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BEAM-BEAM INTERACTIONS AT THE WORKING POINT (5.15; 5.21)

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Abstract

Numerical simulations[1] have been undertaken in order to find a suitable working point for beam-beam collisions with a single interaction point (IP) during the DAΦNE commissioning. The simulations have been also applied to investigate the influence of the horizontal and vertical beam-beam separations at the second IP on the luminosity and lifetime. A possible degradation of the machine performance due to the vertical crossing angle and to the sextupolar nonlinearities has been estimated.

Applying the modeling we have tried to explain some observations made during the machine luminosity runs. In particular, we compare the numerical luminosity scan carried out around the chosen working point with the experimental data, we make an attempt to understand the bunch current saturation during the injection into the nearest bucket while performing a phase jump procedure and analyze a sudden horizontal bunch widening of both the electron and positron bunches at low currents.

Finally, we propose modifications of the machine lattice necessary to provide successful DAΦNE operation with two interaction points.

For the Introduction

Numerical simulations [1] have shown that the optimal working point for DAΦNE is (Q_x = 5.09; Q_y = 6.07), where Q_x, Q_y are the horizontal and vertical tunes, respectively. At this working point the nominal luminosity of $4*10^{30}$ cm^{-2} s^{-1} in single bunch collisions can be reached with both the horizontal and vertical tune shift parameters ξ_x, ξ_y equal to 0.04.

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1 In this Note we use the results of the beam-beam simulation codes LIFETRAC and TURN which have been developed in the framework of INTAS project 94-4772.

However, during the commissioning stage it was decided to adopt a working point which is situated farther from integer numbers than the nominal one. In particular, as it will be explained in the following, the point (5.15; 5.21) has been chosen. Such a choice has been dictated by some reasons which were taken into account during the machine start up. Among these are:

a) The closed orbit distortions are more sensitive to machine errors for the tunes closer to integers. For example, the orbit distortion Δx_{co} due to an error kick $\delta\theta$ is proportional to:

$$\Delta x_{co} \propto \frac{\delta\theta}{\sin(\pi Q_x)} \tag{1}$$

b) The machine straight sections and temporary "day-one" interaction regions, which were used only during the commissioning, were not baked out. Because of that the pressure in these regions was substantially higher than the project value of 10^{-9} Torr, thus inducing notable positive tune shifts due to the trapped ions of the residual gas in the electron storage ring. It is known that the tune shifts are proportional to the beam current I, to the neutralization factor η depending on the gas pressure and inversely proportional to the transverse beam sizes σ_x and σ_y:

$$\Delta Q_{x,y} \propto \frac{I\eta}{\sigma_{x,y}\left(\sigma_x + \sigma_y\right)} \tag{2}$$

Since the vertical beam size in DAΦNE is much smaller than the horizontal one, the vertical tune shift ΔQ_y is much higher than the horizontal one. This means that for the nominal working point (5.09; 5.07) the vertical tune is shifted towards to the horizontal one, i. e. closer to the main coupling resonance $Q_x = Q_y$, increasing the machine coupling much above the project value of 1%. This does not happen for the working points above the main coupling resonance ($Q_y > Q_x$).

c) It is known from general considerations that the closer a working point is to integers or to the resonances excited by sextupoles (like $Q_x = 2Q_y$; $3Q_x$ = n etc.), the smaller the dynamic aperture will be. For on-energy particles an indirect indicator of the dynamic aperture variations versus the working point position is the dependence of the tunes on the particle oscillation amplitudes. Usually, for a stronger dependence of tunes on amplitudes one should expect a reduction of the dynamic aperture.

To the first order of perturbation the tune shifts depend linearly on the action variables:

$$\begin{aligned} \Delta Q_x &= 2c11 J_x + c12 J_y \\ \Delta Q_y &= c12 J_x + 2c22 J_y \end{aligned} \tag{3}$$

Here the action variables J_x and J_y are proportional to the second power of the normalized betatron amplitudes A_x and A_y:

$$J_x = \frac{\varepsilon_x A_x^2}{2}; \quad J_y = \frac{\varepsilon_y A_y^2}{2} \tag{4}$$

with ε_x and ε_y being the horizontal and vertical emittances, respectively. The coefficients c11, c12, c22 depend on sextupole strengths, phase advances between the sextupoles and on the actual working point.

The working point (5.09; 5.07) is rather close to integers and to the sextupole resonance $Q_x = 2Q_y$. So, we expect stronger dependencies of the tune shifts on amplitudes and a smaller dynamic aperture for this point rather than for one shifted far from the integers and from the sextupole resonance lines. Indeed, as analytical calculations have shown for the case when only the sextupoles necessary to correct the chromaticity in DAΦNE are switched on, the coefficients for the working point (5.09; 5.07) (c11 = 914; c12 = -39; c22 = 758) are substantially higher than those for the point (5.15; 5.21) where c11 = 294; c12 = 36; c22 =117.

d) The second order chromaticity, responsible for the parabolic tune variation as a function of momentum deviation, is very sensitive to the tune choice [2]:

$$Q''_{x,y} \propto \frac{\cos^3\left(2\pi Q_{x,y}\right)}{\sin\left(2\pi Q_{x,y}\right)} \qquad (5)$$

According to (5), the chromaticity behavior for tunes closer to integers gets highly nonlinear and, therefore, the chromaticity correction becomes more problematic.

Moreover, the tunes of off-momentum particles decrease as the momentum deviation grows. This implies that when the tunes are close to the integers, the particles having a momentum deviation above a certain value fall into the integer resonance stop-band and will be lost. In particular, the short lifetime observed during the machine tuning at the working point (5.09; 5.07) may, probably, be attributed to this effect [3].

Choice of the working point

The above considerations pushed us to perform a study aimed to find a working point situated far from integers and from sextupole resonances and, at the same time, providing a reasonable beam-beam performance, i. e. a decent luminosity and acceptable lifetime. Due to the lattice constraints the allowed tune space is limited for the horizontal tunes in the range of 5.10 - 5.20 and for the vertical ones between 5.20 and 5.30.

We have used the numerical code BBC [4], modeling weak-strong beam-beam interactions to perform a rough luminosity scan in the allowable tune space with a step of 0.01 in both directions. In order to examine the equilibrium beam sizes we tracked 50 particles of the weak beam over 10 radiation damping times (~ 1000000 revolution turns) interacting with a gaussian strong beam divided longitudinally in 5 slices.

The results of the simulations with $\xi_{x,y} = 0.04$ are summarized in Table 1. The first number in each cell represents the calculated luminosity normalized to the nominal luminosity, i. e. the maximum luminosity that can be reached for a given $\xi_{x,y}$ and with no blow up of the beam sizes. The second and the third numbers are the maximum horizontal and vertical amplitudes, respectively, reached by the particles during 10 damping times and normalized to the rms beam sizes at zero current, σ_{x0} and σ_{y0} . These numbers give a preliminary idea on the bunch distribution tail growth for different tunes.

Table 1. DAΦNE luminosity tune scan with $\xi_{x,y}$ = 0.04.

Q_y \ Q_x	0.10	0.11	0.12	0.13	0.14	0.15	0.16	0.17	0.18	0.19
0.20	0.7224 3.132 23.52	0.5568 2.857 16.46	0.4197 4.324 17.05	0.4173 2.964 35.12	0.5872 7.271 30.10	0.7076 3.496 14.81	0.4984 4.592 20.19	0.3047 3.361 34.68	0.1145 3.161 41.45	0.1222 4.152 67.49
0.21	0.6925 2.940 13.85	0.5216 3.383 18.67	0.2660 4.333 24.07	0.3475 3.396 30.80	0.6843 7.145 39.60	0.6384 3.162 23.56	0.5512 4.622 10.87	0.5060 3.308 18.74	0.5209 3.231 17.82	0.2954 3.626 35.48
0.22	0.4821 3.494 36.92	0.4980 3.350 15.89	0.3988 4.617 21.17	0.3932 3.846 38.36	0.6204 2.707 17.03	0.5024 3.824 23.02	0.3656 4.570 29.53	0.5717 3.159 13.77	0.6132 3.696 20.73	0.6007 3.498 12.63
0.23	0.3541 3.539 12.07	0.3136 3.009 12.51	0.2538 5.019 18.70	0.4299 3.612 25.24	0.3677 4.392 20.27	0.3380 3.690 17.14	0.3160 4.516 17.63	0.4401 3.348 19.47	0.4102 3.480 16.85	0.3812 3.682 21.57
0.24	0.1702 3.662 25.75	0.1291 3.476 23.18	0.1333 4.933 23.59	0.1791 3.449 20.74	0.1782 4.920 23.40	0.1350 3.074 28.88	0.1846 4.724 24.81	0.1831 3.324 20.71	0.1536 3.080 26.85	0.1449 3.636 27.27
0.25	0.1179 3.089 46.60	0.0847 3.669 48.95	0.3658 5.295 51.18	0.1698 3.091 40.72	0.1204 4.547 42.79	0.0752 3.242 41.89	0.1671 4.870 40.71	0.5331 3.326 38.51	0.356 3.442 43.27	0.1636 3.520 38.32
0.26	0.5394 3.718 16.75	0.5465 3.579 26.99	0.6680 4.327 14.35	0.5413 3.550 12.41	0.5964 3.726 17.64	0.5485 3.990 18.72	0.5339 4.601 20.57	0.5990 3.226 12.68	0.3840 2.905 24.33	0.2516 3.584 24.43
0.27	0.5582 3.669 20.24	0.7437 5.141 25.86	0.468 4.676 17.47	0.5311 3.713 20.37	0.5667 5.170 26.59	0.6647 3.564 23.21	0.6086 4.431 19.25	0.4321 4.159 25.11	0.3551 3.449 23.15	0.1970 3.804 24.12
0.28	0.5196 3.693 29.37	0.3982 3.218 24.01	0.358 4.975 23.88	0.4011 3.183 24.93	0.7884 7.431 35.63	0.7063 3.350 25.48	0.4572 4.653 11.59	0.4043 3.624 11.54	0.2124 3.616 14.77	0.1338 3.740 19.71
0.29	0.5165 3.970 29.48	0.3691 3.507 27.46	0.4959 4.400 38.50	0.5069 3.365 31.40	0.7724 7.508 34.46	0.5606 3.336 12.81	0.2777 4.430 15.38	0.2149 3.092 18.13	0.1046 3.106 28.80	0.0762 4.025 38.45

Unfortunately, as it is shown in Table 1, no working point within the given tune limits can withstand the strong beam-beam interaction with $\xi_{x,y}$ = 0.04 without beam blow up. There are no points with 100% luminosity. Besides, the long vertical tails created within the first 10 damping times have been observed for almost all the scanned area, thus setting a severe limit on the beam lifetime.

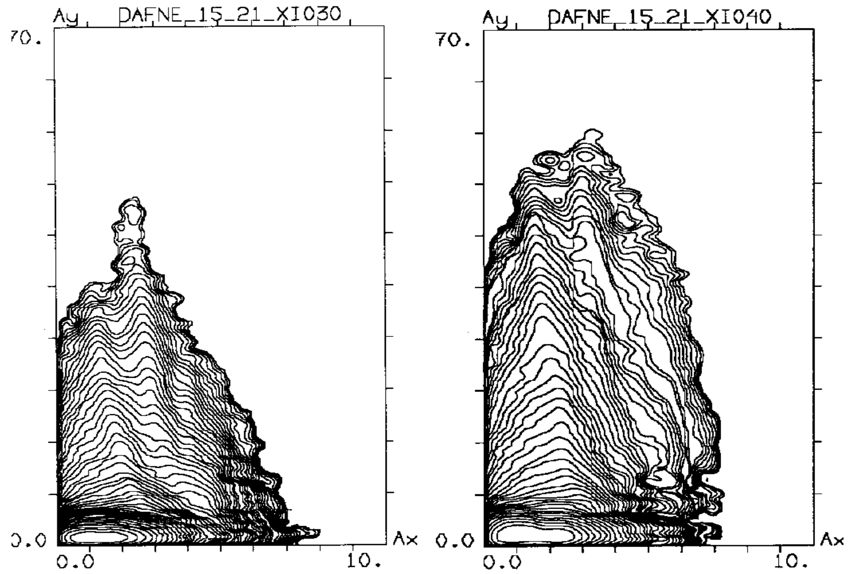
The beam blow up can be avoided and the lifetime can be improved for some working points (at the expense of some luminosity reduction) by reducing the space charge parameter $\xi_{x,y}$. Table 2 shows the results of the numerical simulation for $\xi_{x,y}$ decreased by a factor of 2. As we can see, the working point (5.15; 5.21) is the best one in this set of simulations, having more than 100% luminosity and the bunch distribution confined within 4 σ_{x0} in the horizontal plane and 3 σ_{y0} in the vertical one.

Table 2. DAΦNE luminosity tune scan with $\xi_{x,y} = 0.02$.

Q_y \ Q_x	0.10	0.11	0.12	0.13	0.14	0.15	0.16	0.17	0.18	0.19
0.2	0.9092 3.264 29.19	0.9105 2.887 5.755	0.8771 3.421 5.405	0.7383 2.602 7.064	0.6120 3.422 17.47	0.9893 3.163 4.731	0.8064 3.603 5.680	0.9733 3.466 9.042	0.6498 2.827 15.98	0.181 3.448 27.17
0.21	0.7144 2.950 10.94	0.9256 2.786 6.827	0.8724 3.178 9.429	0.4306 2.958 15.06	0.6175 4.808 22.76	1.006 3.536 2.938	0.8359 3.345 3.689	0.8357 3.196 4.116	0.8367 2.980 7.535	0.7833 3.326 10.78
0.22	0.7177 2.709 10.85	0.8623 3.501 12.89	0.815 3.171 5.735	0.6424 3.130 13.81	0.8687 3.314 10.48	0.8916 3.339 5.674	0.8270 3.750 5.066	0.7059 3.429 16.60	0.8479 3.269 9.512	0.8064 3.229 4.671
0.23	0.8418 3.552 8.965	0.6872 2.661 12.69	0.5902 3.542 8.429	0.7120 3.494 17.12	0.8116 3.586 4.880	0.8214 2.861 10.25	0.6128 3.541 5.320	0.7340 3.172 10.01	0.8609 2.942 5.042	0.8143 3.004 4.038
0.24	0.3407 3.256 8.555	0.3262 2.728 12.05	0.2429 3.582 14.03	0.342 2.998 13.40	0.3474 3.241 11.79	0.3395 3.224 12.02	0.2665 3.572 16.43	0.3196 3.559 13.99	0.363 2.875 11.49	0.3114 3.117 10.26
0.25	0.4910 2.921 20.86	0.2173 2.923 20.64	0.9101 3.891 26.00	0.3509 3.362 19.87	0.4197 3.364 21.45	0.2324 3.787 21.01	0.2056 3.212 20.93	0.3446 2.906 20.93	0.3983 3.315 20.70	0.3205 2.946 20.69
0.26	0.8449 3.209 6.512	0.5409 2.858 12.64	0.8024 3.597 8.895	0.9318 2.899 8.053	0.7542 3.187 6.675	0.7768 2.888 10.26	0.7655 3.578 7.184	0.8148 3.708 8.982	0.8969 2.909 4.085	0.8538 3.293 4.996
0.27	0.6213 3.029 8.697	0.8628 3.673 17.23	0.9089 3.223 3.227	0.7034 2.940 11.93	0.7016 3.298 9.139	0.9291 3.269 12.96	0.8668 3.828 5.438	0.8274 2.680 9.614	0.8994 2.519 14.79	0.7837 3.163 8.938
0.28	0.5687 3.056 17.86	0.9638 2.954 5.888	0.890 3.754 5.992	0.536 2.761 11.30	0.7106 3.314 17.61	0.9577 3.380 5.754	0.8580 3.511 3.195	0.9698 3.085 2.992	0.7899 2.719 6.169	0.5401 3.107 7.556
0.29	0.8465 3.018 14.24	0.9315 3.385 10.53	0.7271 3.329 12.72	0.7413 3.005 17.20	0.7401 3.305 13.15	0.9872 2.969 2.966	0.8929 3.520 3.711	0.8603 3.421 3.995	0.5453 2.722 8.910	0.1950 2.844 16.23

In order to evaluate the maximum luminosity that can be reached for the best point and to estimate the corresponding lifetime we have performed simulations with LIFETRAC code [5] changing the parameter $\xi_{x,y}$ from 0.02 to 0.04. Figure 1 shows the density contour plots for the cases with $\xi_{x,y}$ equal to 0.03 and to 0.04. These plots and all the other contour plots in this paper are made in the same style: displayed area is 10 σ_{x0} times 70 σ_{y0} (it is the DAΦNE designed dynamic aperture for the machine coupling of 1%), contours present the lines of equal density of the equilibrium distribution in the space of normalized betatron amplitudes, with the distance between adjacent lines equal to $\sqrt{e}$. One may compare these plots with Fig. 9 (a), where the almost unperturbed (Gaussian) distribution is shown. The long tails of distributions shown in many plots can limit the beam lifetime and affect the detector background. From such figures one can learn how the nonlinear resonances disturb the equilibrium beam distribution.

$\xi_{x,y}$ = 0.03 can be considered as a maximum space charge tune shift parameter for the working point (5.15; 5.21) when the beam sizes are not blown up yet. The normalized horizontal and vertical beam sizes are σ_x/σ_{x0} = 1.08; σ_y/σ_{y0} = 1.04, respectively. The calculated luminosity corresponding to this tune shift is equal to 2.2*10^{30} cm^{-2} s^{-1}. The beam distribution tails are well within the machine dynamic aperture (see Fig.1 (a)).



a) b)

Figure 1: *Equilibrium density in the space of normalized betatron amplitudes for DAΦNE working point (5.15; 5.21) with $\xi_{x,y}$ = 0.03 (a) and $\xi_{x,y}$ = 0.04 (b).*

On the contrary, the beam sizes are notably blown up for $\xi_{x,y}$ = 0.04. This can be seen comparing the contour levels in the beam core at low amplitudes in Fig. 1 (a) and (b). The normalized sizes are equal to 1.20 and to 1.46 for the horizontal and vertical planes, respectively. The beam tails get larger for $\xi_{x,y}$ = 0.04, but still they are contained within the dynamic aperture. Nevertheless, we have to stress here, that bunches with longer tails are more strongly affected by machine nonlinearities, thus limiting the resulting lifetime.

Despite the blown sizes, the luminosity for $\xi_{x,y}$ = 0.04 is somewhat higher than that for $\xi_{x,y}$ = 0.03 and is equal to 3.0*10^{30} cm^{-2} s^{-1}. However, we should note that in the weak-strong simulations the strong beam is supposed to be gaussian and having nominal (not blown up) beam sizes. The correct answer about the luminosity value in this case can be given only by a strong-strong simulation which takes into account the evolution of both the interacting beams.

Luminosity scan around the working point (5.15; 5.21)

In order to evaluate the dimensions of a “safe” area around the best working point (5.15; 5.21) we have carried out a numerical scan with LIFETRAC code in the vicinity of this point.

The resulting beam distributions in the amplitude plane are shown in Fig. 2.

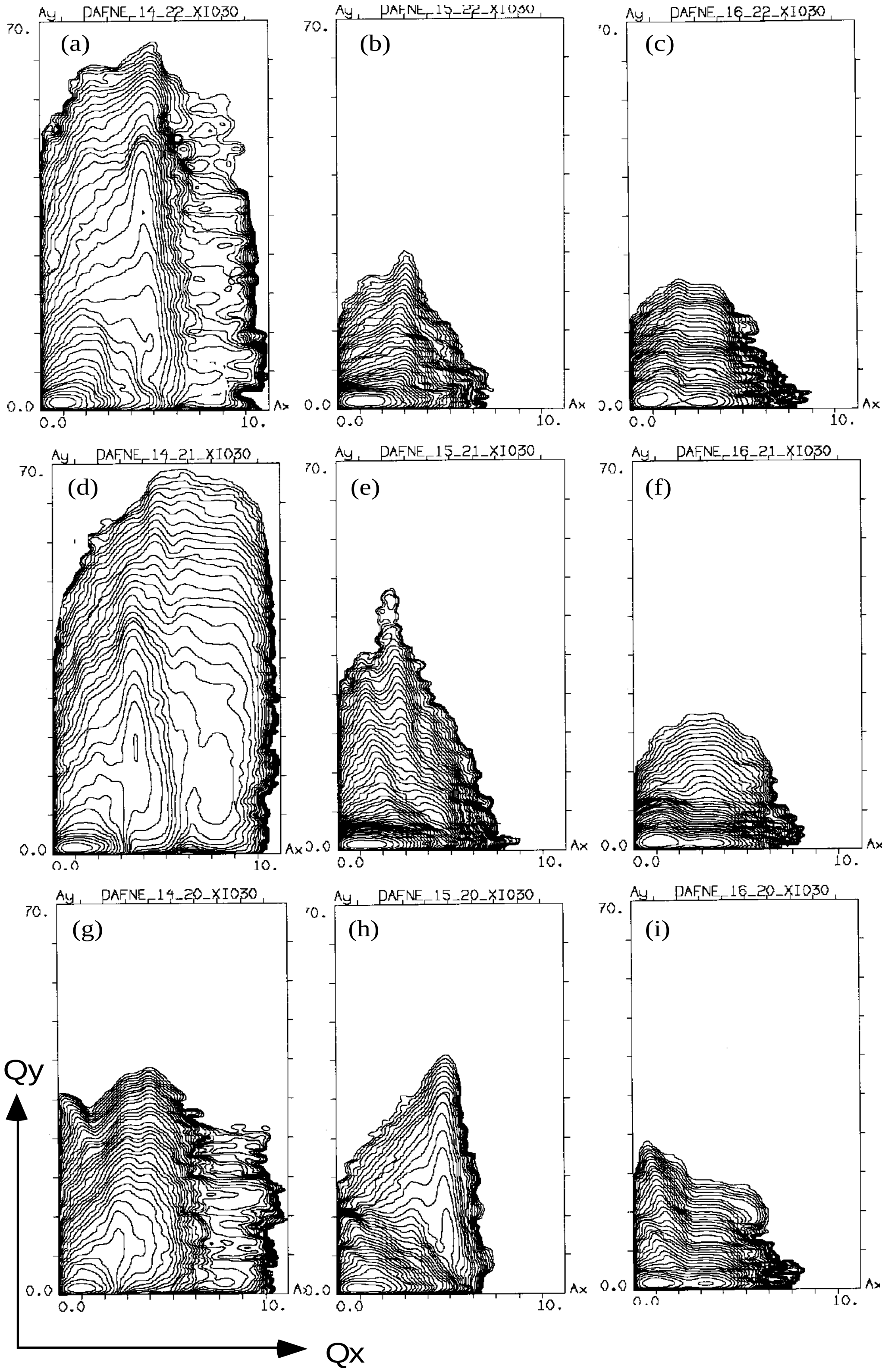


Figure 2: *Luminosity scan around the working point (5.15; 5.21) with a tune step of 0.01; a) (5.14; 5.22); b) (5.15; 5.22); c) (5.16; 5.22); d) (5.14; 5.21); e) (5.15; 5.21); f) (5.16; 5.21); g) (5.14; 5.20); h) (5.15; 5.20); i) (5.16; 5.20)*

Unfortunately, as is seen in Fig. 2, the working point is very sensitive to small tune variations. Even tune shifts as small as 0.01 in any direction lead to a luminosity reduction. Moreover, a decrease of the radial tune from 5.15 to 5.14 much worsens the beam lifetime. The fast tail growth, both horizontal and vertical, is observed in Fig. 2 (a), (d) and (g).

At present some experimental data are available to perform a comparison with the above numerical results. First of all, a good lifetime and the present record of single bunch luminosity of $1.5*10^{30}$ cm^{-2} s^{-1} have been reached at the working point (5.15; 5.21). This luminosity is somewhat smaller than the maximum value of $2.2*10^{30}$ cm^{-2} s^{-1} predicted numerically for the given point because the collisions have been done at lower current (25 mA per bunch), i. e. with $\xi_{x,y} = 0.025$ instead of the allowable $\xi_{x,y} = 0.03$. This means that a further improvement is still possible.

A direct comparison of the numerical results, presented in Fig. 2, with the experimental luminosity tune scan around the point (5.15; 5.21) performed with a step of 0.01 [6] showed a good qualitative agreement. An increase of the horizontal tune from 5.15 to 5.16 resulted in a substantial increase of the horizontal beam size while the lifetime was slightly improved. This is in accordance with the numerical simulations. In fact, for the points having $Q_x = 5.16$, as it is seen in Fig. 2 (c), (f) and (i), the bunch core is blown up horizontally and the vertical distribution tails are shorter, especially for the point (5.16; 5.20), than for the central working point.

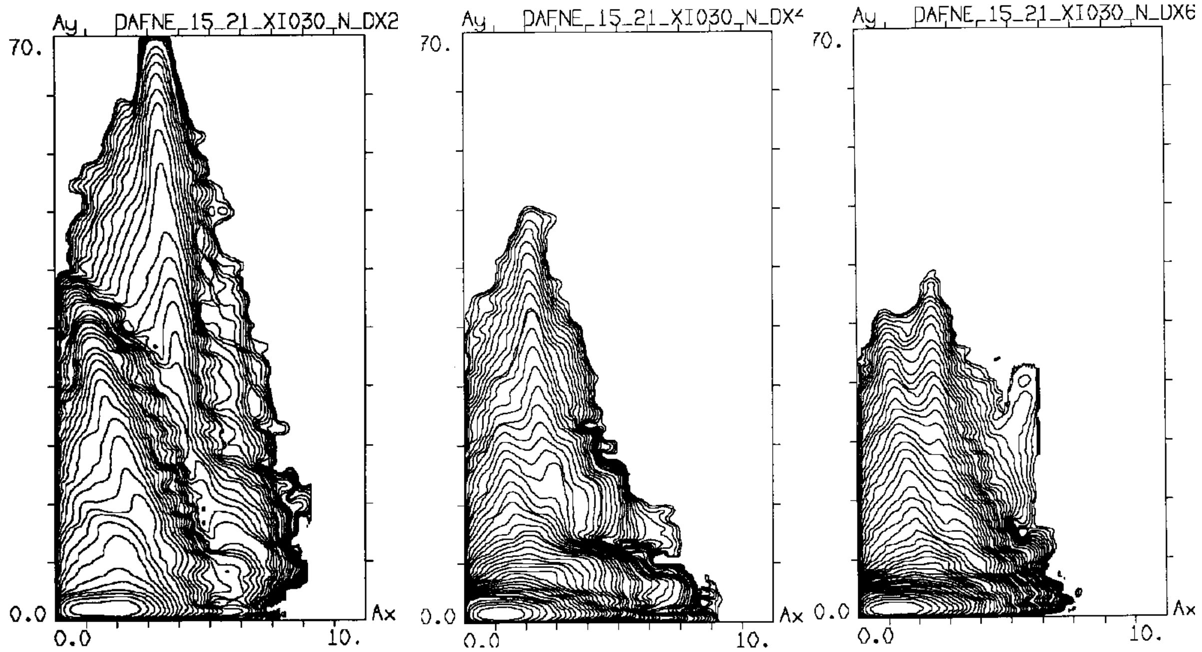
In turn, by decreasing the vertical tune to 5.14 a sharp degradation of the lifetime was experimentally detected. This is also in agreement with the tail growth predicted numerically for the points (5.14; 5.20), (5.14; 5.21) and (5.14; 5.22) (see Fig. 2 (a), (d) and (g), respectively).

Beam-beam separations at the second IP

In order to reduce the effect of the parasitic interactions due to the second IP, while exploiting the single IP collisions, special horizontal and vertical localized orbit bumps have been applied to separate the electron and positron beams at the second IP. Numerical simulations have been carried out to investigate how the machine luminosity and lifetime depend on the beam-beam separations and estimate the separation limits necessary to avoid beam-beam performance degradation.

The simulations have been performed for the working point (5.15; 5.21) taking into account the phase advance difference between the two IPs in the horizontal plane. The tune advance ΔQ_x for the short-half of DAΦNE used in the simulation is 2.453 and that taken for the long-half of the machine is 2.697 [7].

Figure 3 shows the bunch distributions with horizontal beam separations at the second IP of 2 σ_{x0} (a), 4 σ_{x0} (b) and 6 σ_{x0} (c), respectively. Here we remind that the nominal rms horizontal beam size at the IP σ_{x0} is 2.12 mm. The beam separation of 6 σ_{x0} (c), i. e. about 12.7 mm, allows practically to cancel the influence of the parasitic second IP.



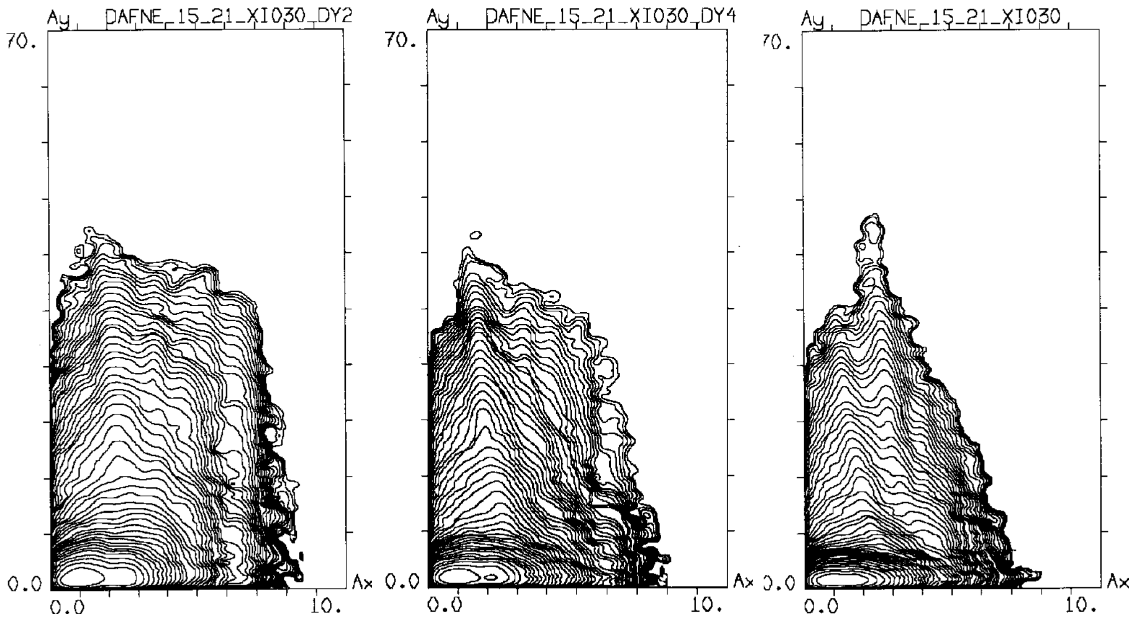
a) b) c)

Figure 3: *Equilibrium density contour plots for the working point (5.15; 5.21) with horizontal separations at the second IP of 2σx0 (a), 4σ_{x0} (b) and 6σ_{x0} (c).*

The luminosity maintains the value of 2.2*10^{30} cm^{-2} s^{-1} with $\xi_{x,y}$ = 0.03 and the distribution tails are not strongly affected by the parasitic collisions. A decrease of the horizontal separation to 4 σ_{x0} (b) (~ 8.5 mm) does not lead to a luminosity decrease, but the vertical tails are slightly longer. In turn, further horizontal separation reduction to 2 σ_{x0} (a) (~ 4.2 mm) results in a luminosity drop to 1.5*10^{30} cm^{-2} s^{-1}. Moreover, the long tails reaching the borders of the DAΦNE dynamic aperture are clearly seen in Fig. 3. The beam-beam induced tails together with the machine nonlinearities (which were not taken into account in the present simulations) can drastically limit the lifetime.

The beams arriving at the second IP can also be separated in the vertical plane. Since the bunch is very flat in DAΦNE, the vertical separation has to be greater than the horizontal rms beam size in order to diminish the parasitic collision consequences [8], i. e. the vertical separation should be bigger than ~ 1 σ_{x0} = 100 σ_{y0}.

Figure 4 compares beam distributions calculated considering the vertical beam separation at the second IP of 100 σ_{y0} (a), 200 σ_{y0} (b) and the case without the second IP interaction (c). As it can be seen, the distribution enlarges horizontally by decreasing the bunch separation and tends to occupy almost all the horizontal dynamic aperture when the vertical separation is equal to 100 σ_{y0} (~ 2 mm). The luminosity value corresponding to this case is 1.6*10^{30} cm^{-2} s^{-1}. The situation gets better by doubling the vertical separation (see Fig. 4 (b)). The luminosity with such a separation is 1.9*10^{30} cm^{-2} s^{-1} which is not much lower than that in collisions without the second IP.



a) b) c)

Figure 4: *Equilibrium density contour plots for the working point (5.15; 5.21) with vertical separations at the second IP of 100 σ_{y0} (a), 200 σ_{y0} (b) and without the second IP (c).*

A comparison of the vertical and horizontal separations shows that the vertical separations seem to be more effective, that is for equal absolute bumps (measured in mm) the higher luminosity and shorter distribution tails can be obtained with the vertical separation.

Vertical crossing angle

Since the electron and positron beams are stored in two different rings, they follow two different orbits. Even if the beam positions are carefully monitored and overlapped at the IP, the probability of a vertical crossing angle is not negligible, since any orbit change or drift translates in angle at the low beta position. The possible vertical crossing angle is estimated to be of the order of 100 - 200 μrad.

We have estimated numerically whether such an angle can result in a bad lifetime or luminosity degradation for the chosen working point.

Figure 5 compares the amplitude bunch distributions for the different crossing angles: 100 μrad (a), 200 μrad (b), 300 μrad (c) and 400 μrad (d). As we can see, the distribution tails are practically not affected by the vertical crossing angle up to 400 μrad. Instead, a moderate beam core blow up is observed while increasing the vertical crossing angle. Figure 6 shows the calculated luminosity as a function of the crossing angle.

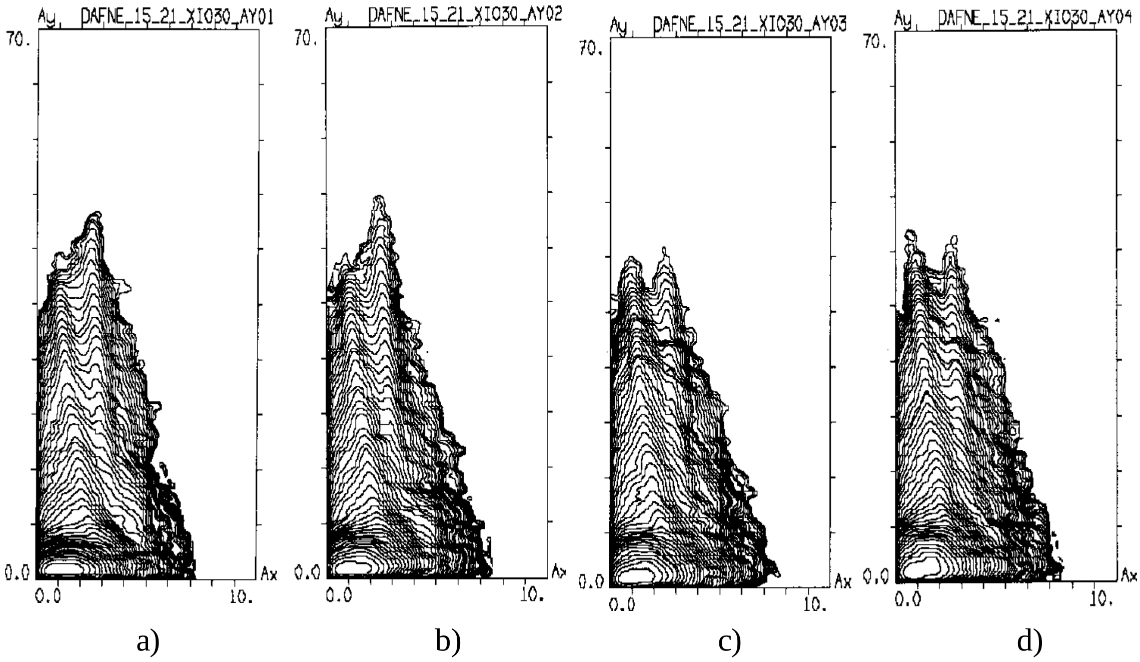


Figure 5: *Equilibrium density contour plots for the working point (5.15; 5.21) with vertical crossing angle of 100 μrad (a), 200 μrad (b), 300 μrad (c) and 400 μrad (d)*

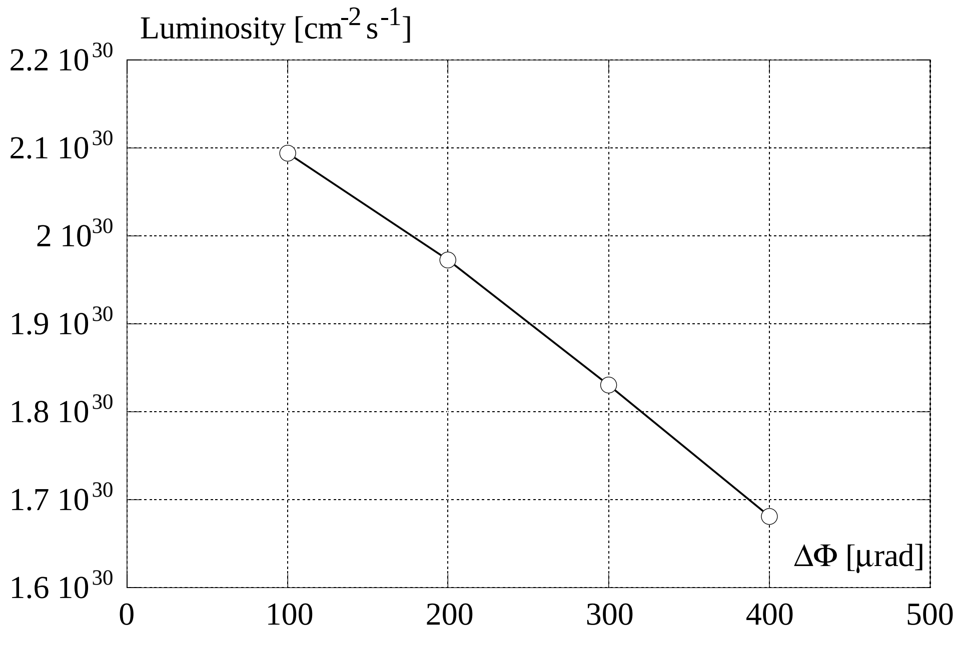


Figure 6: *Luminosity as a function of the vertical crossing angle.*

We can conclude that the estimated vertical crossing angle of 100 - 200 μrad should neither limit the machine lifetime nor reduce substantially the luminosity.

Machine nonlinearities

Lattice nonlinearities can significantly change the beam-beam performance with respect to that expected from simulations which do not take them into account. Besides, the combined effect of the nonlinearities and beam-beam collisions can differ from what is obtained when the two factors are considered separately.

The beam-beam interaction drives particles to higher amplitudes where the nonlinearities get stronger thus changing the distribution tails. Very often this reduces the lifetime. However, strong nonlinearities may also affect the beam core and lead to luminosity decrease.

The machine sextupoles are the strongest source of nonlinearities in DAΦNE. We have estimated numerically with the LIFETRAC code the contribution of the sextupoles into the tail growth. In particular, we have simulated the situation very close to one realized during the luminosity commissioning runs when only the sextupoles for the chromaticity correction were switched on. The coefficients of the cubic nonlinearity introduced by the sextupoles have been calculated analytically, assuming the model beta functions and phase advances between the sextupoles.

Figure 7 (b) shows the resulting beam distribution for the working point (5.15; 5.21). As it is seen, the beam core remains unchanged in comparison with the case of the beam-beam interaction without nonlinearities, presented in Fig.7 (a). But the distribution tails have strongly grown reaching the dynamic aperture boundaries thus limiting the lifetime.

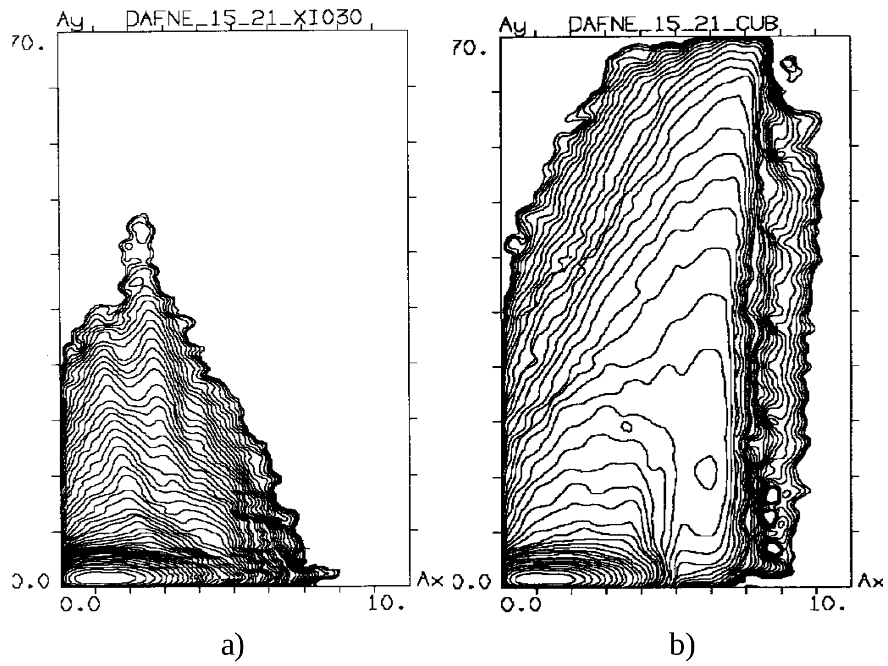


Figure 7: *Equilibrium density in the space of normalized betatron amplitudes for the working point (5.15; 5.21): (a) without lattice nonlinearities; (b) with sextupole nonlinearities.*

The actual DAΦNE nonlinearities and the dynamic aperture have not been measured yet and the above example can not be considered as a final answer about the machine lifetime. It just demonstrates that one should be very careful managing the sextupoles in order to avoid lifetime problems.

Injection with parasitic crossings (PC)

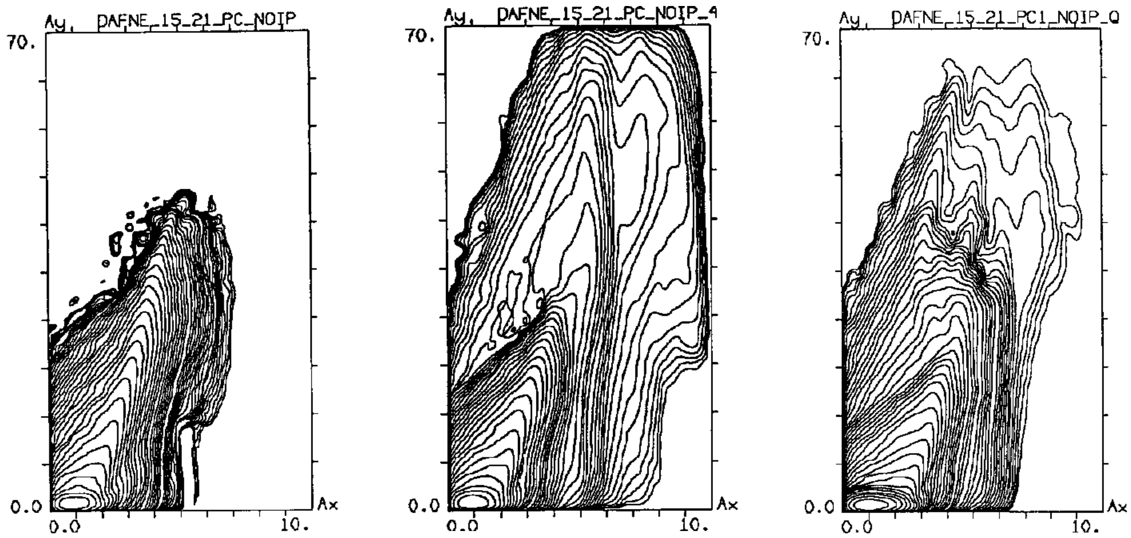
During injection it has been observed that in the collision mode the intensity of the beam which was being injected saturated much below the nominal level. This has been explained by the fact that the injected bunch performs both longitudinal and transverse oscillations for a period of time comparable with a radiation damping time. Such a bunch interacting with an opposite, already stored bunch, looses its intensity.

A "phase jump" procedure has been adopted to fix this problem [9]. Initially, the two bunches are injected into different RF buckets in order to avoid beam-beam interactions during the intensity accumulation. Then, when the nominal intensity is reached, the stored bunches are brought into collisions by changing rapidly the phase of one of the RF cavities. In this way the orbit length in one of the main rings changes to compensate the initial longitudinal separation of the bunches.

The procedure has been proved to be efficient when initially the bunches are separated by two RF buckets. However, when the longitudinal separation is reduced to a single bucket the injection is still limited.

In our opinion this can be explained in terms of parasitic crossings of the two bunches at a distance equal to a half bucket length from the main interaction point. In order to confirm this guess we have simulated this parasitic interaction with the LIFETRAC code. In particular, we have considered the situation when the opposite bunches do not collide at the main IP and the electromagnetic beam-beam interaction occurs only at a single parasitic crossing about 40 cm away from the main IP. The simulations have been carried out for both the "Day One" interaction region (IR) optics including the central quadrupole and the Dear IR optics with the quadrupole removed. With the "DAY-ONE" IR optics the interacting bunches are separated horizontally by 5.6 σ_x at the parasitic crossing point and the respective vertical beta function is 4.11 m. In case of the Dear IR optics the horizontal separation is 4.7 σ_x and the β_y is equal to 3.69 m at the parasitic collision point.

Figure 8 (a) shows the equilibrium bunch distribution for the DEAR IR optics (lattice nonlinearities are not included). It can be noticed that the tails grow beyond the parasitic crossing horizontal position (~ 5 σ_x). However, the tails are well within the hypothetical dynamic aperture. But, when the sextupole nonlinearities are taken into account (see Fig. 8 (b)), the tails reach the dynamic aperture boundary and the lifetime gets as short as 3 min. This means that the parasitic crossings acting together with the lattice nonlinearities may complicate the injection into the bucket next to that where the opposite bunch is stored.



a) b) c)

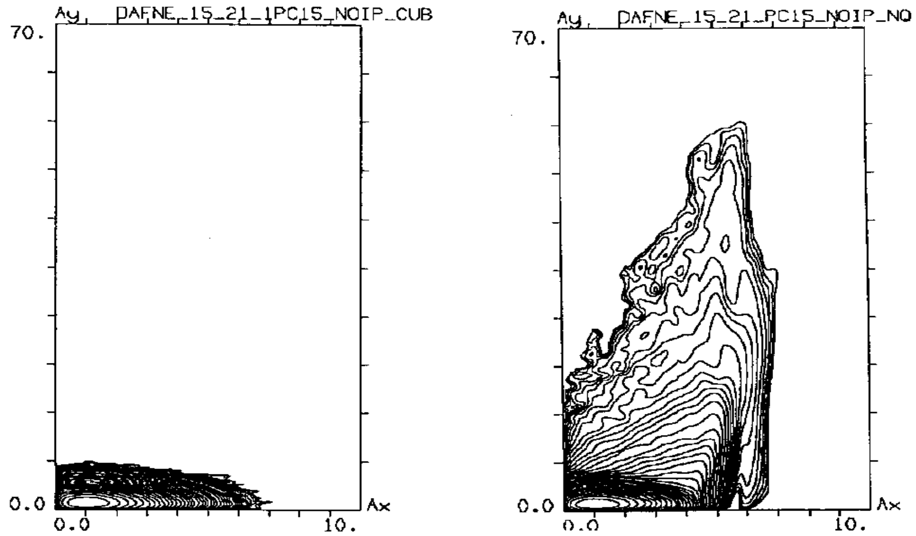
Figure 8: *Tail growth due to parasitic collisions of bunches separated by one RF bucket: a) DEAR IR optics without sextupole nonlinearities; b) DEAR IR optics with sextupole nonlinearities; c) DAY-ONE IR optics with sextupole nonlinearities.*

However, during the commissioning the DAY-ONE optics has been exploited Since the horizontal separation for the optics is bigger than that for the DEAR optics, the resulting distribution tails are shorter (see Fig. 8 (c)) and the calculated lifetime is long enough (about 20 hours when only the beam-beam interaction is taken into account). But, we should stress here that the actual dynamic aperture and the machine nonlinearities are not known yet and the sextupole correction has not been applied yet. This implies that the real situation can be significantly worse that that considered in the simulations, i. e. the dynamic aperture is smaller and the stronger actual nonlinearities may drastically reduce the machine lifetime with respect to the simulated one.

In our opinion, the common effect of the parasitic crossings and the nonlinearities could explain the injection saturation during the experimental luminosity runs.

At this point we have to answer the question how large the separation between the opposite bunches should be in order to avoid the parasitic crossing problem, or, in the other words, how many bunches can be stored in each beam in order to apply the phase jump procedure without a luminosity degradation due to injection saturation.

As the numerical simulations have shown, an increase of the separation to 1.5 bucket practically eliminate the problem of the parasitic crossings. Fig. 9 (a) shows the bunch equilibrium density for the DAY-ONE IR optics, while the distribution for the DEAR optics is seen in Fig. 9 (b). In the former case the distribution remains almost gaussian, in the latter one we observe growth of low populated tails which do not limit the lifetime.



a) b)

Figure 9: *Tail growth due to parasitic collisions of bunches separated by 1.5 RF buckets and taking into account the sextupole machine nonlinearities: a) DAY-ONE IR optics; b) DEAR IR optics.*

We can conclude that the phase jump procedure can be applied successfully for 40 bunches stored in each colliding beam. The collisions of beams composed of 60 equidistant bunches is complicated by parasitic crossings forced by the lattice nonlinearities. However, we believe that one can try to improve the situation by adjusting the machine sextupoles to compensate the cubic nonlinearity and by increasing the dynamic aperture. Nevertheless, in our opinion, the most effective solution for the problem is an increase of the horizontal separation in terms of σ_x, as it has been already proposed to avoid the PC problem in the multibunch operations [10]. In particular, the horizontal beta function at the IP β_x has to be decreased by a factor of 2, while increasing the vertical emittance by the same factor. In this way the separation at the PC would increase by a factor of $\sqrt{2}$ in terms of σ_x, while the tune shifts and the luminosity are kept unchanged.

Horizontal beam size widening

During DAΦNE luminosity operation a sudden widening of the horizontal beam sizes was observed at some working conditions [11]. In particular, the horizontal size of both the interacting bunches seen at the synchrotron light monitor was blown up by a factor of 2 - 3, while the vertical one remained unchanged. Sometimes we could distinguish two local density peaks separated horizontally on the monitor image. Usually, this happened at rather low and equal currents in the two bunches (2 - 10 mA).

In order to understand the origin of the phenomena the strong-strong beam-beam simulation taking into account lattice nonlinearities would be necessary. Due to the absence of a reliable 3D strong-strong code at present it is a practically impossible task. However, we can advance a hypothesis giving a possible explanation of the phenomena based on the weak-strong simulations. While performing the weak-strong simulations reported above we have already seen distributions with blown up horizontal dimentions and having two local maxima.

Figure 10 shows the two examples: (a) single IP interaction at the working point (5.16; 5.20) which is very close to the nominal working point (5.15; 5.21); (b) interaction at the nominal working point (5.15; 5.21) with vertical separation of 4 mm at the second IP. We can conclude that even small deviations from the nominal working conditions can result in a horizontal blow up with an appearance of the two local maxima.

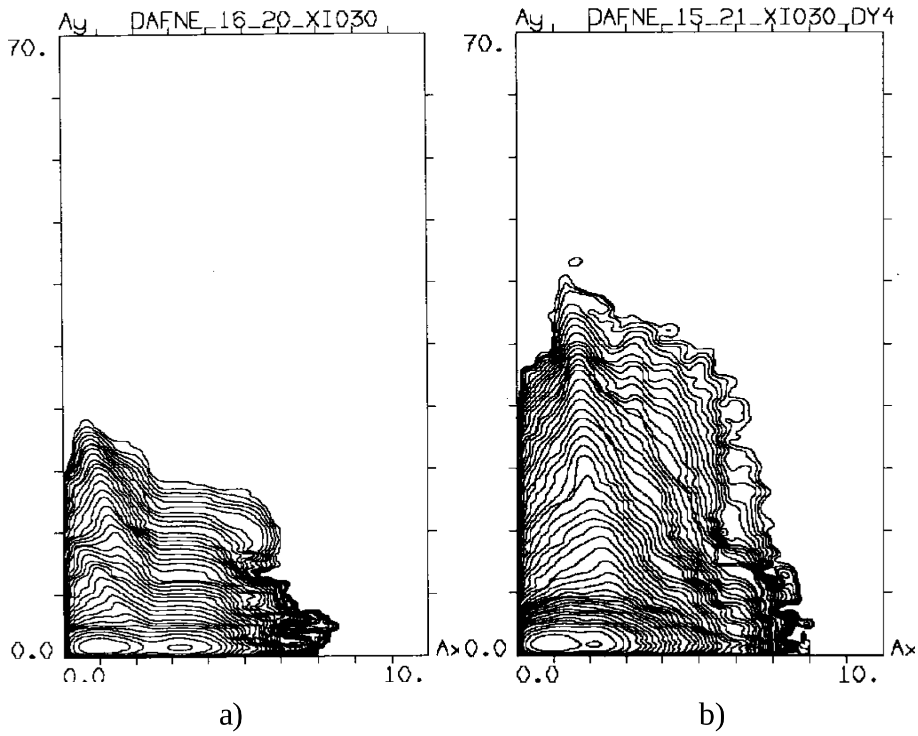


Figure 10: *Examples of the horizontal bunch widening: (a) single IP interaction at (5.16; 5.20); (b) interaction at (5.15; 5.21) with the vertical separation of 4 mm at the second IP.*

Our analysis has shown that in both cases a strong betatron resonance of the sixth order $6\,Q_x = n$ was responsible for the effect. We can also add that the external nonlinearity can increase or decrease significantly the resonance bandwidth, depending on the nonlinearity sign [12, 13]. In the most unfortunate case the bandwidth can be very large if the beam-beam induced nonlinearity is canceled by the machine nonlinearity.

So, we can not exclude that the sixth order resonance was driving the effect. On the other hand, it is difficult to imagine a coherent strong-strong effect which could cause the phenomena since it was observed at very low currents (and low tune shift parameters of 0.002 - 0.01).

Interactions with two IPs

It is highly desirable to collide beams at the two interaction points in DAΦNE. This would allow to perform two DAΦNE experiments simultaneously.

However, an increase of the number of IPs usually leads to a luminosity reduction per each IP. One may expect a strong luminosity performance degradation if the phase advances of betatron oscillations between the IPs are different since the phase advance differences introduce the new beam-beam resonances of low order [14,15]. Because of that a choice of a suitable working point for the two IP collision scheme in DAΦNE is not a simple task. Such a working point must satisfy the following, often contradicting, requirements:

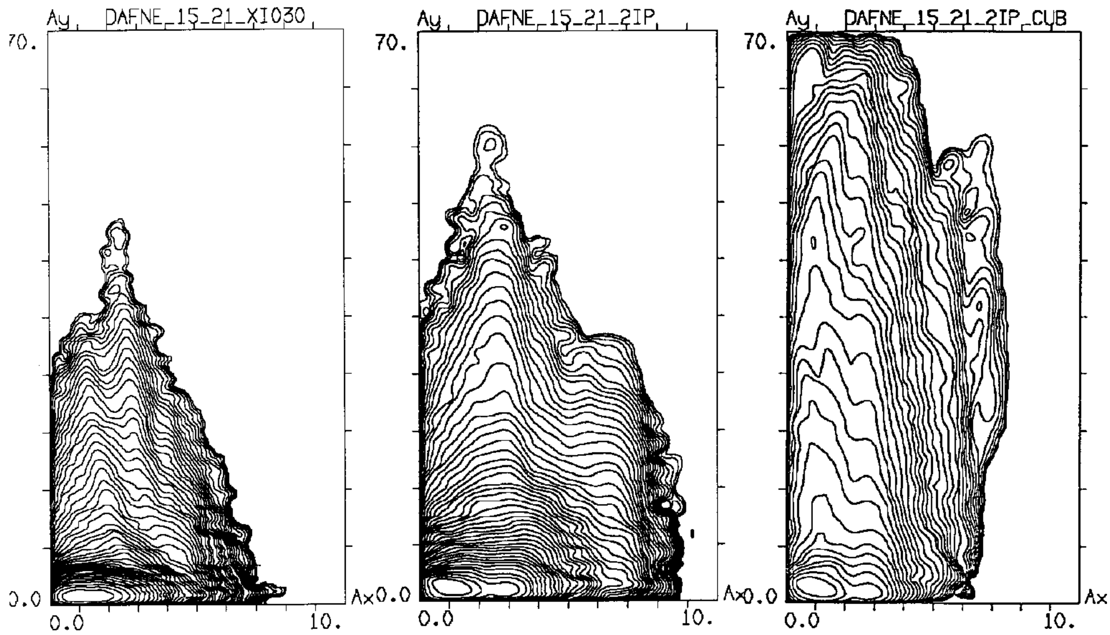
- provide a good luminosity and a satisfactory lifetime with two IPs;

- provide a good beam-beam performance with a single IP since the luminosity should be maintained at a good level at the first IP while performing the luminosity adjustment (transverse beam-beam scan, longitudinal timing etc.) at the second IP;

- provide a good dynamic aperture.

It appears that there are only few working points which can satisfy these conditions. Their description is the subject of another DAΦNE Note. Here we consider a possibility to adopt the actual working point (5.15; 5.21) for the two IP collisions.

Figure 11 (b) shows the beam equilibrium density distribution for the working point (5.15; 5.21) with the two collision points and no lattice nonlinearity. As in the previous calculations, we have assumed that the horizontal phase advance difference between the two IPs is ΔQ_x = 0.24 as predicted by the machine lattice model [7]. For a comparison the density distribution for the same working point, but for the case of a single collision point is reported in Fig. 11 (a).



a) b) c)

Figure 11: *Equilibrium density in the space of normalized betatron amplitudes for the working point (5.15; 5.21): (a) single IP collisions without lattice nonlinearities; (b) two IP collisions without lattice nonlinearities; c) two IP collisions with cubic (sextupole) nonlinearities (c11 = -86; c12 = -144; c22 = 136).*

As it is clearly seen, the beam core is larger when the beams collide at the 2 IPs. The calculated luminosity decreases from $2.2*10^{30}$ cm^{-2} s^{-1} in the single IP collisions to $1.7*10^{30}$ cm^{-2} s^{-1} (per each IP) for the beams colliding at the two IPs.

But the most important point is that the tail distribution gets much wider with two IPs. As it is shown in Fig. 11 (b) it occupies almost all the allowable horizontal dynamic aperture. This means that practically any small lattice nonlinearities could drive the particles beyond the dynamic aperture limits. We have performed the numerical simulations with the cubic nonlinearities estimated analytically for the most favorable case when the sextupoles for chromaticity correction are adjusted to weaken the tune dependence on the betatron amplitudes [16]. Indeed, as shown in Fig. 11 (c), the density distribution in this case has very long relatively highly populated tails spreading beyond the vertical aperture boundary thus drastically reducing the lifetime to about 25 sec. This could be an explanation why the first experimental attempt to collide the bunches with currents higher than 10 mA at the two IPs without the working point change and without any lattice correction has failed.

The only possibility to improve the situation without changing the working point is to try to vary the phase advance difference between the IPs.

Figure 12 shows the dependence of the luminosity (per each IP) calculated with the LIFETRAC code as a function of the horizontal phase advance difference at $\xi_{x,y} = 0.03$. We have assumed that the vertical phase advances are equal between the IPs. This assumption is very close to the reality, since the vertical phase advance difference is small (about 0.04) and can be easily corrected.

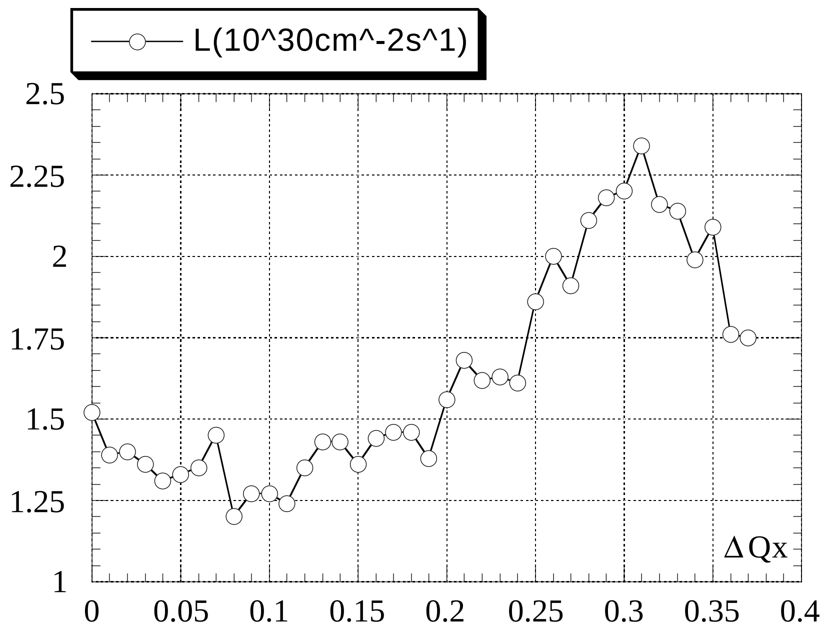


Figure 12: *Luminosity as a function of the horizontal tune advance difference.*

The result presented in Fig. 12 is rather surprising for us since we were expecting that the maximum luminosity would be reached when the phase (tune) advance difference is equal to zero. Instead, the maximum luminosity of $2.35*10^{30}$ cm^{-2} s^{-1} corresponds to $\Delta Q_X = 0.31$. It seems that the phase advance differences not only create new beam-beam resonances, but can destroy some of the old strong ones. It would be highly desirable to investigate the phenomena theoretically.

Fortunately, the tail growth is limited in such a way that all the bunch distribution stays well within the dynamic aperture for $\Delta Q_X = 0.31$. Fig. 13 compares the equilibrium density distributions for $\Delta Q_X = 0.24$ (a) and $\Delta Q_X = 0.31$ (b).

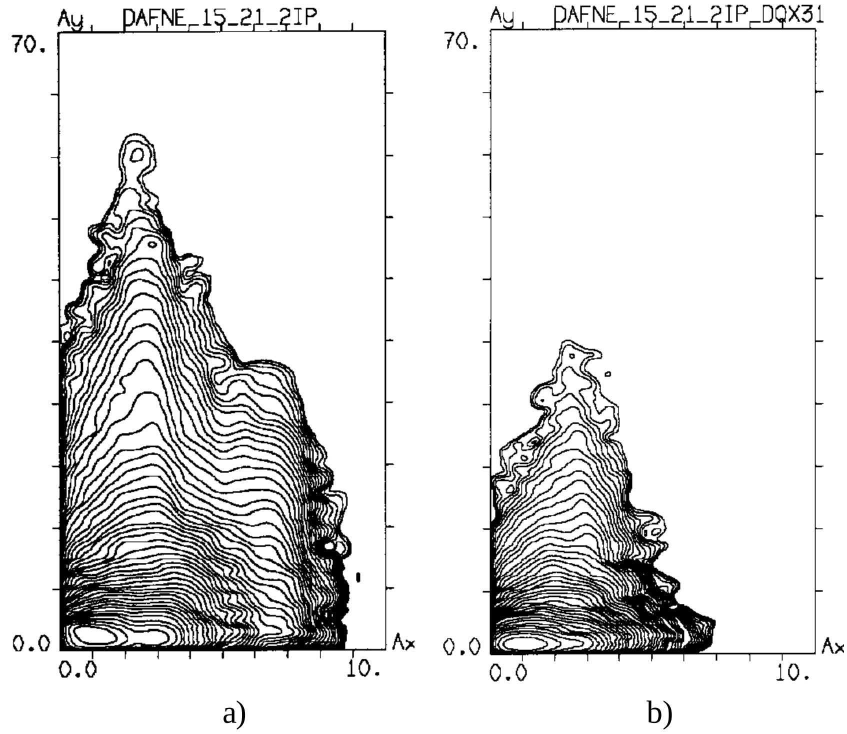


Figure 13: Equilibrium density in the space of normalized betatron amplitudes for the working point (5.15; 5.21) with two IPs and tune advance difference between the two IPs of : (a) $\Delta Q_X = 0.24$; (b) $\Delta Q_X = 0.31$.

As we can conclude observing Figs. 12 and 13, the slight readjustment of the machine lattice aimed to increase the tune advance difference between the IPs from 0.24 to 0.31 can greatly improve the beam-beam machine performance with the two interaction points.

We have also checked the above result simulating the quasi strong-strong beam-beam interaction with the dedicated code TURN [17].

Figure 14 shows the dependence of the machine luminosity on the bunch current. In the simulations it has been assumed that both the interacting bunches have equal currents.

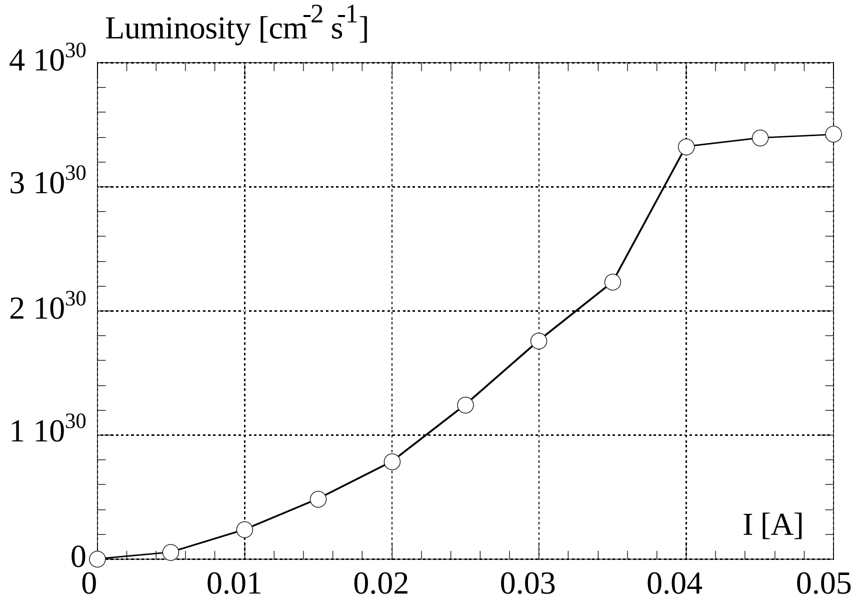


Figure 14: *Luminosity as a function of the bunch current (quasi strong-strong simulation).*

As it is seen in Fig. 14, according to the quasi strong-strong simulations the luminosity that can be reached by increasing the tune advance difference to 0.31 exceeds $3.0*10^{30}$ cm^{-2} s^{-1} per each IP and saturates at the level of $3.4*10^{30}$ cm^{-2} s^{-1} for the currents close to the nominal DAΦNE current per bunch of 43 mA.

We have repeated the weak-strong simulations with LIFETRAC with $\xi_{x,y}$ = 0.04, corresponding to the nominal current of 43 mA, and found exactly the same luminosity as given by TURN code ($3.4*10^{30}$ cm^{-2} s^{-1}) with slightly blown up beam sizes of the weak beam: σ_x/σ_{x0} = 1.24 and σ_y/σ_{y0} = 1.29.

Conclusions

1) The numerical simulations have predicted that the working point (5.15; 5.21) seems to be the best one in the given tune range to provide a reasonable DAΦNE beam-beam performance at the commissioning stage. The experimental luminosity runs have confirmed the numerical predictions. According to the simulations the maximum luminosity that can be reached at this point is $2.2*10^{30}$ cm^{-2} s^{-1} without a notable beam size blow up.

2) Unfortunately, as the numerical scan have shown, the “safe” area around the working point is very restricted. The tune shifts of 0.01 in either direction lead either to a bunch core blow up or to a drastic lifetime reduction. This conclusion has been checked experimentally and the experimental data are in a good agreement with the simulation results.

3) A set of numerical simulations has been carried out to estimate the influence of the beam-beam separations at the second IP, both horizontal and vertical, on the machine luminosity performance. It has been found that the vertical separation at the second IP is more effective than the horizontal one. A vertical separation of more than 4 mm at the second IP would allow to minimize luminosity loss and lifetime reduction in the single IP collisions.

4) It has been shown numerically that the possible vertical crossing angle of the order of 100 - 200 μrad neither limit the lifetime nor reduce significantly the luminosity. For the vertical angle of 200 μrad the luminosity reduction is estimated to be of the order of 10 %.

5) According to the simulations the sextupole nonlinearities can drastically reduce the lifetime. In order to minimize their effect one has to pay attention while performing the chromaticity and dynamic aperture correction.

6) The numerical simulations indicates that the phase jump procedure can be applied successfully for equidistant 40 bunches stored in each colliding beam. The phase jump procedure for the beams composed of 60 equidistant bunches is complicated by the parasitic crossings forced by the lattice nonlinearities. However, since the parasitic crossing themselves are not strong enough to limit the machine lifetime one should try to adjust the machine sextupoles to compensate or weaken the cubic nonlinearity and to increase the dynamic aperture in order to make the phase jump procedure with 60 bunches possible.

7) We have advanced the hypothesis that the bunch widening observed at rather low currents for the given working point could be explained by the strong horizontal betatron resonance of the sixth order $6\ Q_x = n$. It should not be excluded that the bandwidth of the resonance is largely increased due to the compensation of the beam-beam nonlinearity by the machine nonlinearity (or the nonlinearitity due to the parasitic beam-beam interaction at the second IP).

8) The numerical simulations of the beam-beam interactions with the two IPs at the working point (5.15; 5.21) taking into account the cubic sextupole nonlinearity have shown a luminosity drop and the fast tail growth of the bunch density distribution limiting the machine lifetime to about 20 sec. This seems to be an explanation why the first attempt to collide beams at the two IPs with a reasonable current per bunch (higher than 10 mA) has failed. In order to fix the problem we propose to increase the horizontal tune advance difference between the IPs from 0.24 to 0.31. In this case, according to the LIFETRAC simulations, the luminosity at $\xi_{x,y} = 0.03$ is estimated to be of $2.35 {*} 10^{30}$ cm^{-2} s^{-1} per each IP with distribution tails well within the dynamic aperture. Moreover, both the quasi strong-strong code TURN and the weak-strong code LIFETRAC predict a possibility to increase the luminosity farther to about $3.4 {*} 10^{30}$ cm^{-2} s^{-1} with moderate beam size blow up by increasing the current per bunch to 40 - 43 mA, corresponding to $\xi_{x,y} = 0.04$.

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