\pi}$, $\delta_{K\pi\pi}$ *etc*. Their values are used for mixing measurements at the $\Upsilon(4S)$. The data collected at the charm threshold should improve substantially the precision in mixing parameters x_D and y_D to the level of the order of 10^{-4}.

2.4. Electroweak neutral current measurements

The combination of high luminosity and the polarization of electron beam offers a unique opportunity to measure at SuperB electroweak neutral current parameters with the precision comparable to the one obtained at SLC and LEP but at $Q^2 \approx (10.58\ \text{GeV})^2$. It exploits the fact that cross sections for $e^+e^- \to f\overline{f}$ (where f denotes the fermion) are sensitive to the beam polarization through $Z - \gamma$ interference.

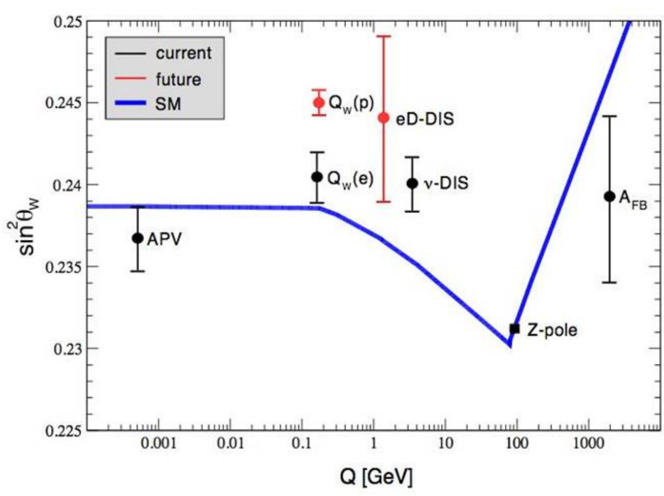

Fig. 1. Summary of experiments that have measured or are proposing to measure $\sin^2\theta_W$ as compiled in [22]. The SM running of $\sin^2\theta_W$ is overlaid on the data points. SuperB will provide a point (not shown on the plot) at $Q^2 \approx (10.58\ \text{GeV})^2$ with an error comparable to that of the measurement at the Z pole [9].

The $\sin^2\theta_W$ will be determined at SuperB via measurement of the left–right asymmetry using $\mu^+\mu^-$, $\tau^+\tau^-$ and $c\bar{c}$ pairs in the final state (Fig. 1). The energy region around 10.58 GeV is very interesting as the $\sin^2\theta_W$ is changing there and no measurement has been done there so far. Moreover, it is the energy range in which the measurement is devoid from the b-quark fragmentation uncertainties. The latter were significant in case of LEP/SLC measurements. For the muon pairs and an integrated luminosity of 75 ab^{-1} and for 80% polarization of the electron beam, the statistical error on the left–right asymmetry is expected to be of 5×10^{-6} which corresponds to a relative error of $\mathcal{O}(1\%)$.

The physics programme of the SuperB project encompasses also many other topics like spectroscopy and direct searches for a light Higgs boson, invisible decays and dark forces. Due to limitations in paper's volume, these issues are not discussed here and the relevant information can be found in [9, 23].

3. The accelerator

The SuperB accelerator is being designed according to the new collision scheme (so-called nanobeams). Its basic features are: relatively small circumference of 1258 m, asymmetric beams (the center-of-mass boost $\beta\gamma = 0.28$) which cross at 66 mrad, small collision area, very small beta function at the interaction point (β_y^*), large Piwinski angle together with the "crabbed waist" correction scheme [1, 24]. This concept allows to reach the luminosity of at least 1×10^{36} cm^{-2} s^{-1} with beam currents, and thus also wall plug power, at the same level as those of the current B-factories. The basic parameters of the SuperB accelerator are collected in Table III.

TABLE III

SuperB nominal beam parameters. The acronym LER (HER) refers to the Low (High) Energy Ring, respectively.

Parameter	LER	HER
Particle type	e^-	e^+
Energy [GeV]	4.2	6.7
Beam current [A]	2.45	1.89
β_y^* [cm]	0.0205	0.0253
β_x^* [cm]	3.2	2.6
ϵ_y^* [pm]	6.15	5
ϵ_x^* [nm]	2.46	2.0
σ_y^* [μm]	0.036	0.036
σ_x^* [μm]	8.87	7.21

4. The detector

The concept of the SuperB detector is based on the existing BaBar apparatus [4] (Fig. 2). The regime of operation at higher event rates (higher beam related backgrounds) and with a reduced center-of-mass boost $\beta\gamma$ (slightly different topology of events) dictates, however, the necessity to take into account several modifications. The SuperB spectrometer [4] will be composed of a tracking system with a silicon strip vertex detector (SVT), a drift chamber (DCH) inside a 1.5 T magnetic field, a Cherenkov detector with fused silica bar radiators (DIRC), an electromagnetic calorimeter (EMC) and an instrumented flux return (IFR) for muon identification and neutral hadrons detection. The following components of BaBar's apparatus can be reused at the SuperB: the superconducting solenoid, the barrel part of the EMC, the fused silica bars of the DIRC and the flux-return steel.

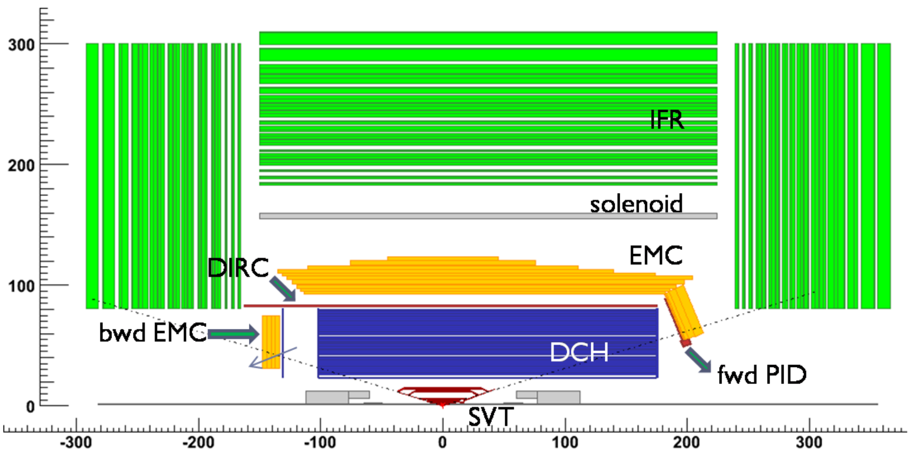

Fig. 2. Concept for the SuperB detector.

5. Summary

SuperB is a second generation asymmetric energy e^+e^- collider planned to operate in a wide range of energies spanning from the charm threshold up to the $\Upsilon(5S)$. The main set of data will be collected at the center-of-mass energy corresponding to the $\Upsilon(4S)$ with the baseline luminosity of 10^{36} cm^{-2} s^{-1}. It is expected that SuperB can collect 75 ab^{-1} of data in five years. Such dataset would allow to test the flavour sector of the Standard Model with unprecedented precision with the potential to elucidate effects of New Physics. The collaboration is currently in the phase of preparation of the Technical Design Report. The first collisions at the SuperB are expected in 2016.

The SuperB project has been approved and received the funding from the Italian Government in December 2010. The Nicola Cabibbo Laboratory in Tor Vergata, which will host the SuperB experimental setup, was formally approved during the summer 2011.

REFERENCES

[1] `http://www.pi.infn.it/SuperB/`; The SuperB Conceptual Design Report, `arXiv:0709.0451v2 [hep-ex]`.

[2] `http://www.slac.stanford.edu/grp/ad/ADPEPII/ADPEPII.html`

[3] `http://www-acc.kek.jp/kekb/`; S. Kurokawa, *Nucl. Instrum. Methods* **A499**, 1 (2003).

[4] B. Aubert *et al.* [BABAR Collab.], *Nucl. Instrum. Methods Phys. Res., Sect.* **A479**, 1 (2002).

[5] A. Abashian *et al.* [Belle Collab.], *Nucl. Instrum. Methods* **A479**, 117 (2002).

[6] N. Cabibbo, *Phys. Rev. Lett.* **10**, 531 (1963); M. Kobayashi, T. Maskawa, *Prog. Theor. Phys.* **49**, 652 (1973).

[7] B. Golob, *Nuovo Cim.* **C33**, 319 (2010) [`arXiv:1006.4208v1 [hep-ex]`].

[8] M. Rama, `arXiv:0909.1239v1 [hep-ex]`.

[9] SuperB Progress Reports, `arXiv:1008.1541v1 [hep-ex]`.

[10] A.J. Bevan, `arXiv:0905.2305v1 [hep-ex]`.

[11] T. Browder *et al.*, *J. High Energy Phys.* **0802**, 110 (2008) [`arXiv:0710.3799v1 [hep-ph]`].

[12] T. Browder *et al.*, *Rev. Mod. Phys.* **81**, 1887 (2009) [`arXiv:0802.3201v2 [hep-ph]`].

[13] M. Bona *et al.*, `arXiv:0709.0451v2 [hep-ex]`.

[14] S. Antusch, E. Arganda, M.J. Herrero, A.M. Teixeira, *J. High Energy Phys.* **11**, 090 (2006).

[15] E. Baracchini, `arXiv:1005.2569v1 [hep-ex]`.

[16] D. Delepine, G. Lopez Castro, L.T. Lopez Lozano, *Phys. Rev.* **D72**, 033009 (2005).

[17] H.K. Dreiner, M. Kramer, B. O'Leary, *Phys. Rev.* **D75**, 114016 (2007); D. Delepine, G. Feisel, S. Khahil, *Phys. Rev.* **D77**, 016003 (2008).

[18] A. Datta *et al.*, *Phys. Rev.* **D75**, 074007 (2007); K. Kiers *et al.*, *Phys. Rev.* **D78**, 113008 (2008); D. Kimura *et al.*, `arXiv:0808.0674v2 [hep-ph]`.

[19] G. Bonvicini *et al.* [CLEO Collab.], *Phys. Rev. Lett.* **88**, 111803 (2002).

[20] G.A. Gonzalez-Sprinberg, J. Bernabeu, J. Vidal, `arXiv:0707.1658v1 [hep-ph]`; J. Bernabeu, G.A. Gonzalez-Sprinberg, J. Vidal, *Nucl. Phys.* **B763**, 283 (2007).

[21] J. Bernabeu *et al.*, *Nucl. Phys.* **B790**, 160 (2008).

[22] D.S. Armstrong *et al.* [Qweak Collab.], Expt. Proposal for JLab E02-020; `http://qweak.jlab.org/DocDB/0007/000703/005/Qweak_Update_final2.pdf`

[23] A.J. Bevan, `arXiv:1110.3901v1 [hep-ex]`.

[24] M. Zobov *et al.*, `arXiv:0802.2667v1 [physics.acc-ph]`.