DAΦNE PERFORMANCE WITH THE EXPERIMENTAL DETECTOR

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Abstract

After successful commissioning of the Φ-factory DAΦNE with two provisional interaction regions, the experimental detector KLOE, embedded into a 2.4 Tm solenoid, was installed and the beam was stored in this configuration at the end of March 1999. The first physics events including a CP violating candidate event were observed in mid April 1999.

At present work is in progress to compensate correctly the perturbation introduced in the machine optics by the experimental detector solenoid, to optimize beam parameters at the interaction point in order to improve the single bunch luminosity and to increase beam currents in multibunch operation. The results achieved so far are described in this paper.

1 INTRODUCTION

The first commissioning phase of DAΦNE, the Frascati 1.02 GeV c.m. electron/positron Φ-factory, with two provisional interaction regions without experimental detectors ("Day-one" IRs) was concluded with the installation of the KLOE [1] detector (Fig. 1) in November 1998. The main results achieved before the detector installation in approximately 6 months of beam time can be summarized as follows (see [2] for details).

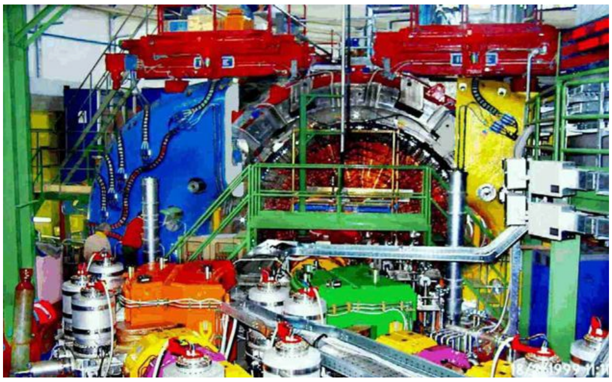

Figure 1: The KLOE detector during installation.

The strategy of the commissioning phase was aimed at tuning the machine for collisions and optimizing the single bunch luminosity. This should guarantee that, after correcting the perturbation introduced by the KLOE solenoidal magnet, the machine is ready for two beams operation.

Single beam commissioning of the two rings, in single bunch mode, is completed: electron and positron currents larger than twice the design value (110 mA reached, 44 mA design) have been stored without instabilities and machine parameters have been measured and found in good agreement with the predictions of theoretical models. In particular, a coupling factor much smaller than the design value has been obtained.

Multibunch feedback systems have been put into operation and currents of 0.54 A electrons and 0.56 A positrons have been stored, only limited by vacuum.

A maximum single bunch luminosity of 1.6 10^{30} cm^{-2} s^{-1} has been reached, while in multibunch collision, less extensively tested, ~ 10^{31} cm^{-2} s^{-1} in 13+13 bunches configuration has been achieved.

The KLOE detector was installed and the first beam was stored at the end of March 1999. Since then, the commissioning efforts have been dedicated to the correct compensation of the perturbation introduced in the machine optics by the experimental detector solenoid, to the optimization of beam parameters at the interaction point in order to improve the single bunch collision luminosity and increase of the beam current in multibunch operation.

In this paper we give a brief description of the DAΦNE collider, emphasizing common features and principal differences between the low energy particle factory and the higher energy factories, like PEP-II [3] and KEKB [4], we describe the main results obtained so far and discuss the difficulties encountered on the way to high luminosity.

2 GENERAL DESCRIPTION

The main DAΦNE [5] design parameters are listed in Table 1, while the magnetic layout is shown in Fig. 2.

High current, multibunch and flat beam approach has been adopted for DAΦNE, similar to that of PEP-II and KEKB, to reach high luminosity. Electron and positron beams, stored in two separate rings, travel in a common vacuum chamber in the Interaction Regions (IR) and collide at two Interaction Points (IP). Crossing at a horizontal angle of 25 mrad minimizes the effect of parasitic collisions and allows to store many bunches, increasing the luminosity by a factor equal to the number of bunches.

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Table 1: DAΦNE Design Parameters

Energy [GeV]	0.51
Trajectory length [m]	97.69
RF frequency [MHz]	368.26
Harmonic number	120
Damping time, τ_E/τ_x [ms]	17.8/36.0
Bunch length [cm]	3
Emittance, $\varepsilon_x/\varepsilon_y$ [mm·mrad]	1/0.01
Beta function, β_x^* / β_y^* [m]	4.5/0.045
Particles/bunch [10^{10}]	8.9
Single bunch luminosity [$cm^{-2} s^{-1}$]	$4.4\,10^{30}$

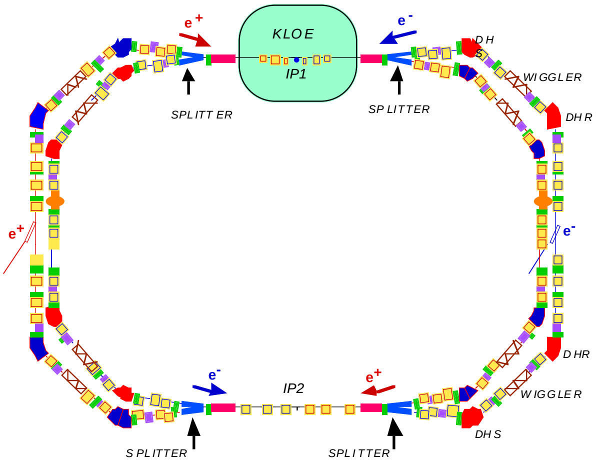

Figure 2: Main Rings magnetic layout (March 99).

DAΦNE's design accepts a maximum number of 120 bunches and all the critical subsystems (injector, RF, vacuum system, diagnostics) are dimensioned to cope with a stored current of ~ 5 A.

The Phase I luminosity target is 10^{32} cm^{-2} s^{-1} with 30 bunches. Once this target is obtained, in parallel with physics runs, we will progressively tune the machine systems for higher currents and increase the number of bunches, and consequently the luminosity, by a factor of 4. To operate with 120 bunches further investment on the longitudinal feedback and additional work on the cures of the parasitic crossings effects will be needed.

Although similar to high energy factories from the conceptual point of view, DAΦNE, being a low energy machine, has some distinct features which complicate the achievement of the ultimate luminosity:

a) in a low energy short machine the large ratio between the aperture and the length of the magnets introduces large nonlinear contributions to the magnetic fields, thus complicating machine modeling and tuning;

b) the high integrated field of the experimental detector solenoid is a strong perturbation for the low energy beam. This requires a special scheme to compensate a 45 degree beam rotation and to cancel the coupling introduced by the solenoid;

c) the Touchek effect is the principal lifetime limiting factor in low energy machines. For DAΦNE the maximum lifetime in single bunch operation is foreseen to be 2-3 hours. During beam-beam collisions the lifetime may decrease further. Because of that a "topping up" injection procedure, where the beam is often refilled without dump, is important for DAΦNE to increase the average luminosity;

d) at low energy the noise is weak and the damping time is long, by a factor of 10 longer than that of KEKB and PEP-II (in terms of the number of revolution turns). This means that even high order beam-beam resonances can affect luminosity performance. Indeed, as shown in [6], tune variations with respect to the optimum working point of the order of 0.01 affect the luminosity, while the lifetime is sensitive to tune variations as small as 0.001.

3 KLOE IR

The KLOE detector consists of a cylindrical drift chamber surrounded by a lead-scintillating fiber electromagnetic calorimeter, immersed in the 0.6 T magnetic field of a 2.5 m radius superconducting solenoid.

In order to leave the maximum free solid angle around the IP, SmC permanent magnet low-β quadrupoles, built by Aster Enterprises, have been adopted. They are confined inside a 9° half-aperture cone around the IP and the solid angle available for the detector is 99%. There are three of these quadrupoles on each side of the IP, supported by the detector.

The high integrated field of the KLOE solenoid (2.4 Tm) is a strong perturbation for the low energy DAΦNE beam (510 MeV). It rotates the beam by ~ 45° in the transverse plane and it is the main source of beam coupling. A compensation scheme, the Rotating Frame Method [7], has been adopted to cancel this coupling. This scheme requires two compensating solenoids in a position symmetric to the main one and a rotation of the low-β quadrupoles.

The three quadrupoles are carefully aligned and rigidly connected as shown in Fig. 3. After installation each triplet can be rigidly moved with 5 degrees of freedom (displacement and tilt in the x and y plane and rotation around the axis) by means of a cam system.

The beam pipe around the IP has to be as transparent as possible for the outcoming particles. In order to avoid K_S^0 regeneration, it is required that the K_S^0 decay before hitting the pipe. In order to have a large enough fiducial volume for the K_S^0, the cylindrical pipe around the IP is welded to a 500 μm thick sphere of 10 cm radius. A 50 μm cylindrical shield is welded inside the sphere to prevent coupling between the beam and the sphere resonant modes.

The chamber, built by BrushWellman, is made of a Be-Al alloy (AlBeMet, 68% Be, 32% Al). The chamber, before insertion in the KLOE detector, is shown in Fig. 4.

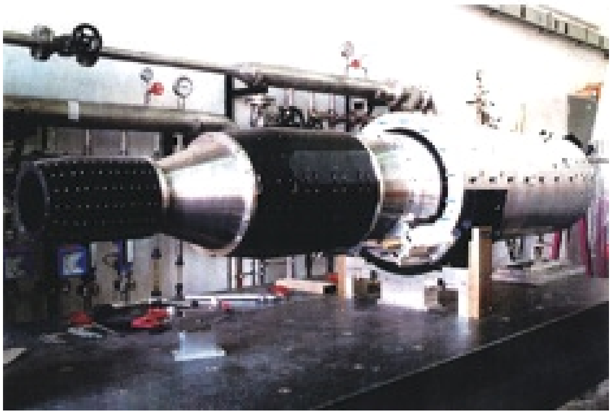

Figure 3: One of the KLOE low-β triplets on the alignment bench.

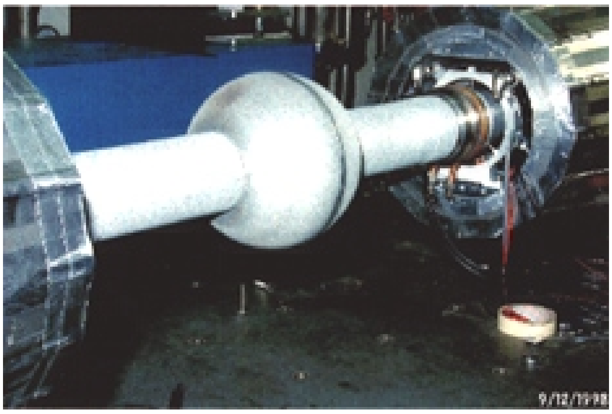

Figure 4: The KLOE vacuum chamber.

4 COLLIDER OPTICS

The two rings of the collider should have the same nominal optics with the same nominal magnetic elements.

For the “Day-one” commissioning phase an unique model applied to both rings was accurate enough to tune the rings, correct coupling better than nominal values and optimize collisions. The rings had a two-fold symmetry, same optics for the two Interaction Regions and diagnostic around the Interaction Point which helped in overlapping the beams and the beta waists. All the symmetries of the colliders were maintained in the model, and equal calibration constants for families of magnets were used.

The installation of KLOE has changed the scenario. The KLOE IR optics, the coupling compensation scheme, the analysis of off-axis dynamics, have been elsewhere described [7,19]. The preliminary optical model has shown to be accurate enough to ensure the correction of the coupling within the nominal values in few days of commissioning describing the rings with the model developed for the "Day-one" configuration. The whole KLOE Interaction Region transfer matrix, measured by localized bumps, is very close to the calculated one.

The optimization of the collision is now more challenging than before: the rings have lost the two-fold symmetry. The energy of the collider have been moved to fit the Φ-resonance, with a not straightforward energy dependence of the optics (wigglers, dipoles, splitters, orbit dependence,...) and in this moment we have lost the good correction for the coupling of the electron ring.

The diagnostics in the KLOE IR lacks a BPM at the IP which was present in the “Day-one” IR chamber. Due to lack of space no coils on the low beta triplets could be placed so that the betatron functions are not measurable with the quadrupole gradient method. The accuracy of IR BPMs where the beams pass far from the center following the off-axis trajectories is not enough to be used in Response Matrix calculation of optical parameters.

All these conditions have led to the necessity of more accurate and distinct models for each ring. The flexibility of individually powered quadrupoles is now fully exploited, and the presence of straw fields from the injection transfer lines and from the cross-talk of the rings is included in the model. We have bartered the elegance of symmetry against the practicality.

The updated models are being applied in these days to overlap the beta waists at the IP and tightly control the beam sizes of the two beams.

5 MAIN SUBSYSTEMS

Special RF cavities, with low impedance parasitic high order mode (HOM) content, have been developed to allow stable high current-multibunch operation [8]. The cavities, one per ring, are normal conducting copper single cells, with a system of HOM damping waveguides which couple out and dissipate the HOM energy induced by the beam on external 50 Ω loads. The HOM shunt impedance has been reduced by up to three orders of magnitude. No evidence of arcing or multipacting effects due to the loading waveguides has been observed and the performance of the damped cavities under high beam loading is quite satisfactory.

A longitudinal bunch-by-bunch feedback system [9], implemented in collaboration with the SLAC/LBL PEP II group, is operational in both rings. It consists of a time domain system exploiting digital techniques. Damping time faster than ~200 μsec has been demonstrated in the positron ring with 30 bunches.

The specially designed arc vacuum chambers [10] and the Ti sublimation pumps have shown to be very effective and the static gas pressure in the arcs was in the 10^{-10} Torr range. The vacuum in the *“Day-one”* IRs was poor since they were not baked, in view of replacing them with the final ones. The bad IR vacuum, specially under high beam loading, was the main limit to high current operation.

During the shutdown for KLOE’s installation some operations to substantially improve the vacuum of the rings interaction regions have been performed.

Two special design NEG pumps capable of a pumping speed for CO of 2000l/s have been installed in the KLOE IR, the distributed ion pumps inside the splitter magnets have been activated and the straight sections vacuum chambers adjacent to the IRs have been baked out.

6 BEAM DYNAMICS

6.1 Single Beam Dynamics

Before the detector installation the maximum current stored in single bunch mode in both rings was 110 mA, i. e. by a factor of 2.5 higher than the design value of 44 mA. No destructive single bunch instability has been observed. The maximum current reached was limited administratively in order to avoid a damage of machine electronics due to the high peak current.

The bunch length has been measured as a function of bunch current and found in very good agreement with numerical simulations based on machine impedance estimates [11]. According to these data the normalized coupling impedance |Z/n| is below 0.6 Ω. During the bunch length measurements at V_{rf} = 100 kV we observed the appearance of quadrupole and dipole oscillations at currents of 26 mA and 35 mA respectively. By increasing the RF voltage to 150 kV, the quadrupole mode threshold was shifted to 38 mA, while the dipole one was pushed beyond the nominal single bunch current value. It has been shown analytically [12], by applying the double water bag model [13], that the observed thresholds correspond exactly to the radial mode coupling of modes with low azimuthal numbers. At higher RF voltages there was not evidence of the microwave instability, even for currents much higher than the design value.

However, after the experimental IRs installation the microwave instability scenario changed significantly. Despite we did not expect significant contributions to the machine impedance from the new IRs vacuum chambers, the unstable quadrupole mode was detected in both rings even at high RF voltages. It has been found that the mode threshold is very sensitive to the RF voltage. Moreover, the instability threshold increases by decreasing the RF voltage, i. e. the mode behavior is opposite to that observed in the early commissioning stage. Perhaps, this can be explained by modification of the impedance at high frequencies where the quadrupole mode spectrum has a maximum. An increase of the bunch length due to RF voltage reduction shifts the mode spectrum to lower frequencies and the threshold increases.

This interpretation has been confirmed by measuring the instability threshold changing the momentum compaction at fixed RF voltage: the results show that by lengthening the bunch through a momentum compaction increase the quadrupole thresholds shift up and the instability can be eliminated in this way.

No dedicated measurements were carried out to estimate the exact value of the transverse impedance since some observations have shown that it is low. In particular, a head-tail instability threshold as high as 13 mA with sextupoles off has been achieved after an accurate orbit correction. Moreover, the observed vertical tune shift is a small fraction of the synchrotron tune in the whole current range from zero to the nominal value, indicating that the DAΦNE operating point is quite far from the transverse mode coupling threshold.

6.2 Multibunch operation

With the “Day-one” configuration in multibunch mode (all 120 bunches filled) 0.3 A in the positron beam and 0.23 A in the electron one were stored without feedback systems. With the longitudinal feedback on, up to 0.54 A of electrons have been stored in 25 bunches with a spacing of four RF buckets and an ion clearing gap of 5 consecutive bunches. With the positron beam 0.56 A have been stored in 30 equally spaced bunches. The uniformity of the stored current in the different bunches was quite satisfactory for both beams. These currents correspond to half the design value for 30 bunches and were limited mainly by bad vacuum in the provisional IRs and straight sections.

After vacuum improvement due to the new pumps in the KLOE IR, baking out the straight sections and beam scrubbing, we managed to store 750 mA in the positron ring and 600 mA in the electron one in 120 bunches without exploiting the feedback systems. At this level of currents and tuning the machine on the working point (5.15, 5.21) for two beams operation, transverse vertical oscillations have been observed. We attribute this multibunch instability to the interaction of the beam with parasitic higher order modes trapped in the injection kickers. A special dedicated study [14] has been carried out to solve the problem. At present new kickers equipped with HOM damping antennas are being built to eliminate the instability.

7 BEAM-BEAM INTERACTION

7.1 Luminosity measurements

The DAΦNE luminosity monitors [15] (see Fig. 5) are based on the measurement of photon production in the single bremsstrahlung (SB) electromagnetic reaction at the interaction point during the collisions. Among other possible reactions, SB has been selected for DAΦNE since its high counting rate allows to perform “on line” luminosity measurements which are very useful during machine tune-up. Moreover, the sharp SB angular distribution significantly simplifies the geometry of the detector and makes the counting rate almost independent on the position and angle of the beams at the IP.

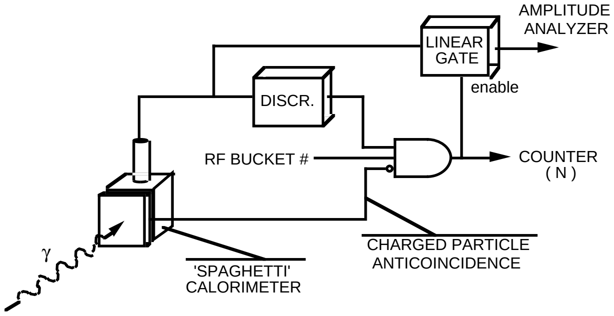

Figure 5: Schematic layout of the luminosity monitor.

The detector is a proportional counter consisting of alternated layers of lead and scintillating fibers with photomultiplier read-out. The integrated current signal from the detector is proportional to the incoming photon energy. Energy analysis and photon rates are provided by an analog chain.

The main background affecting the measurement is due to photons from bremsstrahlung on the residual gas (GB). This contribution is statistically subtracted by measuring the GB rate with longitudinally separated beams.

The results of the luminosity monitors were cross-checked and found in agreement with the coherent tune split measurements which allow to estimate the space charge tune shift parameters. The fractional part of the vertical and horizontal tunes were measured simultaneously in both the positron and the electron rings during the beam-beam collisions.

After the experimental detector installation we have the possibility to perform a direct comparison of the luminosity measured by the DAΦNE luminosity monitors and that counted by the KLOE detector. The two measurements agree within 10%.

7.2 *Luminosity optimization*

In order to achieve high luminosity the longitudinal and transverse positions of the two beams must be adjusted to provide maximum overlap at the IP. Moreover, the waists of the vertical beta functions should be the same for the two rings and coincide with the crossing point.

The longitudinal overlap of colliding bunches at the nominal IP has been synchronized by monitoring the distance between the combined signals of the two beams on two sets of symmetric BPMs on either side of the IP. The final precise longitudinal timing has been achieved by varying the RF phase of one of the two beams in order to maximize the luminosity monitor signal. In Figure 6 we can see an image from the luminosity monitor showing the counting rate as a functions of time (full scale is equal to 10 min.). The dip in the counting rate corresponds to the beam separation obtained with an RF phase change.

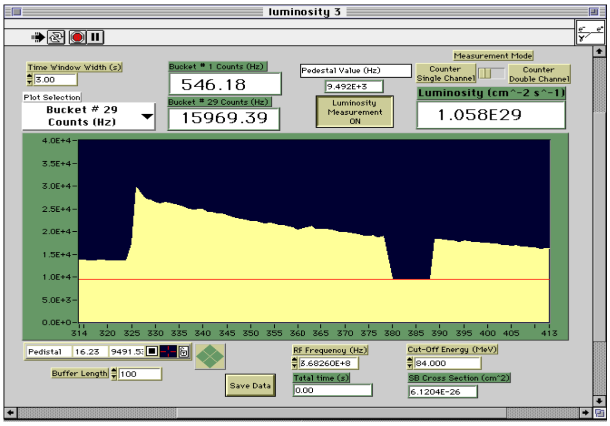

Figure 6: Luminosity monitor output.

The beam orbit measurements in the IRs are performed by six BPMs distributed along each IR. Since the position of both beams is measured by the same monitors, monitor offsets cancel out. Averaging over 100 BPM readings provides precise beam position measurements in the IRs with a standard deviation below 10 μm. Closed orbit bumps in the IR with four correctors are applied to adjust angle and displacement at the IP and overlap the beams. Orbit bumps have been also used to separate vertically the beams in one of the IRs when colliding in only one IP.

In the “Day-one” configuration a seventh BPM in each IR was installed at the IP position. This simplified beam superposition and beta function measurements (thanks to the IP quadrupole) at the IP during that commissioning stage. This BPM was removed before KLOE detector roll-in. At present the optimization of the beam collision parameters is performed by measuring the luminosity as a function of calibrated vertical and horizontal bumps at the IP. The fit of these dependencies gives us the mean geometric rms beam sizes at the collision point which have to be minimized. Figure 7 shows the luminosity as a function of the vertical bump at the IP in steps of 20 μm measured by the luminosity monitor.

7.3 *Numerical simulation and experimental results*

During the first commissioning stage without the detector solenoid it was decided to run on the working point (5.15; 5.21) situated farther from integers than an earlier proposed one (5.09; 5.07) [16]. This choice was based on beam-beam numerical simulations with the LIFETRAC code [17] and dictated by several reasons taken into account during machine start up. Among these:

(a) the closed orbit distortions are less sensitive to machine errors for working points placed far from the integers;

(b) the second order chromaticity responsible for the parabolic tune variation as a function of the particle momentum deviation is much smaller for these points;

(c) at these tunes the dynamic aperture with the chromaticity correcting sextupoles is large enough to avoid any further optimization with other sextupoles in vanishing dispersion regions

(d) it is easier to correct machine coupling during the initial operation when the residual pressure is higher than the design value of 10^{-9} Torr.

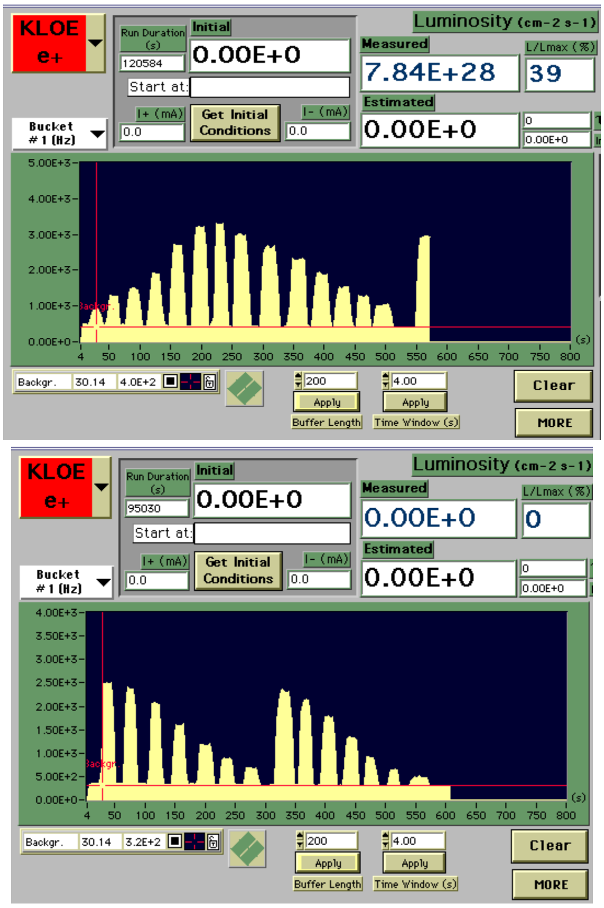

Figure 7: Measured luminosity as a function of the calibrated horizontal (upper plot) bump in steps of 0.5 mm and vertical (lower plot) bump in steps of 20 µm.

According to the numerical simulations, the maximum luminosity in single bunch collisions which can be reached on this working point without significant beam blow up is $2.2*10^{30}$ cm^{-2} s^{-1} [18]. This value corresponds to tune shift parameters $\xi_{x,y}$ of 0.03. The equilibrium density contours on this working point are shown in Fig. 8 (b).

As it can be seen, the tails of the distributions are well within the machine dynamic aperture, which is 10 σ_x times 70 σ_y for a coupling of 1%. Experimentally, a good lifetime and the present maximum achieved single bunch luminosity of $1.6*10^{30}$ cm^{-2} s^{-1} have been reached at this working point. The measured luminosity is somewhat smaller than that predicted numerically since collisions have been performed at somewhat lower currents with smaller tune shift parameters.

We have performed a luminosity scan changing the tunes around the working point (5.15; 5.21) in steps of 0.01 in both horizontal and vertical directions. The experimental results are in a good qualitative agreement with the numerical ones. For example, an increase of the horizontal tune from 5.15 to 5.16 resulted in a substantial increase of the horizontal beam size observed on the synchrotron light monitor while the lifetime was improved, in agreement with the simulations. In fact, at the point (5.16; 5.21) (see Fig. 8 (c)) the beam core is blown up horizontally and the vertical distribution tails are shorter than at (5.15; 5.21). In turn, by decreasing the vertical tune to 5.14 a sharp degradation of the lifetime was observed, as foreseen from the tail growth predicted numerically in Fig.8 (a).

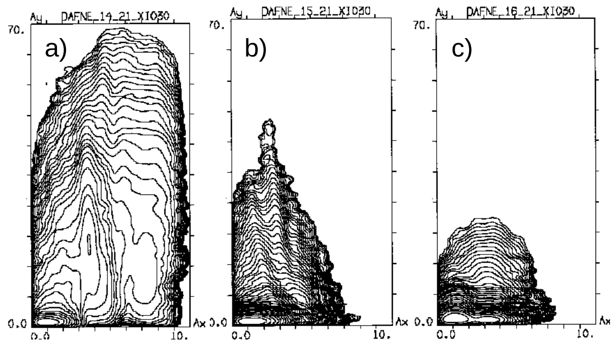

Figure 8: Equilibrium density in the normalized betatron amplitudes space.

Before KLOE roll-in only two days were dedicated to multibunch beam collision operation. During these days a luminosity in the range of 10^{31} cm^{-2} s^{-1} was obtained by accumulating about 200 mA in 13 bunches in each beam.

We started the commissioning with the KLOE detector running DAΦNE on the same working point (5.150; 5.210). It has been confirmed by measurements that this working point provides the best luminosity in the given tune range in the lattice configuration with the detector.

Experimentally it has been also found that the lifetime is rather sensible to tune variations as small as 0.001 [6]. This is in agreement with numerical simulation performed with LIFETRAC. Following the numerical predictions the working point has been slightly shifted in the vertical plane to (5.150; 5.214) and the lifetime was improved. This allowed us to deliver to the KLOE experiment data-taking runs with lifetime of about 1 hour and initial luminosity of $\sim 2.5*10^{30}$ cm^{-2} s^{-1} with about 200 mA stored in 10-15 bunches. The “topping up” operation also has been successfully tested.

However, further luminosity increase is limited by single bunch luminosity. Its improvement is our main goal at present. The maximum luminosity obtained in single bunch collisions running DAΦNE with the experimental detector is $3.0*10^{29}$ cm^{-2} s^{-1} which is about one order of magnitude lower than the expected value. In order to achieve the design goal our main efforts are in the direction of solving the following problems:

a) we have to find a source and to compensate the residual coupling in the electron ring which is 4% instead of the design value of 1%;

b) optimize beam overlap at the collisions point. Now, with the experimental IR wihout the BPM at the IP, this is not a simple task. Several iterations are required, varying machine parameters to provide optimal overlap of the colliding beams both in time and space and measuring carefully the beam sizes at the IP;

c) the present lattice has an emittance smaller than the design one by a factor of 2. Since the tune shift parameter is inversely proportional to the emittance this limits the maximum single bunch current by a factor of two and, respectively, the single bunch luminosity decreases by the same factor. A modified lattice with higher emittance is under test.

Finally, we are working in the direction of increasing the current in multibunch operation.

8 ACKNOWLEDGMENTS

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