

BEAM-BEAM EXPERIENCE AT DAΦNE

D. Alesini, S. Bertolucci, C. Biscari, M. Boscolo, G. Di Pirro, A. Drago, A. Gallo, A. Ghigo, S. Guiducci, F. Marcellini, G. Mazzitelli, C. Milardi, M. A. Preger, F. Sannibale, M. Serio, A. Stecchi, A. Stella, C. Vaccarezza, M. Zobov, INFN LNF Frascati Italy
 E. Perevedentsev, BINP, Novosibirsk, RUSSIA; P. Raimondi, SLAC, Stanford, USA

Abstract

This paper summarizes the results of experimental observations and measurements of beam-beam interactions in DAΦNE, the Frascati Phi-factory. The achieved results are reported with analysis of present limitations in both single and multibunch operation modes and compared with numerical simulations.

1 INTRODUCTION

DAΦNE is a double ring electron-positron collider, designed to provide very high luminosity at the energy of the Φ resonance of 1.02 GeV c. m., the Φ -factory built at the Frascati National Laboratories of INFN (Italy) [1, 2]. After storing the first beam in fall 1997 and the successful commissioning without solenoidal detectors, the experimental detector KLOE [3] was rolled-in and the collider operation in the present configuration started in spring 1999. Since then DAΦNE alternates machine study and physics data taking shifts. Recently, peak luminosity of $10^{30} \text{ cm}^{-2}\text{s}^{-1}$ in single bunch collisions and $2.8 \cdot 10^{31} \text{ cm}^{-2}\text{s}^{-1}$ in the multibunch regime have been measured by the KLOE detector. A maximum integrated luminosity of 1.4 pb^{-1} per day has been registered, while the total luminosity integrated by the KLOE experiment amounts to about 50 pb^{-1} . In Section 2 we summarize the luminosity achievements and discuss measures that have allowed to improve gradually the collider luminosity performance. Section 3 describes the results obtained in single bunch collisions, compares the experimental data with numerical simulations and discusses present single bunch luminosity limitations. Section 4 is dedicated to the multibunch luminosity operation with analysis of the achieved results.

2 LUMINOSITY HISTORY

Figure 1 shows DAΦNE luminosity achievements, the maximum peak luminosity and the integrated luminosity per day, since the KLOE detector installation in spring 1999. The steady improvement is accounted by continuous machine study. Indeed, the first two years of collider runs were dedicated mainly to machine development, with limited time allocated for experimental physics. Much effort in this period was devoted to measurements and careful analysis of machine optics necessary to create an adequate linear model and to perform coupling correction. Now coupling is corrected down to 0.3%, much better than the design value of 1%.

As experience has shown in agreement with numerical simulations, the coupling reduction has improved substantially the luminosity performance [5].

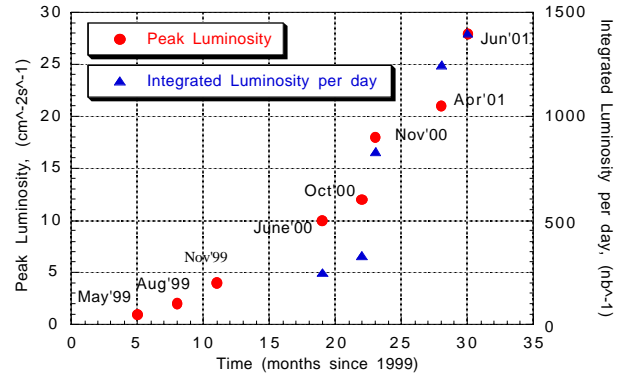


Figure 1: DAΦNE peak and daily integrated luminosity.

Together with machine modelling, the measures for optimization of the collision point parameters, such as bunch overlap in time and in both transverse planes, correction of the vertical crossing angle and residual dispersion at the IP etc., were studied [6].

The most intensive study of nonlinear dynamics was performed during last year. A dynamic tracking system was implemented in the main rings. This system allows to estimate trajectories in the transverse phase space and to measure the lattice cubic nonlinearity. As we will see later, the crosstalk between beam-beam effects and nonlinearity affects strongly the luminosity and the lifetime. By performing dedicated localized bumps and measuring the betatron tune, it was found that wigglers give a strong octupole term [7], while the “C” corrector magnets have non-negligible sextupole component [8] influencing the beam dynamics.

A real break-through in single bunch luminosity has been obtained when the newly proposed “detuned” structure [9] has been applied to DAΦNE. This new lattice avoids the low beta scheme at the second interaction point when the machine is tuned to collide only at the IP for the KLOE experiment. As a consequence, the lattice has lower chromaticity and smaller sextupole strengths are necessary to compensate the chromaticity. Moreover, it accepts a large vertical separation at the second IP decreasing therefore the problem of parasitic interactions at the second IP.

Besides, the separation bump at the IP is performed with very low currents in the nonlinear ‘‘C’’ corrector magnets, thus minimizing their contribution to the overall machine nonlinearity and coupling. Another important point is that the ‘‘detuned’’ lattice can be adjusted to have smaller beta functions in the wiggler decreasing the effect of their octupole terms. All these features allowed to achieve for the first time since KLOE installation a single bunch peak luminosity of $10^{30} \text{ cm}^{-2} \text{ s}^{-1}$ with currents of the order of 18mA per bunch and reasonable lifetimes. For the first time it has been possible to increase the bunch currents in collision up to the nominal value (44mA), with no drastic reduction of lifetime, even if the beam-beam blowup not only limits but even reduces the luminosity.

The steep jump in the integrated luminosity per day in November 2000 and its further increase in April 2001 was due to the possibility of performing the ‘‘topping up’’ procedure without switching off the experimental detector. Careful tuning of lattice, orbit, and scrapers positions for the background reduction made this possible. nonlinearities in the machine, whose overall contribution is compensated by the wiggler non-linearity. One of these is a sextupolar term in the ‘‘C’’ corrector magnets [6].

3 SINGLE BUNCH LUMINOSITY

For a long time the single bunch luminosity could not exceed $4\text{-}5 \cdot 10^{29} \text{ cm}^{-2} \text{ s}^{-1}$. And only recently, we managed to increase the luminosity to $10^{30} \text{ cm}^{-2} \text{ s}^{-1}$.

During collider tune up for collisions it has been found that the cubic nonlinearity can change in a wide range depending on lattice functions and orbit. Moreover, the sign of the nonlinearity can even change, as it is when wigglers are switched off [7]. The coefficient of the cubic nonlinearity as measured by the dynamic tracking system, varies between $-600 < c_{11} < +400$. Besides, we have found correlations between the nonlinearity strength and sign and the attainable luminosity. Numerical simulations with the weak-strong code LIFETRAC [10] that allows including implicitly the cubic nonlinearity coefficient c_{11} have been undertaken to explain the crosstalk between the beam-beam effects and nonlinearity. We have assumed that the tune shift parameters are equal in both transverse planes $\xi_x = \xi_y = 0.03$ and the working point is at (0.15; 0.21). The examples of equilibrium density distributions in the space of normalized betatron amplitudes are shown in Fig. 2. Table 1 summarizes the beam-beam blow up factors in the both transverse planes and the lifetime as a function of c_{11} . We should remark here that in the simulations the lifetime is limited only by beam-beam effects and the dynamic aperture is considered to be rectangular with boundaries at $A_x = 10\sigma_x$ and $A_y = 70\sigma_y$ (or $10\sigma_y$ at full coupling). As it is seen in Fig. 2, both positive and negative nonlinearities are harmful for beam-beam effects. Above $|c_{11}| > 200$ the distribution tails start growing and the bunch core blows up.

So, it is difficult to say which sign of the nonlinearity is more preferable. For positive c_{11} the horizontal tails reach the horizontal dynamic aperture and the horizontal size is blown up, while for negative c_{11} the tails expand in both transverse directions and the bunch blows up vertically.

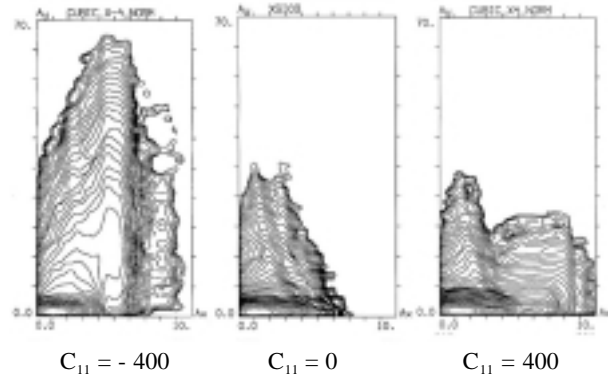


Figure 2: Equilibrium distributions for different cubic nonlinearities in space of normalised betatron amplitudes.

Table 1: Beam-beam blow up and lifetime

c_{11}	σ_x/σ_{x0}	σ_y/σ_{y0}	τ
- 600	1.064	2.431	2.4 h
- 400	1.053	1.300	9.9 h
- 200	1.075	1.038	∞
0	1.067	1.047	∞
+ 200	1.110	1.055	∞
+ 400	1.160	1.044	7.7 h
+ 600	1.400	1.108	4 min

According to the simulations, the nonlinearity strength can be considered acceptable when c_{11} remains within the range $-200 < c_{11} < +200$. Within this range the tails are well confined inside the dynamic aperture and blow up is negligible. This agrees well with experimental observations: the highest single bunch luminosity of $10^{30} \text{ cm}^{-2} \text{ s}^{-1}$ was reached in a reliable way when both collider rings were adjusted at the working point (0.15; 0.21) and the measured c_{11} was equal to -170 . Instead, during collisions in the KLOE IP in November – December 2000 the measured c_{11} was about -600 and the maximum achievable single bunch luminosity was at a level of $5 \cdot 10^{29} \text{ cm}^{-2} \text{ s}^{-1}$. As it is seen in Table 1, such a strong cubic nonlinearity leads to both beam-beam blow up and lifetime reduction. In the present collider configuration, the electron ring has $c_{11} = -300$ and the positron one has $c_{11} = -350$. The nonlinearity is higher for this configuration due to the increase of the horizontal beta functions in the wigglers, which was necessary to cope with background problems and to damp horizontal transverse instability. However, c_{11} values of the order of -300 are still acceptable giving relatively small blow up and moderate tail growth and in fact the measured single bunch luminosity in this case is again of the order of $10^{30} \text{ cm}^{-2} \text{ s}^{-1}$.

Therefore, the present lattice can be considered as a reasonable compromise between beam-beam performance and allowable background level. From this point of view, beam-beam and background problems can be separated if we use an independent (and variable) source of cubic nonlinearity. Additional octupoles could play this role and they will be installed in fall 2001.

4 MULTIBUNCH LUMINOSITY

Passing from single bunch to multibunch collisions the luminosity does not scale linearly with the number of bunches. One of the reasons is that the maximum beam currents I_{\max}^{\pm} cannot be stored simultaneously, since both rings are filled by the same injector chain. Few minutes are necessary to convert the injector between the two beams and the lifetimes are of the order of 2000 sec. Presently the I_{\max} is limited to ~ 850 mA by vacuum, and does not reach the beam-beam limit of positrons. The I_{\max}^+ is limited to ~ 800 mA by KLOE background acceptable rate and is near to the e- beam-beam limit. The optimum number of bunches, taking into account all these considerations and the gap which limits ion trapping, is found during the luminosity shifts.

The peak luminosity is usually obtained with total currents of 600 to 700 mA per beam, with 45 : 49 bunches, corresponding to currents per bunch lower than the one giving the maximum luminosity. The maximum measured peak luminosity, $2.8 \cdot 10^{31} \text{ cm}^{-2} \text{ s}^{-1}$, has been achieved with 47 bunches in each beam, i.e. with the luminosity of $6 \cdot 10^{29} \text{ cm}^{-2} \text{ s}^{-1}$ per each bunch. Another limit could come from parasitic crossings (PC) reinforced by the cubic machine nonlinearity.

There are some experimental observations confirming that the PC effect is significant for the multibunch collider performance. In particular, when injecting one beam out of collision in the nearby bucket, the already stored opposite beam lifetime drops. Yet another observation is that it has been possible to scale the luminosity with the number of bunches with bunches separated by 3 empty buckets. In order to clarify the situation we have simulated with LIFETRAC the beam-beam interaction with two parasitic crossings at either side of the interaction point (IP) and taking into account the measured cubic nonlinearity $c_{11} = -350$. The PCs were at a distance of 81 cm from the IP, which corresponds to the actual fill pattern with 1 empty bucket between bunches. We have also considered that the coupling has been corrected down to 0.3%. The simulations have been carried out a bunch current of 25 mA. Figure 3 compares the results of the following simulation runs taking into account:

- Only IP without PCs and without nonlinearity;
- IP with two PC and without nonlinearity;
- IP with two PCs and with cubic nonlinearity.

As it is clearly seen, the PCs reinforced by the nonlinearity strongly affect the bunch tails and, as a result, the

lifetime drops. So, one of the solutions aimed at increasing the luminosity in the multibunch regime is further reduction of the nonlinearity. Installation of additional octupoles capable of controlling the nonlinearity would be extremely useful.

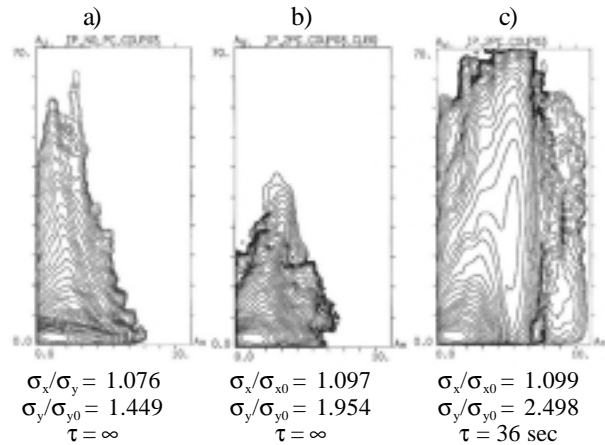


Figure 3: Equilibrium distributions taking into account parasitic crossing and cubic nonlinearities.

5 CONCLUSIONS

Obtaining high luminosity in the low-energy range of a Φ -factory is an interesting challenge. Beams are extremely sensitive to nonlinearities, instabilities and coupling. The beam-beam effect is a strong perturbation of the bunch distributions. Long damping times ask for very efficient feedback system.

The design DAΦNE luminosity is an ambitious number, but with the present results the integrated luminosity needed by the experiments to reach their physics goals is a reachable aim..

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