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Study on Sextupole-free Circular Accelerator

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1. 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 bunch-by-bunch transverse feedback system has long been used as a tool to suppress transverse instabilities. This paper proposes to install no sextupole magnet at all or smaller number of sextupole magnets than required for chromaticity correction. Instead, this paper proposes; first, to use dielectric materials, such as ceramics or glass which create no image current, for the vacuum chamber material to minimize the chamber broadband impedance which is responsible for the head-tail instability and, secondly, to adopt an appropriate bunch-by-bunch transverse feedback kicker system to suppress the remaining head-tail instability. The result would be a simple linear lattice 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 very small orbit bump, which will significantly improve the operation quality of light sources.

2. Transverse 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 [4] 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 is shown in Fig. 1.

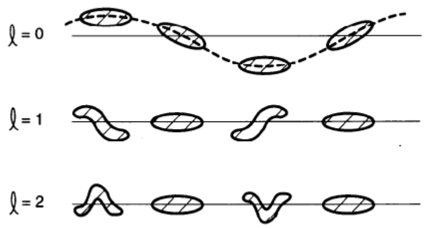


Fig. 1. The lowest a few modes of the head-tail instability. The lowest rigid-bunch mode (*l*=0) is executed for the negative chromaticity of an above-transition ring, when the two-particle model is valid.

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 (rigid-bunch mode) would be excited while all higher modes damped. The dipole mode can be suppressed by a typical narrow band bunch-by-bunch transverse feedback kicker system. Figure 2 below shows the schematic figure of how the bunch-bunch transverse feedback system works.

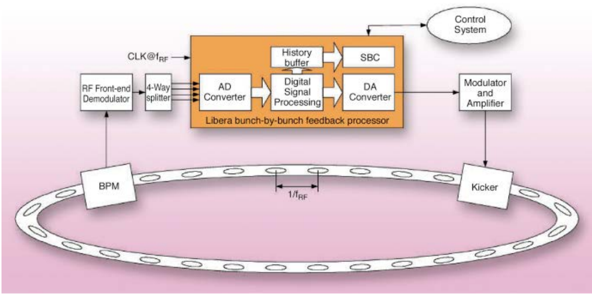


Fig. 2. Schematic figure of how the bunch-bunch transverse feedback system works.

3. Dielectric vacuum chamber material without image current

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, ξ is the ring chromaticity, 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 sextupole-free ring would be more realizable with very low wake. To have such low wake, this paper proposes to adopt dielectric materials such as ceramics or glass, which creates almost no image current and consequently would create very low broadband impedance.

(a) (b)

Fig. 3. This figure shows two candidate dielectric materials (a) ceramics and (b) glass.

Any such material to be used for the light source vacuum chamber should be able to maintain good vacuum state. Also, it has to have a sufficiently high melting point and good durability. Ceramics and glass are such dielectric materials. Glass may be brittle, but with suitable strengthening (e.g., wrapped by hard dielectrics such as hard plastics or rubber) it can be as strong as required. Basic properties of ceramics and glass are listed in Table 1.

Table I: Acceptable frequency of beam trips for each beam trip duration [5].

	Ceramics	Glass
Melting Point	> 3000 °C	1400~1600 °C
Durability	Good	Good with strengthening
Cost	High	Varies

However, there are problems to be resolved. First, the impedance of a dielectric material has high frequency resonance peaks with very high impedance values, approximately when an odd multiple of a quarter wavelength in the dielectric equals the wall thickness.

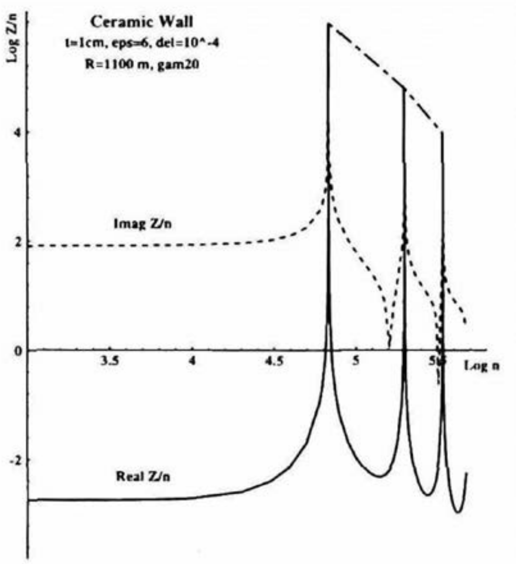


Fig. 4. Computed ceramic wall impedance Z/n versus n in the logarithmic scale in both axes [6].

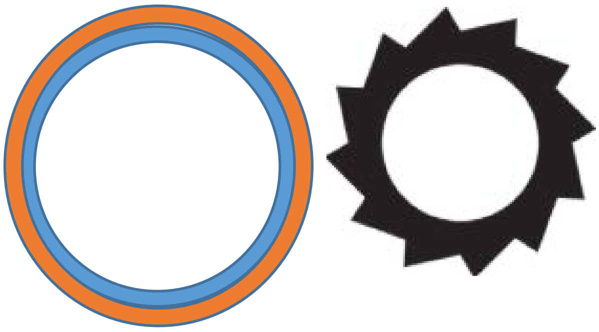
At a low frequency, the impedance is negligibly low. However, in the high frequency region, there are resonances of the penetrating fields, approximately when an odd multiple of a quarter wavelength equals the dielectric wall thickness t [6]:

$$(2\mathrm{p}+1)\frac{\lambda}{4\sqrt{\beta^2\varepsilon'-1}} = t\ , \qquad (1)$$

where p is an integer, λ is the wavelength, and βc is the electron velocity. And, ε' is the complex permittivity defined as $\varepsilon' = \varepsilon_r(1 + i\tan\delta_E) + i\sigma/\omega\varepsilon_0$ where ε_r is the relative permittivity, σ is the conductivity and $\tan\delta_E$ is the electric loss tangent. The longitudinal impedance of the ceramic wall is shown in Fig. 1 as a function of $n = \omega/\omega_0$, in the logarithmic scale, where ω_0 is the revolution frequency of electrons circulating the ring. The transversal impedance of the ceramic wall also shows similar behavior.

However, these resonances can be avoided if it is noted that Equation 1 cannot hold if the wall thickness t

varies from t_{min} to t_{max} over the ring circumference or if the wall is made of layers so that there is no unique resonant frequency of the wall.



(a) (b)

Fig. 5. Figure (a) shows the case of double layered wall and (b) shows the case of varying wall thickness.

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