THE EFFECTS OF SPACE-CHARGE ON THE DYNAMICS OF THE ION BOOSTER IN THE JEFFERSON LAB EIC (JLEIC)*

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Abstract

Optimization of the booster synchrotron design to operate in the extreme space-charge dominated regime is proposed. This study is motivated by the ultra-high luminosity promised by the JLEIC accelerator complex, which poses several beam dynamics and lattice design challenges for its individual components. We examine the effects of space charge on the dynamics of the booster synchrotron for the proposed JLEIC electron ion collider. This booster will inject and accumulate protons and heavy ions at an energy of 280 MeV and then engage in a process of acceleration and electron cooling to bring it to its extraction energy of 8 GeV. This would then be sent into the ion collider ring part of JLEIC. In order to examine the effects of space charge on the dynamics of this process we use the software SYNERGIA.

INTRODUCTION

The Jefferson Lab Electron Ion Collider (JLEIC) is a proposed e-p machine that would collide 3-10 GeV electrons with up to 100 GeV protons for nuclear physics studies. The current plan involves using the existing CEBAF recirculating linac as a full energy injector, and a train of machines going from the ion source, through a linac to a booster and finally a collider ring [1]. The booster plays a pivotal role, bringing 280 MeV protons (or equivalent ions) from the linac up to 8 GeV for injection into the collider ring [2]. In this work we study the effects of space charge on this process.

The Booster has a three level cycle. Soon after injection the energy is brought up to 2 GeV where a conventional electron cooler will be applied to lower the emittance of the beam. Once this is accomplished it is ramped up to its extraction energy of 8 GeV and then extracted to the collider ring. The parameters for these processes [3] are shown in Table 1.

Table 1: The Parameters Used for the Three Studied Phases of the Booster Cycle

	Injection	Cooling	Extraction
Energy	280 MeV	2 GeV	8 GeV
n_p	8.3×10^{11}	8.3×10^{11}	8.3×10^{11}
x,y emittance (m)	1.21×10^{-6}	3.38×10^{-7}	1.06×10^{-7}
σ_z (m)	1.3275	1.3275	1.3275
$\delta p/p$	4.64×10^{-4}	8.72×10^{-4}	2.6×10^{-4}

These initial studies are focused on the transverse effects of space charge in the machine. In order to model the effects of space charge as accurately and efficiently as possible we are using the accelerator code Synergia 2 [4]. We are using a 2-d open Hockney space charge algorithm, which is one method in Synergia [5]. We do not simulate the RF system which was still being designed at the time of these studies. While Synergia does support detailed injection modelling we have begun these initial simulations with a simple test run at maximum current for the number of turns envisioned for the injection cycle.

In this work, we will move backwards from the top level extraction energy down to the injection process, calculating the effects of space charge on the emittances and sizes of the beam. Then we will discuss some proposed studies of the halo formation process in the booster.

EXTRACTION ENERGY

At the top extraction energy space charge is less of an issue than at any of the other parts of the process. The evolution of the emittances is shown in Fig. 1.

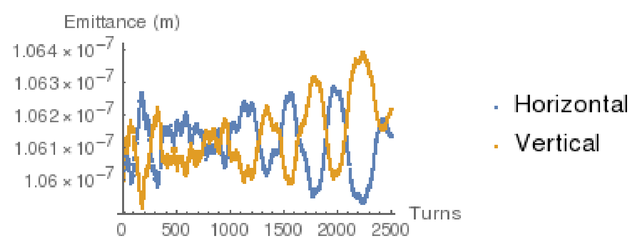

Figure 1: Emittance evolution of the beam at extraction energy. The differences shown are small enough that during the brief period in which the beam is still in the booster, space charge induced emittance growth can be ignored.

The changes recorded in this simulation are small enough to be effectively ignored, and as the evolution of the beam sizes shows in Fig. 2. The apertures and acceptances of the accelerator do not pose any problems at the extraction energy level for the booster.

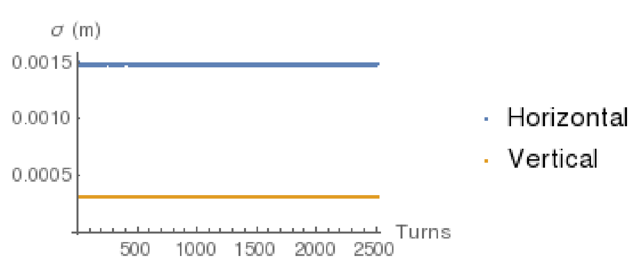

Figure 2: Here we see the horizontal and vertical standard deviations of the beam at extraction energy.

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COOLING ENERGY

After being brought out of the low injection energy regime, the booster will pause at 2 GeV to cool down the proton beam using a conventional electron cooler. Currently the cooler is modelled separately from the booster so this particular simulation could not include its effects, though this is a future goal. The evolution of the emittances is shown in Fig. 3. As we see in this plot the vertical emittance doubles, and the horizontal comes close. This is very high, but we can see that the values have more or less levelled off within a few hundred turns. Since cooling times are significantly longer than that we can take this emittance increase as an upper limit.

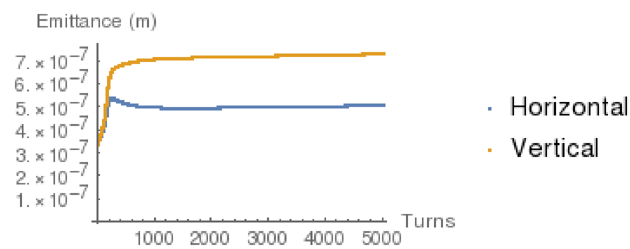

Figure 3: Here we see the emittances of the beam at the cooling pause. The current design calls for electron cooling which is not included in this early simulation, but we can determine an upper limit to the emittance growth of the beam due to space charge.

These plateauing effects are also visible if we plot the beam size over the same period; this is shown in Fig. 4.

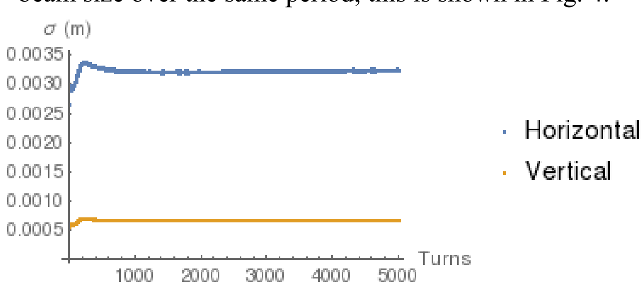

Figure 4: The beam sizes at the injection point of the beam are plotted for the horizontal and vertical dimensions during the cooling phase of the booster cycle.

INJECTION ENERGY

The current plan for JLEIC involves foil stripping injection of protons or other ions into the booster from a linac. The current design of the bunch structure in the linac shows a continuous train of bunches with a total length which would require 273 full turns in the booster to be completely filled.

In order to get an initial estimate of the stability of the injected beam under space charge we have run the beam with the fully injected current over 300 turns, the results are shown in Fig. 5.

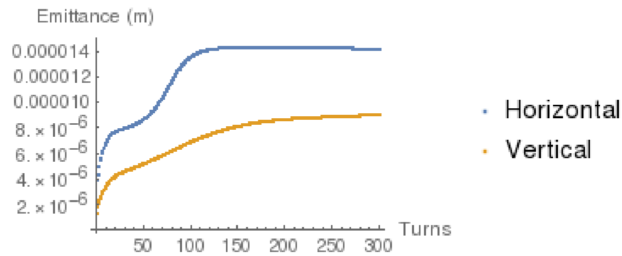

Figure 5: Here we see the evolution of the beam emittances at injection. This is not a complete injection simulation, but shows that even at full charge the emittance growth is not a runaway effect.

While there is significant emittance growth in this regime, the effects are not runaway, there is even a plateau. It should be remembered that this simulation tracks the beam at full current while the actual injection stage will not have as much charge in the bunch until the very end. It does however show the rapidity with which the emittance will grow as the current increases, so a rapid move from injection to acceleration is indicated for this machine. A plot of the beam sizes is shown in Fig. 6.

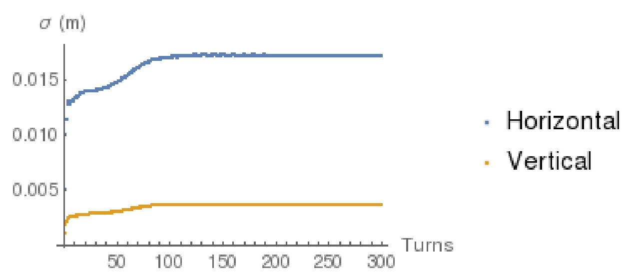

Figure 6: A plot of the beam sizes during the injection phase of the booster ramp cycle

HALO FORMATION, RESONANCE CROSSING STUDIES

Optimization of the Ion Booster design to mitigate halo formation and beam loss will be accomplished through comprehensive numerical studies of resonance crossing in the presence of space-charge, as they affect the beam dynamics. Furthermore, modern resonance compensation schemes such as: stop-band correction and introduction of anti-resonances will be implemented into the final lattice design

Here we consider beam conditions at the injection plateau, where the effect of space-charge is considerable (e.g. Laslett tune shift of about 0.3), and a bunched beam is stored for a long time (10^5 or more turns). When the machine tunes cross a stable resonance, the dynamics of a single particle may follow two distinct patterns [6]:

If the tunes cross the resonance slow enough (adiabatically), the resonance captures the particle and stays 'locked' to it, yielding periodic resonance crossing. The

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consequence is that a particle gains large betatron amplitudes leading to a halo formation and beam loss.

If the tunes cross the resonance fast enough, particles in the beam will receive a small kick by the space-charge induced islands and each single particle invariant will be 'scattered'. Trapping of particles on the islands leads to a halo generation, eventually causing beam loss.

Therefore, a periodic resonance crossing increases the transverse amplitude of particles, as their tunes are getting closer to the resonance. If particles stay within the accelerator acceptance, an emittance increase will appear (for small halo radii), otherwise a slow progressive beam loss will characterize the storage. These processes, along with structure resonances with space-charge, will be studied numerically via multi-particle tracking through the above lattice in the presence of magnet multipole errors. We will use the multipole content of the super-ferric dipoles per design specs provided by Texas A&M University.

The goal of the simulation is to compose the so-called beam-loss tune scan – a fractional beam-loss as a function of the horizontal and vertical tunes - similar to the one carried out for the PS Booster at CERN [7].

If the incoherent space-charge tune shift at injection is large, > 0.3, significant fraction of particles in the beam may move across third-integer resonance lines. To alleviate the resulting beam loss, one can implement third-integer resonance crossing correction measures by creating anti-resonances via properly placed pairs of sextupoles [6]. They would correct the stop-band width of these resonances to minimize the amplitude growth and hence the beam loss. Simulation of the above process will ultimately provide insight into the effectiveness of the correcting scheme and will allow us to optimize the placement of the correcting sextupoles in the ring, as well as their strengths.

Finally, thorough space-charge studies, outlined above, are essential to optimize the present Ion Booster design: to define the optimum injection energy, working point tunes, maximum current, as well as to carry out assessment of the acceptable halo and beam loss.

CONCLUSIONS AND FURTHER WORK

This work has presented some useful initial results about various stages of the booster cycle for JLEIC. While there is large emittance growth in the injection and cooling phases of the beam cycle, there is no runaway effect that would be a show stopper. Further work requires a detailed design and study of the stripping injection scheme. Furthermore the longitudinal dynamics both during the coasting phases shown here and during the energy ramp need to be studied in detail to create an end to end simulation of the entire booster cycle.

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