Test of "Crab-Waist" Collisions at the DAΦNE Φ Factory

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The electron-positron collider DAΦNE, the Italian Φ factory, has been recently upgraded in order to implement an innovative collision scheme based on large crossing angle, small beam sizes at the crossing point, and compensation of beam-beam interaction by means of sextupole pairs creating a "crab-waist" configuration in the interaction region. Experimental tests of the novel scheme exhibited an increase by a factor of 3 in the peak luminosity of the collider with respect to the performances reached before the upgrade. In this Letter we present the new collision scheme, discuss its advantages, describe the hardware modifications realized for the upgrade, and report the results of the experimental tests carried out during commissioning of the machine in the new configuration and standard operation for the users.

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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.

In high luminosity colliders with conventional collision schemes the key requirements to increase the luminosity are: very small vertical beta function β_y at the interaction point (IP), high beam intensity and large horizontal emittance ε_x and beam size σ_x. However, β_y cannot be much smaller than the longitudinal rms bunch size (bunch length) σ_z without incurring the "hour-glass" effect. Unfortunately, it is very difficult to shorten the bunch in a high current ring without exciting collective instabilities. Even then, the large beam current may result in high power losses, beam instabilities and dramatic increase of the wall-plug power. These problems can be overcome with the recently proposed crab-waist (CW) scheme of beam-beam collisions [1,2] where a substantial luminosity increase can be achieved without bunch length reduction and with moderate beam currents.

The CW scheme has been successfully tested at the electron-positron collider DAΦNE, the Italian Φ factory [3,4] 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 is a factor of 3 higher than the maximum value obtained with the original configuration based on the standard collision scheme.

The successful test has provided the opportunity to continue the DAΦNE physics program. Moreover, the advantages of the crab-waist collision scheme have triggered several collider projects exploiting its potential. In particular, physics and accelerator communities are discussing new projects of a SuperB factory [5,6] and a Super-Tau-Charm factory [7] with luminosities about 2 orders of magnitude beyond those achieved at the present *B*- [8] and Tau-charm factories [9].

In this Letter we briefly introduce the CW concept, shortly discuss the hardware modifications implemented and summarize principal results achieved during collider commissioning and experimental tests.

The crab-waist scheme of beam-beam collisions can substantially increase luminosity of a collider since it combines several potentially advantageous ideas. Let us consider two bunches colliding at a horizontal crossing angle θ [as shown in Fig. 1(a)]. Then, the CW principle

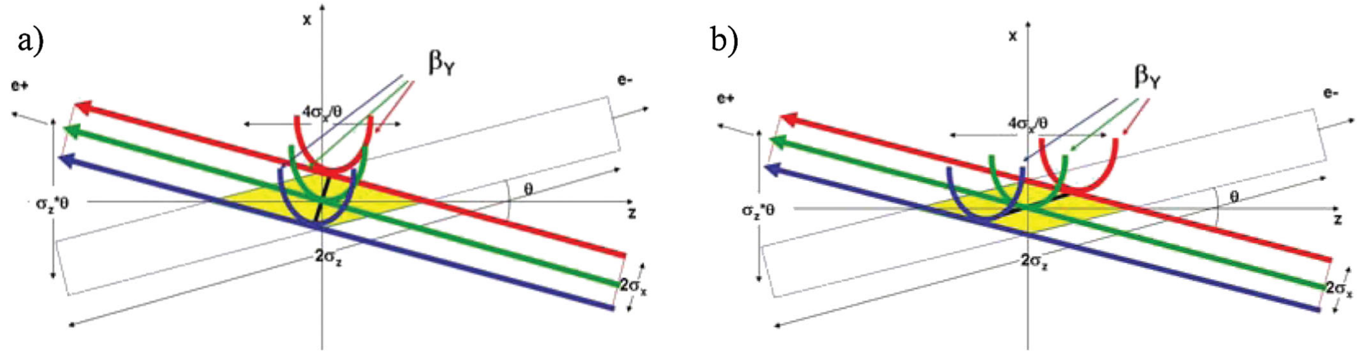

FIG. 1 (color). Crab-waist collision scheme. The color straight lines show directions of motion for particles with different horizontal deviations from the central orbit. The arrows indicate the corresponding β function variations along these trajectories.

can be explained, somewhat artificially, in three basic steps. The first one is large Piwinski angle.

For collisions at a crossing angle θ the luminosity L and the beam-beam tune shifts scale as [10]

$$L \propto \frac{N\xi_y}{\beta_y^*}; \qquad \xi_y \propto \frac{N\sqrt{\beta_y^*/\varepsilon_y}}{\sigma_z\theta}; \qquad \xi_x \propto \frac{N}{(\sigma_z\theta)^2}, \quad (1)$$

N being the number of particles per bunch. Here we consider the case of flat beams, small horizontal crossing angle $\theta \ll 1$ and large Piwinski angle $\varphi \gg 1$, defined as

$$\varphi = \frac{\sigma_z}{\sigma_x}\tan\left(\frac{\theta}{2}\right) \approx \frac{\sigma_z}{\sigma_x}\frac{\theta}{2}. \quad (2)$$

The idea of colliding with a large Piwinski angle is not new (see, for example, [11]). It has been also proposed for hadron colliders [12,13] to increase the bunch length and the crossing angle. 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 $\sigma_z\theta$; see (1). Moreover, the horizontal tune shift ξ_x drops like $1/\sigma_z\theta$. However, unlike [12,13], in the present 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 becomes larger in terms of σ_x. But the most important effect is that the length of the overlap region 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 length of the overlap region (i.e., much smaller than the bunch length):

$$\beta_y^* \approx \frac{\sigma_x}{\theta} \ll \sigma_z. \quad (3)$$

It is worth remarking 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: (i) Luminosity increase with the same bunch current. (ii) The possibility of bunch current increase and corresponding luminosity increase as follows from (1). (iii) Suppression of vertical synchrobetatron resonances [14]. (iv) Reduction of the vertical tune shift with synchrotron oscillation amplitude [14].

Besides, there are additional advantages in such a collision scheme: there is no need to decrease the bunch length in order to increase the luminosity as proposed in standard upgrade plans for B and Φ factories in the past [15]. This will certainly help to solve the problems of electromagnetic high order mode heating, coherent synchrotron radiation of short bunches, excessive power consumption, etc.

However, the large Piwinski angle itself introduces new beam-beam resonances which may strongly limit the maximum achievable tune shifts (see [16], for example). At this point the third step, the crab-waist transformation, enters the game and boosts the luminosity. As can be seen in Fig. 1(b), the beta function waist of one beam depends on the horizontal position of the particles and is oriented along the central trajectory of the other one. The CW vertical β function rotation is provided by sextupole magnets placed on both sides of the IP in counterphase with the IP in the horizontal plane and at $\pi/2$ 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 β functions at the interaction point (IP) (indicated with an aster-

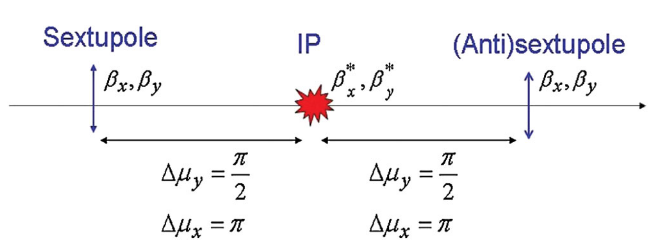

FIG. 2 (color). Crab sextupole locations.

isk) and the sextupole locations:

$$K = \frac{1}{\theta} \frac{1}{\beta_y^* \beta_y} \sqrt{\frac{\beta_x^*}{\beta_x}}. \quad (4)$$

The crab-waist transformation yields a small geometric luminosity gain due to the vertical β function redistribution along the overlap area. It is estimated to be of the order of several percent [17]. 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 [2,18,19].

In 2007, during a five-month shutdown for the installation of the new experimental detector SIDDHARTA, DAΦNE was upgraded implementing the new collision scheme based on the large Piwinski angle and the crab-waist transformation. This required major changes in the design of the mechanical and magnetic layout of both collider interaction regions [3,20]. Table I shows a comparison of the main beam parameters for the DAΦNE upgrade with those of the previous collider runs for the KLOE and FINUDA experiments [21].

As one can see from Table I, 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 β function at the interaction point was decreased by a factor of 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 of 5 higher than that of normal sextupoles used for chromaticity correction.

In addition, several other hardware modifications were made to improve performance. Among them are [22]: (i) New low impedance bellows design; (ii) new fast injection kicker design; (iii) commissioning of a new luminosity monitor consisting of three different devices; (iv) upgrades of the control and feedback system; (v) removal of ion clearing electrodes; (vi) repositioning of several magnetic elements to provide optics flexibility and better dynamic aperture.

DAΦNE operation restarted at the end of November 2007. Careful machine optics modeling (both linear and nonlinear) plus misalignment and error correction helped to achieve the required parameters at the IP and to obtain a transverse emittance ratio as low as 0.2% for both electron and positron beams. The low coupling together with the low beta function provided the smallest vertical beam size at the IP (3.5 μm) ever measured at DAΦNE.

The design of the upgraded vacuum chamber, including smoother interaction region vacuum pipes, new bellows, new injection kickers, and removal of ion clearing electrodes reduced the coupling impedances of the positron and electron rings by about 50% and 70%. This provided shorter bunches and more stable colliding beams [23].

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 a luminosity reduction was recorded by all the luminosity monitors (see Fig. 3). This behavior is compatible with the prediction of additional beam-beam resonances when the crab sextupoles are off.

The best peak luminosity of 4.53×10^{32} cm^{-2} s^{-1} was obtained in June 2009 together with a daily integrated luminosity exceeding 15 pb^{-1}. Table I summarizes the luminosity and tune shifts for the best DAΦNE luminosity runs for the three main experiments carried out on the collider. As one can see from this Table, the best present luminosity is a factor of 3 higher than that in the runs before the upgrade. The maximum peak luminosity is already very close to the design value of 5×10^{32} cm^{-2} s^{-1}, and work is still in progress to achieve this ultimate goal.

TABLE I. DAΦNE luminosity and IP parameters for 3 experimental runs.

Parameter	KLOE	FINUDA	SIDDHARTA
Date	September 2005	April 2007	June 2009
Luminosity (cm^{-2} s^{-1})	1.53×10^{32}	1.60×10^{32}	4.53×10^{32}
$e-$ current (A)	1.38	1.50	1.52
$e+$, 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
Bunch length, σ_z (cm)	1.5–2.0	1.5–2.0	1.5–2.0
Crossing angle (mrad)	2×12.5	2×12.5	2×25
ξ_y	0.025	0.029	0.044

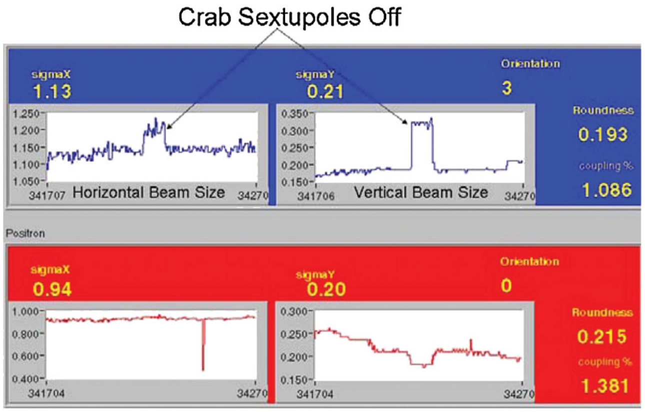

FIG. 3 (color). Transverse beam sizes at the synchrotron light monitors (electrons: blue windows, positrons: red windows).

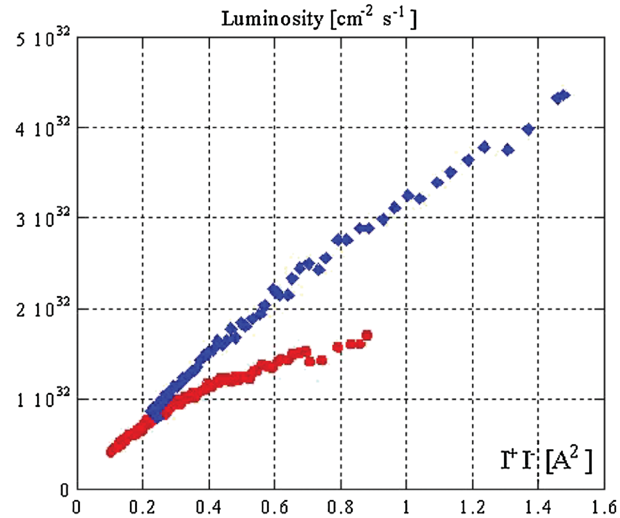

FIG. 4 (color). Measured luminosity as a function of beam current product for crab sextupoles on (blue) and off (red).

The luminosity gain was obtained partly from the ‘‘micro-beta’’ collision optics—the high Piwinski angle with the smaller vertical beta function (a factor of 2) comparable to the small collision region length (step 1 and step 2). Another factor in the luminosity increase comes from improvements in beam dynamics, especially the beam-beam resonance suppression in crab-waist collisions (step 3). Indeed, as can be seen in the last row of Table I, the vertical tune shift parameter has been significantly improved and now it is as high as 0.044 (a factor of 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 exceeded 0.074 (as inferred from measurements of luminosity and beam parameters in collision).

A comprehensive numerical simulation study has been undertaken for comparison with the experimental data and test once more the effectiveness of the crab-waist collision scheme [24]. In particular, we have found that the measured luminosity is only 15%–20% lower than predicted by the strong-strong simulations. In our opinion, this is a good agreement given that the ideal strong-strong simulations do not take into account many factors, both single- and multibunch, affecting the luminosity such as: lattice nonlinearities, *e*-cloud effects, trapped ions, wake fields, gap transients, hardware noise, etc.

To complete the CW scheme studies with a kind of control experiment, we have devoted several hours to tuning the collider with the crab sextupoles off. Figure 4 shows a comparison of the luminosity as a function of beam current product obtained with the crab sextupoles on and off.

The maximum luminosity reached in the latter case was only 1.6–1.7 $\times 10^{32}$ cm^{-2} s^{-1}. It is worth remarking that another drawback becomes very important in collision without the crab sextupoles: besides much bigger vertical blow up leading to luminosity decrease, a sharp lifetime reduction was observed at single bunch currents as low as 8–10 mA. For this reason the red curve in Fig. 4 stops at much lower beam currents. Such a behavior is also consistent with numerical predictions based on beam-beam simulations taking into account realistic lattice nonlinearities [24].

In conclusion we can say that the crab-waist collision test at the electron-positron collider, Φ-factory, DAΦNE has been successful providing a factor of 3 luminosity increase. The achieved peak luminosity is close (within 10%) to the design value and is in a good agreement with numerical simulations.

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