CRAB WAIST COLLISION SCHEME: NUMERICAL SIMULATIONS VERSUS EXPERIMENTAL RESULTS

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Abstract

A novel scheme of crab waist collisions has been successfully tested at the electron-positron collider DAΦNE, Italian Φ-factory. In this paper we compare numerical simulations of the crab waist beam-beam interaction with obtained experimental results. For this purpose we perform strong-strong simulations and weak-strong beam-beam simulations using a realistic DAΦNE lattice model that has proven to reproduce reliably both linear and nonlinear collider optics.

INTRODUCTION

In colliders with standard collision schemes the key requirements to achieve a high luminosity are: very small vertical beta function β_y at the interaction point (IP); high beam intensity I; small vertical emittance ε_y and large horizontal beam size σ_x and horizontal emittance ε_x. However, β_y can not be much smaller than the bunch length σ_z without incurring in the "hour-glass" effect. It is, unfortunately, very difficult to shorten the bunch in a high current ring without exciting instabilities. In turn, the beam current increase may result in high beam power losses, beam instabilities and a remarkable enhancement 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 already successfully tested at DAΦNE, the Italian Φ-factory [3, 4] and the most recent results of the experiment are reported in this Conference [5]. The main purpose of this paper is to compare the obtained experimental data with numerical simulation results. This is required in order to accomplish the following tasks:

- to prove that the crab waist concept works as predicted by numerical simulations,
- to benchmark existing numerical codes versus experimental measurements.

Such tasks are particularly important for the design of the future e+e- factories based on the crab waist idea, such as the SuperB factory in Italy [6], the Tau-Charm factory in Novosibirsk [7] and others.

In the following we briefly summarize the results achieved at DAΦNE with the new collision scheme and compare the experimental results with those obtained numerically. For this purpose we use both weak-strong and strong-strong beam-beam simulations.

ACHIEVED RESULTS

Table 1 summarizes the luminosity and corresponding parameters at the interaction point (IP) for the best DAΦNE luminosity runs for the three main experiments carried out on the collider. The first and the second column correspond to the results achieved with the KLOE and FINUDA detectors before the DAΦNE upgrade based on the crab waist concept [8, 9]. The third column shows results obtained during the current run with the SIDDHARTA experiment after the collider upgrade [5].

As one can see from Table 1, the best present luminosity is by almost a factor of 3 higher than in the previous runs before the upgrade. The obtained luminosity of $4.4\text{x}10^{32}$ $cm^{-2}s^{-1}$ is already very close to the upgrade design value of $5\text{x}10^{32}$ $cm^{-2}s^{-1}$, and work is still in progress to achieve this ultimate goal.

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

Parameters	KLOE	FINUDA	Siddharta
Date	Sept 05	Apr 07	Apr 09
Luminosity, $cm^{-2}s^{-1}$	$1.5\text{x}10^{32}$	$1.6\text{x}10^{32}$	$4.5\text{x}10^{32}$
e– current, A	1.38	1.50	1.43
e+ current, A	1.18	1.10	1.10
Number of bunches	111	106	107
ε_x, mm mrad	0.34	0.34	0.25
β_x, m	1.5	2.0	0.25
β_y, m	1.8	1.9	0.93
Crossing angle, mrad	2x12.5	2x12.5	2x25
Tune shift, ξ_y	0.0245	0.0291	0.042

Partly the luminosity gain has been reached due to implementation of the "micro-beta" collision optics – the large Piwinski angle with the smaller vertical beta function comparable to the small collision area (see, steps 1 and 2 in [10]). Another factor in the luminosity increase coming from improvements in beam dynamics, first of all due to beam-beam resonance suppression in the crab waist collisions [11]. Indeed, as it is seen in the last row of Table 1, the vertical tune shift has been significantly increased and now it is as high as 0.042. It is worth mentioning that in weak-strong collisions when the electron beam current was much higher than the positron one the vertical tune shift has exceeded 0.06.

IDEAL STRONG-STRONG SIMULATIONS

In order to benchmark the numerical codes that have been used for the crab waist collision studies for the DAΦNE upgrade [12] and SuperB CDR [6] we have compared the DAΦNE experimental data with numerical results. For this purpose we have used both weak-strong and strong-strong beam-beam numerical simulations.

First preliminary simulations with the weak-strong code LIFETRAC [15] have shown that for present DAΦNE parameters (tunes, bunch length, crab waist sextupole strength etc.) both beams are blown up that correspond to experimental observations. For this reason we have passed to strong-strong simulations with the BBSS [17] code. Some of the simulation results are shown in Fig.1 and Fig. 2. The single bunch luminosity with CW sextupoles on (red curve) and off (blue curve) as a function of the number of revolution turns is shown in Fig.1. Here we remind that the radiation damping time is very long for DAΦNE (110.000 turns). In turn, the corresponding vertical size blow up for the electron (blue) and positron (red) beams for the cases with CW sextupoles on (left picture) and off (right picture) are shown in Fig. 2.

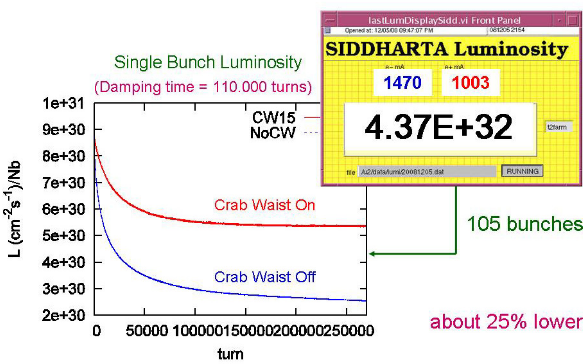

Figure 1: Simulated DAΦNE luminosity for CW on (red curve) and off (blue curve) versus number of turns.

As we can see, a high luminosity gain is predicted by the simulations with the crab sextupoles on. However, even with CW on both beams are remarkably blown up and the blow up becomes dramatic when the CW sextupoles are off.

Comparing the numerical result with the best single bunch luminosity of 4.2x10^{30} cm^{-2}s^{-1} achieved in collision with 105 bunches, we see that the experimental result is by about 20-25% lower than the numerical one. In our opinion, this is a good agreement since the very ideal single bunch simulations do not take into account many other factors, both single- and multibunch, affecting the luminosity such as: lattice nonlinearities, e-cloud effects, trapped ions, wake fields, gap transients, hardware noise etc. Indeed, when colliding 20 bunches instead of nominal 105 in order to decrease the influence of the multibunch high current effects we have measured a higher single bunch luminosity of 4.4x10^{30} cm^{-2}s^{-1}, closer to the ideal simulations.

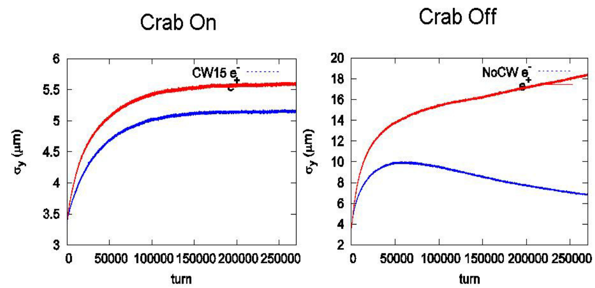

Figure 2: Vertical size blow up for CW on (left plot) and off (right plot).

Anyway, the maximum luminosity achieved experimentally with the CW sextupoles on is by a factor of 1.7 higher than the ideal one predicted numerically for the case of CW sextupoles switched off. This is a clear proof that the crab waist concept works. However, in order to complete the studies we have dedicated several hours tuning the collider with the CW sextupoles off. Fig. 3 shows a comparison of the luminosity as a function of beam current product obtained with crab sextupoles on and off. The maximum single bunch luminosity reached in the latter case was of the order of 1.6-1.7x10^{30} cm^{-2}s^{-1}. This result is also consistent with numerical predictions. However, another limitation becomes very important in collision without crab waist sextupoles: besides much bigger vertical blow up, a sharp lifetime reduction is observed already at single bunch currents of 8-10 mA. That is why the red curve in Fig.3 is interrupted at much lower currents. A reasonable explanation of the lifetime reduction is given in the next paragraph.

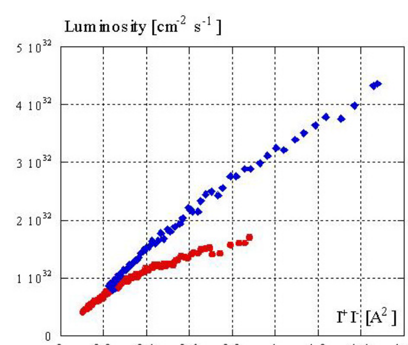

Figure 3: Measured luminosity as a function of beam currents product, CW on (blue) and off (red).

BEAM-BEAM SIMULATIONS WITH REALISTIC LATTICE

According to the past DAΦNE experience we learned that both luminosity and especially beam lifetime can be affected by a crosstalk between lattice nonlinearities and beam-beam interactions [13]. In particular, dedicated octupoles installed in DAΦNE in order to correct cubic lattice nonlinearities have been found to be very useful for lifetime improvement in beam-beam collisions [14].

So, in order to estimate the impact of machine nonlinearities on the luminosity performance in the crab waist scheme, we have carried out computer simulations of beam dynamics and luminosity at DAΦNE with a realistic lattice including crab and chromatic sextupoles, damping wigglers, magnet fringe fields, etc. During this study the beam-beam interaction simulation was provided by the LIFETRAC code [15], while tracking of the particles along the machine lattice was performed by another software called ACCELERATICUM [16] allowing particles to pass through the variety of storage ring lattice elements in a symplectic way.

Initially we have performed a detailed study of the DAΦNE nonlinear lattice without beam collisions to better understand particle's motion with nonlinear perturbations. In particular, dynamic aperture scans for on- and off-energy particles have been revealed that there are no dangerous resonances in the vicinity of the present working point and the dynamic aperture is reasonably large in both planes, see Fig. 4. As can be seen, the on-energy dynamic aperture exceeds 12 σ_x, while the vertical one is about 80 σ_y. The aperture remains reasonable also for energy deviations of ±0.3% corresponding to ±7.5 σ_E.

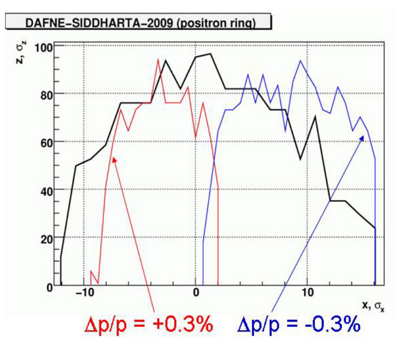

Figure 4: DAΦNE on- and off-energy dynamic apertures for the nominal working point (positron beam).

By including beam-beam interaction in the simulations we see that the effect of the lattice nonlinearities is not dramatic for the case of the crab sextupoles on (see Fig.5). The beam size blow up is only by about 8% higher with respect to the ideal simulations. The beam distribution tails propagate to somewhat higher amplitudes, but still remain confined within the dynamic aperture. No lifetime reduction is indicated by the simulations.

Instead, in the case of the CW sextupoles off the beam tails are much longer for the nonlinear lattice exceeding 80 σ_y in the vertical plane (see Fig. 6) that was estimated to be the dynamic aperture limit. Already at 10 mA per bunch the calculated lifetime sharply drops down in agreement with our experimental observations. However, the luminosity and the vertical emittance blow up still remain comparable for linear and nonlinear lattices even in this case.

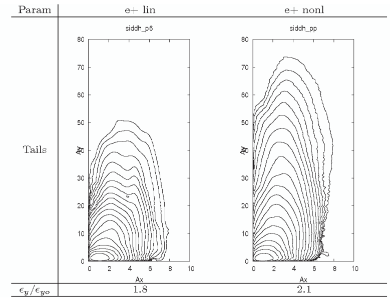

Figure 5: Equilibrium densities in the space of normalized betatron amplitudes for linear lattice (left) and realistic nonlinear lattice (right) with crab sextupoles on.

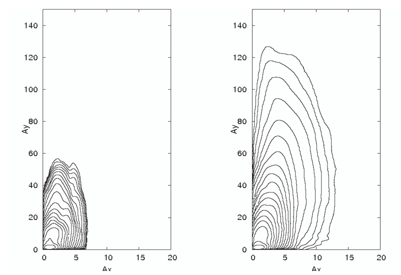

Figure 6: Beam-beam tails for linear lattice (left) and realistic nonlinear lattice (right) with crab sextupoles off.

CONCLUSIONS

The crab waist concept definitely works, ideal strong-strong simulations agree within 20-25% with experimental results. The agreement is expected to be even better if we include in simulations other luminosity limiting factors.

Much lower luminosity is achieved with crab sextupoles off. Besides stronger blow up, a sharp lifetime reduction is observed for bunch currents > 8-10 mA. This is in accordance with beam-beam simulations taking into account the realistic DAΦNE nonlinear lattice.

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