POSSIBLE SUPPRESSION OF HEAD-TAIL INSTABILITY BY A FEEDBACK KICKER FOR A LIGHT SOURCE WITHOUT ANY SEXTUPOLE*

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Abstract

As storage ring based light sources pursue as low emittance as possible down to the diffraction limited number by adopting as many bending magnets and quadrupoles in a cell, the number of sextupole magnets required to correct chromaticity and secure a sufficiently big dynamic aperture grows substantially. As a result, the circumference of a multi-bend achromatic lattice storage ring is typically very long. This paper discusses over a possible scheme to run a storage ring without sextupole magnets at all and suppress the head-tail instability by using a transverse feedback kicker.

INTRODUCTION

The simplest and best method to cope with any instability is certainly to eliminate the instability source and one of the most well-known examples is to install sextupole magnets over a storage ring to set the chromaticity zero both horizontally and vertically and, thus, prohibit the head-tail instability caused by (negative) finite natural chromaticity generated by quadrupole magnets. The price for this cure is that nonlinearity introduced by sextupole magnets reduce the dynamic aperture of the ring. A lower emittance lattice generates higher chromatic strengths. To correct these, stronger sextupole magnets are required and this, in turn, leads to even lower dynamic aperture. Early light sources used to deploy two families of sextupole magnets over the ring just to make zero chromaticity values. However, as lower and lower emittance machines were developed, at some point, a sufficiently large dynamic aperture could not be obtained and so additional families of sextupole magnets were needed for harmonic correction to enlarge the dynamic aperture. Major light sources in the world in the 1-3 nm rad emittance range typically have about 6-8 sextupole families. For example, DIAMOND light source [1] in the UK which is 3 GeV machine with double bend achromatic (DBA) lattice in about 560 m circumference uses 8 families of sextupole magnets for chromaticity correction and harmonic correction. In the recent multi-bend achromatic (MBA) lattices, even more sextupole magnets are used although in this case the number of bending magnets and quarupole magnets increase more. For example, MAX-IV the multi-bend sub-nm emittance ring in Sweden [2], has 5 families of sextupole magnets and 3 families of octupole magnets for harmonic correction. There are lattices that use fewer sextupole magnets than others but in those cases, the dynamic aperture is smaller as can be seen from the ESRF-EBS lattice [3].

Therefore, we may conclude that securing both low emittance and sufficient dynamic aperture requires many sextupole magnets and substantial space, which raises the construction cost of a storage ring. Too much space and high cost are used just to remove the head-tail instability. Securing a sufficient dynamic aperture through harmonic correction is also a technical difficulty. Hence, removing the head-tail instability through sextupole magnets is becoming a challenge technically and economically as the emittance is lowered. Perhaps, it is a time to think of another method to suppress the instability.

In this regard, the transverse feedback kicker has long been used as a tool to suppress transverse instabilities. This paper proposes to use an appropriate transverse bunch-by-bunch feedback kicker system to suppress the head-tail instability and not to install sextupole magnets at all. The purpose is to design and construct a simple linear element storage ring with minor non-linearity coming from multipole magnet errors and insertion devices. The advantage of this scheme is obviously to achieve low beam emittance in a reduced ring circumference and save the construction cost. Another interesting advantage would be the large dynamic aperture which can enable injection with no orbit bump for a typical facility with no particular technique. This will significantly improve the operation quality of light sources.

There are certainly potential problems of this scheme. The most important one is the risk of betatron resonance crossing due to large chromatic tune spread. It should be assured that this tune spread will not cause betatron resonance and consequential beam loss. Fortunately, the absence of sextupole magnets significantly weakens third order resonances to such a low level that they can practically be harmless.

Below, the feasibility of this scheme is discussed. Design strategies trying to have as small natural chromatic strength and low growth rate of the head-tail instability as possible are explained. Head-tail instability is explained with emphasis put on the two-particle model, and how it can be suppressed by a transverse bunch-by-bunch feedback kicker system is also explained.

STRATEGY

Although the scheme of this paper is to cope with large chromatic strength (negatively large chromaticity values), smaller chromatic strength is definitely favoured. Hence, the strategy is trying to minimize the natural chromatic strength and related effects such as tune spread and the growth rate of head-tail instability for a given emittance through careful design. Note that the 1-3 nm rad emittance DIAMOND has the natural chromaticity of (-79, -35) whereas the smaller emittance 7-bend MAX-IV has

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the natural chromaticity of (-50, -44). So, lower emittance facility can have low natural chromatic strength. For example, installation of damping wigglers can lower the emittance without increasing the natural chromatic strength.

LARGE TUNE SPREAD

A clear difficulty of this scheme would be large tune spread of each electron bunch caused by natural chromaticity and relative momentum (energy) spread as given by:

$$\Delta \upsilon = \xi \frac{\Delta p}{p}. \tag{1}$$

The planned multi-bend upgrade of Spring-8, Spring-8 II [4] which will be a 6 GeV machine will have the largest natural chromatic strength given by (-155, -142). This huge chromatic strength of the 1436 m long storage ring will generate huge tune spread. But, the target storage ring of this paper is a 3 GeV sub-nm emittance light source in a 300-400 m circumference storage ring. The natural chromaticity may be in the range of $-80 < \xi < -40$ for the cases we consider here and this would give 0.04-0.08 tune spread for a typical 0.1% beam energy spread. This is manageable but can be reduced further in accordance with the above strategy. Recall that the electron beam energy spread for an isomagnetic ring is given by$C_q \gamma^2/(J_s \rho)$, where $C_q = 3.84 \times 10^{-13}$ m and ρ is the bending radius. Hence, in general, larger bending radius can lower the energy spread. For example, the National Synchrotron Light Source II (NSLS-II) in Brookhaven, USA has larger bending radius (25 m) than other light sources and, consequently, has smaller energy spread [5].

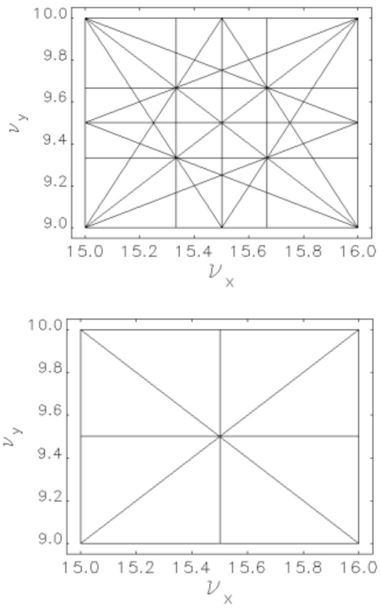

Figure 1: Resonance diagrams for a 12-superperiod lattice up to 2nd (top) and 3rd order (bottom) resonances.

Also, a large free space should be secured in the tune space. Fortunately, the absence of sextupole magnets significantly weakens or virtually eliminates high order resonances leaving only dipole and quadrupole driven resonances as major resonances. Particularly, third order sextupole-driven resonances which are very important for low emittance storage rings are significantly weakened because they would be driven only by errors in dipole and quadrupole magnets. Tune diagrams with and without third order resonances are compared in Figure 1. Without sextupole magnets, we included only the first and second order resonances as fatal resonances, and this has a wide safety margin for tune spread.

ADDITIONAL ADVANTAGES

What technical advantages would we have in addition to that the storage ring would be relatively compact and the effort for harmonic correction would be saved?

Strong Landau Damping

The large tune spread mentioned above as a disadvantage, however, would also be an advantage because the large chromatic tune spread would strongly act against any potential transverse instability. Hence, the large chromatic tune spread is a potential risk that may lead to loss of particles due to resonance crossing but it is also a potential advantage that can suppress possible transverse instabilities.

Large Dynamic Aperture and Injection with No Orbit Bump

Under the scheme of this paper, the light source lattice is practically a linear lattice without non-linear elements. The only non-linearity comes from multipole errors in dipole magnets and quadrupole magnets and insertion devices. Consequently, the dynamic aperture would be very large regardless of momentum deviations and this helps not only longer lifetime but also much easier injection. The large dynamic aperture can lift the constraint put on injection by dynamic aperture. Physical aperture would be the limiting aperture. Then, injection into the storage ring can be performed without the familiar bumped orbit, if physical space is large enough to allow the large horizontal betatron amplitude increased by the absence of orbit bump, and this would make top-up injection entirely harmless for users. It is true that this is possible even with sextupole magnets if the initial amplitude is made sufficiently small, however, elimination of sextupole magnets would certainly make the injection scheme applicable for any facility without special effort or technique.

HEAD-TAIL INSTABILITY AND ITS SUPPRESSION BY FEEDBACK SYSTEM

As the electron bunch length of a low-emittance light source is in general so small that the two-particle model of Sacherer [6] is an approximation good enough to describe the head-tail instability at least qualitatively. With details of the model omitted, an important result regarding the instability modes and chromaticity values can be summarized as in Table 1, where ξ is the storage ring chromaticity.

Table 1: Head-tail Instability Modes and Chromaticity

Mode		**ξ > 0**	**ξ < 0**
Dipole Mode	Above Transition	Damped	Unstable
	Below Transition	Unstable	Damped
Higher Modes	Above Transition	Unstable	Damped
	Below Transition	Damped	Unstable

Without sextupole magnets, the storage ring chromaticity is negative, and as we need to consider only the above-transition region for an electron storage ring, only the simplest dipole mode would be excited while all higher modes damped. Fortunately, the dipole mode can be suppressed by a typical narrow band bunch-by-bunch transverse feedback kicker, without a wide band kicker, because there is no intra-bunch oscillation in the dipole mode. Figure 2 below shows the schematic figures of the head-tail instability dipole mode and two of the higher modes.

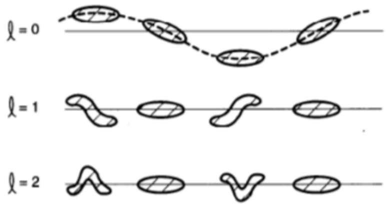

Figure 2: Modes of the head-tail instability. The *l*=0 is the dipole mode and *l*=1 and *l*=2 are the next higher modes. [7]

The head-tail instability is suppressed by sextupole magnets at a light source but often damped by the transverse bunch-by-bunch feedback kicker at a proton synchrotron as can be seen from the Main Ring of J-Parc [8]. Thanks to modern technology, the transverse bunch-by-bunch feedback has been developed to such a level to be able to suppress more complicated single bunch instabilities [9].

The two-particle model evaluates the growth rate of the head-tail instability as:

$$\tau^{-1} = \frac{e^2}{2\pi}\frac{N\xi\hat{z}}{p_0\eta}\left(\frac{W_0}{C}\right). \qquad (3)$$

where N is the number of electrons in a bunch, $\hat{z}$ is bunch length, η is the slippage factor, p_0 is the nominal momentum of electron beam, and W_0/C is the wake per unit length along the storage ring. For efficient suppression of the head-tail instability, a smaller growth rate is favoured. This means that the sextupoleless ring would be more realizable with small bunch current, small bunch length and low wake. To have small bunch length, small bunch current while keeping high beam current for a given circumference, high frequency (such as 500 MHz) RF system should be adopted unlike a few recently designed multi-bend lattices adopted 100 MHz level RF system. Also, special efforts should be given to make the wake function (impedance) as low as possible.

CONCLUSION

To save space, cost and effort, a low-emittance electron storage ring can be operated with no sextupole magnet by suppressing the hard-tail instability with a transverse bunch-by-bunch feedback kicker system. But, the design strategy is to minimize the natural chromaticity, tune spread, growth rate of head-tail instability as far as possible, by adopting damping wiggler, larger bending radius, and high frequency RF system etc. Also, extra effort should be given to minimizing the wake. The absence of sextupole magnets generates very weak 3rd order resonances and very large dynamic aperture. The weakened 3rd order resonances provide a safe margin for the large chromatic tune spread, which in return provides strong Landau damping against any possible transverse instability. The large dynamic aperture will make injection process very easy and even enable injection without bump magnets. This way, a multi-bend low emittance light source can be built in a smaller size without any efforts for harmonic correction, dynamic aperture enlargement and smooth injection.

REFERENCES

[1] V. P. Suller, “Status of the DIAMOND light source project”, in *Proc. 8th European Particle Accelerator Conference*, Paris, France, Jun. 2002, pp. 757-759.

[2] “Detailed design report on the MAX IV facility”, MAX-lab, Lund, Sweden.

[3] S. M. Liuzzo, “Beam dynamics studies for the Hybrid Multi Bend Achromat lattice of the ESRF-EBS 6GeV upgrade and future 3GeV storage rings”, talk given at KEK, Tsukuba, Jul. 2016.

[4] Y. Shimosaki et al., “Lattice design of a very low-emittance storage ring for Spring-8 II”, in *Proc. 2nd International Particle Accelerator Conference*, San Sebastian, Spain, Sep. 2011, paper TUOAB01, pp. 942-044.

[5] J. Ablett et al., “National Synchrotron Light Source II Conceptual Design Report”, Brookhaven National Laboratory, Upton, NY, USA, Dec. 2006.

[6] F.J Sacherer, “Transverse Bunched Beam Instabilities”, CERN, Geneva, Switzerland, Rep. CERN/PS/BR76-21, 1976.

[7] A. W. Chao, “Physics of collective Beam Instabilities in High Energy Accelerators”, New York, NY, USA: John Wiley & Sons, Inc., 1993.

[8] Y. H. Chin et al., “Head-tail instabilities observed at J-PARC MR and their using a feedback system”, in *Proc. 9th Annual Meeting of Particle Accelerator Society of Japan*, Osaka, Japan, Aug. 2012, pp. 97-101.

[9] V. Smaluk, D. Sukhanov, V. Oreshonok, V. Cherepanov and V. Kiselev, “Feedback for suppression of single-bunch transverse instability in electron-positron storage rings”, *JINST*, Vo.7, p. 01007, Jan. 2012.