THE BEAM-BEAM EFFECT AND ITS CONSEQUENCES FOR THE JEFFERSON LAB EIC*

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Abstract

In this work we address the effect of beam jitter on emittance growth as caused by the beam-beam effect on the Jefferson Lab Electron Ion Collider (JLEIC). This proposed collider would collide up to 100 GeV proton beams with up to 10 GeV electron beams. Due to the asymmetric rigidities of the beams and their non-linear lensing action on each other during a collision, collective effects can limit beam storage times. Using simulations we determined that one of JLEIC's synchronization concepts would require a new set of software tools to accurately understand phase space evolution.

INTRODUCTION

The proposed Jefferson Lab Electron Ion Collider (JLEIC) will collide up to 100 GeV protons (or ions of equivalent rigidity) with up to 10 GeV electrons for nuclear physics [1]. The beam lifetime will be limited by beam-beam interactions between beams of asymmetric rigidities. Estimates can be made of the growth rate of the emittance of the proton beams based on numerical simulations. Such studies have been made of other EIC projects such as the LHeC [2]. The parameters of the beams being modelled are shown in Table 1. Some of the parameters for the electron ring are taken from earlier designs [1], and others were chosen to match I.P. beam sizes with the proton beam.

Table 1: Beam Parameters used in this Study

	Protons	**Electrons**
Energy (GeV)	100	10
β^*_x (m)	0.10	0.10
β^*_y (m)	0.02	0.02
ε_{xn} (μm)	1.0	182
ε_{yn} (μm)	0.5	91
ν_x	0.22	0.89
ν_y	0.16	0.61

The interactions between beams that are long compared to their transverse dimensions can lead to different parts of each beam receiving different bending from the other, leading to an increase in emittance. Furthermore the lensing action can lead to amplitude dependent tune shifts which can push parts of the beam onto resonances. Due to the path of the electron beam being pulled through the proton beam, the proton beam will receive different kicks on different portions of the beam. Over time this can essentially pull the beam apart.

One of the proposed configurations for the collider involves a process known as gear changing between the electron and proton beams [3]. This process is intended to allow both protons and heavy ions to stay synchronized with the electron beam [4]. Within the energy range envisioned for JLEIC the speed of the ions is sufficiently below c that beam synchronization can become problematic over varied energies. This means that each electron bunch will interact with each proton bunch, cycling through all ~3400 bunches in the beam. This will affect the way in which the two beams growth rates are modelled. In a normal synchrotron, where each electron bunch hits the same proton bunch at each interaction, an initial offset will smear out the phase space of the beams until an equilibrium is reached. In a linac-ring system, such as the proposed LHeC, offsets can be considered as random. With the gear changing procedure, since each bunch goes through more than 3400 bunches before repeating it is unclear whether the growth rate can be modelled as a linac, or as a synchrotron.

SIMULATION TOOLS

Two methods have been employed to measure the beam-beam effect. The code Guinea-Pig is a self-consistent PIC code which can calculate the motion of the two beams as they evolve [5]. For long term tracking Guinea-Pig is paired with a simple program that advances the particles through a simplified model of JLEIC.

For other simulations in which a PIC code would be inappropriate, the code COSY Infinity was used [6]. To simulate the beam-beam effect, a zero length Basetti-Erskine kick was added [7]. This code's normal form methods allow the calculation of quantities such as amplitude dependent tune shifts in the system directly.

TUNE SPREAD MEASUREMENTS

Using COSY Infinity along with the Basetti-Erskine kick to simulate the beam-beam effect we are able to create a tune footprint that directly includes the beam-beam effect. This is shown in Fig. 1.
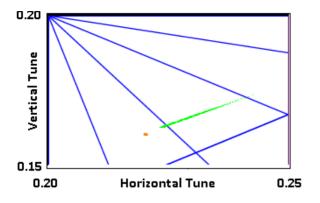
Figure 1: 4σ tune footprint of the system. The orange indicates the tune without beam-beam, while the green represents the altered tune.

As can be seen in these plots the tunes of the various portions of the beam have been pushed onto a 5th order resonance line. A retune will be necessary to maximize the dynamic aperture. To illustrate the problem with this resonance crossing in Fig. 2a, and 2b we see the results of a Poincaré section with the map calculated to 4th and 5th order. The addition of 5th order terms causes large scale beam loss outside of the core.
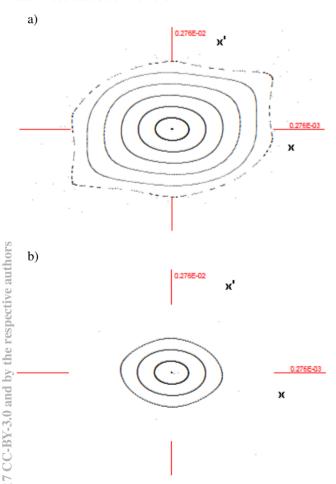
a)

b)

Figure 2: The top, figure 2a) is an example of a horizontal Poincaré section of a beam whose map has been calculated to 4th order, while figure 2b) has been

calculated to 5th order. This shows the effect of the 5th order resonance crossing on the portions of the beam that survive.

GROWTH RATE MEASUREMENTS

In order to measure the growth of the beams due to the beam-beam effect we can run simulations of both linac-like and synchrotron-like systems. This is accomplished with guinea pig as the calculation of the beam-beam effect, and a c++ module with a linear map of the collider ring. In the linac-like simulation the electron beam is shifted randomly across the horizontal axis using gaussian noise with a standard deviation of 5% of the horizontal spot size, while in the synchrotron-like model the electron beam is advanced through a best-guess single turn linear map. Neither model includes longitudinal motion. The results of this model are shown in Fig. 3 and 4.
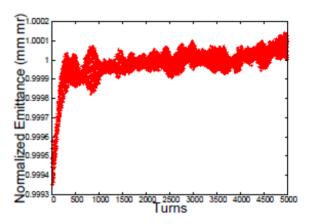

Figure 3: Plot of normalized horizontal emittance in the proton beam over 5000 turns modelled as a synchrotron. The beam begins with an initial 0.05σ horizontal offset.
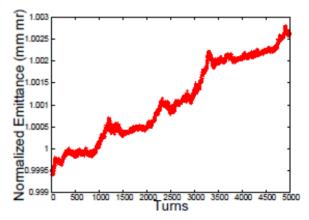

Figure 4: Plot of normalized horizontal emittance in the proton beam over 5000 turns with random 0.05σ horizontal jitter. This will model a linac type system.

In these plots we see how the two different models affect the emittance of the beam. For the synchrotron-like system the beam starts out with an initial offset, as it moves through the collider the non-linear effects of the beam-beam interaction smear it out across the phase space

until it reaches a new equilibrium. Because the beam has the possibility of many new offsets in the linac type system there is not the same tendency towards an equilibrium that we would expect to see in the synchrotron type system. This particular study does not include any type of feedback system.

LINAC OR SYNCHROTRON

When considering gear changing it becomes important to figure out just how much the motion of previous turns affects the subsequent motion, since each beam will go through more than 3400 other pulses before coming back to the original. In order to determine how long the information of a given pulse lasts in the system we have calculated the Lyapunov exponent [8].

This is done by starting with a small offset, and renormalizing it after each iteration through the map. In order to make the phase space dimensions dimensionless we transferred the particles to normal form coordinates. The inverse of the Lyapunov exponents is the so called e-folding time which determines how long information is still valid. This will vary based on where in the beam it is calculated. These times were calculated using COSY Infinity with a Basetti-Erskine kick added to simulate the beam-beam kick. This is an initial investigation along the horizontal direction using only one offset per test particle, the results are shown in Table 2, and Fig. 5.

Table 2: Lyapunov Times for the Beam-Beam Interaction in the Proton Collider Ring

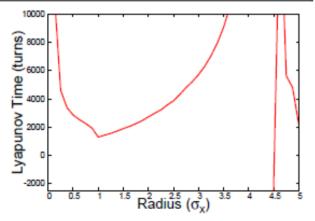| Radius (σx)	Lyapunov time (turns)
1	1284.7
2	2724.8
3	5722.5
4	19579.0
5	2149.3

Figure 5: Here we show the Lyapunov time for the system outlined in Table 2. The time goes to infinity at zero since the beam beam effect is treated as a lens in this system and a particle directly on the centreline will feel no kick.

Since the number of turns in the gear changing system is ~3 e-folding times, we can conclude that using a linac-like model will provide a good starting point, a full simulation of the system with gear changing is needed, especially for the outer portions of the beam. A tool is being developed, called GHOST, to perform this exact calculation [9].

CONCLUSIONS AND FURTHER WORK

These initial studies have built up the infrastructure to study the effects of beam-beam interactions on the emittance evolution for the ion beam. These studies will have to also be repeated for the electron beam. Furthermore, longitudinal effects must be added, since it opens up the tune-space to more possible resonances. A systematic retune is also necessary to suppress the higher order resonances that the amplitude dependent tune shifts are pushing the beam onto. Furthermore it is important to include the effects of radiation damping on the electron beam when determining how the beam-beam effect can cause emittance growth. While gear changing can help solve the synchronization problem across many energies, it does increase the sensitivity of the entire beam to outside noise.

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