DAΦNE TECHNICAL NOTE

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LUMINOSITY OPTIMIZATION WITH BEAM-BEAM DEFLECTION

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1. Introduction

The measurement of the deflection induced on one of the crossing beams by the other is routinely used at SLAC[1] to optimize the luminosity of the SLC collider.

The principle of the measurement is straightforward: if two beams of opposite charge cross with an offset between the two charge distributions, they are deflected towards each other. For small offsets the deflection is linear in the charge of the beam and in the offset itself, as far as the interaction does not modify the charge distribution. If this happens, however, the qualitative dependence of the deflection on the offset does not change significantly and the optimization can be done anyway. The measurement is performed by sweeping the vertical position of one of the two beams and observing the displacement of the other with respect to the position corresponding to a missing interaction. The perfect superposition is obtained when this difference vanishes. One of the advantages of this method with respect to a direct luminosity measurement, where one looks at the counting rate of a well known particle reaction, is that the measured variable has non zero derivative at the optimum, thus allowing a feedback mechanism to be implemented.

This measurement can be easily extended to single storage ring colliders, where electrostatic fields can be used to separate the beams, or two rings colliders, where it is sufficient to sweep one of the two beams, while observing the effect on the closed orbit deviation of the other. The measurement has been carefully studied for the SLAC B-factory[2]. In this note we follow the treatment in [2] in order to evaluate the magnitude of the effect for DAΦNE and compare it with the obtainable resolution of our beam position monitors.

2. Beam-beam deflection

Assume one can create a symmetric vertical orbit distortion, localized around the interaction point, which leaves the orbit unchanged in the rest of the electron ring. A single positron (strong-weak approximation) passing at a vertical distance d from the center-of-mass of an electron bunch, small with respect to the vertical r.m.s. beam size σ_y and with no horizontal offset, will change its slope by:

$$\Delta Y' = -4\pi\xi_y \frac{d}{\beta_y} \tag{1}$$

where β_y is the vertical betatron function at the crossing point and ξ_y the usual linear beam-beam tune shift parameter:

$$\xi_y = \frac{r_o N^- \beta_y}{2\pi\gamma\, \sigma_y[\sigma_x+\sigma_y]} \tag{2}$$

Here r_o is the classical electron radius, N^- the number of electrons in the bunch and σ_x its horizontal r.m.s beam size. Since the derivatives of the betatron functions vanish at the DAΦNE crossing point, the beam-beam induced deflection changes also the position of the positron at the IP by:

$$\Delta Y(o) = 2\pi\xi_y\, d\, \mathrm{cotg}(\pi\nu_y) \tag{3}$$

where ν_y is the vertical betatron wavenumber of the positron ring.

If we have a second particle, stored in a different bucket of the positron beam, which corresponds to a missing electron bunch and we measure its position s in the ring somewhere outside the region shared by the two beams, we will detect the "reference" position, independent from the amplitude of the distortion in the electron ring. Our first positron, instead, will be displaced by the interaction with the electron bunch, and its displacement with respect to the reference one will be:

$$\Delta Y(s) = \frac{\Delta Y'}{2\sin[\pi\nu_y]} \sqrt{\beta_y[o]\beta_y[s]} \quad \cos(\phi(s)-\pi\nu_y) \tag{4}$$

Here $\beta_y(o)$ and $\beta_y(s)$ are the betatron functions at the IP and the monitor respectively and $\phi(s)$ the vertical betatron phase advance from the IP to the beam position monitor.

Expressions (1) and (3) are valid when $d \ll \sigma_y$. There are also similar formulae for the opposite situation, when $d \gg \sigma_x, \sigma_y$, namely when the beam sizes can be neglected with respect to the distance. In this case we find:

$$\Delta Y' = - \frac{2 r_o N^-}{\gamma d} \tag{5}$$

$$\Delta Y(o) = \frac{r_o N^- \beta_y}{\gamma d} \operatorname{cotg}(\pi \nu_y) \tag{6}$$

Formulae (1), (2) and (3) can be generalized to the case when both beams have the same number of particles and same transverse dimensions, under the assumption that the beams are rigid, i.e. the beam-beam interaction does not modify the beam sizes. In this case the effect of one beam on the other must be calculated by averaging over the distributions. If $N^+ = N^-$, $\sigma^+ = \sigma^-$ in both planes, the above quoted formulas still hold, if all r.m.s. distributions are multiplied by $\sqrt{2}$. Of course, in this case each beam deflects the other one, and the distance d in (1) changes to $d + \Delta Y(o)$, so that a self consistent solution must be find by iteration. $\Delta Y(o)$ is typically smaller than d (unless ν_y is closed to an integer) and therefore the convergence is fast.

A useful approximation[2] to the solution of the problem for any distance d can be found when $\sigma_x \gg \sigma_y$, which is of course the case for DAΦNE. In this case:

$$\Delta Y' = \frac{\sqrt{2} N r_o}{\gamma \sigma_x} \left\{ \sqrt{\frac{\pi}{2}} \operatorname{erf}\left[\frac{d}{2\sigma_y}\right] - \frac{d}{\sqrt{2}\sigma_x} \right\} \tag{7}$$

where "erf" is the error function related to the integral of the gaussian distribution.

3. Application to the DAΦNE main rings.

In DAΦNE a vertical localized orbit bump created by six vertical correcting dipoles is foreseen[3] to separate the beams at the most dangerous parasitic crossings at injection (in the case of more than 30 bunches) and also to avoid beam-beam interaction at one of the two IP's when only one crossing is desired. This bump can be used also to sweep one of the beams across the other to detect the beam-beam deflection.

Figure 1 shows the angular kick $\Delta Y'$ as a function of the distance between the two centers-of-mass, as given by (7) with the nominal single bunch parameters of DAΦNE, namely:

$$N = 8.9 \times 10^{10} \qquad \sigma_x = 2.1 \text{ mm} \qquad \sigma_y = 21\ \mu \qquad \gamma = 10^3 \tag{8}$$

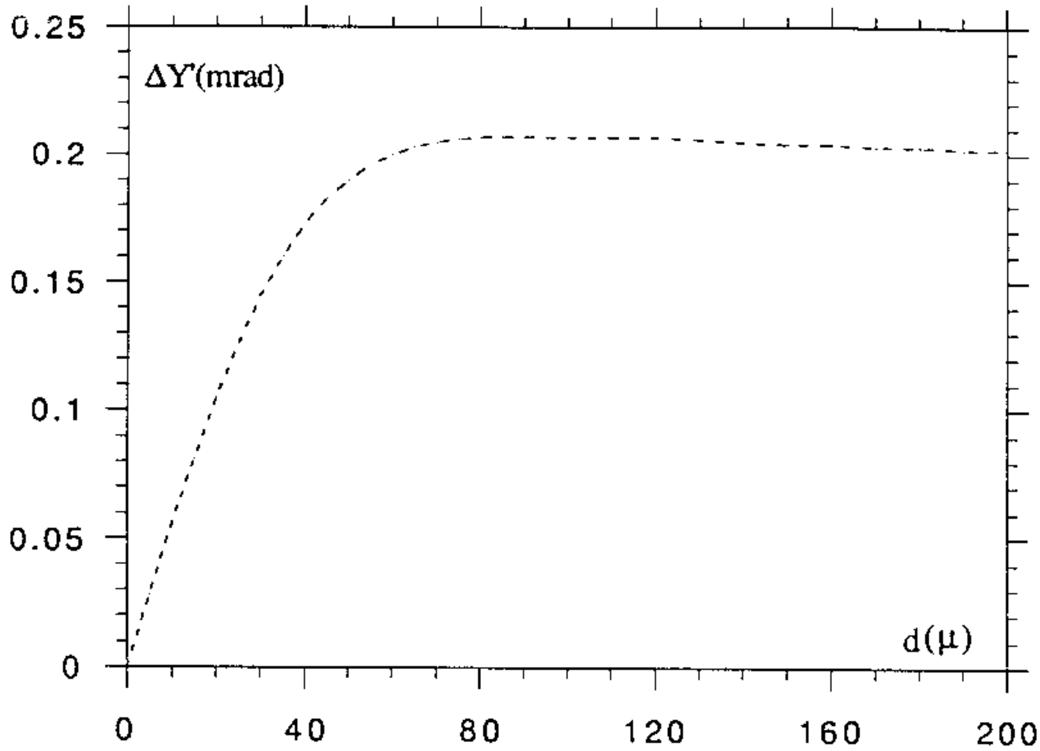

Fig.1 - Beam-beam deflection at the crossing point as a function of vertical distance between the two beam centroids at the nominal DAΦNE single bunch parameters.

It can be seen that there is a sharp dependence between $\pm 2\sigma_y$ with respect to perfect alignment. The deflection reaches a maximum of $\approx$ 0.2 mrad and then remains there until the displacement becomes of the order of σ_x. This behaviour is quite comfortable for luminosity optimization, since the measured position difference between the interacting bunch and the non-interacting one flips between two opposite values, and the optimal superposition can easily be found at the center of the transition from one state to the other.

Fig. 2 shows the position difference between an interacting bunch and a non-interacting one at all beam position monitors in the DAΦNE Main Ring[4], corresponding to the maximum deflection shown in Fig. 1. Empty dots are "button" BPM's, while the full ones are strip-lines near the interaction points.

It should be pointed out that this method not only allows to optimize the vertical superposition of the two beams, but it can be used also to find the best combination of other machine parameters relevant to the luminosity. In fact, one would observe at one of the most sensitive BPM's a curve proportional to that shown in Fig. 1 as a function of the amplitude of the vertical bump at the IP. The slope of the curve near the optimum superposition will increase when the interaction is stronger (at least in the rigid bunch approximation) and one can therefore tune machine parameters, such as the residual coupling and the relative phase of the two RF systems (which determine the vertical beam size and the longitudinal position of the interaction point) by looking at this slope.

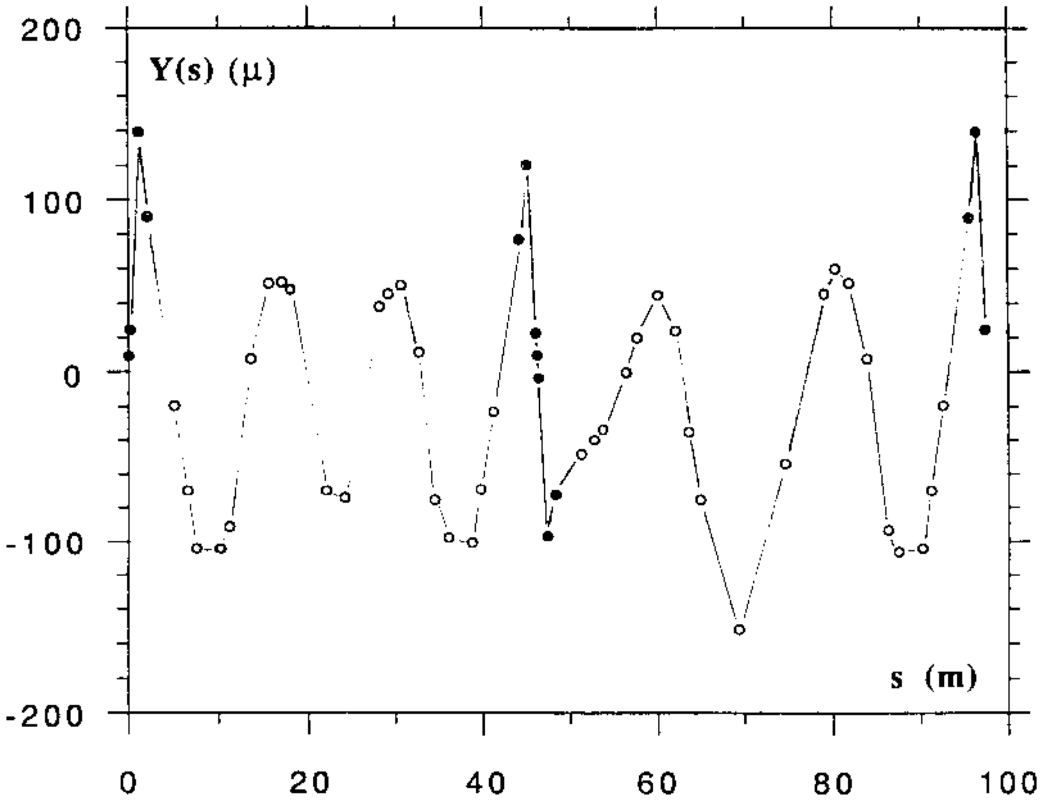

Fig. 2 - Beam displacement (difference between positions of interacting and non-interacting bunches) at all beam position monitors for the maximum beam-beam deflection (ΔY' = 205 μrad).

4. Requirements to beam position measurement system

Assuming one can use all the beam position monitors foreseen for the DAΦNE Main Rings (shown in Fig. 2) in such a way that the beam position from individual bunches (or small trains of bunches) can be measured separately, the beam-beam deflection angle ΔY' can be found from the difference between the position of interacting and non-interacting bunches at each BPM and stripline, with a sensitivity which depends on the vertical β function and phase advance at the monitor.

In order to estimate the sensitivity of the overall beam-beam deflection measurement, let us obtain the deflection angle from a least-square fit of all the measured position differences, under the assumptions that we have a reliable machine model and that the beam-beam interaction does not modify the vertical optical functions. From (4) we know that

$$\Delta Y_i = k_i \, \Delta Y' \tag{9}$$

where ΔY_i is the beam displacement at the i-th monitor and k_i a coefficient which depends on the vertical β function and phase advance at the monitor. The beam-beam deflection is therefore found from:

$$\Delta Y' = \frac{\sum k_i \Delta Y_i}{\sum k_i^2} \tag{10}$$

The systematic errors in the position measurements (such as monitor misalignment or electrical offset) cancel out in the position difference between the interacting and the non-interacting bunches. We are left with the statistical fluctuation (the "resolution") of the monitor. Denoting by δy the vertical resolution, assumed to be the same for all monitors, the r.m.s. uncertainty on the beam-beam deflection is:

$$\delta \Delta Y' = \frac{\delta y}{\sqrt{\sum k_i^2}} \tag{11}$$

With the monitor arrangement displayed in Fig. 2, the denominator in (11) is ≈ 2.5 m. It can be seen from Fig. 1 that 25 μrad beam-beam deflection corresponds to ≈ 5 μ (a distance of 1/4 the r.m.s. vertical distribution between the two beam centroids). To obtain such an accuracy δy should be better than ≈ 60 μ. However, the values of $\Delta Y'$ in Fig. 1 are estimated with the DAΦNE design tune shift (ξ = 0.04), and it is clear that the measurement of beam-beam deflection is mainly useful when the collider is far from the optimum condition. Assuming we want the measurement to be significant at a tune shift value one order of magnitude smaller than design, we need a BPM <u>resolution</u> between 5 and 10 μ.

This resolution is not far from that obtained with the button BPM's used in Adone, where ≈ 3 μ resolution was measured by simulating the beam with a signal from a wire, and ≈ 20 μ with the beam above 0.2 mA average current. Being the measurement in Adone rather slow, the difference was attributed to the beam itself, mainly coming from ripple in the quads. The geometry of the DAΦNE buttons is such that the sensitivity is reduced by a factor ≈ 6 with respect to Adone, but the reduction should be more than compensated by the larger operation current.

5. Conclusions

The beam-beam deflection measurement is a promising tool to find the best vertical superposition of the beams, and in this respect it can also be used as a feedback signal to keep the collider always at the best performance.

It can be used, although at the price of a more time consuming procedure, to optimize some other parameters relevant to luminosity (such as the coupling and the phase between the RF cavities in the two rings, which determine the vertical beam size and the longitudinal position of the interaction point), by looking at the slope of the beam-beam deflection around the optimum superposition.

In order to reach sufficient sensitivity the resolution of the beam position measurement should be kept below ≈10μ, and it must be possible to measure the position of individual or small groups of bunches. One or few missing bunches in one of the two beams must be provided to make the measurement insensitive to systematic errors.

REFERENCES

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