CRAB WAIST APPROACH: FROM DAΦNE TO SUPERB

M. Zobov, INFN LNF, Frascati, Italy
on behalf of the DAΦNE Collaboration Team* and the SuperB Accelerator Team#

Abstract

The crab waist collision scheme (CW) was proposed and successfully tested at the Φ-factory DAΦNE. At present this scheme is considered to be most attractive for the next generation lepton factories. In particular, the novel scheme is a key element of the SuperB project, a new SuperB-factory with luminosity about two orders of magnitude higher than that achieved at the present B-factories (KEKB and PEPII). In this paper we summarize the results achieved at DAΦNE after implementation of the CW collision scheme and discuss the status of the SuperB project.

INTRODUCTION

Pushing the luminosity of storage-ring colliders to unprecedented levels opens up unique opportunities for precision measurements of rare decay modes and extremely small cross sections, which are sensitive to new physics beyond the Standard Model.

Present generation lepton factories have been very successful in achieving their design luminosity performances [1]. However, new ideas were required in order to achieve a further substantial luminosity increase. Indeed, several novel collision concepts and new collision schemes have been proposed to provide such a qualitative step in the luminosity increase. The most known are the following: round beam collision preserving an additional integral of motion [2]; crab crossing [3, 4]; collision with large Piwinski angle [5] ("superbunch" in hadron colliders [6, 7]); longitudinal strong RF focusing [8]; collision with travelling waist [9]; crab waist collision [10, 11].

Now the crab waist collision scheme is considered to be most prominent for the next generation factories since it holds the promise of increasing the luminosity of the storage-ring colliders by 1-2 orders of magnitude beyond the current state-of-art, without any significant increase in beam current and without reducing the bunch length.

The CW scheme has been successfully tested at the electron-positron collider DAΦNE [12], the Italian Φ-factory operating at the energy of 1020 MeV in the center of mass. After an upgrade including the implementation of this novel collision scheme, the specific luminosity at low beam currents has been boosted by more than a factor of 4, while the present peak luminosity, 4.53×10^{32} $cm^{-2}s^{-1}$, is a factor of 3 higher than the maximum value obtained with the original configuration based on the standard collision scheme. The achieved peak luminosity is close (within 10%) to the design value in good agreement with numerical simulations [13].

The successful test has provided the opportunity to continue the DAΦNE Physics program. Moreover, advantages of the CW collision scheme have triggered several collider projects exploiting its potential [14, 15, and 16]. In particular, an international collaboration is pursuing the SuperB project [14] aiming at constructing in Italy a very high luminosity asymmetric collider at the Υ(4S) energy in the center of mass. The new SuperB factory is expected to reach a luminosity as high as 10^{36} $cm^{-2}s^{-1}$, i.e. 2 orders of magnitude higher than that achieved at present B-factories (KEKB and PEPII).

In the first section of this paper we discuss the basic concept and advantages of the CW scheme. In the following section we briefly describe results of the CW experimental test at DAΦNE. Finally, we overview the status of the SuperB accelerator project.

CRAB WAIST COLLISION SCHEME

The CW scheme can substantially increase collider luminosity since it combines several potentially advantageous ideas: collisions with a large Piwinski angle, micro-beta insertions and suppression of beam-beam resonances using dedicated ("crab waist") sextupoles. Let us consider two bunches colliding under a horizontal crossing angle θ (as shown in Fig. 1a). Then, the CW principle can be explained, somewhat artificially, in three basic steps.

*DAΦNE Team: D.Alesini, M.E.Biagini, C.Biscari, A.Bocci, R.Boni, M.Boscolo, F.Bossi, B.Buonomo, A.Clozza, G.O.Delle Monache, T.Demma, E.Di Pasquale, G.Di Pirro, A.Drago, A.Gallo, A.Ghigo, S.Guiducci, C.Ligi, F.Marcellini, G.Mazzitelli, C.Milardi, F.Murtas, L.Pellegrino, M.A.Preger, L.Quintieri, P.Raimondi, R.Ricci, U.Rotundo, C.Sanelli, M.Serio, F.Sgamma, B.Spataro, A.Stecchi, A.Stella, S.Tomassini, C.Vaccarezza, M.Zobov (LNF INFN); M.Schioppa (INFN,Cosenza); M.Esposito (La Sapienza); P.Branchini (INFN, Rome 3); F.Iacoangeli, P.Valente (INFN,Rome); E.Levichev, P.Piminov, D.Shatilov, V.Smaluk (BINP); N.Arnaud, D.Breton, L.Burmistrov, A.Stocchi, A.Variola, B.F.Viaud (LAL); S.Bettoni (CERN); K.Ohmi (KEK); D.Teytelman (Dimtel Inc.).

#SuperB Team: M.E.Biagini, R.Boni, M.Boscolo, B.Buonomo, T.Demma, A.Drago, S.Guiducci, G.Mazzitelli, L.Pellegrino, M.A.Preger, P.Raimondi, R.Ricci, C.Sanelli, M.Serio, A.Stella, S.Tomassini, M.Zobov (LNF INFN); K.Bertsche, A.Brachmann, A.Chao, R.Chestnut, M.Donald, C.Field, A.Fisher, D.Kharakh, A.Krasnykh, K.Moffeit, Y.Nosochkov, A.Novokhatski, M.Pivi, J.Seeman, M.K.Sullivan, A.Weidemann, J.Weisend, U.Wienands, W.Wittmer, M.Woods (SLAC); A.Bogomiagkov, I.Koop, E.Levichev, S.Nikitin, I.Okunev, P.Piminov, S.Siniyatkin, D.Shatilov, P.Vobly (BINP); F.Bosi, S.Liuzzo, E.Paoloni (Pisa University); J.Bonis, R.Chehab, O.Dadoun, G.Le Meur, P.Lepercq, F.Letellier-Cohen, B.Mercier, F.Poirier, C.Prevost, C.Rimbault, F.Touze, A.Variola (LAL); B.Bolzon, L.Brunetti, A.Jeremie (LAPP, Annecy); M.Baylac, O.Bourrion, J.M.DeConto, Y.Gomez, F.Meot, N.Monseu, D.Tourres, C.Vescovi (LPSC, Grenoble); A.Chancé, O.Napoly (CEA Saclay); D.P.Barber (DESY, Cockcroft Institute, Universty of Liverpool); S.Bettoni, D.Quatraro (CERN).

The **first one** is large Piwinski angle. For collisions with $\Phi=\theta\sigma_z/2\sigma_x>>1$ the luminosity L and the beam-beam tune shifts scale as (see, for example, [17]):

$$L \propto \frac{N\xi_y}{\beta_y^*};\quad \xi_y \propto \frac{N\sqrt{\beta_y^*/\varepsilon_y}}{\sigma_z\theta};\quad \xi_x \propto \frac{N}{(\sigma_z\theta)^2}$$

Clearly, in such a case, if it were possible to increase N proportionally to $\sigma_z\theta$, the vertical tune shift ξ_y would remain constant, while the luminosity would grow proportionally to $\sigma_z\theta$. Moreover, the horizontal tune shift would drop as $1/(\sigma_z\theta)$.

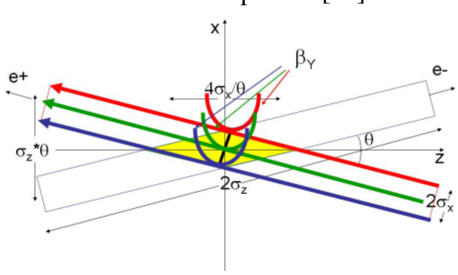
Differently from [6, 7], in the crab waist scheme the Piwinski angle is increased by decreasing the horizontal beam size and increasing the crossing angle. In this way we can gain in luminosity as well, and the horizontal tune shift decreases. Moreover, parasitic collisions (PC) become negligible since with higher crossing angle and smaller horizontal beam size the beam separation at the PC is large in terms of σ_x. But the most important effect is that the length of the overlap area of the colliding bunches is reduced, since it is proportional to σ_x/θ (see Fig. 1).

Then, as the **second step**, the vertical beta function β_y can be made comparable to the overlap area size (i.e. much smaller than the bunch length):

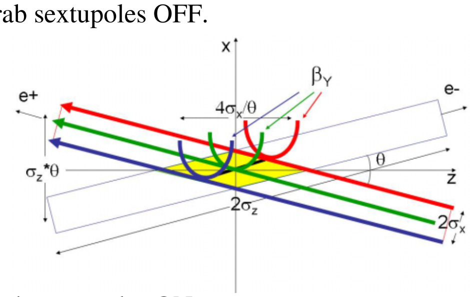
$$\beta_y^* \approx \frac{2\sigma_x}{\theta} \cong \frac{\sigma_z}{\Phi} << \sigma_z$$

It is worth noting that usually it is assumed that ξ_y (see the expression for L in (1)) always reaches the maximum allowed value, the so called "beam-beam limit". So, reducing β_y at the IP gives us several advantages:

- Luminosity increase with the same bunch current;
- Possibility of bunch current increase (if it is limited by ξ_y), thus further increasing the luminosity;
- Suppression of the vertical synchrobetatron resonances [18];
- Reduction of the vertical tune shift with the synchrotron oscillation amplitude [18].



a) Crab sextupoles OFF.



b) Crab sextupoles ON.

Figure 1: Crab Waist collision scheme.

Besides, there is an additional advantage 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. This certainly helps in solving the problems of HOM heating, coherent synchrotron radiation of short bunches, excessive power consumption, etc.

However, implementation of these two steps introduces new beam-beam resonances which may strongly limit the maximum achievable tune shifts. At this point the crab waist transformation enters the game boosting the luminosity. This is the **third step**. As can be seen in Fig. 1b, the beta function waist of one beam is oriented along the central trajectory of the other one. In practice the CW vertical beta function rotation is provided by sextupole magnets placed on both sides of the IP in phase with the IP in the horizontal plane and at π/2 in the vertical one (as shown in Fig. 2). The crab sextupole strength should satisfy the following condition depending on the crossing angle and the beta functions at the IP and the sextupole locations:

$$K = \frac{1}{\theta}\frac{1}{\beta_y^*\beta_y}\sqrt{\frac{\beta_x^*}{\beta_x}}$$

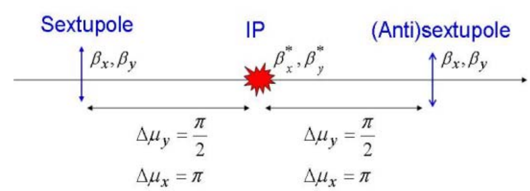


Figure 2: Crab sextupole locations.

The crab waist transformation gives a small geometric luminosity gain due to the vertical beta function redistribution along the overlap area. It is estimated to be of the order of several percent. However, the dominating effect comes from the suppression of betatron (and synchrobetatron) resonances arising (in collisions without CW) from the vertical motion modulation by the horizontal betatron oscillations [19].

Figure 3 demonstrates the resonances suppression applying the frequency map analysis (FMA) for the beam-beam interaction in CW collisions [20]. It shows the beam-beam footprint for DAΦNE with CW sextupoles off (left) and on (right).

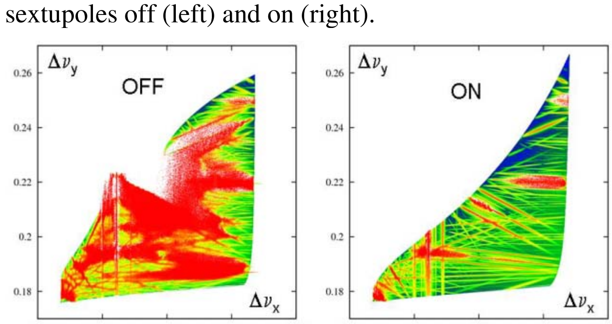


Figure 3: Beam-beam footprint with crab sextupoles off (left) and on (right) obtained by FMA techniques [20].

EXPERIMENTAL TEST AT DAΦNE

In 2007 the Φ-factory DAΦNE was upgraded implementing the crab waist collision scheme. This required major changes in the design of the mechanical and magnetic layout of both collider interaction regions [21]. Table 1 shows a comparison of the main beam parameters for the DAΦNE upgrade with those of the previous runs for the KLOE and FINUDA experiments.

As one can see from Table 1 the Piwinski angle was increased and the collision region length reduced by doubling the crossing angle, decreasing the horizontal beta function almost by an order of magnitude and slightly decreasing the horizontal emittance. In turn, the vertical beta function at the interaction point was decreased by a factor 2. The crab waist transformation is provided by two electromagnetic sextupoles installed at both ends of the experimental interaction region with the required phase advances between them and the IP. Their integrated gradient is about a factor 5 higher than that of normal sextupoles used for chromaticity correction.

Right from the start of commissioning, the effectiveness of the new collision scheme was confirmed by several measurements and qualitative observations of the beam-beam behavior. The simplest and most obvious test consisted in switching off the crab waist sextupoles of one of the colliding beams. This blew up both horizontal and vertical transverse beam sizes of that beam and created non-gaussian tails of the beam distribution, seen on the synchrotron light monitors (Fig. 4). At the same time, a luminosity reduction was recorded by all the luminosity monitors. This behavior is compatible with the prediction of additional beam-beam resonances when the crab sextupoles are off.

Table 1. DAΦNE best luminosity and respective IP parameters for three experimental runs.

Parameters	KLOE	FINUDA	Siddharta
Date	Sept 05	Apr 07	June 09
Luminosity, $cm^{-2}s^{-1}$	$1.53x10^{32}$	$1.60x10^{32}$	$4.53x10^{32}$
e– current, A	1.38	1.50	1.43
e+ current, A	1.18	1.10	1.00
Number of bunches	111	106	105
ε_x, mm mrad	0.34	0.34	0.25
β_x, m	1.5	2.0	0.25
β_y, cm	1.8	1.9	0.93
Crossing angle, mrad	2x12.5	2x12.5	2x25
Tune shift, ξ_y	0.0245	0.0291	0.044

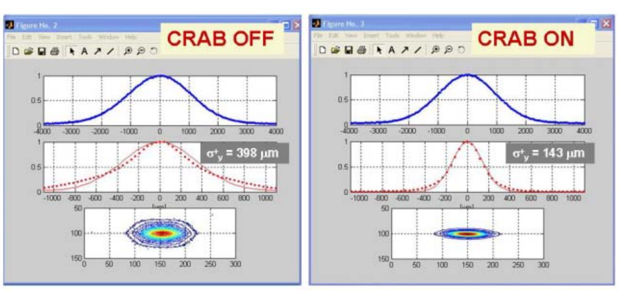


Figure4: Transverse beam profiles with crab on and off.

The best peak luminosity of $4.53x10^{32}$ $cm^{-2}s^{-1}$ was obtained in June 2009 together with a daily integrated luminosity exceeding $15pb^{-1}$. As one can see from Table 1, the best present luminosity is by a factor 3 higher than that in the runs before the upgrade. The maximum peak luminosity is already very close to the design value of $5x10^{32}$ $cm^{-2}s^{-1}$, and work is still in progress to achieve this ultimate goal. The vertical tune shift parameter has been significantly improved and it is now as high as 0.044 (a factor 1.5 higher than before). It is worth mentioning that in weak-strong collisions when the electron beam current is much higher than the positron one the tune shift has reached almost 0.09, in a perfect agreement with numerical simulations [13].

SUPERB ACCELERATOR PROJECT

The crab waist collision is the basic concept of the SuperB project [14] aimed at the construction of a very high luminosity asymmetric e+e- flavour factory with a possible location either near the campus of the University of Rome at Tor Vergata or at the site of the INFN Frascati National Laboratories. Figure 5 shows the SuperB layout at the Frascati (INFN LNF) site.

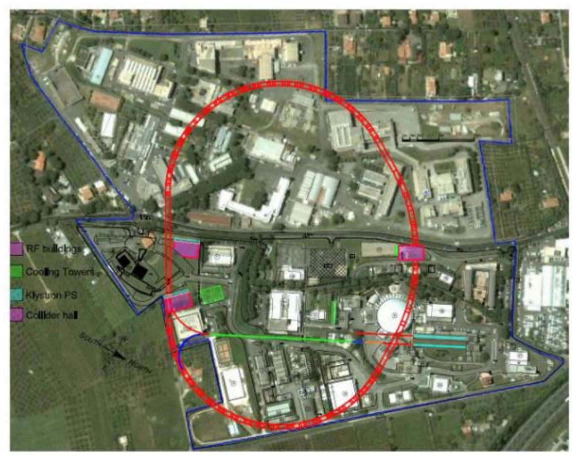


Figure 5: SuperB footprint at LNF.

The SuperB accelerator is being designed to satisfy the following requirements:

- Very high luminosity, > 10^{36} $cm^{-2}s^{-1}$;
- Longitudinally polarized beam (e-) at IP (>80%);
- Ability to collide at charm threshold (3.8 GeV c.m.);
- Flexible parameter choice;
- Flexible lattice.

Column 1 of Table 2 shows the baseline parameter set that relies on the following criteria:

- to maintain wall plug power, beam currents, bunch lengths, and RF requirements comparable to present B-Factories, with parameters as close as possible to those achieved or under study for the ILC Damping Ring and at the ATF ILC-DR test facility;
- to reuse as much as possible of the PEP-II hardware;
- to simplify the IR design as much as possible, reducing the synchrotron radiation in the IR, HOM power and increasing the beam stay-clear;

- to eliminate the effects of the parasitic beam crossing, at the same time relaxing as much as possible the requirements on the beam demagnification at the IP;
- to design a Final Focus (FF) system to follow as closely as possible existing systems, and integrating it as much as possible into the ring design.

The machine is designed to have flexibility for the parameters choice with respect to the baseline: the horizontal emittance can be decreased by a factor of ~2 in both rings by changing the partition number (by changing the RF frequency, as done in LEP, or the orbit in the arcs) and the natural emittance by readjusting β functions.

Moreover the FF system has a built-in capability for decreasing the IP β functions by a factor of ~2, and the RF system will be able to support higher beam currents than the baseline, when all the available PEP RF units will be installed.

Based on these considerations, columns 2 and 3 in Table 2 show different parameters options:

- "Low Emittance" case relaxes RF requirements and problems related to high current operations (including wall-plug power) but puts more strain on the optics and the tuning capabilities;
- "High Current" case relaxes requirements on vertical emittance and IP β functions, but high currents issues are enhanced in terms of instabilities, HOM, synchrotron radiation, wall-plug power, etc.

The cases considered have several parameters kept as much constant as possible (bunch length, IP stay clear etc…), in order to reduce their impact on other unwanted effects (Detector background, HOM heating etc…).

SuperB can also operate at lower cm energy (τ/charm threshold energies near 3.8 GeV) with a somewhat reduced luminosity and minimal modifications to the machine: the beam energies will be scaled, maintaining the nominal energy asymmetry ratio used for operation at the cm energy of the Y (4S). The last column in Table 2 shows preliminary parameters for the run at the τ/charm.

Table 2: SuperB parameters for baseline, low emittance and high current options, and for τ/charm running.

		Base Line		Low Emittance		High Current		τ-charm	
Parameter	**Units**	**HER (e+)**	**LER (e-)**	**HER (e+)**	**LER (e-)**	**HER (e+)**	**LER (e-)**	**HER (e+)**	**LER (e-)**
LUMINOSITY	**$cm^{-2} s^{-1}$**	**1.00E+36**		**1.00E+36**		**1.00E+36**		**1.00E+35**	
Energy	**GeV**	6.7	4.18	6.7	4.18	6.7	4.18	2.58	1.61
Circumference	**m**	1258.4		1258.4		1258.4		1258.4	
X-Angle (full)	**mrad**	66		66		66		66	
β_x @ IP	**cm**	2.6	3.2	2.6	3.2	5.06	6.22	6.76	8.32
β_y @ IP	**cm**	0.0253	0.0205	0.0179	0.0145	0.0292	0.0237	0.0658	0.0533
Coupling (full current)	**%**	0.25	0.25	0.25	0.25	0.5	0.5	0.25	0.25
Emittance x (with IBS)	**nm**	2.00	2.46	1.00	1.23	2.00	2.46	5.20	6.4
Emittance y	**pm**	5	6.15	2.5	3.075	10	12.3	13	16
Bunch length (full current)	**mm**	5	5	5	5	4.4	4.4	5	5
Beam current	**mA**	1892	2447	1460	1888	3094	4000	1365	1766
RF frequency	**MHz**	476.		476.		476.		476.	
Number of bunches	**#**	978		978		1956		1956	
Tune shift x		0.0021	0.0033	0.0017	0.0025	0.0044	0.0067	0.0052	0.0080
Tune shift y		0.097	0.097	0.0891	0.0892	0.0684	0.0687	0.0909	0.0910
Total RF Wall Plug Power	**MW**	16.38		12.37		28.83		2.81	

RINGS LATTICE

The SuperB HER and LER ring lattices need to comply with several constraints: first of all extremely low emittances and IP beam sizes, needed for the high luminosity, damping times, beam lifetimes and polarization for the electron beam. The rings can be basically considered as two Damping Rings (similar to ILC and CLIC ones) with the constraint to include a FF section for collisions. So, the challenge is not only how to achieve low emittance beams but how to choose the other beam parameters to be able to reach design luminosity with reasonable lifetimes and small beams degradation. For this purpose a new "Arc cell" design has been adopted for SuperB [22]. The extremely low-β in the FF system, together with the Crab Waist scheme, requires a special optics that provides the necessary beam demagnification at the IP, corrects its relative chromaticity and provides the necessary conditions and constraints for the "Crab Waist" optics.

Both rings are located in the horizontal plane. The FF is combined with the two arcs in two half-rings (one inner, one outer) and a straight section on the opposite side, which comes naturally to close the ring and readily accommodate the RF system and other necessities (e.g. injection). In this utility region crossing without collisions for the two rings will be provided. More details on the lattice can be found in Ref [22].

INTERACTION REGION

The high luminosity is achieved primarily with the implementation of very small β_x^* and β_y^* values at IP. These conditions are principal driving terms in the design of the IR. The FF doublet (QD0 and QF1) must be as close as possible to the IP in order to minimize chromatic and other higher-order aberrations from these magnet fields. The present IR design with a crossing angle of +/-33 mrad uses separate focusing elements for each beam. The QD0 magnet is now a twin design of side-by-side super-conducting quadrupoles. The magnet windings are designed so that the fringe field of the neighbouring magnet can be cancelled maintaining high quality quadrupole fields for both beams. Further details about the IR design can be found in the Ref [23].

POLARIZATION

SuperB will achieve polarized beams by injecting polarized electrons into the LER. We chose the LER rather than the HER because the spin rotators employ solenoids which scale in strength with energy.

In SuperB at high luminosity the beam lifetime will be only 3…5 minutes and continuous-injection ("trickle-charge") operation is a key component of the proposal. By injecting at a high rate with a polarized beam one can overcome the depolarization in the ring as long as the spin diffusion is not too rapid. In the ring arcs the polarization must be close to vertical to minimize depolarization. In order to obtain longitudinal polarization at the IP, a rotation of the spin by 90° about the radial axis is required. A rotation of 90° in a solenoid followed by a spin rotation of 90° in the horizontal plane by dipoles also provides the required net rotation about the radial axis without vertical bending and was therefore adopted. The solenoid field integral required is 21.88 Tm for 90° spin rotation, well within the technical capabilities of superconducting solenoids of the required aperture. After the IP, the polarization has to be restored to vertical by a second spin rotator. Due to the low beam lifetime, it turns out that a symmetric spin-rotator scheme is feasible and can achieve 70% polarization or better. More details on these studies can be found in Ref [24].

INJECTION SYSTEM

The injection system for SuperB [25] is capable of injecting electrons and positrons into their respective rings at full energies. The HER requires positrons at 6.7 GeV and the LER 4.18 GeV polarized electrons. At full luminosity and beam currents, up to 4 A, the HER and LER have expected beam lifetimes in the range of 3÷5 minutes. Thus, the injection process must be continuous, to keep nearly constant beam current and luminosity. Multiple bunches are injected on each linac pulse into one or the other of the two rings. Electrons from the gun source are longitudinally polarized: the spins are rotated to the vertical plane in a special transport section downstream the gun. The spins then remain vertical for the rest of the injection system and injected in this vertical state into the LER. Positron bunches are generated by striking a high charge electron bunch onto a positron converter target and collecting the emergent positrons. Electron to positron conversion is done at about 0.6 GeV using a newly designed capture section to produce a yield of more than 10% [26]. The transverse and longitudinal emittances of both beams are larger than the LER and HER acceptances and must be pre-damped. A specially designed Damping Ring at 1 GeV, shared by both beams to reduce costs, is used to reduce the injected beam emittances.

REFERENCES

[1] ICFA Beam Dynamics Letter 48, April 2009.
[2] V.V.Danilov et al., EPAC96, p.1149.
[3] R.B.Palmer, SLAC-PUB-4707, 1988.
[4] K.Oide, K.Yokoya, Phys.Rev.A40:315-316, 1989.
[5] K.Hirata, Phys.Rev.Lett.74:2228-2231,1995.
[6] K.Takayama et al., Phys.Rev.Lett.88:144801,2002.
[7] F.Ruggiero, F.Zimmermann, Phys. Rev. ST Accel. Beams 5:061001, 2002.
[8] A.Gallo et al., e-Print:physics/0404020, 2004. A.Gallo et al., e-Print:physics/0309066, 2003.
[9] Y.Ohnishi, ICFA Beam Dyn.Newslett.48:252, 2009.
[10] P.Raimondi, in 2nd SuperB Workshop, 2006.
[11] P.Raimondi et al., e-Print:physics/0702033, 2007.
[12] M.Zobov et al., Phys.Rev.Lett.104:174801, 2010. C.Milardi et al., Nuovo Cim.32C:379-382, 2009. C.Milardi et al., Int.J.Mod.Phys.A24:360-368, 2009.
[13] M.Zobov, e-Print: arXiv:1006.1207, 2010. M.Zobov et al., ICFA Beam Dyn.Newslett. 48, p.34, 2009.
[14] SuperB CDR, e-Print: arXiv:0709.0451, 2007. M.E.Biagini et al., Nuovo Cim.123B:987-990, 2008.
[15] M.Masuzawa, IPAC10, p. 4764.
[16] E.Levichev, Phys.Part.Nucl.Lett.5:554-559, 2008.
[17] D.Shatilov, M.Zobov, ICFA Beam Dyn.Newslett. 37, p.99, 2005.
[18] D.V.Pestrikov, Nucl.Instrum.A336:427-437, 1993.
[19] P.Raimondi, D.Shatilov and M.Zobov, EPAC08, p.2620.
[20] E.Levichev at al., e-Print: arXiv:1002.3733, 2010.
[21] C.Milardi et al., e-Print: arXiv:0803.1450.
[22] M.Biagini et al., IPAC10, p.1521.
[23] M.K.Sullivan et al., IPAC10, p.1581.
[24] U.Wienands et al., IPAC10, p.1587.
[25] R.Boni et al., IPAC10, p.3685.
[26] F. Poirier et al., IPAC10, p.1650.