COLLIDERS FOR B-FACTORIES

H. Koiso, KEK, Tsukuba, Ibaraki, Japan

Abstract

Both SuperB and SuperKEKB projects have been approved and are being constructed based on the achievements of PEP-II and KEKB. The new B-factories are aiming at $\sim 10^{36}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ by squeezing the vertical beam sizes to 40-60 nanometer at the interaction point with relatively modest beam currents. In this paper, recent progress on design and construction status of both projects will be presented.

INTRODUCTION

The PEP-II and KEKB B-Factories, which are e^+e^- energy-asymmetric double-ring colliders, have been successfully operated until their run ends. They have achieved the world's highest luminosities: 1.21 (PEP-II) and 2.11 (KEKB) $\times 10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$. The integrated luminosity combined in both factories has amounted to over 1.5 ab^{-1}, resulting fruitful outputs by the BaBar and Belle experiments such as proofs of the Kobayashi-Maskawa theory and some hints for new physics beyond the Standard Model. Then, boosting the luminosity of B-factories to $\sim 10^{36}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ at Υ(4S) is strongly required to integrate 50-75 ab^{-1} for further investigations.

The two projects reported at IPAC10[1], SuperB[2] and SuperKEKB[3], have been approved and a new generation of B-factories has kicked off. Both colliders are constructed by utilizing experiences and resources of the precedent B-factories as much as possible. This paper reports design and construction status of the two projects.

DESIGN CONCEPT

As it is well-known, the luminosity is expressed as

$$L = \frac{\gamma_\pm}{2er_e}\left(1+\frac{\sigma_y^*}{\sigma_x^*}\right)\left(\frac{I_\pm \xi_{y\pm}}{\beta_{y\pm}^*}\right)\left(\frac{R_L}{R_{\xi_y}}\right), \tag{1}$$

when the beam sizes and beta functions of both beams are equal at the interaction point (IP). The parameters R_L and R_{ξ_y} are reduction factors for the luminosity and the vertical beam-beam tune-shift parameter, respectively, due to the crossing angle and the hourglass effect. Higher beam current (I), larger vertical beam-beam parameter (ξ_y) and smaller β_y^* are to be pursued for higher luminosity.

From the practical view point, lower beam currents are preferable for hardware feasibility and also for reducing the running cost which is strongly demanded. It is not realistic to expect much higher ξ_y than those ever achieved in real colliders. Thus, extremely small β_y^* is required in order to increase the luminosity to a large extent. For this purpose, a large Piwinski angle ($\phi_{\mathrm{Piw}} = \theta_x\sigma_z/\sigma_x^*$) and "Crab Waist " (CW) scheme is proposed for SuperB[4]. The design of SuperKEKB is also based on large ϕ_{Piw} after having changed from the high current and crab crossing scheme.

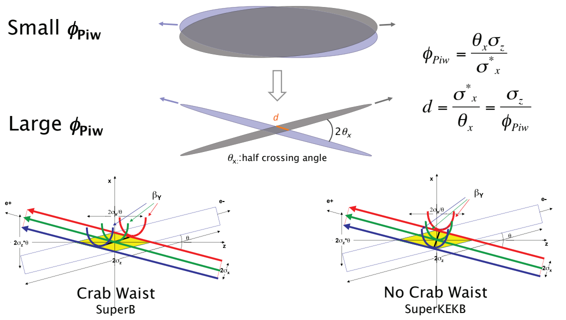


Figure 1: Schematic view of beam collision with a large Piwinski angle and with/without the Crab Waist scheme in the horizontal plane. In the CW scheme[4], the vertical waist positions are adjusted by a pair of sextupoles, each of which is on each side of the IP at suitable betatron phase differences.

In the case of collision with large ϕ_{Piw}, beams with sufficiently small σ_x^* collide at a large horizontal crossing angle as shown in Fig. 1. The longitudinal size of the overlap region is decreased to $\sigma_z/\phi_{\mathrm{Piw}}$, therefore β_y^* can be squeezed to $\sim \sigma_z/\phi_{\mathrm{Piw}}$ which is much smaller than σ_z, avoiding the hourglass effect. For sufficiently small σ_x^*, both low horizontal emittance ε_x and low β_x^* are required.

It is concerned that the luminosity may be degraded by large ϕ_{Piw} due to enhancement of x-y coupling and/or synchrotron-betatron resonances. In order to mitigate these adverse effects, the CW scheme has been innovated and has worked successfully in a test at DAΦNE. In this scheme, the vertical waist positions of beam particles with any horizontal offsets can always be matched on the central orbit of the counter-rotating beam by using the CW sextupoles as shown in Fig. 1.

On the other hand, even the CW sextupoles are connected with the I or $-I$ transformer, their nonlinearities influence the dynamic aperture[2, 5], thus careful consideration should be necessary. Different selections have been made: SuperB has adopted the CW scheme, but SuperKEKB does not use it as the baseline design.

Machine parameters of SuperB and SuperKEKB are listed in Table 1. There are main common features as follows:

- Low β_y^*: 200$\sim$300 μm.
- Low β_x^*: 25$\sim$32 mm.
- Large Piwinski angles: $\sim$20.
- Low emittances and flat beams: 2$\sim$5 nm (horizontal), 5$\sim$12 pm (vertical), and 0.25$\sim$0.28% coupling. Note that the horizontal emittances are increased by

Table 1: Machine Parameters of SuperB and SuperKEKB. The parameters of SuperB are based on the latest design report [2]. Values in parentheses denote parameters without intra-beam scattering.

		SuperB		SuperKEKB		
		LER (e-)	HER (e+)	LER (e+)	HER (e-)	units
Beam energy	E	4.18	6.7	4	7.007	GeV
Circumference	C	1258.4		3016.3		m
Half crossing angle	θ_x	33		41.5		mrad
Piwinski angle	$\phi_{\rm Piw}$	18.60	22.88	24.6	19.3	rad
Horizontal emittance	ε_x	2.46 (1.82)	2.0 (1.97)	3.2 (1.9)	4.6 (4.4)	nm
Vertical emittance	ε_y	6.15	5.0	8.64	11.5	pm
Coupling		0.25	0.25	0.27	0.28	%
Beta function at IP	β_x^*/β_y^*	32 / 0.205	26 / 0.253	32 / 0.27	25 / 0.30	mm
Horizontal beam size	σ_x^*	8.872	7.211	10.1	10.7	μm
Vertical beam size	σ_y^*	36	36	48	62	nm
Betatron tune	ν_x/ν_y	42.575/18.595	40.575/17.595	44.530/44.570	45.530 / 43.570	
Momentum compaction	α_p	4.05	4.36	3.25	4.55	10^{-4}
Energy spread	σ_ε	7.34	6.43	8.14(7.96)	6.49(6.34)	10^{-4}
Natural chromaticity	$(x)/(y)$	-137 / -449	-134 / -447	-107 / -785	-168 / -1131	
Beam current	I	2.447	1.892	3.60	2.60	A
Number of bunches	n_b	978		2500		
Particles / bunch	N	6.56	5.08	9.04	6.53	10^{10}
Energy loss/turn	U_0	0.865	2.11	1.87	2.45	MeV
Long. damping time	τ_z	20.3	13.4	21.6	29.0	msec
RF frequency	f_{RF}	476.		508.9		MHz
Synchrotron tune	ν_s	-0.0129	-0.0135	-0.0247	-0.0280	
Bunch length	σ_z	5.0 (4.29)	5.0 (4.69)	6.0 (5.0)	5.0 (4.9)	mm
Beam-beam parameter	ξ_x/ξ_y	0.0033/0.097	0.0021/0.097	0.0028/0.088	0.0012/0.081	
Total beam lifetime	$\tau_{\rm beam}$	269	254	346	332	sec
Luminosity	L	10×10^{35}		8×10^{35}		cm^{-2}s^{-1}
Integrated luminosity	$\int L$	75		50		ab^{-1}

30-70% due to the intra-beam scattering.

- Small σ_y^*: 40$\sim$60 nm.
- Modest beam currents: 1.9$\sim$3.6 A.
- Modest bunch lengths: 5$\sim$6 mm.
- Modest vertical beam-beam parameters: 0.09$\sim$0.10. The horizontal beam-beam parameters are very small, which may help the vertical beam-beam performance.
- Smaller energy asymmetries than PEP-II and KEKB. These values are still acceptable for physics experiments.
- Short beam lifetimes: 250$\sim$350 sec. Thus powerful injectors are necessary.
- Minimize construction and running costs.

Each project will be individually reviewed in the following sections.

SUPERB

Status

The SuperB project has been approved by the Italian Research Minister as part of the Italian National Research Plan, with a 5 years construction budget. The construction site has been recently selected in the campus of the Tor Vergata Rome II University, 5 km away from the IFNF Frascati National Lab. The international "Cabbibo Laboratory" will de newly constituted and will host the SuperB project [6].

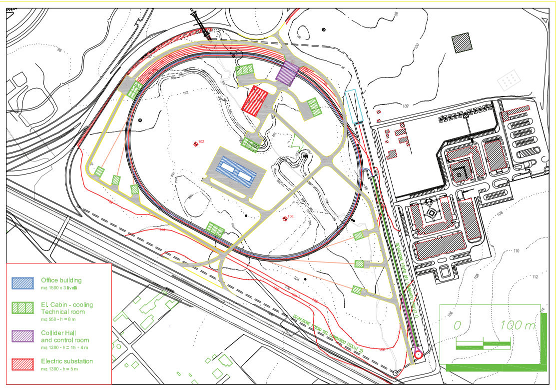


Figure 2: SuperB rings in the Tor Vergata University site.

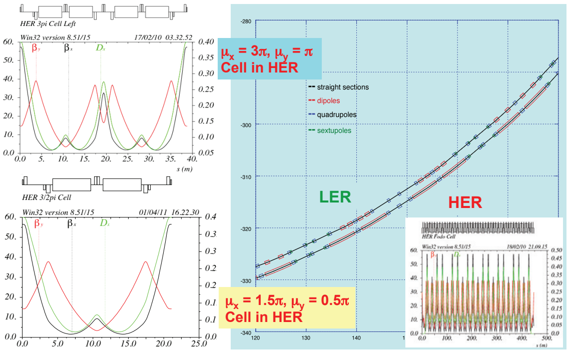
Parameters and Lattice

The SuperB collider whose target luminosity is 10^{36}cm^{-2}s^{-1} has own characteristics as [7]:

- Longitudinally polarized electron beam in the LER.
- Wide ranges of flexibility for machine parameters. Beside the baseline design, two options, lower emit-

Table 2: Two Options

	Low emittance		High current		
	LER	HER	LER	HER	units
ε_x	1.23	1.00	2.46	2.00	nm
ε_y	3.075	2.5	12.3	10	pm
β_y^*	0.145	0.179	0.237	0.292	mm
I	1.888	1.460	4.000	3.094	A
n_b	978		1956		
ξ_y	0.0892	0.0891	0.0687	0.0684	



P. Raimondi, XVII SuperB WS and Kick-off Meeting, May-June 2011

Figure 3: Arc optics [8].

tance and higher current options, are prepared as Table 2.

- Possibility to run at τ/charm threshold with $10^{35}\mathrm{cm}^{-2}\mathrm{s}^{-1}$.
- Possibility to be a good light source. The lattice has recently been modified to install Insertion Devices in the HER.
- Most of the PEP-II hardware can be used. The HER will use the PEP-II HER dipoles.

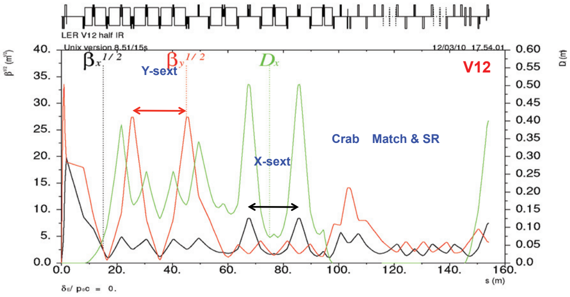


Figure 4: Final focus optics (LER) [8].

The arcs of both rings have conceptually the same structure which consists of short and long cells as shown in Fig. 3. The arc dipoles in the LER are shorter (bending radius about 3 times smaller) than those in the HER. Sextupoles are paired with the $-I$ transformer to cancel their major nonlinearities.

In the final focus section, large chromaticities arising from final focus quadrupoles are locally corrected by $-I$ sextupole pairs in both planes as shown in Fig. 4. The CW sextupoles are placed at the ends of the local chromaticity correction sections. The spin rotators are placed only in the LER. The CW scheme demands for particular care in designing the chromaticity correction in the final focus section.

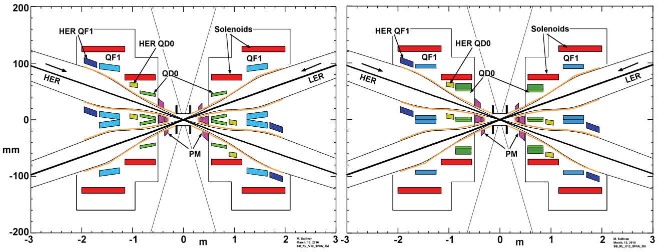


Figure 5: Layout of IR with two types of QD0: vanadium permendur design (left) and air-core design (right) [9].

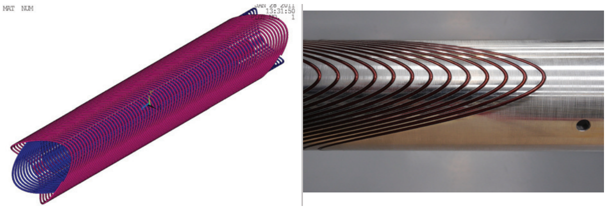


Figure 6: Air-core quadrupole based on the double helix principle [10].

IR Design

The final focus quadrupoles are a set of permanent (PM) and superconducting (QD0, QF1) magnets with warm bore cryostats. The permanent magnets are installed so that their front pole faces are at 30 (38) cm from the IP in the LER (HER). There are two types of QD0; super-ferric design with vanadium permendur yoke and air-core design. Additional vanadium permendur quadrupoles are installed only for the HER in both cases. Advanced design of air-core dual quadrupoles whose axises are parallel to the beam orbit is being developed [11]. A prototype is being constructed and will be tested soon.

Practical solutions of collimation against Touschek particle losses have been found. Four horizontal collimators are placed near the peaks of the horizontal dispersion in the final focus sections. The reduction of Touschek lifetime by this collimation is estimated to be from 7.8 (40) to 6.6 (33.2) min in the LER (HER)[12].

Tolerances for the vibrations have been comprehensively estimated, including ground motion, motion sensitivity of machine components and performance of beam feedback system. Ground vibration measurements of the Tor Vergata site have shown very good stabilities[13]. The measured values of the vertical displacement (20-40, 20-30, 20-30 nm) are much smaller than the required values (300, 300, 500 nm rms for the IP, final focus quadrupoles, and arc quadrupoles respectively). It is noted that the vibration sensitivity is greatly reduced for coherent motion of the IR components in a common cryostat. Similar robustness for the coherent motion is also pointed out at SuperKEKB.

Injector and Others

The injector complex has been updated for high efficiency of positron production and top-up injection of polarized electrons. The present design features are: one damping ring only for positrons, positron production at low energy (0.6 GeV) and polarized electron gun[14].

Many works are making progress on beam dynamic issues such as e-cloud instability, Low Emittance Tuning (LET) procedures[15], intra-beam scattering[16]. R&D works are also going on as longitudinal and transverse bunch-by-bunch feedbacks and luminosity IP feedback.

SUPERKEKB

Parameters and Lattice

KEKB is upgraded to SuperKEKB based on the scheme with large Piwinski angle, which is called the Nano-Beam scheme. Compared with KEKB, three key parameters are: beam currents are doubled, ξ_ys are same, and β_y^*s are reduced by a factor of 1/20, resulting 40 times higher luminosity.

The beam energies are changed from 3.5 to 4 GeV for the LER and from 8 to 7 GeV for the HER. For the LER, the higher energy is necessary to suppress emittance growth due to the intra-beam scattering and also to make Touschek lifetime longer. For the HER, the lower energy is better to reduce ε_x and the synchrotron radiation power.

SuperKEKB is constructed in the KEKB tunnel. The required values of beam optical parameters such as ε_x will be achieved by reusing the components of KEKB as much as possible:

- Preserve the present arcs in the HER because ε_x can be decreased to an acceptable level by utilizing the tunability of the 2.5π cell as shown in Fig. 7. Then, the magnets, vacuum chambers and beam position monitors etc. can be reused.
- Replace dipoles to longer ones (from 0.89 to 4.2 m), reusing other main magnets in the LER arc sections.
- Final focus sections (~300 m) are fully reconstructed in both ring. Like SuperB, the local chromaticity correction sections with $-I'$ sextupole pairs for both vertical and horizontal planes are installed in both rings as shown in Fig. 8.
- Wiggler sections only in the LER at KEKB are modified to shorten the wiggler period to half. One third of LER wigglers are reused in the HER.

IR Design

All of final focus quadrupoles are superconducting magnets which are placed on axis of the beam orbits as shown in Fig. 9 [17]. Each quadrupole has four correctors of horizontal and vertical dipoles, skew quadrupole, and octupole windings as shown in Fig. 10. Except two innermost quadrupoles, iron yokes are used in order to eliminate nonlinear leakage fields which significantly decrease dynamic apertures of the counter-rotating beams[18, 19]. Cannel correctors of 6-, 8-, 10-, 12-poles are wounded on the HER beam pipes against the leakage fields of the LER innermost quadrupoles (QC1RP, QC1LP). The detector solenoid field is cancelled with compensation solenoids so that the integrated field on each side of the IP is to be zero, and is also canceled at the center of each final quadrupole as small as possible.

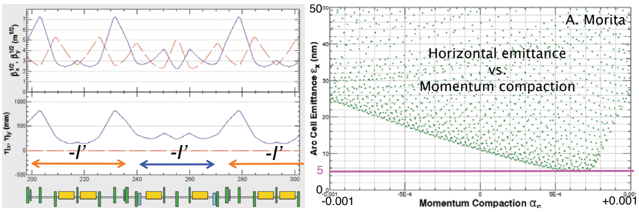


Figure 7: HER 2.5π unit cell with noninterleaved $-I'$ sextuple pairs (left) and its tunability (right). It is possible to decrease ε_x to 5.2 nm only by adjusting quadrupoles, and to 4.4 nm with wigglers.

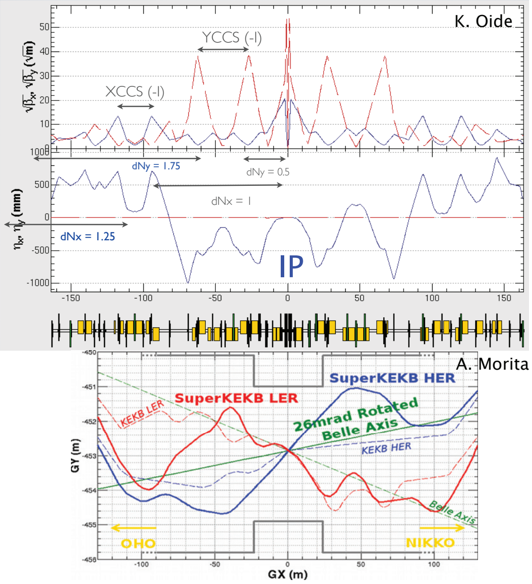


Figure 8: Final focus optics of the LER (top) and layout of both rings in the final focus section (bottom). The beam lines are fitted into the existing tunnel.

As well as sextupoles, octupole correctors of the final quadrupoles and skew sextupoles installed in the rings are used to optimize the dynamic aperture. Because solutions with sufficient dynamic aperture have not yet found, the CW scheme is not used as the baseline lattice. If a good solution is found, the CW sextupoles will be installed afterward in the other straight section than that of the final focus.

Beam background simulation and design of machine detector interface are in progress[20, 21].

Construction

A budget was announced for the high performance upgrade program of KEKB over the three years starting

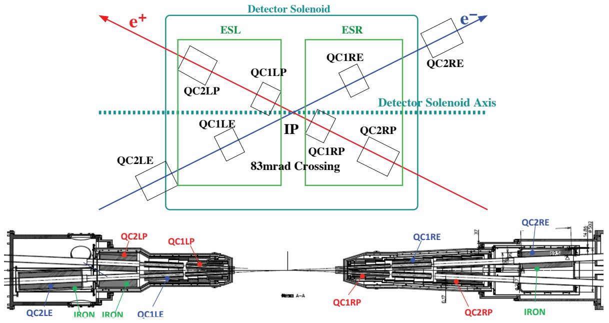


Figure 9: Layout of IR magnets[17, 18]. ESL and ESR are superconducting compensation solenoids.

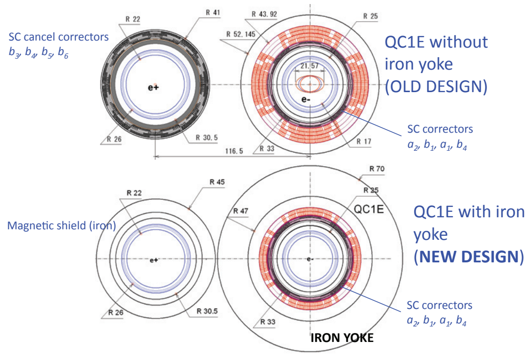


Figure 10: Design of superconducting quadrupole with and without iron yoke (N. Ohuchi).

Japanese fiscal year of 2010 and KEKB operation ended in June 2010. Subsequently SuperKEKB was approved in JFY2011 budget in Dec. 2010. The construction of SuperKEKB has now started and mass fabrication of magnets, beam pipes, etc is going on.

Beam pipes of the LER arc section are replaced with TiN-coated aluminum-alloy pipes with antechambers. In the HER arc section, present copper beam pipes are reused since the power of synchrotron radiation at 7 GeV remains same as that of KEKB at 8 GeV. New copper beam pipes with antechamber are used in both rings. Clearing electrodes in the wiggler sections, groove surfaces in dipoles, and solenoid windings in drift spaces are adopted in the LER to suppress electron cloud instabilities[22].

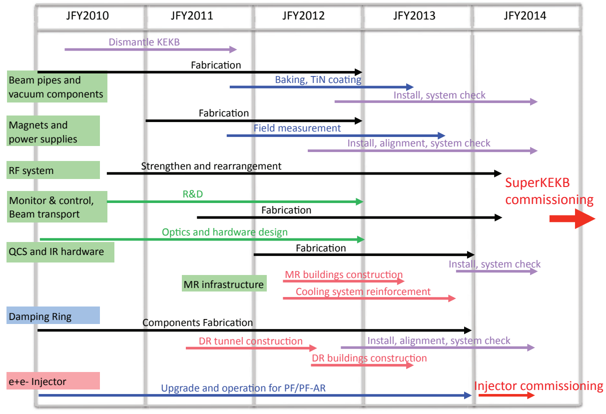


Figure 11: Construction schedule (K. Akai).

The construction schedule including a new positron damping ring and upgrade of the injector linac[23] are summarized in Fig. 11. The commissioning of SuperKEKB rings will start in the second half of JFY2014.

SUMMARY

Both SuperB and SuperKEKB projects have been approved and a new generation of B-factories has started. To realize the luminosity of $\sim 10^{36}\mathrm{cm}^{-2}\mathrm{s}^{-1}$, many other works not mentioned here are also steadily in progress. Both projects will push the luminosity frontier with competition and collaboration.

ACKNOWLEDGMENT

The authors would thank colleagues of SuperB and SuperKEKB Teams, especially M.E. Biagini for their stimulating discussion and helping with this report.

REFERENCES

[1] M. Masuzawa, FRXBNH01, IPAC10, Kyoto, Japan.
[2] SuperB Progress Report: The Collider, `http://arxiv.org/abs/1009.6178v3`.
[3] Belle II Technical Design Report, `http://xxx.lanl.gov/abs/1011.0352`.
[4] P. Raimondi, 2nd SuperB Meeting, Frascati (2006). P. Raimondi, MOZAKI02, PAC07, Albuquerque, USA. P. Raimondi, 11th SuperB Meeting, Frascati (2009).
[5] K. Ohmi, TUPEB015, IPAC10, Kyoto, Japan.
[6] M.E. Biagini, THPZ003, IPAC'11, San Sebastián, Spain.
[7] M.E. Biagini, 17th SuperB Meeting, Isola d'Elba (2011).
[8] P. Raimondi, 17th SuperB Meeting, Isola d'Elba (2011).
[9] M. Sullivan, 17th SuperB Meeting, Isola d'Elba (2011).
[10] P. Fabbricatore, 17th SuperB Meeting, Isola d'Elba (2011).
[11] E. Paoloni et al., WEPO026, IPAC'11, San Sebastián, Spain.
[12] M. Boscolo, 17th SuperB Meeting, Isola d'Elba (2011).
[13] S. Tomassini et al., TUPZ041, IPAC'11, San Sebastián, Spain. S. Tomassini et al., 17th SuperB Meeting, Isola d'Elba (2011).
[14] S. Guiducci et al., THPZ024, IPAC'11, San Sebastián, Spain.
[15] S. Liuzzo et al., WEPO013, IPAC'11, San Sebastián, Spain.
[16] T. Demma et al., WEPO105, IPAC'11, San Sebastián, Spain.
[17] M. Tawada et al., WEPO027, IPAC'11, San Sebastián, Spain.
[18] A. Morita et al., THPZ007, IPAC'11, San Sebastián, Spain.
[19] Y. Ohnishi et al., THPZ008, IPAC'11, San Sebastián, Spain.
[20] H. Nakano et al., THPZ009, IPAC'11, San Sebastián, Spain.
[21] H. Nakayama et al., THPZ010, IPAC'11, San Sebastián, Spain.
[22] K. Shibata et al., Europhysics Conf. on High-Energy Physics, Grenoble (2011).
[23] N. Iida et al., THYA01, IPAC'11, San Sebastián, Spain.