Intrabeam Stripping of H^- Ions in the JLEIC Ion Linac with PyORBIT

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Abstract

Jefferson Lab is designing an Electron-Ion Collider Facility (EIC) to meet the experimental needs of the international nuclear physics community. In Jefferson Lab's Electron-Ion Collider (JLEIC), a potential mechanism for beam loss is intrabeam stripping of the H^- ions in the linear accelerator (linac), which is part of the low energy region of the ion injector complex. As the hydrogen ions interact with each other through Coulomb scattering, there is a chance that an electron will be stripped from each of the ions. This creates neutral particles that are unaffected by the electromagnetic fields and are thus lost.

The focus of this project was to show whether intrabeam stripping is a relevant form of beam loss for JLEIC. To accomplish this, the pyORBIT code, a python code developed at Oak Ridge National Lab (ORNL), was modified to model the JLEIC linac and simulate the beam dynamics, including the effects of intrabeam stripping. Then plots were created of relativistic velocity throughout the linac to determine the likelihood of beam loss from intrabeam stripping. From these plots, it was found that the maximum relativistic velocity of the H^- ion beam is similar to values from previous studies on other linacs; however, the average current per pulse of JLEIC is significantly lower than the current of other linacs. Previous predictions and numerical simulations have shown that intrabeam stripping is proportional to the bunch density squared, therefore meaning increasing the current increases the likelihood of intrabeam stripping. This project revealed that JLEIC's value for average current is below the values from other linacs that have experienced beam loss from intrabeam stripping. These results confirmed that intrabeam stripping of the H^- ions will have negligible effects on the amount of beam loss in the JLEIC ion linac.

Jefferson Lab Electron-Ion Collider

The driving motivation behind all that happens at Jefferson Lab is the eagerness to define and understand the nuclear physics behind quarks and gluons, and how they combine to build the world around us. For the past twenty-five years, researchers at Jefferson Lab have been studying the inner workings of the atom by accelerating beams of electrons towards stationary atomic nuclei targets in the Continuous Electron Beam Accelerator Facility (CEBAF). However, as the need for a higher-resolution accelerator increases within the nuclear physics community, Jefferson Lab has designed an Electron-Ion Collider Facility to study higher-energy collisions at an even higher precision. The layout for JLEIC can be found in Figure 1.

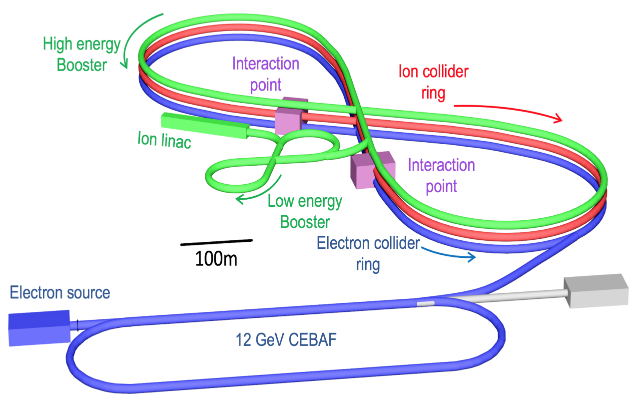

Figure 1: JLEIC facility design with the superconducting linac located between the Ion Source and Booster synchrotron

The EIC will accelerate both beams of electrons and ions to collide together so we can then study the high-energy collisions. These collisions will give a new and unique perspective on the building blocks of matter. CEBAF already has the capability to produce and accelerate beams of electrons, but on the other hand JLEIC will have to include a new ion injector complex that produces negatively charged hydrogen ions in an ion source. These ions will then be accelerated through a superconducting ion linac that will accelerate the ion beams up to an energy of 150 MeV [1].

Charge-Exchange Injection

The hydrogen ion beam will then be injected into the figure-8 Booster synchrotron after leaving the superconducting linac of the ion injector complex. Once reaching the synchrotron a dipole magnet will change the trajectory of the ions to accelerate them in a circular path. However, once those particles circle around and reach the initial dipole again, they enter at a different angle, that is off axis to its original route. This deflects the bunches of ions away from the original circular path and results in beam loss. Therefore, there must be some way for the bunches to enter the bending magnet at different angles and leave with the same trajectory. However, according to Liouville's Thereom this is an impossible task.

Therefore, JLEIC will incorporate a beam of negatively charged hydrogen ions, H^-, that will be stripped of their electrons once leaving the initial dipole. These positively charged ions will re-enter the initial dipole at an angle opposite to which the H^- beam did, and will be deflected with the same trajectory to continue to accelerate in a circular motion. Therefore, H^- beams will be used in the superconducting linac of the ion injector complex because we can "stack" the beam in the Booster synchrotron, accumulating a much higher intensity of beam than if we had used H^+ ion beams.

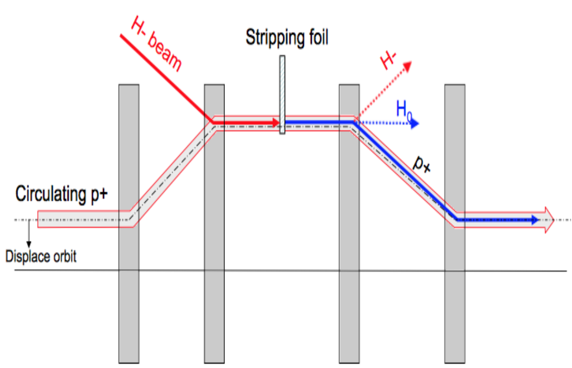

Figure 2: Visual representation of the charge-exchange injection for the JLEIC H^- ion beam leaving the linac and being stripped of its electrons to create a proton beam in the Booster synchrotron

Intrabeam Stripping

First observed in the H^- beam of the Spallation Neutron Source (SNS) linear accelerator at Oak Ridge National Laboratory (ORNL) [2], intrabeam stripping occurs as the hydrogen ions interact with each other within the beam. Inelastic scattering between the ions results in the stripping of an electron from the H^- ions, creating a neutral hydrogen atom:

$$H^- + H^- \rightarrow H^- + H^0 + e$$

The neutral particle is unaffected by the electromagnetic fields within the linac and therefore crashes into the accelerator wall and consequentially results in beam loss and residual radiation. According to [2], the beam loss rate inside each bunch of ions is proportional to the square of the bunch density. This phenomena can be observed in Figure 3 below from the SNS linac, where the beam loss increases with the current/ion density squared.

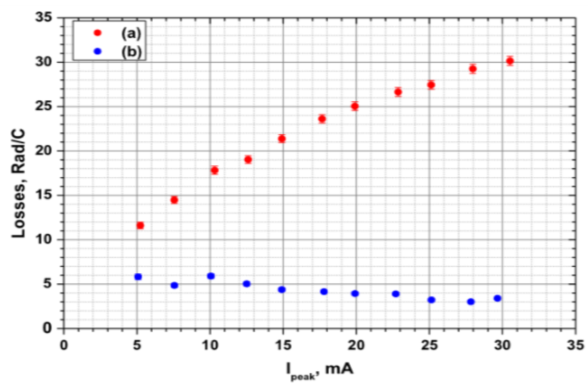

Figure 3: The beam loss in the SNS linac vs peak current for (a) H^- ions and (b) protons [2]

Thus, tightly focusing the beam and pushing all of the particles into a smaller area or generating a greater intensity/current increases the risk for intrabeam stripping. However, a larger beam results in beam loss as well, since the particles crash into the wall of the linac more easily. The purpose of this project was to optimize between these beam loss scenorios and to determine whether intrabeam stripping is a relevant mechanism of beam loss for the JLEIC ion linac. These scenarios were simulated using pyORBIT.

PyORBIT

PyORBIT is a code created for the SNS accelerator at ORNL [3]. This code is comprised of both python and C++ libraries that are designed to simulate beam dynamics and track particle trajectories throughout accelerators. The flexible structure of py-ORBIT allowed it to be easily extended and modified to simulate the effects of the JLEIC superconducting ion linac. So all of the elements within the linac, like the quadrupoles, solenoids, RF cavities, and drifts were defined and arranged in the code to simulate the correct ordering of these elements in the JLEIC ion linac. A diagram of the ordering of the RF cavities and Solenoid elements in the linac can be found in the figure below. All of the relevant plots were created using gnuplot.

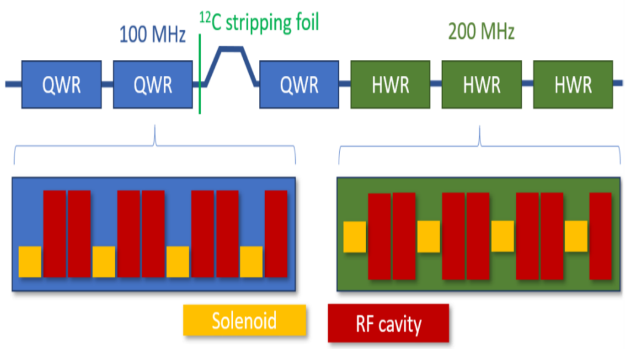

Figure 4: Diagram of the ordering of the JLEIC superconducting ion linac elements

Previous Observations of Intrabeam Stripping

According to [4] the cross-section of the intrabeam stripping can be approximated by the following equation:

$$\sigma_H = \frac{240\alpha_{FS}^2 a_0^2}{(\beta+\alpha_{FS})^2}\frac{(\beta-\beta_m)^6}{(\beta-\beta_m)^6+\beta_m^6}\ln\left(1.79\frac{\beta+\alpha_{FS}}{\alpha_{FS}}\right) \quad (1)$$

where $a_0 \approx 0.529 \times 10^{-8}$ cm is the Bohr radius, $\alpha_{FS} \approx 1/137$ is the fine structure constant, $\beta \equiv \frac{v}{c}$, and $\beta_m \approx 7.5 \times 10^{-5}$. This β_m value is when the hydrogen ions are travelling at a speed so low that they will repel each other before they can get close enough for intrabeam stripping to take over.

This cross-section of intrabeam stripping is proportional to the probability of the electrons being stripped from the ions. So this equation of the cross-section tells us the probability of two ions getting close enough to interact and the process of intrabeam stripping to take over. Equation 1 is only valid when β is greater than β_m, the velocity where the cross-section approaches zero due to ion repulsion. This phenomenon can be observed in Figure 5 below, where the cross-section is plotted as relativistic velocity β increases. Note that β_m is off the left hand side of the plot where the cross-section approaches zero and can be neglected. Also, a plateau can be seen in Figure 5, where the intrabeam stripping cross-section is at its maximum, between a velocity of 10^{-4} and 10^{-1}. The Born approximation is the first order approximate of the quantum mechanics solution to the cross-section of intrabeam stripping.

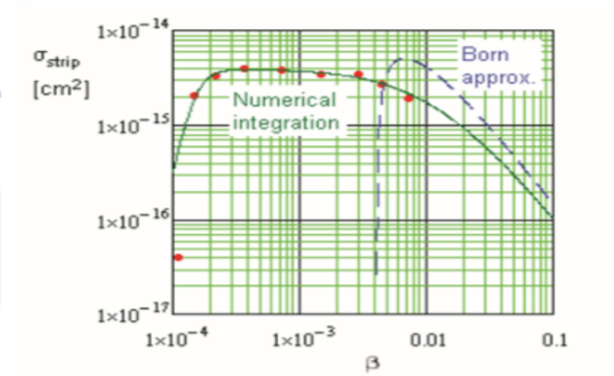

Figure 5: Comparison numerical predictions of the SNS to the results of the Born approximation [4]

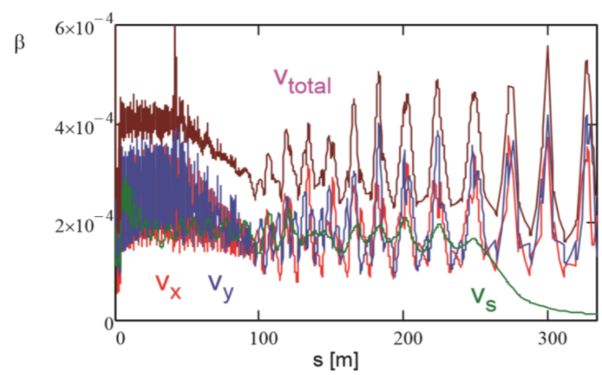

Figure 6: RMS relativistic velocities along the SNS linac [4]

The average relativistic velocites plotted along the length of the SNS linac in Figure 6 are located on this cross-section plateau with the average $\beta \approx 4 \times 10^{-4}$. These velocity values confirm the observations of intrabeam stripping in the SNS linac at

ORNL, with the measured fractional beam loss approximately equal to 3×10^{-5}. A beam loss mechanism becomes a problem when the fractional beam loss is a couple percent, which was the problem for the SNS. This proves that along this plateau of the cross-section, intrabeam stripping can be a relevant form of beam loss. Therefore, the relativistic velocity values along the length of the JLEIC ion linac need to be compared to the SNS linac's velocity values to determine whether they lie along this plateau of the cross-section and thus validate the concern for intrabeam stripping.

Relativistic Velocity Plots

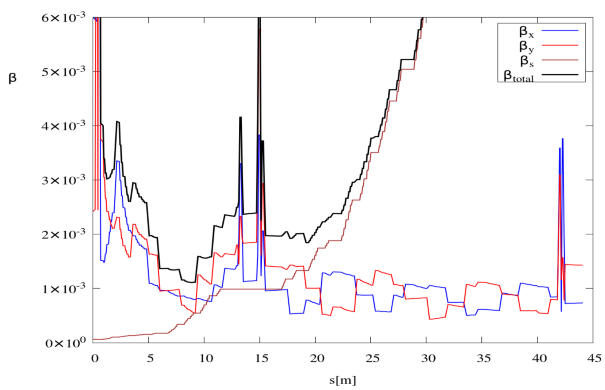

Figure 7: RMS relativistic velocities along the JLEIC ion linac

Using PyORBIT, plots of relativistic velocity were created to compare to the plots in Figures 5 and 6. However, our linac is much shorter than the SNS linac and therefore it was necessary to split up the lattice that desribes the elements within JLEIC's ion linac. This was done to observe the oscillatory motion of the relativistic values within the linac elements more distinctly. For each RF cavity, two more cavities were created and each were given an electric voltage one-third of the original. This allowed three separate "kicks" from a single RF cavity to observe the velocity values within these cavities. We had to implement the accelerating fields as zero-length "kicks" rather than complex field maps that described the electric and magnetic fields within each area of the cavities. Thus, the RF cavities were modified in a simplified manner that could be improved upon in the future if need be.

Another thing to note in Figure 7, β_s (the brown line defining the longitudinal velocity along the length of the linac) increases at the end of the JLEIC linac, but decreases to zero in the SNS linac. This is due to the fact that the longitudinal focusing in JLEIC is not completely optimized.

Nevertheless, the average velocities along the JLEIC ion linac are in a similar range of the RMS velocities from the SNS linac in Figure 5, $\beta \approx 10^{-3}$. Looking back at Figure 5, this average relativistic velocity value for JLEIC's ion linac does lie along the plateau of the cross-section. Therefore, the probability for intrabeam stripping to occur increases at this velocity value. This confirms that, within the JLEIC superconducting ion linac, the velocity values are in the right range where intrabeam stripping is a relevant form of beam loss to be concerned about.

Average Power Calculations

It is also useful to compare the average power within JLEIC to the more intense linacs such as the Fermi National Accelerator Lab (FNAL) Continuous wave (CW), the FNAL Pulsed, and the ORNL SNS. In Table 1 the parameters for the energy, repetition rate, average current per pulse, and the pulse width for the JLEIC linac are listed. Baseline parameters and the associated average power for these three comparable linacs are listed in Table 2.

Table 1: Parameters for JLEIC H^- ion linac

Kinetic Energy	150 MeV
Repetition Rate	5-10 Hz
Average Current	2 mA
Pulse width	0.5 ms

Table 2: Parameters for the FNAL CW and Pulsed linacs and the ORNL SNS linac [5]

Parameter	FNAL CW	FNAL Pulsed	ORNL SNS
Kinetic Energy	3 GeV	8 GeV	1 GeV
Repetition Rate	CW	10 Hz	60 Hz
Average Current	1 mA	26 mA	25 mA
Pulse width	1 s	0.986 ms	0.99 ms
Average Power	3 MW	2 MW	1 MW

The average power in a linac can be calculated using the following equation:

$$P = IVfT \tag{2}$$

where P is the power, I is the current per pulse, V is the beam kinetic energy, f is the repetition rate, and T defines the pulse width. Thus, the average power of the JLEIC linac was calculated to be within the range 0.75-1.5 kW. Comparing this value to the average powers for the three linacs in Table 2 shows a much smaller power for the JLEIC linac. In [5] the authors are concerned with linac powers in the megawatt range, while our linac is only in the kilowatt range.

As power increases there are more H^- ions accelerated per unit time, which does indicate that the probability of beam loss due to intrabeam stripping should increase. However, power is also proportional to the energy per hydrogen ion in the ion beam. JLEIC's ion linac will operate at an energy much lower, 150 MeV, than the SNS linac, 1 GeV, and FNAL linacs. Therefore, the average power calculations cannot determine whether intrabeam stripping is a relevant form of beam loss for JLEIC.

Average Current Comparisons

The average power of JLEIC linac might also be lower than the other comparable linacs because of the density of H^- ions within the beam. If the density of the ions is smaller, it is valid to conclude that the probability of intrabeam stripping is negligible since the interaction rate will be lower due to the decreased amount of ions in the beam. Thus, it was necessary to to compare the average current of the bunches of ions to determine whether intrabeam stripping will be a concern.

Looking at Table 1 and 2, the average current for the SNS linac is 25 mA, while the current in JLEIC's ion linac will be only 2 mA. Even more so, for SNS the pulse current is 25 mA over a pulse width approximately equal to 1 ms, while for JLEIC the pulse current is 2 mA over 0.5 ms pulse width. This confirms that the density of ions in the JLEIC ion linac is much lower than the SNS linac, which means intrabeam stripping should not be a problem for JLEIC.

To observe what happens when increasing the current per pulse, TRACK, a program designed by Argonne National Laboratory that simulates beam dynamics of ion beams in linear accelerators, was used to simulate the JLEIC ion linac and observe the beam loss. Increasing the average current per pulse to 4.6 mA on TRACK simulates approximately a 9.5% beam loss in the linac and increasing the current per pulse to 7 mA creates a 24.5% beam loss. Increasing the current to values this high increases the emittance of the beam to a size where a majority of the ions are crashing into the wall of the linac and are thus lost. Therefore, the current per pulse values where intrabeam stripping is a relevant form of beam loss, like in the SNS, are far beyond any of the JLEIC requirements.

Conclusion

Since JLEIC"s velocity values lie along the plateau of the cross-section of intrabeam stripping, like the SNS linac that does deal with intrabeam stripping, we know that beam loss due to intrabeam stripping is a possibility. However, comparing other parameters of JLEIC, like average power and pulse current, to linacs which deal with intrabeam stripping has diminished this concern. From these comparisons, it can be concluded that since JLEIC's ion linac is lower in average current, energy, and power, beam loss from intrabeam stripping is not a valid concern for the construction and operation of this new high-resolution accelerator facility.

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