REVIEW OF CROSSTALK BETWEEN BEAM-BEAM INTERACTION AND LATTICE NONLINEARITY IN e^+e^- COLLIDERS *

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Abstract

According to the conventional knowledge, it is believed that the nonlinearity in the arc would not reduce the beam-beam performance, since the beam-beam force is dominated in the beam core region while the lattice nonlinearity is dominated in the beam halo region. However in the recent few e^+e^- storage ring colliders, it has been shown that the lattice nonlinearity may be important to the luminosity performance. In this paper, we'll try to review the related story in DAFNE, and its upgrade with crab waist scheme, KEKB, Super-KEKB and BEPCII.

INTRODUCTION

The luminosity performance of a collider may be affected by many factors, such as linear optics parameters, emittance coupling and collective instability.

As a conventional view, the beam-beam performance has nothing to do with the nonlinearity in the arc, since the beam-beam force is dominated in the beam core region while the lattice nonlinarity is dominated in the beam halo region. When we talk about this, it is usually assumed that the dyanmic aperture is much larger than the beam size. The assumption is usually true. With the increase of peak luminosity of a machine, we've to squeeze the β function at IP. This has bring a lot of problems and make the design of such a machine harder and harder. One of the consequence is that the dynamic aperture is very hard to enlarge and beam lifetime is very critical. In this case, the nonlinearity maybe harmful to the luminosity.

When we talk about the chromaticity, we usually refer to the tune chromacitiy. For a collider, we also care the the twiss parameters versus the momentum, especially at IP. The linear chromatic distortion could be represeted by the so-called W-paramters. These momentum depedent optics distortion including the higher order terms, could excite the synchro-betatron resonances and reduce the beam-beam performance.

The recent electron-positron storage ring colliders are all high energy machines and run above transistion. The natural negative tune chromaticity needs to be corrected to a small positive value, where the sextupoles are used and the nonlinear elements are included. The fringe field of a magnet may also contribute a nonlinear magnetic field even without sextupole or octupoles.

In the recent decades, there exist some experience in different machines on the crosstalk between beam-beam and lattice nonlinerity. We try to summarize the work, but not try to tell all the story in the paper.

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EXPERIENCES OF MACHINES

DAΦNE [1]

DAΦNE is a low energy (~ 0.5GeV) lepton collider. It started operation in May 1999. We focus its early commissioning before 2002.

Three main techniques were adopted for the nonlinear dynamics : tune scans, localized orbit bumps inside critical magnetic elements and beam decoherence measurements. The tune scan was used to define safe areas for beam-beam collisions on the tune diagram not affected by nonlinear lattice resonances. By changing the tunes, the lifetime and blow up of a single bunch at the synchrotron light monitor is observed. It is found that for some tunes the lifetime was strongly reduced or the beam size increased. It is found that nonlinear resonances up to 6th order were responsible for these effects by analyzing the results. Since such resonances can be driven only by strong nonlinear magnetic elements, dedicated orbit bumps were performed and tune shifts versus bump amplitude were measured in order to recognize such elements. In particular, it was found that the wigglers are a strong source of octupole-like terms providing a cubic nonlinearity [2]. Then the beam decoherence was directly measured and the the coefficient c_{11} of the horizontal tune shift versus amplitude was estimated. Numerical simulations carried out taking into account the measured cubic nonlinearity have shown that they have a dramatic impact on the collider luminosity performance [3]. Beam blow up and tails growth could be observed in the simulations if the coefficient $|c_{11}|$ characterizing the cubic nonlinearity exceeded 200 m^{-1}. The value is as high as 600 m^{-1} for some lattice configurations . In the multibunch regime the maximum achievable luminosity is mainly limited by the combined effect of parasitic crossings and nonlinearities.

Experimentally, a strong correlation between the luminosity and the measured cubic nonlinearity was observed. Indeed, the peak luminosity of 5.2×10^{31} $cm^{-2}s^{-1}$ at that time was obtained when $|c_{11}|$ was reduced below 200 m^{-1} in both rings. In this case the luminosity scales linearly with the number of bunches.

The beam-beam experience obtained in DAΦNE proved the importance of the machine cubic nonlinearity control and demonstrated that the cubic nonlinearity tuning may lead to substantial gain in luminosity and beam-beam performance.

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DAΦNE with crab waist [4]

In high luminosity colliders with conventional collision schemes the key requirements to increase the luminosity are: very small vertical beta function β_y at the interaction point (IP), high beam intensity and large horizontal emittance ϵ_x and beam size σ_x. However, β_y cannot be much smaller than the longitudinal rms bunch size (bunch length) σ_z without incurring the “hour-glass” effect. Unfortunately, it is very difficult to shorten the bunch in a high current ring without exciting collective instabilities. Even then, the large beam current may result in high power losses, beam instabilities and dramatic increase of the wallplug power. These problems can be overcome with the recently proposed crab-waist (CW) scheme of beambeam collisions [5, 6] , where a substantial luminosity increase can be achieved without bunch length reduction and with moderate beam currents.

The CW scheme(see Fig. 1 can substantially increase collider luminosity since it combines several potentially advantageous ideas: collisions with a large Piwinski angle, micro-beta insertions and suppression of beambeam resonances using dedicated (“crab waist”) sextupoles.

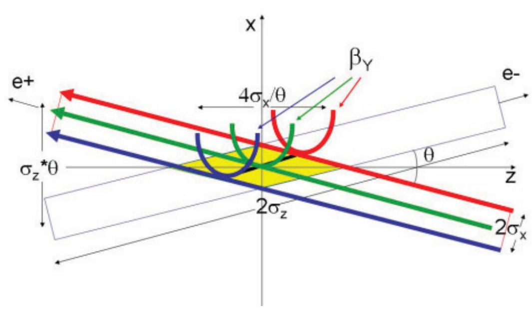

Figure 1: Crab-waist collision scheme. The color straight lines show directions of motion for particles with different horizontal deviations from the central orbit. The arrows indicate the corresponding β function variations along these trajectories.

The CW vertical β function rotation is provided by sextupole magnets placed on both sides of the IP in phase with the IP in the horizontal plane and at $\pi/2$ in the vertical one (as shown in Fig. 2). The crab sextupole strength should satisfy the following condition depending on the crossing angle and the β functions at the interaction point (IP) (indicated with an asterisk) and the sextupole locations:

$$K = \frac{1}{\theta}\frac{1}{\beta_y^*\beta_y}\sqrt{\frac{\beta_x^*}{\beta_x}} \tag{1}$$

The one-turn map could be represented as follows,

$$\exp(:-axp_y^2:)\exp(:H_{bb}:)\exp(:axp_y^2:)\exp(:H_{arc}:) \tag{2}$$

The pure lattice one-turn map at IP without beam-beam interaction could be represented as

$$\exp(:axp_y^2:)\exp(:H_{arc}:)\exp(:-axp_y^2:) \tag{3}$$

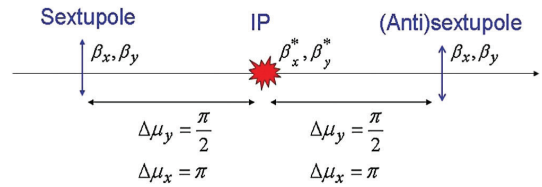

Figure 2: Crab sextupole locations.

In order to do the normal form analysis, the one-turn map could be rewritten in the format like this

$$\exp^{:f_2(X):}\exp^{:f_3(X):}\exp^{:f_4(X):} \tag{4}$$

where f_2 represent the linear map, and

$$f_3 = b(\cos\mu_x x - \sin\mu_x p_x)(\sin\mu_y y + \cos\mu_y p_y)^2 - bxp_y^2 \tag{5}$$

$$f_4 = -\frac{1}{2} : \exp^{:-f_2(X):} bxp_y^2 : bxp_y^2 \tag{6}$$

with $b \equiv \frac{a\sqrt{\beta_x}}{\beta_y}$. Then it is easily to obtain the generating function at IP. And one could check the lattice if the crab-waist transformation is good enough for on/off-momentum particles using MADX/PTC for example.

Fig. 3 demonstrates the resonances suppression applying the frequency map analysis (FMA) for the beam-beam interaction in CW collisions [7]. It shows the beam-beam footprint for DAΦNE with CW sextupoles off (left) and on (right).

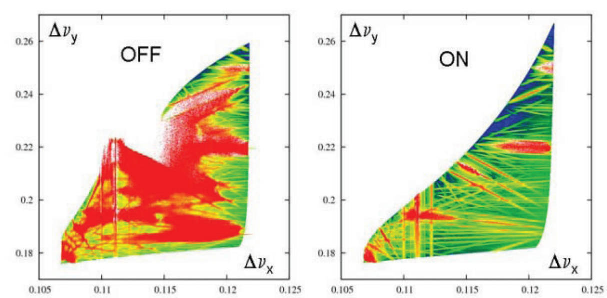

Figure 3: Beam-beam footprint with crab sextupoles off (left) and on (right) obtained by FMA techniques [7]

The CW scheme has been successfully tested at the electron-positron collider DAΦNE. After an upgrade including the implementation of this novel collision scheme, the specific luminosity at low beam currents has been boosted by more than a factor of 4, while the present peak luminosity, 4.53x1032 cm-2s-1, is a factor of 3 higher than the maximum value obtained with the original configuration based on the standard collision scheme [4].

The success of cw scheme shows us that the nonlinearity may also contribute to the beam-beam performance and help us increase the luminosity.

KEKB [9–12]

KEKB B-Factory has been operating at KEK since 1999 for the e+e- collision experiment mainly at the ϒ(4S) reso-

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nance. The highest luminosity (without crab cavity), $1.72 \times 10^{34} cm^{-2} s^{-1}$, was achieved in Nov. 2006. The peak luminosity is higher than the design by 70% mainly due to smaller β_y^* (6 mm vs. 10 mm), horizontal betatron tune closer to a half integer (LER:0.505 / HER:0.511 vs. 0.52), and higher stored current in the HER (1.35 A vs. 1.1 A).

One of the main design features of KEKB is the horizontal crossing angle of 22 mrad at IP. Although there are many merits in the crossing angle scheme, the beam-beam performance may degrade. Beam-beam simulations showed that the crab crossing is expected to boost the luminosity by a factor of 2 [13]. The commissioning of KEKB with crab cavities began in February 2007. However, the luminosity is lower than that predicted at high beam currents at the beginning [9].

The existence of the chromatic x-y coupling was known by a measurement of the synchro-beta sideband in the beam size on the x-y tune space [14]. Simulations including the chromatic coupling has been performed using a symplectic integration method of the chromaticity [11]. The chromaticities of Twiss parameters and X-Y couplings can be represented as

$$\alpha_u(\delta) = \sum_{i=0}^{\infty} \alpha_{ui}\delta^i \quad \beta_u(\delta) = \sum_{i=0}^{\infty} \beta_{ui}\delta^i$$
$$\nu_u(\delta) = \sum_{i=0}^{\infty} \nu_{ui}\delta^i \quad r_i(\delta) = \sum_{i=0}^{\infty} r_{ji}\delta^i$$
$$u = x, y \quad \text{and} \quad j = 1,2,3,4 \tag{7}$$

The δ-depedent Cournant-Snyder like transfer matrix $M(\delta)$ can be split as

$$M(\delta) = M(0)M_H(\delta) \tag{8}$$

All the chromatic dependences are lumped into $M_H(\delta)$. Generating function F_2 is used to reprensent the transformation of $M_H(\delta)$

$$F_2(x,\bar{p}_x,y,\bar{p}_y,z,\bar{\delta}) = x\bar{p}_x + y\bar{p}_y + z\bar{\delta} + H_I(x,\bar{p}_x,y,\bar{p}_y,\bar{\delta}) \tag{9}$$

where H_I expresses generalized chromaticity

$$H_I(x,\bar{p}_x,y,\bar{p}_y,\bar{\delta}) = \sum_{n=1}(a_n x^2 + 2b_n x\bar{p}_x + c_n\bar{p}_x^2 + 2d_n xy + 2e_n x\bar{p}_y + 2f_n y\bar{p}_x + 2g_n\bar{p}_x\bar{p}_y + u_n y^2 + 2v_n y\bar{p}_y + w_n\bar{p}_y^2)\bar{\delta}^n/2 \tag{10}$$

The coefficients $10\times n$ are related to n-th order chromaticity of 10 twiss parameters, $\alpha_{x,y}$, $\beta_{x,y}$, $\nu_{x,y}$ and four local coupling parameters $r_i, i = 1,4$. Transfer map using F_2 as a generating function guarantees the 6D symplectic condition.

Twiss parameters at the interaction point is measured by turn by turn position monitors located at the both sides of the interaction point[8].Figure 4 shows the measured x-y coupling parameters as functions the momentum deviation. The parameters are fitted by polynomial of the momentum deviation. The coefficients, which are chromaticity, varies run by run, and differ from prediction of the optics design code like SAD. Therefore the accelerator model based on the measured chromaticity is important.

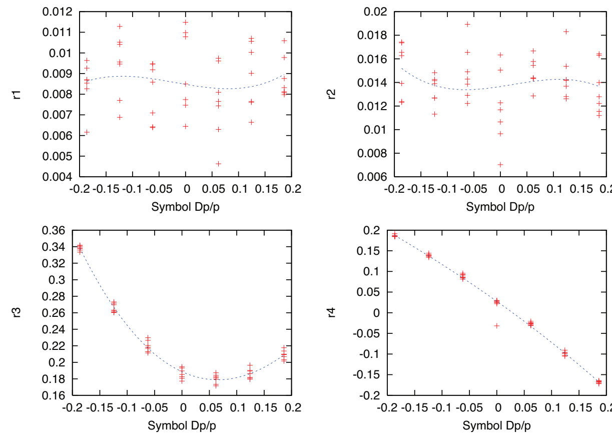

Figure 4: Measurement of the chromaticity for x-y coupling in KEKB-LER.

Using these transformation, synchro-beta resonances and their effects on the beam-beam interaction have been studied. It was found that the chromatic X-Y couplings are not small enough and can affect the luminosity at the present KEKB work point at around (44.515, 41.606) [11]. When chromaticity of one ring in ideal optics is considered in simulations, results of weak-strong simulations show that the luminosity degradation is around 5%. Further results of strong-strong simulations show that the luminosity may decrease by around 10% and that the decrease depends slightly on bunch currents.

Since skew sextupoles can be used to control the chromatic X-Y couplings, in the end of 2008, it was decided that skew sextupoles should be installed at both the HER and the LER. Tuning with skew sextupoles was commenced from May 2, 2009, at KEKB. Since then, beam operation at KEKB has been very successful and the chromatic X-Y couplings at the IP have been reduced dramatically [8]. The corresponding luminosity gain was above 15% [10], and the peak luminosity exceeded $2 \times 10^{34} cm^{-2} s^{-1}$, which is twice the designed value.

The story is the success of simulation. It shows that the coupling chromaticity would be important if the detector solenoid is not well compensated with/without crab crossing.

SuperKEKB

The SuperKEKB [15] is an asymmetric-energy double ring collider to achieve 40 times higher luminosity than that of the KEKB B-factory. To achieve such high luminosity, the SuperKEKB interaction region (IR) is designed for large Piwinski angle collision scheme so called "nano-beam scheme". For the nano-beam scheme, the beta functions at the interaction point (IP) are designed to 32mm / 270μm(horizontal/vertical) for the low energy positron ring

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(LER) and 25mm / 300μm for the high energy electron ring (HER), respectively. In order to realize 1/20 times smaller beta function at the IP than that achieved by the KEKB B-factory, the SuperKEKB IR is designed to use both super-conducting quadrupole doublets for final focus and horizontal/vertical local chromaticity correctors for compensating large natural chromaticity. The dynamic aperture is restricted by strong nonlinearities of final focus magnets.

The luminosity performance as a function of bunch current products are shown in Fig. 5 [16]. In the figure, the red solid lines indicate results of using pure weak-strong model. The blue dashed lines indicates results of using pure weak-strong model plus perturbations of chromatic aberrations. The green dashed lines indicates results of using SAD code with weak-strong model. The cyan lines represent the design values of luminosity and beam current products. It is seen that significant loss of luminosity appears at high bunch currents due to interplay of BB and LN in the LER. Especially, the specific luminosity drops quickly at very low beam currents. These phenomena can not be explained by the momentum-dependent LN. The luminosity loss due to interplay of BB and LN in the HER is not as serious as in the LER, and can be well attributed to the chromatic aberrations in the HER lattice.

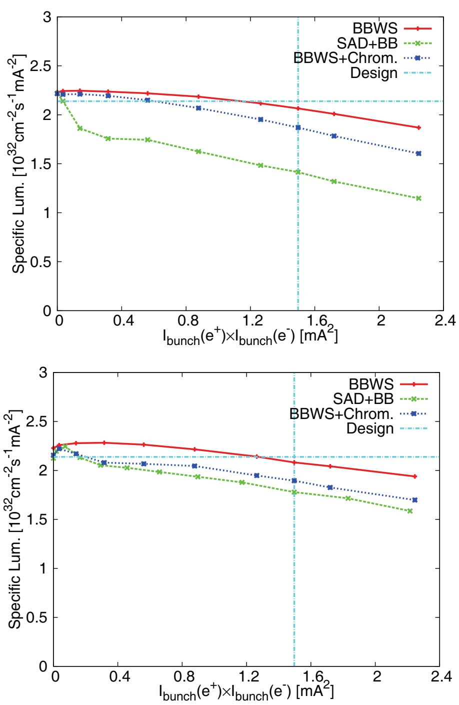

Figure 5: Specific luminosity as a function of bunch current products at SuperKEKB. Top picture is for LER, and bottom picture is for HER.

By comparing the turn-by-turn data between LER and HER with an initial horizontal offset, it is found that the horizontal oscillation is coupled to vertical direction in spite of the local coupling is 0 at IP in LER, and there exist a clear obit offset in vertical direction(about $1\sigma_y$ for $5\sigma_x$) [17]. The contribution comes from a skew sextupole like component by spectrum analysis (See Fig. 6). The strength of the skew sextupole and the phase advance from IP is also determined by analysis of turn-by-turn data. The COD and oscillation amplitude in y is well suppressed as expected by inserting a map of $H = K * x^2 y$ into the LER lattice. The luminosity loss at low bunch current is also reduced (see Fig. 7). However the map bring loss in dyanmic aperture and lifetime, it should be understood.

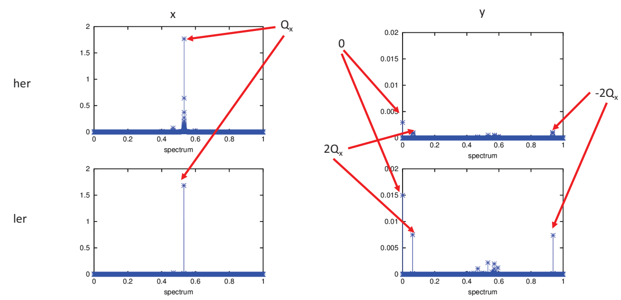

Figure 6: The spectrum of turn-by-turn data at SuperKEKB with an intial horizontal oscillation amplitude $3\sigma_x$.

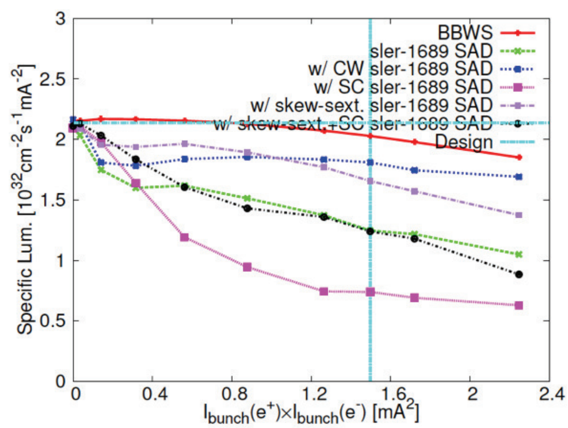

Figure 7: Luminosity can be partially recovered by inserting a skew sextupole map into LER of SuperKEKB.

BEPCII

BEPCII is an upgrade project from BEPC. It is a double ring machine. Following the success of KEKB, the crossing scheme was adopted in BEPCII, where two beams collide with a horizontal crossing angle of 2 × 11mrad. The design luminosity of BEPCII is $1.0\times10^{33}cm^{-2}s^{-1}$ at 1.89GeV, which is about 100 times higher than BEPC. In March, 2013, the peak luminosity achieves $7.0\times10^{32}cm^{-2}s^{-1}$ with 120 bunches and beam current 730mA, where a lower α_p lattice was used.

In May, 2014, we begin to knob the chromaticity online in order to suppress the resonance $2\nu_x + \nu_s = N$, since the resonance strength is determined by the first order chromaticity ($\frac{d\nu}{d\delta}$, $\frac{d\alpha^*}{d\delta}$, $\frac{d\beta^*}{d\delta}$) and we've many enough sextupoles. This knob help us increase the luminosity by about 10% in some cases. And the BBWS simulation with up to 3rd order chromaticity coincides very well with the

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real machine [18]. In some other cases, the expected better lattice cannot achive higher luminosity in real machine.

All the magnets are using hard edge model till now. We try to evaluate if the fringe field model affect the luminosity performance in the following steps: (1) A lattice is optimized with the original hard edge model, (2) The dipole and quadrupole magnets are modeled with soft edge fringe, (3) LOCO method is used to correct the new lattice to the theory (hard edge) model where the quadrupole strength is changed, (4) Luminosity with the corrected lattice is calculated to evaluate if the performance is reduced. The procedure repeat what we do at the real machine. The twiss parameters is nearly same between the corrected soft edge and orignial hard edge model. There exist some difference for the dispersion function in the arc and the chromaticity is also changed, see Fig. 8 for α_x at IP. According to the simulation, the luminsoity loss is about 15% due to the model, see Fig. 9. More detailed work should be done to understand the loss.

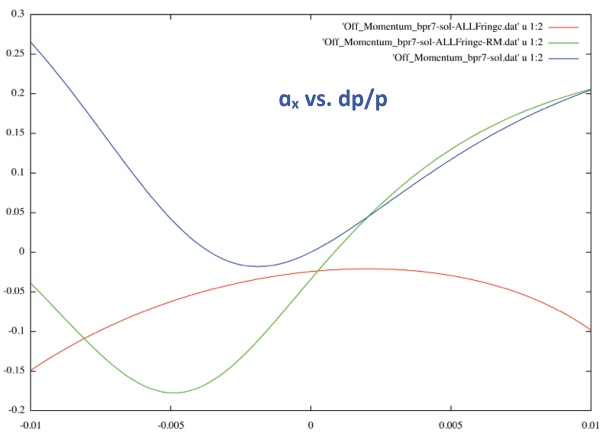

Figure 8: The α_x versus δ at IP for original hard-edge(blue)/soft-edge(red) model and corrected(green) soft-edge model.

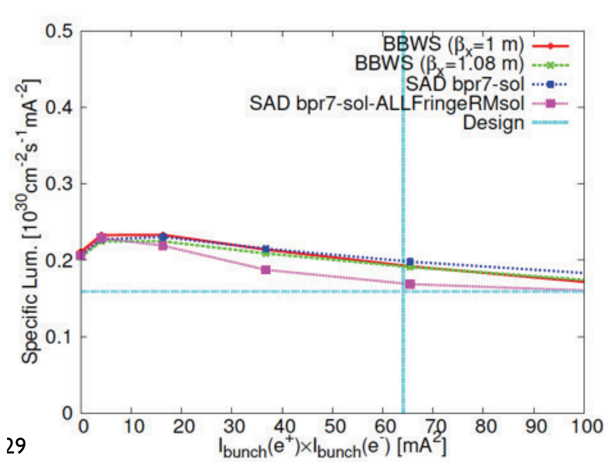

Figure 9: The luminosity for different model. The pink is corrected soft-edge model. The blue is the hard-edge model.

SUMMARY

In this paper we recall some story on the crosstalk between lattice nonlineairty and beam-beam interaction. It seems that nearly all kinds of lattice nonlinearity has shown their impact on the luminosity.

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