

# SIMULATION OF CRAB WAIST COLLISIONS IN DAΦNE WITH KLOE-2 INTERACTION REGION\*

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## Abstract

After the successful completion of the SIDDHARTA experiment run with crab waist collisions, the electron-positron collider DAΦNE has started routine operations for the KLOE-2 detector. The new interaction region also exploits the crab waist collision scheme, but features certain complications including the experimental detector solenoid, compensating anti-solenoids, and tilted quadrupole magnets. We have performed simulations of the beam-beam collisions in the collider taking into account the real DAΦNE nonlinear lattice. In particular, we have evaluated the effect of crab waist sextupoles and beam-beam interactions on the DAΦNE dynamical aperture and energy acceptance, and estimated the luminosity that can be potentially achieved with and without crab waist sextupoles in the present working conditions. A numerical analysis has been performed in order to propose possible steps for further luminosity increase in DAΦNE such as a better working point choice, crab sextupole strength optimization, correction of the phase advance between the sextupoles and the interaction region. The proposed change of the  $e^-$  ring working point was implemented and resulted in a significant performance increase.

## INTRODUCTION

DAΦNE is an accelerator complex the main element of which is a double ring electron-positron collider operating at the c.m. energy of the  $\Phi$ -resonance (1.02 GeV) [1].

The implementation of the Crab Waist collision scheme (CW) has led to the achievement of the record peak luminosity  $L=4.5\times 10^{32}\text{ cm}^{-2}\text{ s}^{-1}$  while working for the SIDDHARTA experiment [2]. This success has led to a decision to reinstall the upgraded KLOE detector, KLOE-2, exploiting the advantages of the CW scheme. For this purpose, the KLOE interaction region (IR) was carefully redesigned [3], and in 2013 the KLOE detector has been upgraded with new layers in the inner part of the apparatus [4]. The new KLOE-2 IR is much more complex as compared to the SIDDHARTA IR because the collisions take place inside the detector solenoid, IR has rotated quadrupoles and additional compensator solenoids.

At present, the luminosity of  $1.9\times 10^{32}\text{ cm}^{-2}\text{ s}^{-1}$  has been achieved to be compared with  $1.5\times 10^{32}$  obtained in the previous KLOE run [5]. Table 1 summarizes the most

relevant machine and beam parameters. It is worth noting that the performance is mostly limited by collective effects such as electron cloud, microwave instability, feedback system noise, etc. [6]. An extensive campaign of experimental and simulation studies is in progress in order to fully exploit the CW potential and push the luminosity to higher values.

Numerical simulations of beam-beam effects with the weak-strong particle tracking code Lifetrac proved to be very efficient for the detailed understanding of the crab-waist collision scheme, and for the collider performance optimization [7,8]. The goal of the present work was to implement the complete model of DAΦNE with the KLOE-2 IR in weak-strong beam-beam simulation and apply the modeling to guide parameter optimization.

In addition to the value for the DAΦNE program, the studies represent a unique opportunity to benchmark the numerical tools against the experimental data to enable further application towards the High Luminosity upgrade of the LHC.

Table 1: DAΦNE machine and beam parameters during 2015 operation with KLOE-2 detector (April 2015).

Parameter	Value
Number of bunches	95
Bunch spacing	2.7 ns
Full horizontal crossing angle	50 mrad
Number of electrons / bunch	$2.05\times 10^{10}$
Number of positrons / bunch	$2.05\times 10^{10}$
Electron emittance, r.m.s. (x,y)	0.28, 0.0021 $\mu\text{m}$
Positron emittance, r.m.s. (x,y)	0.28, 0.0021 $\mu\text{m}$
Momentum spread, r.m.s.	$5.5\times 10^{-4}$
Bunch length, r.m.s. ( $e^-$ , $e^+$ ) $\sigma_z$	1.55, 1.6 cm
Electron betatron tunes ( $\nu_x, \nu_y$ )	0.130, 0.170
Positron betatron tunes ( $\nu_x, \nu_y$ )	0.098, 0.130
Damping decrements (x,y,z)	$(1.1, 1.1, 2.2)\times 10^{-5}$
Beta-function at IP (x,y)	25, 0.84 cm
Beam-beam parameter, $e^\pm$ (x,y)	0.011, 0.04

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## SIMULATION TOOLS

Lifetrac is a weak-strong particle tracking code that was originally developed for the simulation of equilibrium density distributions in lepton colliders [7], and was later expanded to enable non-equilibrium simulations for hadron machines [9,10]. The fully symplectic 6D treatment of beam-beam interaction allows to perform simulations with very large crossing angle, and crabbing of either weak and strong bunches. The capabilities of the code in the equilibrium case include: (i) the ability to calculate 3-D density of the weak beam; (ii) evaluate the specific luminosity and beam lifetime; (iii) calculate the area of stable particle motion (dynamical aperture, DA); (iv) perform Frequency Map Analysis (FMA) [8].

A recent improvement of the code relevant for the present study was the implementation of detailed machine lattice model via element-by-element tracking in thin lens approximation. The optics data for both the weak and the strong beam are imported from MAD-X [11] model files. Such approach enables the proper treatment of element misalignments and related orbit distortions, chromatic aberrations, lattice nonlinearities, betatron and synchro-betatron coupling.

## SIMULATION RESULTS

### *Dynamical Aperture*

The achievement of maximum DA is essential for the improvement of injection efficiency, beam lifetime, and background conditions for the experiment. Figs. 1,2 present the results of FMA and DA simulations for the  $e^-$  beam in the absence of beam-beam interaction. The colour on FMA plots represents the tune jitter in logarithmic scale from red ( $10^{-3}$ ) to blue ( $10^{-7}$ ). The stability boundary established in long-term ( $2 \times 10^5$  turns) tracking agrees well with the FMA data. Note that the DA substantially decreases for off-momentum particles as a consequence of uncorrected chromatic aberrations near the half-integer or the integer resonance. For DAΦNE the betatron tunes farther from the integer should be favoured unless the sextupoles are optimized to correct higher-order lattice aberrations [12].

### *Working Point Optimization*

We performed betatron tune scans for both the  $e^+$  and  $e^-$  rings to determine the optimal running condition in order to achieve the maximum specific luminosity and dynamical aperture (beam lifetime). In Fig. 3, the inverse beam size is plotted. The simulations established that the working point for positron ring was near optimal, while for the electron ring the DA was insufficient. The proposed new working point provides a significantly better DA at the same or marginally better specific luminosity (Figs. 4-6). Fig. 4 suggests that horizontal DA in the new working point improves by about  $2-3\sigma$ , and from Figs. 5(a),6(a) one sees that the vertical tail growth is suppressed. These changes should result in a better injection efficiency and lower particle losses. Figs. 5(c)

and 6(c) demonstrate that the core size in the old and the new working point is essentially the same, and one should expect minimal impact on the specific luminosity. The numerically suggested working point was implemented in the DAΦNE electron ring. A substantial background reduction was observed immediately after the new optics application and multibunch feedback systems tuning [13]. Then, after few days of collider fine-tuning, the best KLOE-2 experiment peak luminosity of  $1.95 \times 10^{32} \text{ cm}^{-2} \text{ s}^{-1}$  and daily integrated luminosity of  $11 \text{ pb}^{-1}$  have been achieved.

### *Effect of Crab Waist*

Simulations with the detailed machine optics clearly demonstrate the benefits of the CW scheme in the KLOE-2 configuration of DAΦNE. In both working points, switching the CW sextupoles off results in a significant blow-up of the beam core, and about a two-fold decrease of the specific luminosity (Figs. 5(b)-5(c) and 6(b)-6(c)).

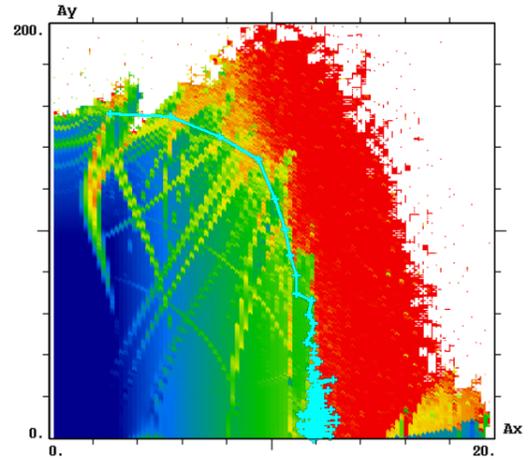


Figure 1: FMA (colour chart) and  $2 \times 10^5$  turns DA (cyan line) for the  $e^-$  beam without beam-beam interaction. Normalized synchrotron amplitude  $A_s=1$ . Betatron tunes ( $\nu_x=0.098$ ,  $\nu_y=0.164$ ). Horizontal and vertical axes are labelled in units of the respective beam size.

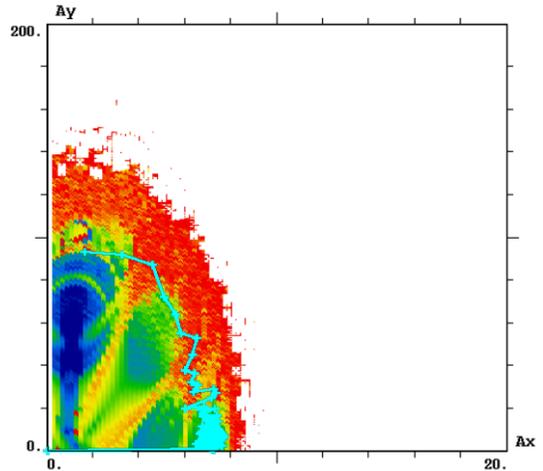


Figure 2: FMA (colour chart) and  $2 \times 10^5$  turns DA (cyan line) for the  $e^-$  beam without beam-beam interaction. Normalized synchrotron amplitude  $A_s=9$ .

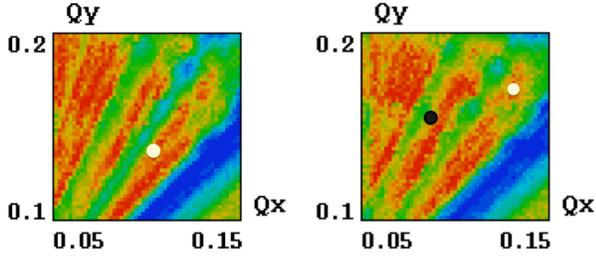


Figure 3: Inverse beam size in colour (red – large, blue – small) as a function of betatron tune for positrons (left), and electrons (right). White point shows the optimal working point; black dot is the original  $e^-$  tune.

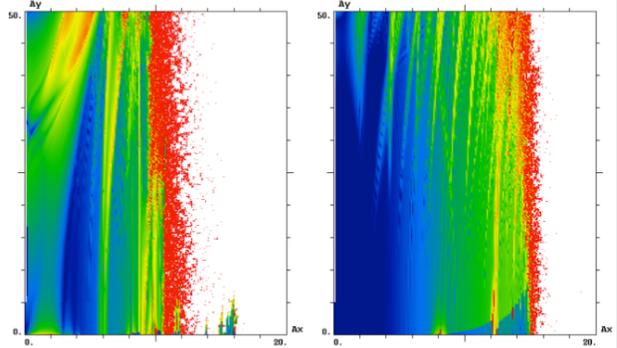


Figure 4: FMA for electron beam particle with energy offset of  $2\sigma$ , beam-beam interaction off. Working point  $\nu_x=0.088$ ,  $\nu_y=0.152$  (left),  $\nu_x=0.130$ ,  $\nu_y=0.170$  (right).

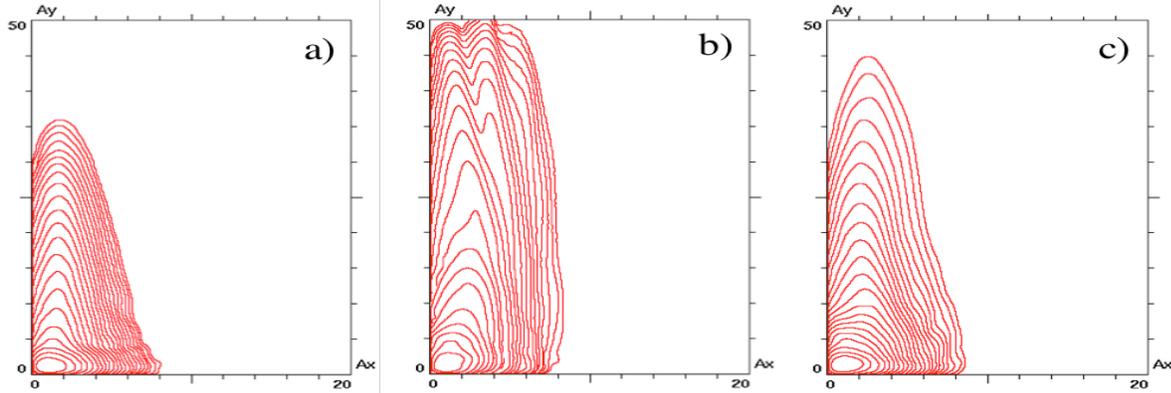


Figure 5: Equilibrium density contour plots in the betatron amplitude space for electron beam in the working point  $\nu_x=0.088$ ,  $\nu_y=0.152$ . a) – beam-beam off; b) – with beam-beam, CW off; c) – with beam-beam, CW on.

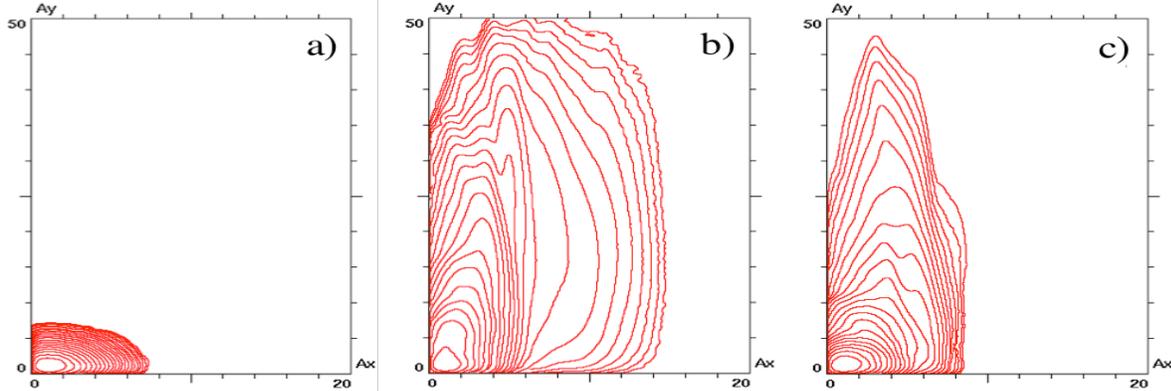


Figure 6: Equilibrium density contour plots in the betatron amplitude space for electron beam in the working point  $\nu_x=0.130$ ,  $\nu_y=0.170$ . Left – beam-beam off; middle – with beam-beam, CW off; right – with beam-beam, CW on.

## CONCLUSIONS

The weak-strong simulations of beam-beam effects in DAFNE taking full account of the KLOE-2 optics clearly demonstrate the advantage of Crab Waist collision scheme.

Simulations established that the configuration of  $e^+$  ring is near optimal, while the dynamical aperture of  $e^-$  ring could be improved by a change of the working point. In full agreement with the model prediction, the new  $e^-$  working point resulted in a substantial improvement of the injection efficiency, beam lifetime and background

conditions [13], with a moderate increase of the specific luminosity. A further 30% increase of the luminosity is possible through the proper alignment of CW sextupoles, correction of the local coupling in IR, and optimization of CW sextupole strength.

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