

FEEDBACK SCHEME FOR KINK INSTABILITY IN ERL BASED ELECTRON ION COLLIDER*

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Abstract

Kink instability presents one of the limiting factors from achieving higher luminosity in ERL based electron ion collider (EIC). However, we can take advantage of the flexibility of the linac and design a feedback system to cure the instability. This scheme raises the threshold of kink instability dramatically and provides opportunity for higher luminosity. We studied the effectiveness of this system and its dependence on the amplitude and phase of the feedback. In this paper we present results of these studies of this scheme and describe its theoretical and practical limitations.

INTRODUCTION

The main advantage of an energy recovery linac (ERL) based electron ion collider (EIC) over a ring-ring type counterpart is the higher achievable luminosity[1]. In ERL-based version, one electron bunch collides with the opposing ion beam only once so that the beam-beam parameter can largely exceed the usual limitation in an electron collider ring, while the beam-beam parameter for the ion beam remains small. In this, so called, linac-ring collision scheme the resulting luminosity may be enhanced by one order of magnitude.

The beam dynamics related challenges also arise as the luminosity boost in the ERL based EIC due to the significant beam-beam effect on the electron beam. The effects on the electron beam are discussed in [2]. The ion beam may develop a head-tail type instability, referred as 'kink instability', through the interaction with the electron beam.

In this paper, we discuss the feasibility of an active feedback system to mitigate the kink instability, by taking advantage of the flexibility of the linac-ring scheme. In the following discussion, we take proton beam for instance and focus on the instability of the infinitesimal dipole offset in both colliding beams, hence the linear approximation of the beam-beam interaction is sufficient.

PRINCIPLE OF THE KINK INSTABILITY AND THE FEEDBACK SCHEME

With the presence of proton beam offset, the electron beam transverse motion can be written under the linear

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beam-beam approximation as:

$$x_e'' + k^2(s) [x_e - \bar{x}_p(s, z = 2s)] = 0 \quad (1)$$

Here, the ion beam transverse offset reads \bar{x}_p , which is a function of the longitudinal coordinate s and the position z within the ion bunch with respect to the reference particle. We assume the electron bunch is very short so that the electron bunch meet the ion at $s = z/2$. The beam-beam interaction strength $k(s)$ has the form[2, 3].

$$k^2(s) = \frac{2N_p r_e}{\sigma_{px}^2 \gamma_e} \lambda(z = 2s) \quad (2)$$

$$= \frac{2\lambda(z = 2s)}{f_e} = \frac{2d_e \lambda(z = 2s)}{\sigma_{pz}} \quad (3)$$

where $f_e = 4\pi\xi_e/\beta_e^*$ is the beam-beam focal length for the electron beam and $d_e = \sigma_{pz}/f_e$ is the disruption parameter[1]. The boundary condition for Eq. 1 can be set as $\bar{x}_e(L/2) = 0$ and $\bar{x}_e'(L/2) = 0$. Here, we assume the electron beam travels along $-\hat{s}$ with zero offset initially and the proton bunch (IR) has total length of L . In this case, the offset of the electron beam at position s solely depends on the imperfection of the portion of proton beam at region $[s, L]$, which it passed.

By taking the average of the entire electron beam, the electron beam centroid $\bar{x}_e(s)$ also follows Eq. 1. In one turn, The proton beam follows

$$x_p''(s, z) + K_\beta^2 x_p = \delta\left(s - \frac{z}{2}\right) \frac{x_p - \bar{x}_e(s)}{f_p} \quad (4)$$

where K_β is the betatron wave number, f_p is the beam-beam focal length for the proton beam. On the right hand side, the first term is beam-beam focusing force, and the second one corresponds to electron beam offset, which is the function of the proton beam offset ahead, i.e., can be characterized by a wake field.

If we assume that both beam sizes are rigid, the proton beam has a uniform longitudinal distribution, i.e. $k^2(s) = 1/(Lf_e)$, and hourglass effect is ignored, equation 1 has solution that reads[4].

$$\bar{x}_e = k \int_s^{L/2} x_p(s', z = 2s') \sin k(s - s') ds' \quad (5)$$

and the wake field is a sinusoidal function.

$$W(s - s') \sim k \sin k(s - s') H(s - s') \quad (6)$$

The more realistic wake field can be obtained by simulation results. In simulation code, the long proton

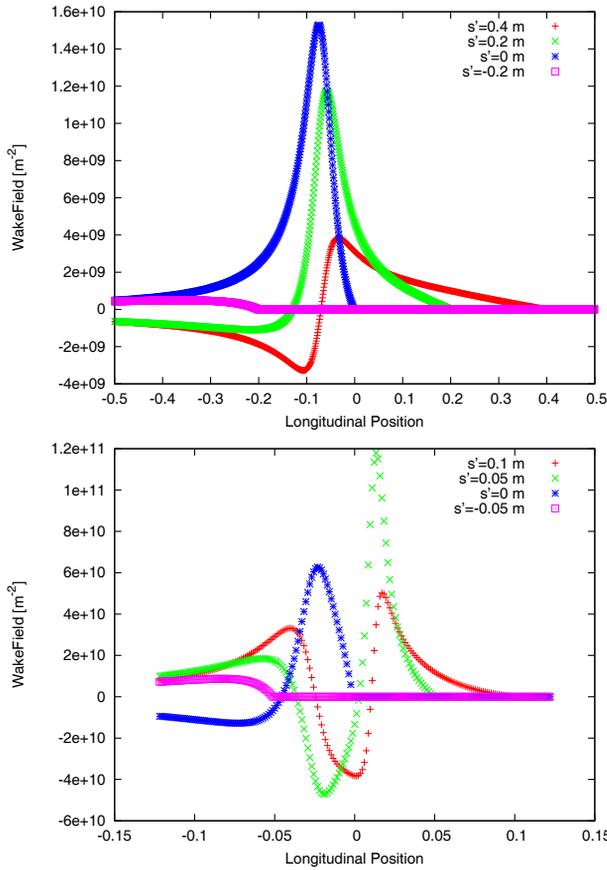


Figure 1: Two examples of the kink wake field with the beam-beam parameter of the proton beam $\xi_p = 0.015$. Top: the electron beam disruption parameter $d_e = 5.7$; bottom: $d_e = 27.1$.

beam is cut into longitudinal slices. We can calculate the transverse kick at s' due to an offset set in slice at s , and get the wake field as:

$$W(s, s') = \frac{\gamma_p}{N_{pb} r_0} \frac{\Delta x'(s')}{\Delta x(s)} \quad (7)$$

With this definition, we may include any effects in beam-beam interaction such as hourglass effect, arbitrary beam distribution and the electron beam size variation during the interaction, which usually referred as 'pinch effect'. Two examples of the wake field are illustrated in Figure 1.

Using a two-particle model, we can calculate the threshold of strong head-tail (SHT) instability due to the beam-beam interaction as:

$$\xi_p d_e < 4\nu_s / \pi \quad (8)$$

where ξ_p is the beam-beam parameter for proton beam and ν_s is the synchrotron tune of the proton ring. A multi-particle linear model using circulant matrix[5] method confirm this threshold at low disruption parameter and show discrepancy at high d_e , as shown in figure 2.

The typical design parameters of the proposed ERL based EIC exceed the threshold. Therefore the instability

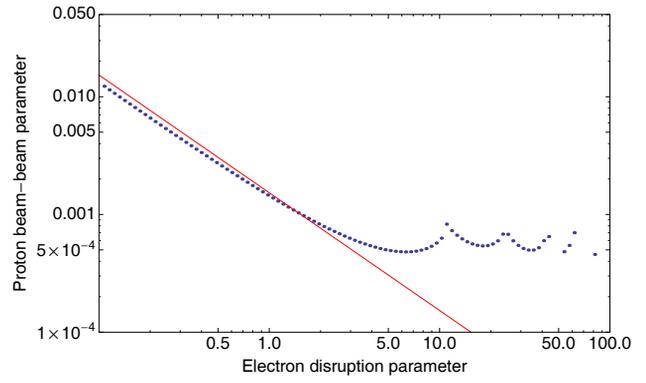


Figure 2: Threshold of SHT kink instability. The synchrotron tune used in the example is 0.0012.

develops and the countermeasures are necessary to mitigate the emittance growth and luminosity loss. The classical way of the instability suppression is by means of Landau damping with introduced transverse tune spread with chromaticity or nonlinear field magnets. However, it will inevitably introduce unwanted nonlinearity to the system. By taking advantage of the flexibility of the linac-ring scheme, we can introduce a feedback system by reading the electron beam centroid position and angle after collision and feeding forward to the kick of the next fresh bunch that interacting with the same proton bunch. Therefore the scheme reads,

$$\begin{pmatrix} x_c \\ x'_c \end{pmatrix}_{n+1,i} = M \begin{pmatrix} x_c \\ x'_c \end{pmatrix}_{n,f} \quad (9)$$

here, M is the map that representing the algorithm of the feedback system, subscripts i and f denote the electron beam centroid phase space coordinates before $(n+1)^{th}$ turn and after n^{th} turn respectively. Generally M can be complicated nonlinear map, however in this paper, we only discuss simple cases linear feedback scheme.

In the feedback scheme, the equation 1 has initial condition $\bar{x}_e(L/2) = x_c$ and $\bar{x}'_e(L/2) = x'_c$. The electron beam propagation inside the proton beam has two terms in additional to Eq. 5 in the simplified case,

$$x_c \cos[k(L/2 - s)] - x'_c \sin[k(L/2 - s)] / k \quad (10)$$

These two terms provide beam-beam kick to the proton beam for correcting the offset. The main goal is correcting the mode $l = 1$, which has the fastest growth rate. It is ideal that electron oscillate only half betatron oscillation inside the proton beam to have the largest feedback efficiency. From the previous study in [2], the number of electron beam oscillation in a proton beam with longitudinal Gaussian distribution is $\sqrt{d_e}/4$. Therefore, the scheme would work best at $d_e \sim 4$. Simulations shows for $d_e > 10$, this scheme has to cooperate with the fast orbit feedback of the single proton bunch and more sophisticate studies are required.

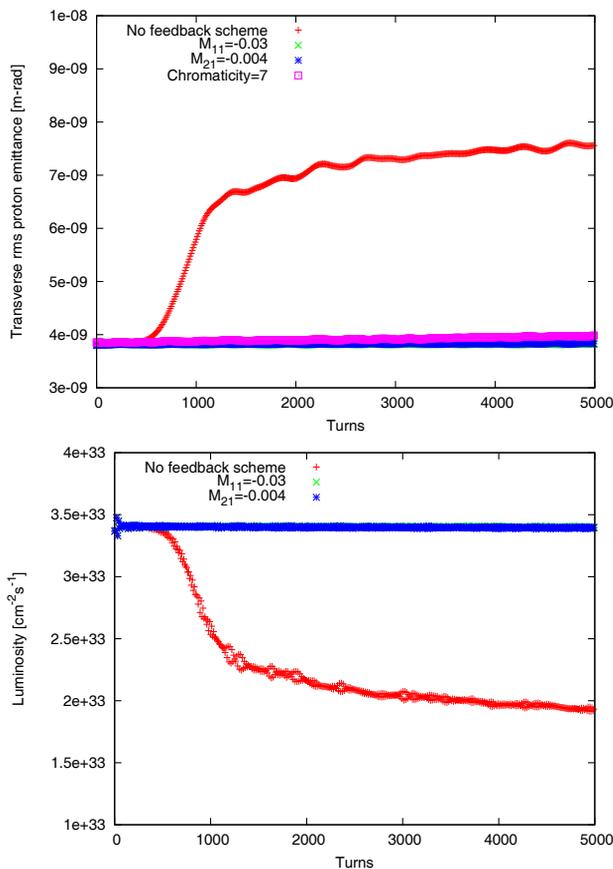


Figure 3: Comparison of instability stabilization scheme. Top: the transverse rms proton emittance growth. Bottom: the luminosity degradation. The energy spread of the proton beam in the simulation is 5×10^{-4} . In the two feedback schemes, the chromaticity is set to zero.

SIMULATION RESULTS

The simulation code EPIC[3] calculates the effect of beam-beam interaction with the linear feedback scheme implemented. As an example, we demonstrate the case with parameters $d_e = 5.7$ and $\xi_p = 0.015$. We virtually measure the electron beam centroid displacement at $L = 3$ m downstream of IP $x_{c,j}$, and feed the information toward the next electron bunch before collision at $L = -3$ m upstream with two cases: (i) a position change $\delta x_{c,j+1} = M_{11}x_{c,j}$ or (ii) an angle kick $\delta x'_{c,j+1} = M_{21}x_{c,j}$.

Figure 3 demonstrates the effect of the feedback scheme and compare it with the stabilization scheme using Landau damping due to chromaticity. We identified that either M_{11} or M_{21} mitigate the emittance growth due to the kink instability with zero tune spread (zero chromaticity). Simulation also shows the initial offsets does not degrade the luminosity because it is much smaller than the rms beam size of both beams.

Further studies show that the feedback kicks can be less frequent and slower response. The information of the j^{th} turn can be delayed to $(j + n)^{th}$ turn; and the feedback

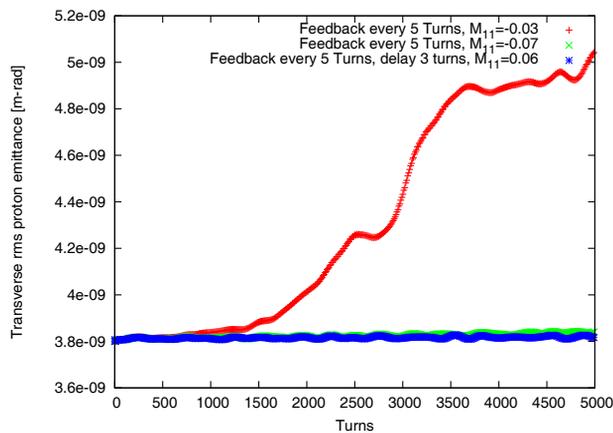


Figure 4: Feedback with lower frequency and slow response.

kick can be enabled only every m turns.

Figure 4 indicates the scheme that enable the feedback kick to the proton beam every $m = 5$ turns with cases of no delay (measurement and kick are in successive turns) and $n = 3$ turn delays. With lower feedback frequency and signal delays, the emittance growth due to kink instability still can be eliminated. In the example, we need use larger feedback strength ($M_{11} = -0.06$ compared with -0.03 as in the previous examples) when we only enable the scheme every 5 turns. This is straightforward because when the more time instability accumulates, the larger feedback strength is necessary. When we delay the signal from 1 turn to 3 turns, the feedback strength becomes positive because of the betatron oscillation phase of the proton beam differs for various delays.

CONCLUSION

We present an new way of eliminating the kink instability in ERL based EIC, without introducing additional nonlinear effects. We demonstrate that, for not too large disruption parameters, the feedback system suppresses the instability flawlessly. The correction for large d_e is under development.

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