RECENT STUDY OF THE BEAM-BEAM INTERACTION WITH PARASITIC COLLISIONS: THEORY AND SIMULATIONS

Kaoru Yokoya, High Energy Accelerator Research Organization (KEK), Oho 1-1, Tsukuba-shi, Japan

Abstract

Recent collider designs adopt many-bunch operation for higher luminosities where parasitic collisions are inevitable. The effect is now a major limiting factor of the performance of hadron colliders. Recent theoretical studies on the parasitic collisions are summarized in this report.

1 INTRODUCTION

Recent designs of ring colliders adopt multiple bunch operation for satisfying the increased demand of high luminosities. A single-ring design is possible for colliders with the same energy and oppositely charged beams. To increase the number of stored bunches it is necessary to avoid unwanted beam collisions by introducing the so-called 'pretzel' or helix orbit such as in CESR and Tevatron. An important issue in such a case is how large a beam separation is needed for the parasitic encounter (collision) effects to be manageable.

Even for the case of two-ring colliders such as KEKB, PEPII and DaFne the parasitic encounters are inevitable because one cannot separate the two beams after the collision quickly enough.

The number of parasitic encounters increases as the evolution of the collider design. The LHC has as many as 120 parasitic encounters while Tevatron up to 72. The total linear tune-shift due to the parasitic encounters can even exceed that of the desired collisions. By now the parasitic collision effect is one of the most serious limitations of the luminosity of hadron colliders. On the other hand it is not a major topic in electron-positron colliders, where the first quads are located close to the IP[1], except for the case of pretzel scheme.

Various effects are brought about by parasitic encounters. Firstly, the dipole kick by the long-range Coulomb field causes a closed-orbit distortion. Secondly, the quadrupole kick causes a linear tune-shift. The sign of the tune-shift is different in the horizontal and vertical plane. It has the opposite sign as that of the IP in the separation plane (i.e., in the horizontal plane for horizontal separation). The third effect is the nonlinearity. The field is quite linear near the center of the kicked beam but is highly nonlinear when the amplitude is large enough to touch the core of the kicking beam. Also, when the parasitic encounter happens at non-zero dispersion region, such as in the most pretzel schemes, additional chromaticities are brought about.

All these effects are obviously current dependent. Moreover, they are different from bunch to bunch when the bunch filling pattern is not uniform.

[1] In this note 'IP' (interaction point) does not include parasitic interaction points.

2 SELF-CONSISTENT CLOSED ORBIT

Non-uniform fill is needed because of the rise/fall time of kickers (injection, extraction, abort) and of avoiding multi-bunch instabilities such as electron-cloud and fast ion instabilities. The combined effect of the non-uniform fill and the parasitic encounters can cause bunch dependence of dynamics, such as the closed orbit, betatron tunes, beta functions, chromaticities, etc. Thus, the first thing to do for the dynamics of parasitic collision is to compute the self-consistent closed orbit and the optics around it.

In spite of the tremendous number of bunches Grote and Herr[1, 2] obtained the self-consistent solution for the LHC using the code TRAIN written by Keil[3]. They found 15 PACMAN[2] bunches among 72 bunch packet but the spread in x position at the IP is only $\sigma_x/10$, which is not expected to cause any serious effect.

Wang et. al.[4] computed the self-consistent orbit for CESR by a tracking study. They found a sizable orbit difference ($\Delta x/\Delta y \sim 100/1\mu$m) and the tune spread ($\approx 0.003$). Sagan[5] suggested a possible compensation scheme using kickers.

Alexahin et. al.[6] pointed out that parasitic collisions at dispersive place cause bunch-dependent chromaticity, which may induce synchrotron-betatron resonances.

3 TUNE FOOTPRINT AND DYNAMIC APERTURE

The second step of the beam-beam study is to compute the amplitude dependence of the tunes (analytically or by tracking plus FFT). It is called footprint when plotted in the (ν_x, ν_y) plane. The plot helps undestanding the reso-

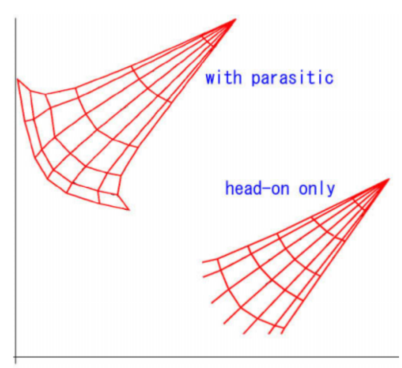

Figure 1: Schematic plot of tune footprint.

[2] PACMAN is a name of a (oldies) computer game. You (monster) chase a train of preys and eat the last one. Then, the second last becomes the last and is eaten next. Likewise the bunches, having different dynamics, may be lost one by one.

nance behavior and one usually tries to minimize the covered area. But the small footprint does not necessarily gives a stable dynamics. It is merely a necessary condition for the stability.

The next step is the dynamic aperture study by weak-strong simulation. Many studies have been done for this issue. (e.g., Leunissen et. al.[8] and Luo and Schmidt[9] for LHC, Sen et. al.[10] and Sen et. al.[11] for Tevatron.)

Papaphilippou and Zimmermann[12] started a study of a new type of dynamic aperture, which they call diffusive aperture. They tracked particles with initial conditions close to each other, traced their deviation in time, and estimated the diffusion coefficient. This method allows to guess the long-term behavior longer than the actual tracking time. An example output is shown later (Figure 4). They found a significant reduction of the dynamic aperture for the LHC compared with the usual brute force tracking, which is limited to some million turns at most.

The study of the diffusive dynamic aperture should always be done together with the normal tracking study.

4 COHERENT EFFECTS

In addition to the single-particle dynamics one has to study coherent effects of the parasitic collision.

When parasitic long-range collisions are included, the coherent tune shift is expected from a naiive consideration, to be given by

$$\Delta\nu_{COH} = \Delta\nu_{IP,COH} + 2 \times \Delta\nu_{LR,INCOH} \quad (1)$$

where $\Delta\nu_{IP,COH}$ is the coherent tune shift from the IP and $\Delta\nu_{LR,INCOH}$ is the incoherent tune shift from the long-range interaction. Owing to the long-range force the π-mode frequency might get into the incoherent frequency region (footprint), as schematically shown in Figure 2, and might cause Laudau damping.

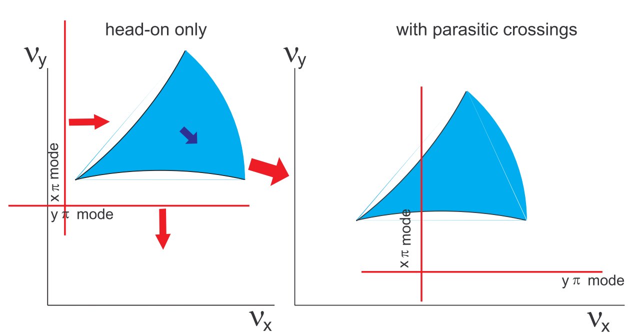

Figure 2: Change of location of π-mode frequency due to the long-range force.

Alexahin[13] developed an excellent analytical theory of the general coherent beam-beam interaction. His conclusion on the above problem of the Landau damping is the following. (See Figure 3.)

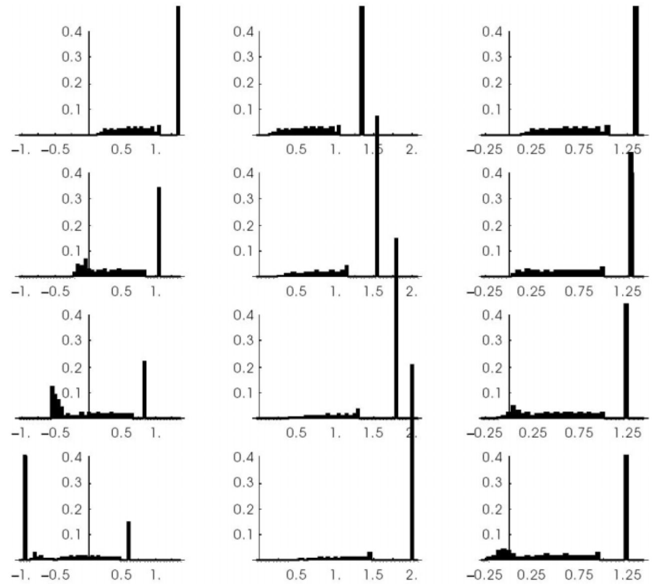

Figure 3: Coherent mode in the presence of parasitic collision (LHC with beam separation 5σ).[13] In each plot the horizontal axis is the horizontal coherent tune shift $\nu_{x,COH}$ normalized by ξ_{IP} (beam-beam parameter at the IP) and the vertical axis is the intensity of the modes. The number of parasitic collision points increases from top to bottom (top: IP only). Plots on the left are for horizontal separation, middle vertical, and right mixed separation.

- For the horizontal separation (horizontal damping is expected), as the long-range interaction becomes stronger, another horizontal π-mode appears on the other side, outside the incoherent band (though the strength is a little weaker than for head-on only). In this case the vertical π-mode becomes stronger, which is consistent with expectation.
- Similar results (but opposite) for vertical separation.
- For mixed separation, π-modes become a little weaker.

Thus, he concludes that useful Landau damping is not expected from the parasitic collision, contrarily to the naiive expectation.

Many tracking studies on coherent beam-beam effects on the LHC have been published[14, 15, 16, 17].

5 COMPENSATION

To overcome the limitation due to the parasitic collisions two different methods of compensation have been proposed.

5.1 Compensation by Wire Current

Koutchouk[18] proposed a method using a current on a wire parallel to the beam. The force due to the current is inversely proportional to the distance, which is identical to the long-range part of the beam-beam force. Therefore, if the betatron phase advance from the parasitic collision point and the wire position is a multiple of π, one can compensate for the beam-beam force. For compensation of the several parasitic encounters near an IP one wire current is enough on each side of the IP since the betatron phase at the parasitic encounters are almost the same ($\sim \pi/2$ from the IP). The required current for the nominal parameters of the LHC is extimated to be about 80A (wire length 1m). It is possible in principle to compensate for the PACMAN effects by pulsing the wire current with the time scale of the bunch-to-bunch distance.

Zimmermann[19] performed a simulation of the wire compensation for the LHC. He found

- The tune footprint drastically shrinks.
- The diffusive dynamics aperture increases from 6.5σ (IP and parasitic) to $7.5 \sim 8\sigma$ (with compensation), while the beam separation is 7.5σ. See Figure.4.
- The results are insensitive to the current strength errors and the betatron phase errors.

Obviously the method cannot compensate for the field at the core of the other beam but the increase of the aperture is still significant.

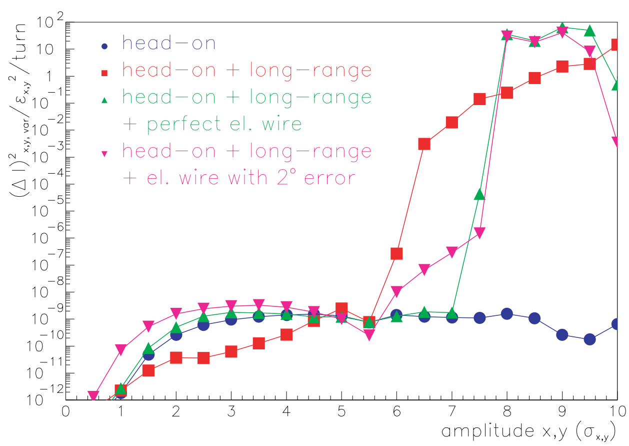

Figure 4: Diffusion coefficient as a function of the amplitude under wire compensation[19]. (The meaning of the vertical scale is that, when the value is 10^{-8}, for example, the diffusion takes effect in 10^{8} turns.) The blue curve (circle), showing the head-on effect, jumps to the red curve (square) when the parasitic collision is included, and is recovered to the green curve (upright triangle) by the compensation. The magenta curve (triangle upside-down) shows the effect of betatron phase error of 2 degrees.

5.2 Compensation by Low-energy Electron Beam

Shiltzev[20] proposed a compensation for anti-proton in Tevatron by using a low-energy electron beam. The method is sketched in Figure.5. If the device is placed at an appropriate location, it can compensate for the head-on as well as the parasitic collisions in principle. The device has already been constructed and the first test was successfully done in 2001 spring[21] to the proton beam rather than antiproton. (The direction of the electron beam is the same as that of proton but the effect is only slightly smaller because the electron beam is non-relativistic.) The employed parameters are

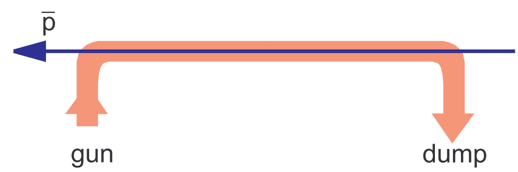

Figure 5: Compensation scheme by a low-energy electron beam.

- The electron beam energy up to 15keV, the current up to 3A.
- Electron beam radius 2mm, interaction length ∼2m.

This causes a tune shift 0.007.

A simulation was done by Alexahin et. al.[22, 23]. There are two regimes: linear and nonlinear compensation. When the electron beam size is much larger than the antiproton size, the force is nearly linear, which can eliminate the bunch-to-bunch tune spread (PACMAN). To this end the electron intensity must be modulated. Two lenses are needed for complete compensation. What is essential in this regime is the stability of the electron position and intensity. When the electron and antiproton beam sizes are comparable, one can compensate for the nonlinear part and thus minimize the intrabunch tune spread (footprint). They found in simulation that a limitation comes from the 'folding' of footprint. (The amplitude dependence of the tune has a turning point when parasitic collisions are included. This causes a concentration of the tune distribution and may cause unstable motion if a resonance touches the point.) The compensation pulls the 'folding' point closer to the core.

6 SUPERBUNCH

Takayama et.al.[24, 25, 26] proposed 'superbunch' hadron collider. They pointed out

- A very long bunch can be created and accelerated by induction accelerating devices and the barrier bucket scheme.[25]
- This opens a way to a drastically higher luminosity for VLHC.
- The long-range tune shift can be cancelled by horizontal-vertical mixed crossings

- 45-degree (together with 135-degree) crossing can give a further knob to reduce the footprint area. (See Figure 6.)

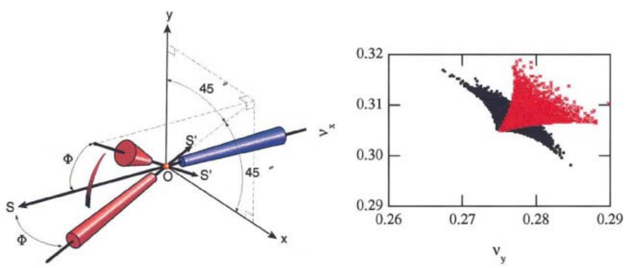

Figure 6: The 45-degree crossing geometry (left) and the footprint (right) for horizontal-vertical crossing (black) and 45-degree crossing (red).

Ruggiero and Zimmermann[27] pointed out the following facts in relation to the superbunch possibility in the LHC. For the given tune shift (round beam, θ is the full crossing angle. Other symbols are hopefully obvious)

$$\Delta\nu = N r_p \beta / [2\pi\gamma\sqrt{\sigma^2 + (\sigma_z\theta/2)^2}] \tag{2}$$

the luminosity can be written as

$$\mathcal{L} = \frac{\pi f \gamma^2 \sigma^2}{r_p^2 \beta^2} \Delta\nu^2 \sqrt{1 + \left(\frac{\theta\sigma_z}{2\sigma}\right)^2} \tag{3}$$

Therefore, the luminosity can be increased by increasing the product (bunch length)$\times$(crossing angle). The luminosity of the LHC can be improved by more than a factor of 5 by superbunch.

So far the study of the beam-beam interaction of superbunch is limited to the tune shift and the footprint. There are many other items to be studied:

- Dynamic aperture including the diffusive process
- Synchrotron oscillation. The synchrotron oscillation makes the dynamics of all the particles equal (no head no tail) so that the PACMAN effect (within a bunch) may disappear. However, the synchrotron oscillation might be very slow so that the PACMAN effect might kill the bunch before synchrotron oscillation.
- Coherent beam-beam stability

There are many more issues on the superbunch other than the beam-beam problem. Zimmermann[28] pointed out that the superbunch scheme may suppress the buildup of the electron cloud because the beam field is nearly static so that the electrons are not accelerated to cause secondary emission.

7 SIMULATION TECHNIQUE

For the study of long-range interactions the soft Gaussian codes (weak-strong and strong-strong) are normally enough (at least for the long-range part). For the head-on part PIC (or PIC like) codes are sometimes needed. There has been considerable progresses in this field, such as Anderson-Rogers (Odyssus)[29], Tsenov-Cai[30], Ohmi[31], Herr-Zorzano-Jones (HFMM)[32]. Recently formalisms using a direct solution of the Vlasov equation are being developed including Perron-Frobenius method (Warnock and Ellison[33] and WMPT (Weighted Macro-Particle Tracking, Ellison and Vogt[34]). My personal opinion, however, is that solving Vlasov equation is best suited for 1D problem like bunch lengthening but is still hard for higher degrees of freedom. At least 10 times faster computing speed is needed.

The code HFMM (Hybid Fast Multipole Method) should be mentioned in relation to the parasitic interaction because it can potentially treat beams of large separation. The method does not compute the field by the empty cells and the multipole expansion is used for distant particles. It has been used for the space-charge study since many years ago (ACCSIM).

8 SUMMARY

- Study methodology has been established. It includes self-consistent closed orbit, footprint, dynamic aperture (including diffusive aperture), and many simulation codes.
- Compensation by wire current looks promising for lumped correction near IP like in LHC. Hardware development of pulsed wire is needed for PACMAN effects. Whether it can be applied to the pretzel (or helix) scheme is unknown.
- Compensation by electron beam: the linear compensation seems to work. The electron beam stability is an issue. Nonlinear compensation seems to be limited and requires further study beyond footprint.
- The idea of superbunch is very much exciting. It has a wide application not only for high-luminosity colliders. As a beam-beam problem further studies of dynamics including 3D motion and coherent stabilities are needed. There are much more to do on general beam stability issues. Experiments on superbunch creation and acceleration are desired.

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