BEAM-BEAM INTERACTIONS IN DAΦNE: NUMERICAL SIMULATION AND EXPERIMENTAL RESULTS

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Abstract

The e^+e^- collider DAΦNE is a Φ-factory aimed to reach a luminosity as high as $5{\cdot}10^{32}$ cm^{-2} s^{-1} at the Φ-resonance energy of 1020 MeV in the center of mass. Since the machine energy is relatively low, the damping time takes a large number of revolutions (~100000) and the noise is weak. This means that even high order beam-beam resonances can affect the luminosity performance. The right choice of the working point is very important under these conditions in order to avoid the beam core blow up and distribution tail growth due to beam-beam interactions. Intensive numerical study has been performed in order to find a suitable working point. The point (5.150; 5.214) has been proposed for the beam-beam collisions at the commissioning stage. It has been proven experimentally that the numerically predicted working point provides the maximum luminosity in the allowable range of machine tunes during the commissioning. Moreover, it has been found in experimental runs that small variations of the tunes of the order of 0.001 with respect to that working point lead to a substantial reduction of the beam lifetime. This also agrees well with numerical simulations. In this paper we describe the main numerical simulation results of beam-beam interactions in DAΦNE and compare them with experimental observations and measurements.

1 INTRODUCTION

Numerical simulations [1] have shown that the optimal working point for DAΦNE is ($Q_x = 5.09$; $Q_y = 5.07$), where Q_x, Q_y are the horizontal and vertical tunes, respectively. At this working point the nominal luminosity of $4{\cdot}10^{30}$ 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.

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 below, the point (5.15; 5.21) has been chosen. Such a choice has been dictated by the following reasons:

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

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

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 design value of 10^{-9} Torr, thus inducing notable positive tune shifts due to the trapped ions of the residual gas in the electron beam. 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:

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

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 design 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 the working point is to integers or to resonances excited by sextupoles (like $2Q_y - Q_x = m$; $3Q_x = n$ 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

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

Q_x Q_y	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

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

Q_x Q_y	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

$\xi_{x,y}$ = 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 $2.2 \cdot 10^{30}$ cm^{-2} s^{-1}. The beam distribution tails are well within the machine dynamic aperture (see Fig.1 (a)).

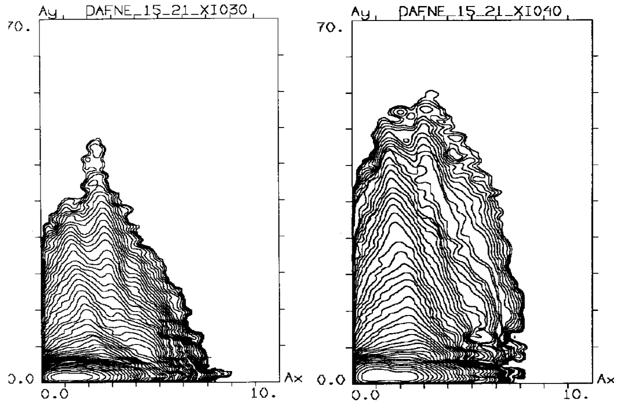

Figure 1: Equilibrium density in the space of normalized betatron amplitudes for DAΦNE working point (5.15; 5.21) with $\xi_{x,y}$ = 0.03 (a) and $\xi_{x,y}$ = 0.04 (b).

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 $3.0 \cdot 10^{30}$ 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.

3 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 in the vicinity of this point. The resulting beam distributions in the amplitude plane are shown in Fig. 2.

Unfortunately, as is seen in Fig. 2, the working point is very sensitive to small tune variations. Even tune changes 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 $1.6 \cdot 10^{30}$ 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 $2.2 \cdot 10^{30}$ 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 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 occured. 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).

4 LIFETIME OPTIMIZATION

It has been measured experimentally that the beam lifetime during collisions is rather sensible to tune variations of the order 10^{-3}. In order to verify the lifetime tune sensitivity a fine tune scan with a tune step of 0.002 has been carried out numerically.

We have found that the luminosity is not so sensitive to the small tune variations. The ratio of the luminosity to the nominal value corresponding to $\xi_{x,y}$ = 0.03 remains unchanged around the value L/L_0 ~ 0.9 until the tune variations do not exceed $\Delta Q_{x,y}$ = 0.006.

On the contrary, tails of the distributions depend strongly on the tunes.

Figure 3 shows an example on how the tails change by varying the vertical tune from 5.210 to 5.220 while keeping the horizontal tune constant at 5.150. As it can be clearly seen, the tails shorten till Qy = 5.214 and reach a minimum at this point. Afterwards, the tails start growing again.

It appears that the working point (5.150; 5.214) has the shortest tails in the numerically explored tune area. So this point should provide the best lifetime. This has been checked experimentally.

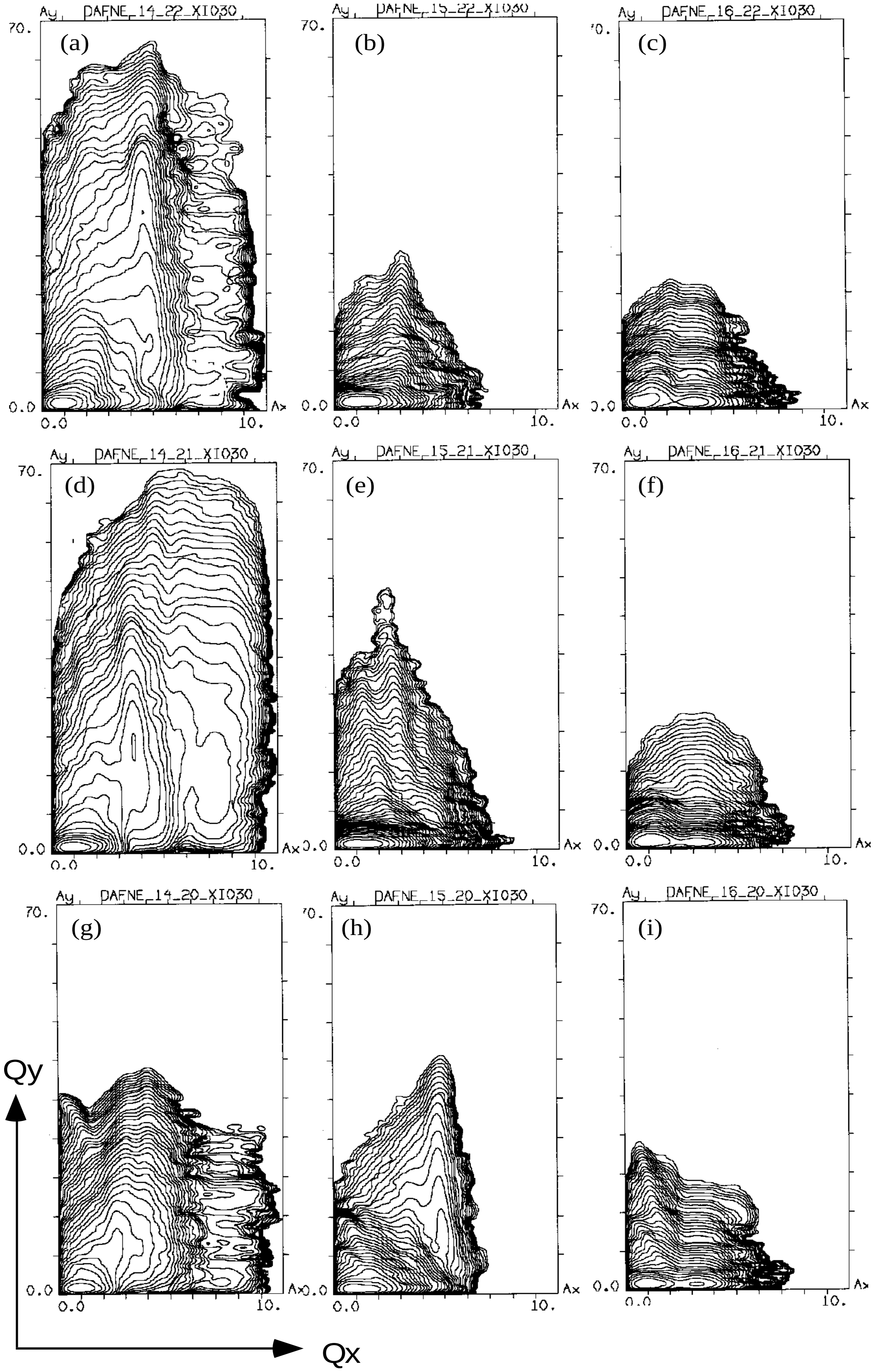

Figure 2: Luminosity scan around the working point (5.15; 5.21) with a tune step of 0.01;
a) (5.14; 5.22); b) (5.15; 5.22); c) (5.16; 5.22); d) (5.14; 5.21); e) (5.15; 5.21);
f) (5.16; 5.21); g) (5.14; 5.20); h) (5.15; 5.20); i) (5.16; 5.20)

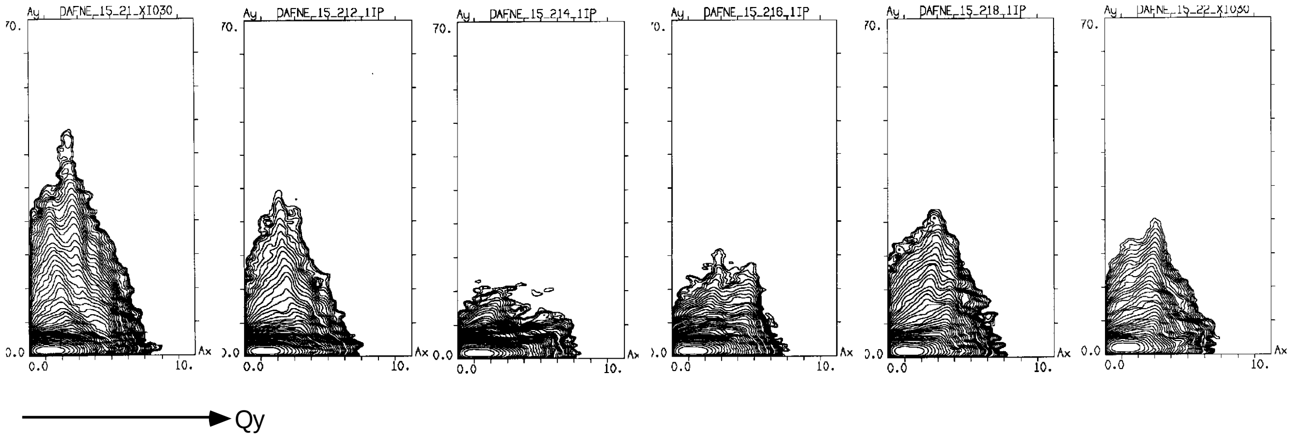

Figure 3: Example of tail growth dependence on small tune variations: Q_x is equal to 5.150; Q_y is varied from 5.210 (first picture) to 5.220 (last picture) with a tune step of 0.002.

Table 3 shows the measured lifetime for different transverse tunes in the vicinity of the point (5.150; 5.210). As predicted numerically, the longest lifetime is reached for the point (5.150; 5.214).

Table 3: Lifetime of a weak beam (electrons) for different tunes.

Q_x^-	Q_y^-	I^+ (mA)	I^- (mA)	τ^- (s)
5.1526	5.2113	15	5	2100
5.1513	5.2126	16.5	5.8	1500
5.1505	5.2124	15.8	5.6	3200
5.1505	5.2141	15.3	5.5	4000
5.1500	5.2141	13.9	5.9	4570

We should note here that the DAΦNE dynamic aperture has not been optimized yet since only the sextupoles for linear chromaticity correction are powered. Further lifetime improvement can be expected by exploiting other sextupole families.

5 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 beam-beam performance at least during 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 $2.2 \cdot 10^{30}$ cm^{-2} s^{-1} without a notable beam size blow up. Experimentally, the present record of single bunch luminosity of $1.6 \cdot 10^{30}$ cm^{-2} s^{-1} has been reached for the given working point.

2) Unfortunately, as the numerical scan has shown, the “safe” area around the working point is very restricted. The tune changes 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. Moreover, it has been found that tune variations as small as 0.001-0.002 can substantially affect the beam lifetime. Based on numerical simulations a slight shift of the working point to (5.150; 5.214) has been proposed. This allowed to increase notably the beam lifetime during collisions.

More details on beam-beam simulations and comparison with the experiment can be found in [5].

6 REFERENCES

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