DAΦNE TECHNICAL NOTE

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BEAM - BEAM TAILS STUDY FOR DAΦNE

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Abstract

The long tails induced by beam - beam interaction can limit the beam lifetime and affect background in the experiment detectors. We used a special beam - beam code [3] to simulate beam tails for DAΦNE [1].

Although the dynamics and physical apertures are large enough, the beam lifetime can be limited by long tails produced by Parasitic Crossings (PC) near the Interaction Point (IP). In the case of the maximum design number of bunches (120), the lifetime drops to an unacceptable value. A new working point and some change in the machine lattice are proposed to avoid the PC problem.

1. Introduction

A preliminary study of beam-beam interaction for DAΦNE, including a scan of working points in the betatron tune space to optimize the expected luminosity has already been performed, and suitable working points have been found [2]. However, due to the small values of the DAΦNE damping decrements (i.e. coefficients determining the damping rate, which are inversely proportional to the damping time), long beam tails can be induced, causing lifetime and background problems.

One of the reason for tails growth are the high order resonances, which can be harmful only in case of weak damping. In Fig. 3(c,d) one can see the equilibrium distributions in the space of normalized betatron amplitudes, obtained for two working points, which are identical except the damping decrements. It appears obvious that the long beam tails represent a serious problem for DAΦNE, emphasized by the weak damping.

Unfortunately, a "brute force" beam - beam simulation would require too much CPU time to collect a satisfactory statistics at large betatron amplitudes. In order to save CPU time (up to several orders of magnitude), we use a specially developed tracking technique [3] to find the equilibrium distribution in the beam tails. A recently performed comparison [4] between this code and Hirata's beam - beam code BBC showed good agreement, confirming our confidence in the validity of our results.

The simulation is performed by a "weak - strong" model, with the strong bunch assumed Gaussian in all three directions, and longitudinally divided into 3 slices. The beam - beam kicks are calculated by means of Bassetti - Erskine formula [5], modified in such a way that it becomes 6-dimensionally simplectic [6]. The lattice is assumed to be linear, with the possibility of including the tune dependence of the betatron amplitudes (i. e. cubic nonlinearity of betatron tunes). The Parasitic Crossings (PC) are also taken into account. The Touschek effect, which is very important for DAΦNE, has not yet been included in the code. We plan to do it in the future in order to improve our simulations.

In our study we concentrate only on the good working points, which were found in [2]: these are small areas around (0.09;0.07) and (0.53;0.06).

2. Simulation without parasitic crossings

First of all we tested the two previously established working points in order to make sure that the dynamic aperture is large enough to avoid lifetime and background problems. Since the nonlinearity of the machine lattice is rather small, it should not influence the equilibrium distribution in the beam core, so that one can neglect it during the simulation of beam sizes and luminosity optimization. The situation changes significantly at large betatron amplitudes, where the contribution of the lattice nonlinearities can be comparable or even large than the beam - beam tune shift. Therefore, in order to get a feeling about the relative importance of the two effects, we tested both the cases with and without the cubic nonlinearity.

Table 1 summarizes the main parameters used in the simulations. The changes in the equilibrium beam sizes, produced by beam - beam interaction, are presented in Table 2. The equilibrium distributions in the plane of normalized betatron amplitudes are shown in Fig. 1 for the working point (0.09;0.07) and Fig. 2 for the working point (0.53;0.06). As one can see, indeed, the cubic nonlinearity does not significantly affect the beam core. When going to large amplitudes, the influence of the nonlinearity increases, so that the equilibrium distribution depends on the interference between the lattice nonlinearity and the beam - beam effects. It turns out that at the working point (0.09;0.07) the beam tail growth is larger than at the working point (0.53;0.06), but anyway the dynamic aperture is large enough to avoid any lifetime problem.

Table 1. DAΦNE parameters relevant for simulations.

Tunes: $\{\nu_x\}$, $\{\nu_y\}$, ν_z [1st working point]	0.09, 0.07, 0.012
Tunes: $\{\nu_x\}$, $\{\nu_y\}$, ν_z [2nd working point]	0.53, 0.06, 0.012
Cubic nonl.: C_x, C_y, C_{xy} [1st working point]	-0.195, 0.472, -1.93
Cubic nonl.: C_x, C_y, C_{xy} [2nd working point]	-0.679, 1.239, -2.0
Damping times: τ_x, τ_y, τ_z [turns]	110540, 109650, 54620
Emittances: ε_x, ε_y [cm · rad]	$1.0 \cdot 10^{-4}$, $1.0 \cdot 10^{-6}$
Beta functions at IP: β_x^*, β_y^* [cm]	450, 4.5
Bunch length: σ_z [cm]	3.0
Energy spread: σ_ε	$5.0 \cdot 10^{-4}$
Tune shifts: ξ_x, ξ_y	0.041, 0.041
Crossing angle: ϕ_x [mrad]	$\pm$ 12.5

Table 2. Equilibrium beam sizes after $2.2 \cdot 10^8$ particle-turns.

Working point	σ_x/σ_{xo}	σ_{Px}/σ_{Pxo}	σ_y/σ_{yo}	σ_{Py}/σ_{Pyo}
(0.09;0.07) cub. nonl. OFF	0.99	1.16	1.11	1.28
(0.09;0.07) cub. nonl. ON	0.99	1.17	1.08	1.25
(0.53;0.06) cub. nonl. OFF	0.86	1.35	1.28	1.46
(0.53;0.06) cub. nonl. ON	0.89	1.37	1.15	1.36

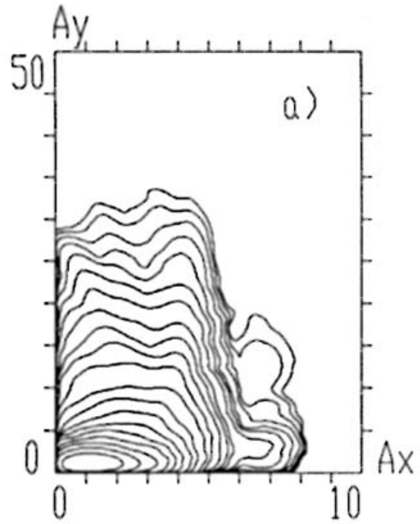

Figure 1. Equilibrium density in the space of normalized betatron amplitudes for DAΦNE working point (0.09;0.07) without (a) and with (b) cubic nonlinearity. The successive contour levels are at a constant ratio *e* below each other.

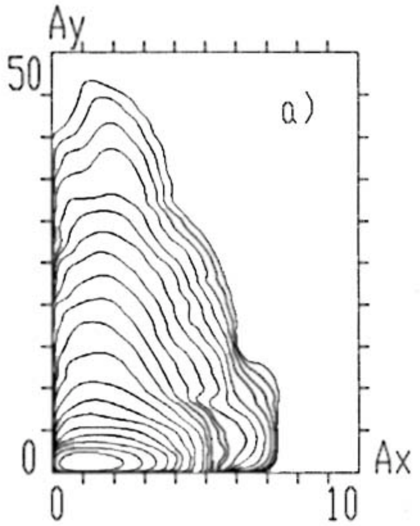

Figure 2. Equilibrium density in the space of normalized betatron amplitudes for DAΦNE working point (0.53;0.06) without (a) and with (b) cubic nonlinearity. The successive contour levels are at a constant ratio *e* below each other.

3. Simulation with parasitic crossings

The next step in our study is the simulation in presence of Parasitic Crossings (PC). We used the parameters of PCs in KLOE interaction region.

Table 3 summarizes the relevant PC data, taken from [8]. As it is seen, in spite of the crossing angle at the IP, the design separation between bunches at the PC in the case of 120 stored bunches is approximately equal to $5\sigma_X$. It turns out that such a separation is absolutely not enough, since PCs induce very long tails, with the lifetime dropping to few seconds. The problem arises from the high value of β_y at the PC, resulting in a very strong normalized vertical kick experienced by a test particle when it drifts horizontally near a PC.

Figure 3 shows the equilibrium distributions obtained in the cases of 120, 60 and 40 bunches (KLOE lattice). It can be noticed that long tails grow beyond the PC's horizontal position ($5\sigma_X$ for 120 bunches, $9.9\sigma_X$ for 60 bunches). In the other words, the horizontal dynamic aperture becomes equal to the separation between the bunches at the PC, and the lifetime is determined by the probability of overlapping the PC in the horizontal direction. In the case of 40 bunches the separation is equal to ~ $17\sigma_X$, so that the probability of overlapping the PC drops to a negligible value and we have actually the same distribution as in the case where the effect of the PCs was not taken into account (see Fig. 1a).

It is important to remark that the PC's effect is strongly enhanced by the very small damping decrements (as a consequence, this leads to a weak noise) in DAΦNE. This can be clearly observed from the comparison between Fig. 3c (60 bunches, normal decrements) and Fig. 3d (the same working point, but with the damping decrements increased by a factor of 10). In the last case the reduction of the tails comes from the crushing of high order synchro - betatron resonances, which are the reason for the horizontal drift of the particles in the case of the nominal decrements.

Table 3. Parasitic crossings in KLOE interaction region.

PC	s(m)	d(m)	d/σ_x		Number of bunches			
		12.5 mrad	12.5 mrad	15.0 mrad	30	40	60	120
1	0.4	0.0100	4.70	5.64	-	-	-	+
2	0.8	0.0175	9.81	11.77	-	-	+	+
3	1.2	0.0301	16.91	20.29	-	+	-	+
4	1.6	0.0510	20.91	25.10	+	-	+	+

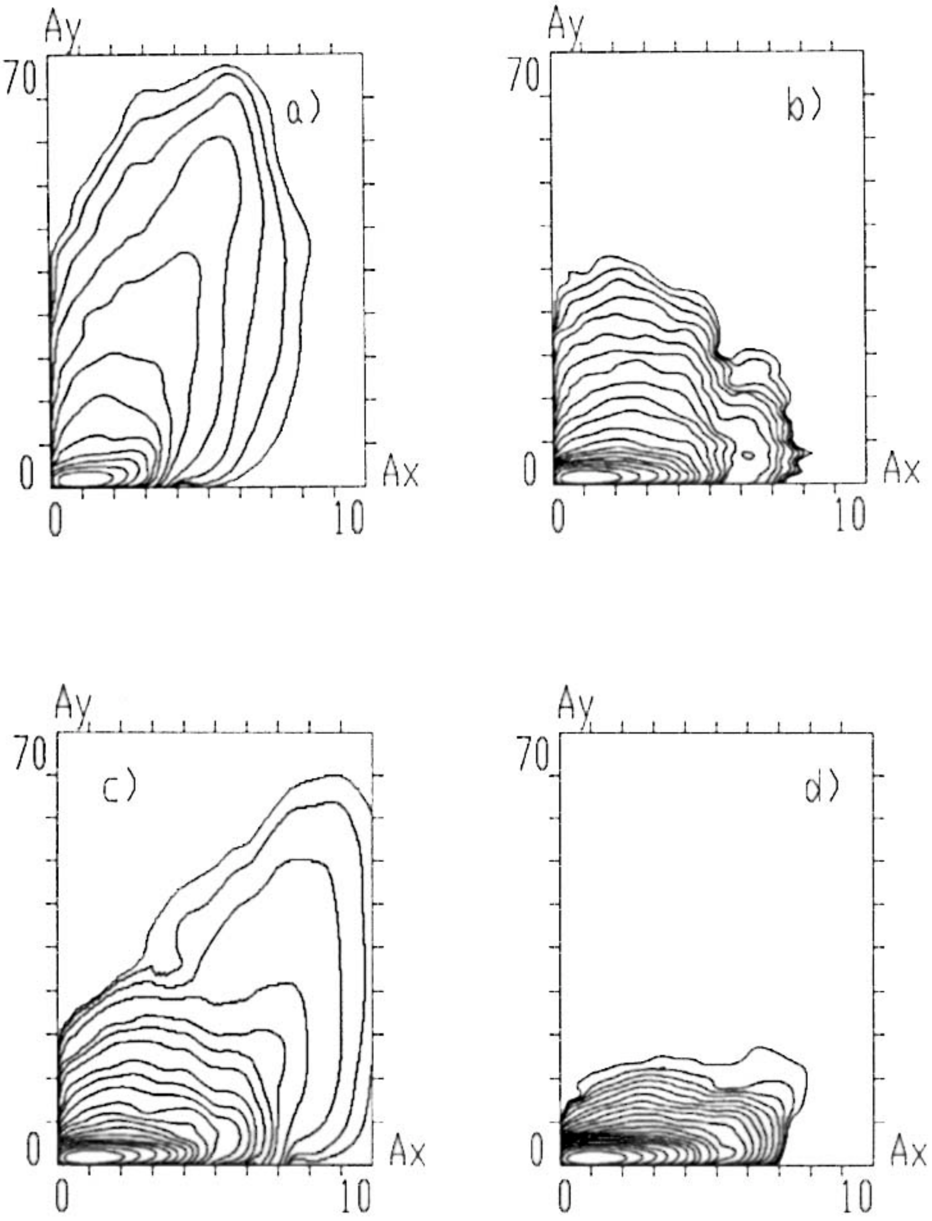

Figure. 3. Equilibrium density in the space of normalized betatron amplitudes for DAΦNE working point (0.09;0.07) with Parasitic Crossings, KLOE lattice. The successive contour levels are at a constant ratio e below each other. The lifetime τ (the vertical aperture is assumed to be 70 σ_y) strongly depends on the separation value and damping decrements:

a) 120 bunches, separation $5\sigma_x$, $\tau \sim 1$ sec

b) 40 bunches, separation $17\sigma_x$, $\tau > 10^7$ sec

c) 60 bunches, separation $9.9\sigma_x$, $\tau \sim 10^4$ sec

d) 60 bunches, separation $9.9\sigma_x$, damping increased by a factor of 10, $\tau > 10^7$ sec

4. Proposals to avoid the PC problem in the case of 120 bunches

In order to operate the collider with the maximum design number of bunches, we need to undertake some additional efforts, which could be summarized in two categories:

1) Increase the separation at the PC (in units of σ_x), which can be obtained in the following ways:
   a) Increase the crossing angle up to ± 15 mrad., namely the maximum value which does not require hardware layout modifications.
   b) Decrease the horizontal emittance ε_x, that results, however, in increasing of the horizontal tune shift ξ_x.
   c) Decrease β_x by a factor of 2, increasing at the same time the vertical emittance ε_y by the same factor. The separation at the PC would increase by a factor of $\sqrt{2}$, while the tune shifts ξ_x, ξ_y and the luminosity are kept unchanged.
2) Change the betatron tunes in order to avoid resonances which provide the horizontal drift of the particles.

Option 1b) has been discarded, since it requires to decrease the stored current in order to keep the horizontal tune shift ξ_x below its designed value. On the other hand, option 1a) seems to be the easiest to be performed, so that we assume $\phi_x = \pm 15$ mrad in all the cases discussed in the following. Nevertheless, the increase of the crossing angle alone is not enough to get an acceptable lifetime, so it is necessary to apply also 1c), or 2) or both.

As shown in Fig. 4, the lifetime improves significantly when getting closer to integer betatron tunes, thus avoiding synchro-betatron resonances (in particular, $11Q_x - Q_z = k$). Nevertheless, a separation of $6\sigma_x$ at the PC seems to be insufficient in any case. On the other hand, only increasing the separation up to $8.5\sigma_x$ by using both 1a) and 1c) is also not enough (see Fig. 5a). We need therefore to realize all the improvements (i. e. 1a, 1c and 2) together to obtain acceptable lifetime and luminosity. We tried to minimize the changes in betatron tunes, since operating very close to an integer may introduce problems with dynamic aperture. Finally, we found that the working point (0.08;0.06) with a separation of $8.5\sigma_x$ (see Fig. 5b) satisfies all our requirements and it can be proposed as a new one, providing acceptable parameters for 120 bunches operation.

Table 4. Equilibrium beam sizes and lifetime for the working points presented in Figs. 3-5

Working point	σ_x/σ_{xo}	σ_{Px}/σ_{Pxo}	σ_y/σ_{yo}	σ_{Py}/σ_{Pyo}	lifetime (sec)
Fig. 3a	0.97	1.13	3.40	3.46	1
Fig. 3b	0.97	1.17	1.24	1.11	$> 10^7$
Fig. 3c	0.93	1.13	1.24	1.14	10^4
Fig. 3d	0.92	1.12	1.17	1.05	$> 10^7$
Fig. 4a	0.96	1.12	1.83	1.78	4
Fig. 4b	0.93	1.11	1.58	1.48	70
Fig. 4c	0.91	1.15	1.75	1.61	$3 \cdot 10^3$
Fig. 5a	0.95	1.13	1.37	1.26	$3 \cdot 10^2$
Fig. 5b	0.93	1.13	1.25	1.11	10^6
Fig. 5c	0.93	1.14	1.27	1.13	10^8

At the end of our study we repeated the last simulation with an increased number of slices (from 3 to 7) in the longitudinal distribution (see Fig. 5c). The initial small number of slices (3) was chosen in order to save CPU time when roughly testing several working points. However, since dividing the bunch into more slices results into smoother kicks, we expected the simulation not to change dramatically, and the results confirmed the validity of this assumption.

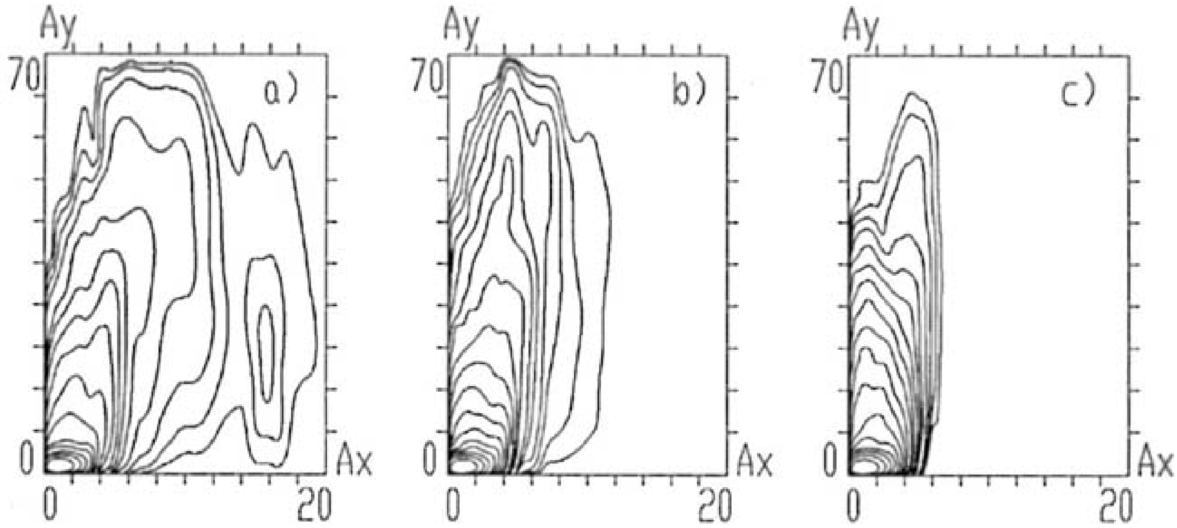

Figure. 4. Equilibrium density in the space of normalized betatron amplitudes, $\phi_x = \pm 15$ mrad, 120 bunches, separation of $6\sigma_x$. The successive contour levels are at a constant ratio e below each other. The betatron tunes are: (0.09;0.07), (0.08;0.06) and (0.06;0.04) for a), b) and c) respectively.

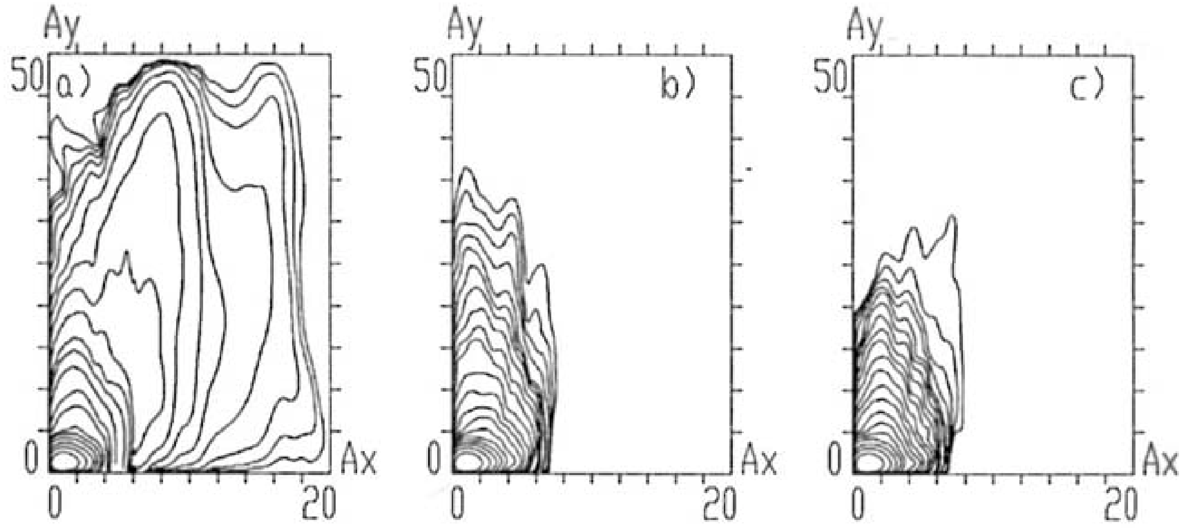

Figure. 5. Equilibrium density in the space of normalized betatron amplitudes, $\phi_x = \pm 15$ mrad, 120 bunches, separation of $8.5\sigma_x$ (new lattice with the changed β_x and ε_y). The successive contour levels are at a constant ratio e below each other. The betatron tunes are: (0.09;0.07) for a), (0.08;0.06) for b) and c). Case c) presents the same working point as b), but with the number of slices in the simulation increased from 3 to 7.

5. Conclusions

Simulations of beam - beam interaction have shown that the nonlinearity of the machine lattice itself is quite acceptable, but the Parasitic Crossings are of crucial importance for the beam lifetime. The maximum number of bunches which can be stored in DAΦNE at an acceptable beam lifetime and luminosity with the present lattice is 60. For the maximum design number of bunches (120) both strong core blow-up and drastic reduction in the lifetime (~ 1 sec) are expected because of the small separation ($5\sigma_x$) between bunches at the PC. In order to fix this problem we propose to increase the separation up to $8.5\sigma_x$ (by increasing the crossing angle and by means of some changes in the machine lattice), and to move the working point closer to the integer, thus avoiding resonances providing horizontal drift of the particles. A new working point has been found, which provides acceptable lifetime with 20% reduction in luminosity.

The beam study will continue in order to include the Touschek effect, which could be important for the DAΦNE parameters.

6. Acknowledgments

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