OPTIMIZATION OF DAΦNE BEAM-BEAM PERFORMANCE

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Abstract

The Φ-factory DAΦNE is an electron-positron collider with a design luminosity of $5.2*10^{32}$ cm^{-2} s^{-1} at the energy of the Φ-resonance (1020 MeV c. m.) [1]. In order to achieve the design luminosity high current multibunch electron and positron beams are stored in two separate rings and collide in two common interaction regions. Since the beams arrive at the interaction points from the different rings, a careful longitudinal timing and precise transverse scan of the colliding bunches are necessary to optimize the collider luminosity. In this paper we describe luminosity measurement techniques adopted in DAΦNE, discuss measures aimed at maximizing the luminosity in the beam-beam collisions and report the achieved results. The experimental data are compared with the results of numerical simulations.

1 INTRODUCTION

We describe DAΦNE beam-beam performance optimization at the commissioning stage before the installation of the experimental detectors. A beam-beam interaction study at this stage was necessary to check and calibrate all the luminosity measurement set-ups, to study and apply methods and techniques for luminosity improvement and to demonstrate DAΦNE's capability of achieving the high luminosity goals in both the single and multibunch modes. In Section 2 we describe the main set-ups used for the luminosity measurements such as the single bremsstrahlung and the beam-beam tune split detectors. Section 3 deals with the techniques and methods applied to optimize the luminosity performance. In particular, longitudinal timing, transverse scanning and the phase jump procedure are discussed. Finally, the results achieved so far in both single and multibunch beam interaction modes are given in Section 4.

2 LUMINOSITY MEASUREMENTS

The DAΦNE luminosity monitors [2] (see Fig. 1) are based on the measurement of the 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 from the position and angle of the beams at the Interaction Point (IP).

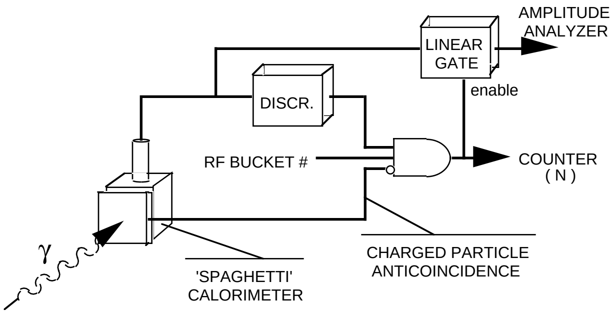

Figure 1: Schematic layout of the luminosity monitor.

The detector is a proportional counter consisting of alternated layers of lead and scintillating fibers with photomultiplier read-out. The charge signal from the photomultiplier is proportional to the photon energy. The data acquisition system provides energy analysis and photon counting.

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 while beams are longitudinally separated, obtaining the SB counting rate $\dot{N}$ and the luminosity:

$$L = \frac{\dot{N}}{\left[\int_{E_T}^{E_{\max}} dE \int_{\Omega_T} d\Omega \frac{\partial^2 \sigma_{SB}}{\partial E \partial \Omega} \right]}$$

where E_{max} is the maximum photon energy; σ_{SB} is the SB theoretical cross section; Ω_T is the solid angle covered by the detector, defined by a collimator placed in front of the proportional counter. The minimum photon energy E_T accepted by the system is found by a calibration procedure using the GB spectrum.

The direct luminosity measurements with the luminosity monitors were supported and cross-checked by 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.

The betatron tunes are measured by exciting the beam at RF frequency with transverse stripline kickers and measuring the beam response in the excitation plane with a transverse pick-up. Two different setups have been adopted to perform the tune measurements: in the first one a Network Analyzer HP 4195A (10 Hz - 500 MHz) RF output, amplified up to 100 W by class A amplifiers,

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provides the sweeping excitation. The horizontal and vertical coherent beam response is picked-up by strip line pairs and detected with the Network Analyzer. In the second system the other beam is excited with white noise and the beam oscillations signal, from a dedicated beam position monitor (BPM), is sent to a Spectrum Analyzer (HP 70000 system) operating in zero span (detector) mode. The Spectrum Analyzer IF output is down-converted with a HP 89411 module and processed by a real time FFT analyzer HP 3587S.

The knowledge of the tune shift parameter ξ_y contributes to the luminosity evaluation from the following expression:

$$L = f\frac{N_p}{2r_e}\frac{\xi_y}{\beta_y}\left(1+\frac{\sigma_y}{\sigma_x}\right)$$

Here the beta function at the IP β_y is found from lattice measurements; the beam size ratio is measured by the DAΦNE synchrotron light monitors [3] while the number of particles per bunch N_p is calculated from the current measured by a DCCT. The results from the two kinds of measurement are in agreement.

3 LUMINOSITY OPTIMIZATION

For the collider commissioning two provisional Interaction Regions (IR) with seven conventional quadrupoles were installed in the experimental pits. One of the quadrupoles is placed at the IP. Such a scheme allows to reduce the machine chromaticity.

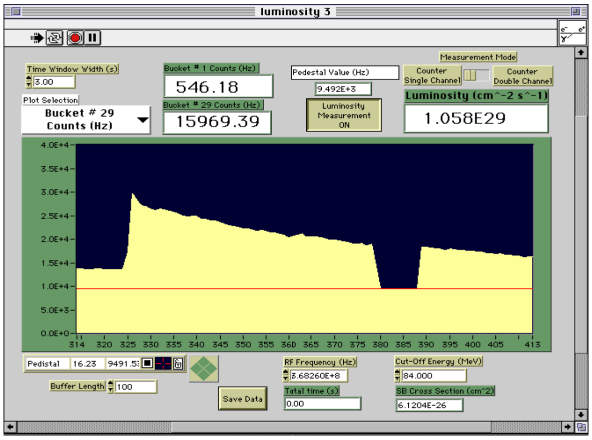
The beam orbit measurements in the IRs are performed by seven BPMs distributed along each IR. Since the position of both beams is measured by the same monitors, monitor offsets cancel out. One of the BPMs in each IR is installed at the IP position. This simplified beam superposition and beta functions measurements at the IP during collision tuning. Averaging over 100 BPM readings provided precise beam position measurements in the IRs with a standard deviation below 10 µm.

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. Since the IP is not a symmetry point of the machine, the tuning of the IR optics has been done iteratively to obtain symmetric beta functions with equal minima for the two rings.

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 2 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.

Closed orbit bumps in the IR with four correctors have been applied to adjust angle and displacement at the IP and overlap the beams. Bumps have been also used to separate vertically the beams in one of the IRs when colliding in only one IP. In the horizontal plane the crossing angle has been set to be 25 mrad and the horizontal orbit displacement has been adjusted to be much smaller than the horizontal beam size of 2.1 mm at the IP. Since the vertical beam size is much smaller than the horizontal one (~ 20 µm), fine tuning of the vertical orbit has been performed by changing the position at the IP in steps of 5 µm and the angle in steps of 50 µrad. The optimal collision configuration has been found by scanning the beam in the vertical plane looking for maximum luminosity monitor signal.


luminosity 3

Time Window Width (s): 3.00
Plot Selection: Bucket # 29 Counts (Hz)
Bucket # 1 Counts (Hz): 546.18
Bucket # 29 Counts (Hz): 15969.39
Pedestal Value (Hz): 9.492E+3
Luminosity Measurement ON
Measurement Mode: Counter Single Channel / Counter Double Channel
Luminosity (cm^-2 s^-1): 1.058E29
Pedistal 16.23 9491.5
Buffer Length: 100
RF Frequency (Hz): 3.68260E+8
Total time (s): 0.00
Cut-Off Energy (MeV): 84.000
SB Cross Section (cm^2): 6.1204E-26

Figure 2: Luminosity monitor output.

It has been observed that during injection in the collision mode the intensity of the beam being injected saturated below the nominal level. This has been explained by the fact that the injected bunch performs both longitudinal and transverse oscillations during a time comparable with the radiation damping one. Such a bunch interacting with an opposite, already stored bunch, looses current. A “phase jump” procedure has been adopted to fix this problem [4]. Initially, the two bunches are injected into non-interacting RF buckets in order to avoid beam-beam interactions during accumulation. Then, when the nominal intensity is reached, the stored bunches are brought into collision by changing rapidly the phase of one of the two RF cavities. In this way the orbit length in one of the main rings is changed for a short time to cancel the initial longitudinal separation of the bunches. If the phase shift is performed with a fast ramp (of the order of few synchrotron oscillation periods) the bunch follows the RF phase and no synchrotron oscillations are excited. The procedure has proved to be efficient in both single and multibunch collision modes. The highest luminosity values reached so far have been achieved by applying the “phase jump” technique.

4 NUMERICAL SIMULATIONS AND EXPERIMENTAL RESULTS

During commissioning it was decided to run on the working point (5.15; 5.21) situated farther from integers than the one (5.09; 5.07) proposed earlier [5]. This choice was based on beam-beam numerical simulations with the LIFETRAC code [6] and dictated by several reasons taken into account during machine start up. Among these:

(a) closed orbit distortions are less sensitive to machine errors for working points situated 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) the dynamic aperture is large enough for this working point even without switching on the dedicated sextupoles for the dynamic aperture correction;

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

According to the numerical simulations, the maximum luminosity in single bunch collisions which can be reached on this working point without remarkable beam blow up is $2.2*10^{30}$ cm^{-2} s^{-1} [7]. 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. 3 (b).

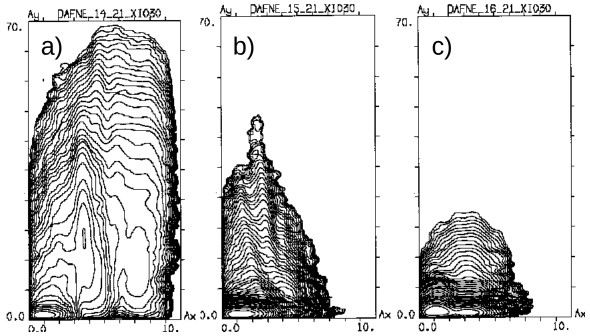


Figure 3: Equilibrium density in the normalized betatron amplitudes space. Adjacent contour levels are at a constant ratio $\sqrt{e}$.

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 machine 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 the collisions have been performed at somewhat lower currents with smaller tune shift parameters.

The results of all single bunch luminosity measurements during different machine shifts are shown in Fig. 4, where the luminosity is given as a function of the product of the electron times positron bunch currents. The dashed line shows the luminosity calculated with the design parameters at the same currents.

We have performed a luminosity scan changing the tunes around the working point (5.15; 5.21) with 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, for the point (5.16; 5.21) (see Fig. 3 (c)) the beam core is blown up horizontally and the vertical distribution tails are shorter than for the point (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. 3 (a).

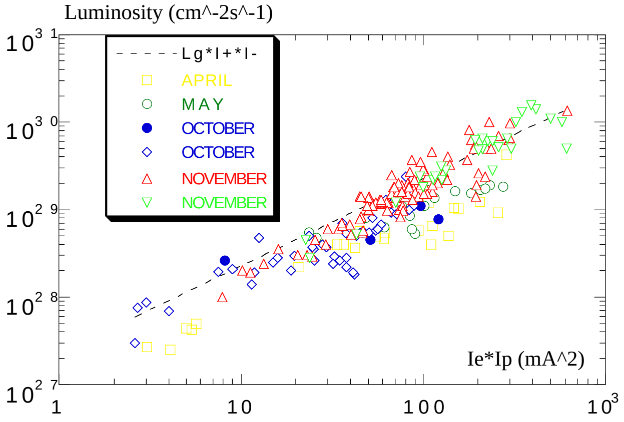


Figure 4: Measured luminosity versus beam current.

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 and applying the “phase jump” procedure. Just a first attempt has been made to collide the bunches at the two IPs simultaneously. The reached luminosity per IP was lower than in the single IP configuration. At present, a simulation study [7] has been performed to find optimal working conditions for two IP interactions and the lattice adjustments have been prepared for the next shifts with two experiments in DAΦNE.

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