FEEDBACK SYSTEMS FOR SUPPRESSING THE KINK INSTABILITY IN AN ERL-BASED ELECTRON ION COLLIDER*

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Abstract

The kink instability presents one of the limiting factors from achieving higher luminosity in an ERL based electron ion collider (EIC). We present two possible dedicated feedback systems to suppress the instability, both of which benefit from the latest development of beam instrumentation. The first takes advantage of the flexibility of the linac-ring scheme to adjust the initial condition of the electron beam; the second uses a pickup and kicker setup with proper bandwidth on the ion ring. Both schemes raise the threshold of the kink instability dramatically and provide opportunities for higher luminosity. We studied the effectiveness of the systems and their dependence on the feedback parameters and beam parameters.

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. Feedback systems are necessary to suppress the instability of the ion beam to achieve the desire luminosity.

In this paper, we discuss two possible feedback system to mitigate the kink instability. The first system, taking advantage of the flexibility of the linac-ring scheme, adjusts the electron beam position at IR based on the information of last collisions. The second system adopts the similar hardware of transverse stochastic cooling with the proper bandwidth of the kink instability.

THE KINK INSTABILITY OVERVIEW

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

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

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 $k(s)$ depends the proton beam current and longitudinal distribution [2, 3]. It can be expressed as:

$$k^2(s) = \frac{2d_e\lambda(z = 2s)}{\sigma_{pz}} \tag{2}$$

where $d_e = \sigma_{pz}/f_e$ is the disruption parameter with σ_{pz} as the rms proton bunch length and $f_e = 4\pi\xi_e/\beta_e^*$ is the beam-beam focal length for the electron beam, $\lambda(z)$ is the normalized longitudinal proton beam distribution function. 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

$$x_p''(s, z) + K_\beta^2 x_p = \delta\left(s - \frac{z}{2}\right)\frac{x_p - \bar{x}_e(s)}{f_p} \tag{3}$$

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

$$W(s, s') = \frac{\gamma_p}{N_{pb}r_0}\frac{\Delta x'(s')}{\Delta x(s)} \tag{4}$$

A examples of the wake field are illustrated in Figure 1 when the disruption parameter is 27.1.

Using a two-particle model, we can calculate the threshold of strong head-tail (SHT) instability due to the beam-beam interaction as $\xi_p d_e < 4\nu_s/\pi$, where ξ_p is the beam-beam parameter for proton beam and ν_s is the synchrotron tune of the proton ring.

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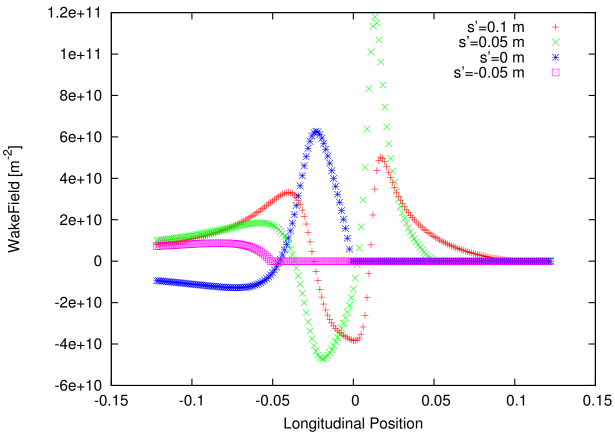

Figure 1: Example of the kink wake field with the beam-beam parameter of the proton beam $\xi_p = 0.015$ and $d_e = 27.1$.

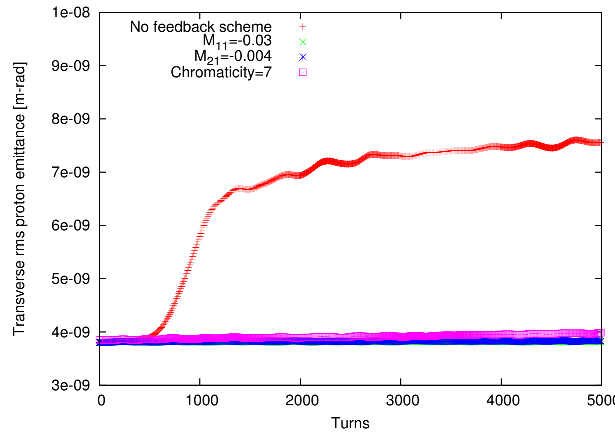

Figure 2: Comparison of instability stabilization scheme. Plot shows the transverse rms proton emittance growth. The energy spread of the proton beam in the simulation is 5×10^{-4}. In the two feedback schemes, the chromaticity is set to zero.

The typical design parameters of the proposed ERL based EIC exceed the threshold. Therefore the instability develops and the countermeasures are necessary to mitigate the emittance growth and luminosity losses. Nonlinearities introduce transverse tune spread to the ion beam transverse motion. However, the resulting Landau damping do not fully mitigate the emittance growth when large disruption parameter is present.

FEEDBACK SYSTEM I

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,

$$\begin{pmatrix} x_c \\ x'_c \end{pmatrix}_{n+1,i} = M \begin{pmatrix} x_c \\ x'_c \end{pmatrix}_{n,f} \tag{5}$$

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 this 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. **??** in the simplified case,

$$x_c \cos[k(L/2-s)] - x'_c \sin[k(L/2-s)]/k \tag{6}$$

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 $d_e \sim 4$. For larger disruption parameter ($d_e \geq 10$), this feedback system suppress the mode $l = 1$ and excite zero mode simultaneously. The zero mode must be eliminate by separate bunch by bunch orbit feedback system in the ion ring.

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 2 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 kick can be enabled only every m turns. Figure 3 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

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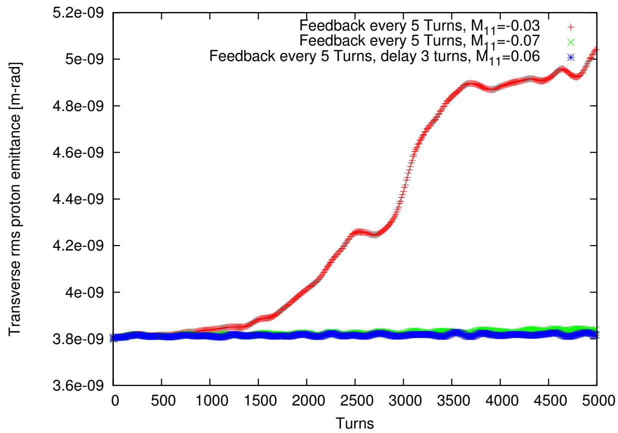

Figure 3: Feedback with lower frequency and slow response.

every 5 turns, since 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.

FEEDBACK SYSTEM II

The feedback system I loose its efficiency when the disruption parameter is high. Simulation study shows that it stop working when d_e is greater than 20. In such high d_e cases, the phase advance of the electron beam inside the proton beam become significant and destroy the information we want to carry through the electron beam.. A traditional pick-up and kicker system (the feedback system II) overcomes this limitation. This feedback system consists a high bandwidth pick-up (BPMs) that samples the offset within one ion bunch, and a set of wide bandwidth kicker (usually RF cavities or strip lines) that correct the offsets accordingly. It is expected that the instability will be suppress if the instability mode frequencies fall in the bandwidth of the feedback system.

Consider the feedback system as a bandpass filter with sharp edges at lower frequency limit f_L and high frequency limit f_H. The corresponding wake field of this system reads [4] :

$$W(\tau) = R\int_{f_L}^{f_H} \cos(2\pi f\tau)\, df \qquad (7)$$

In simulations using the same code, we choose the proton beam with 8.3cm bunch length and beam-beam parameter 0.015. As we will demonstrate with d_e value 36 and 144, this system works for different disruption parameters of the electron beam. In figure 4, we show that with same frequency range (1-3 GHz), the instability is successfully suppress for both $d_e = 36$ and 144. Further study is undergoing to find the required band width and performance degradation due to the noise.

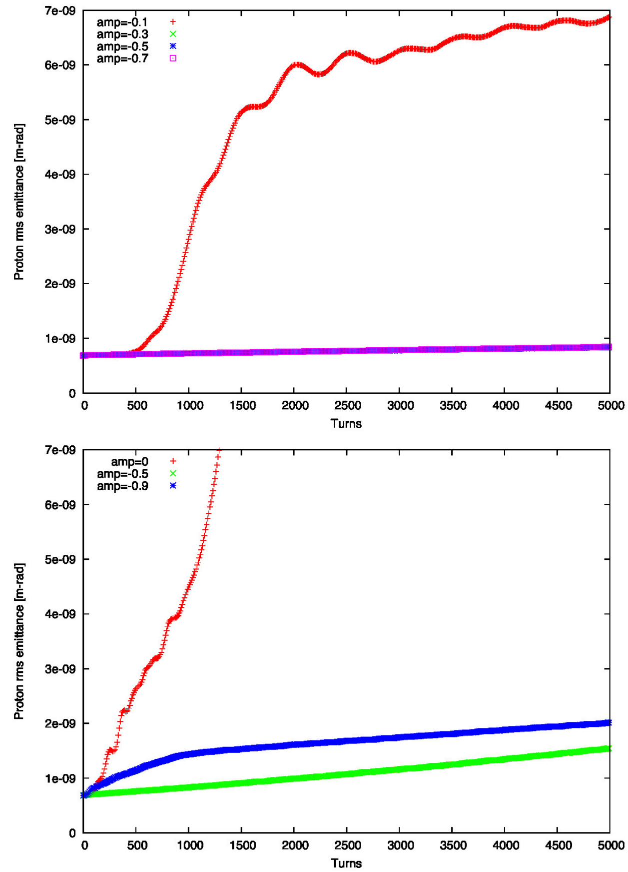

Figure 4: Feedback system with pickup and kicker with $f_L = 1$ GHz and $f_H = 3$ GHz. Top: disruption parameter is 36; bottom: disruption parameter is 144.

CONCLUSION

We present two feedback scheme for eliminating the kink instability in ERL based EIC. We demonstrate that, the feedback system on the electron beam, with very easy setup, can suppress the instability up to disruption parameter 20. The pickup and kicker setup with proper bandwidth can suppress the instability regardless the value of disruption parameter.

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