Coherent Electron Cooling: Optimizing Beam Width and Emittance with IMPACT-T

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Motivation

At Brookhaven National Laboratory, the CeC proof-of-principle experiment takes place as a part of the Relativistic Heavy Ion Collider. We aim to validate the ability of CeC through the plasma-cascade microbunching instability (PCI) of the electron beam [1]. CeC uses the electrostatic interaction between electrons and hadrons to drastically reduce the cooling times of accelerators and colliders, with an LHC-like simulation showing a significant decrease from about 13 hours to 1 hour [2].

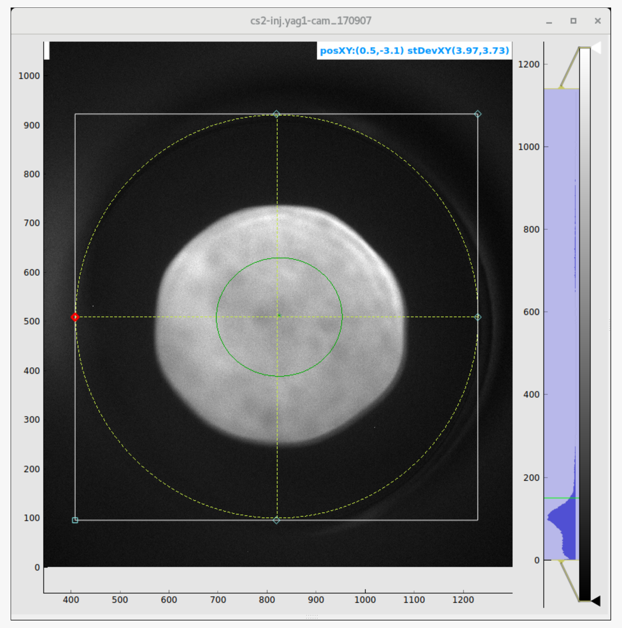

Figure 1: Unfocused beam profile at YAG1.

Background

Particle beams have a property called emittance, the area that the particles take up when plotting the beam in position-momentum phase space. For example, the normalized RMS emittance in the x-direction can be defined as

$$\varepsilon_x = \gamma\beta\sqrt{\sigma_x^2\sigma_{p_x}^2 - \sigma_{xp_x}^2}.$$

From this, a smaller beam has lower emittance. PCI-based CeC requires an electron beam with low emittance. Two factors are considered in this study:

- Solenoid current of Low Energy Beam Transports (LEBTs)
- Solenoid current of the 112 MHz SRF electron gun

To find the optimal currents, we used simulation software known as IMPACT-T. IMPACT-T is a three-dimensional program that tracks relativistic charged particles [3]. We simulated and measured at the sections shown in Fig. 1.

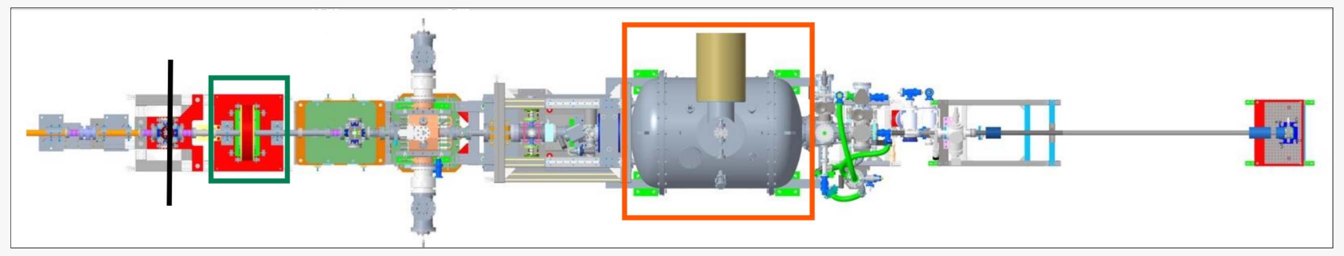

Figure 2: Focused scope of beamline. The orange box encloses the SRF electron gun, the green box encloses the first solenoid in the beamline "LEBT1," and the black line placed at YAG1 shows where we collected data in simulations and experiments.

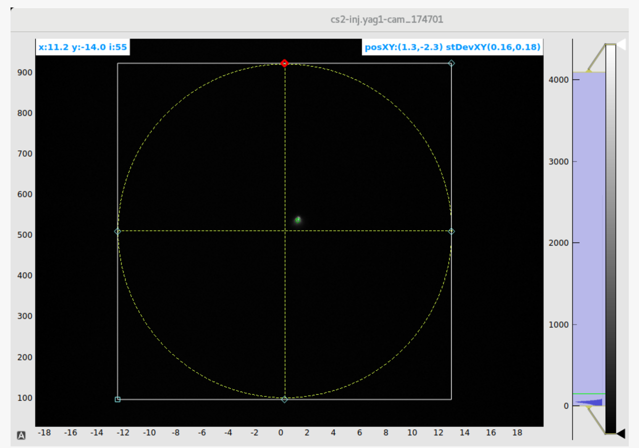

Figure 3: Profile of focused beam at YAG1.

Once optimized, the beam should no longer look like Fig. 1. Rather, it will be smaller and have a low measured emittance, visually resembling the profile in Fig. 3.

Procedure

Using the YAG1 profile monitor, we looked at beam width as a function of LEBT1 and gun solenoid currents, and beam emittance as a function of gun solenoid current. Optimizing beam width and emittance each had different steps:

- Beam width:
  1. Simulate each current for 800 pC bunches
  2. Vary LEBT1 & gun solenoid current
  3. Measure average RMS x- and y-widths at YAG1
- Beam emittance:
  1. Simulate each current with varying size bunches
  2. Vary electron gun solenoid current
  3. Measure the projected emittance at YAG1

Results

Our work in minimizing beam width found the optimal current settings of ±4.5 A for LEBT1. It also revealed a large mismatch between our expectations and experimental data, seen by the overshooting simulations in Fig. 4 that shift down in Fig. 5. This was caused by our outdated IMPACT-T beamline setup.

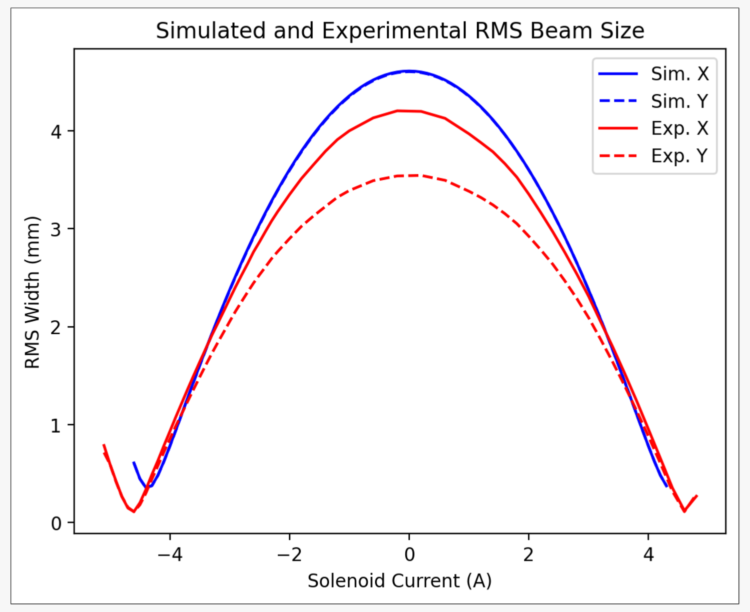

Figure 4: First simulation comparison.

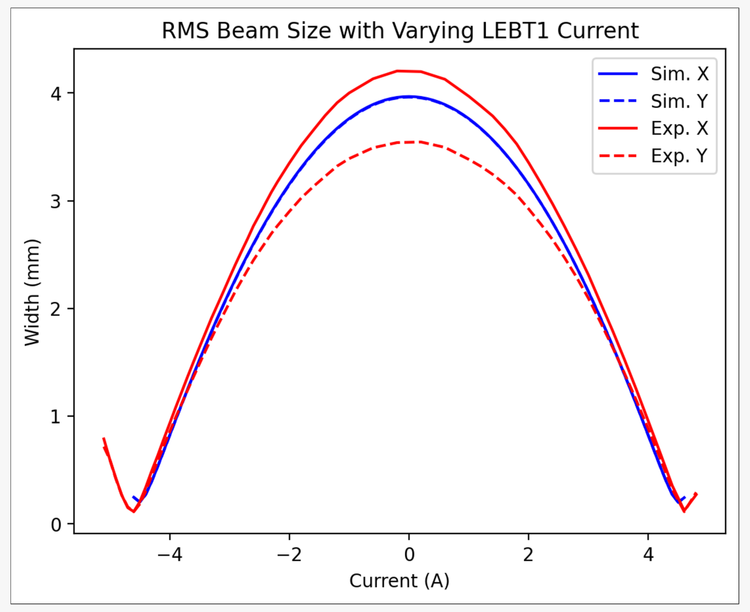

Figure 5: Updated simulation comparison.

0 pC bunches and 800 pC bunches were tested to further verify simulation accuracy. Fig. 6 is unaffected by space-charge, thus simulations should, but do not, match the experiment. Fig. 7 uses the experimental bunch setting. It mostly agrees until about 8.7 A and is optimal around 8.6 A.

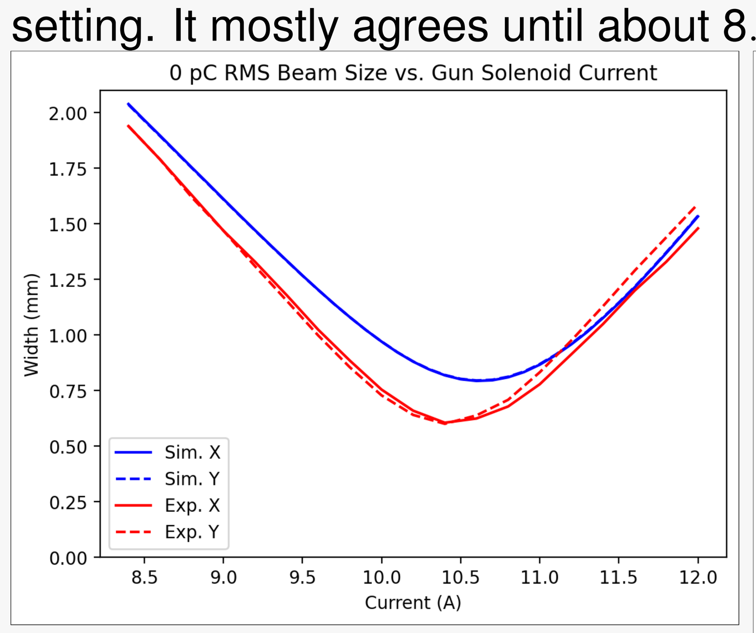

Figure 6: RMS width using 0 pC bunches, shows a mismatch.

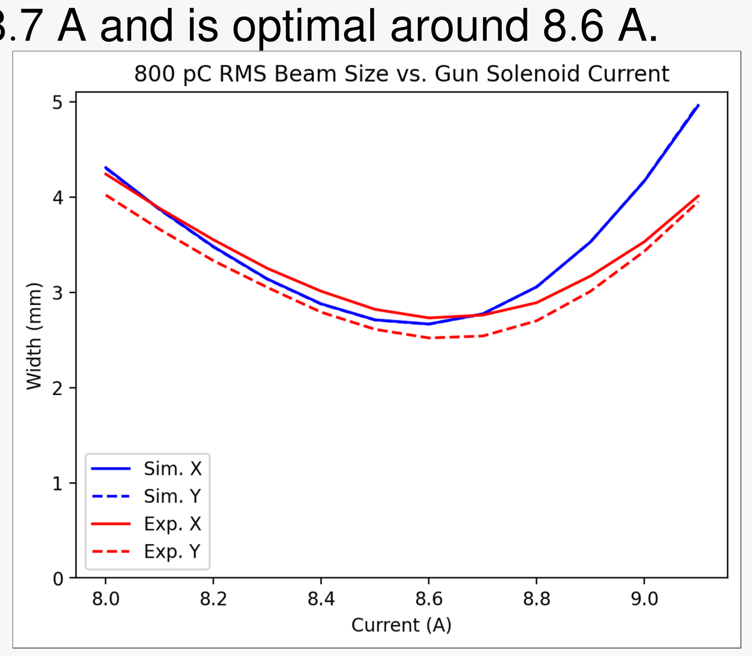

Figure 7: RMS width using 800 pC bunches, shows departure.

The projected X and Y emittance comparisons helped confirm where the minimum emittance is for the 800 pC bunches but were otherwise inconclusive. The large mismatch in Fig. 9 prompted us to see how 0 pC would change given the absence of space-charge, with results shown in Fig. 8.

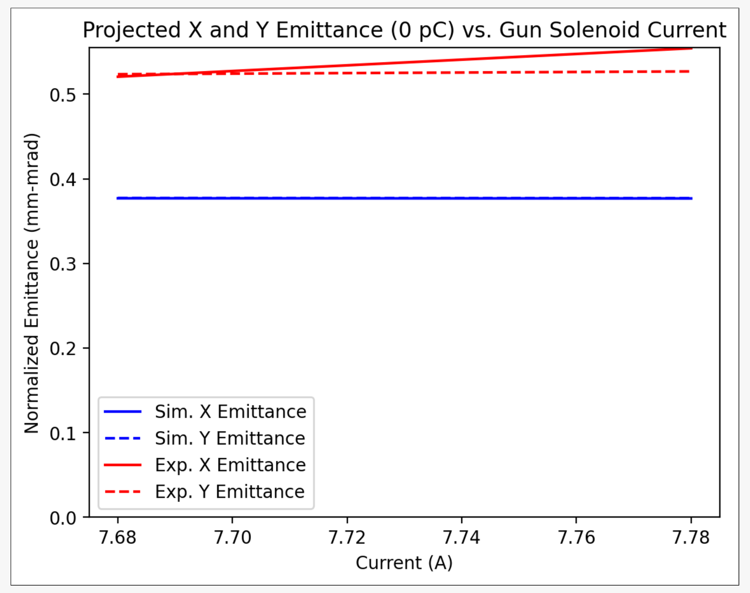

Figure 8: 0 pC simulation comparison.

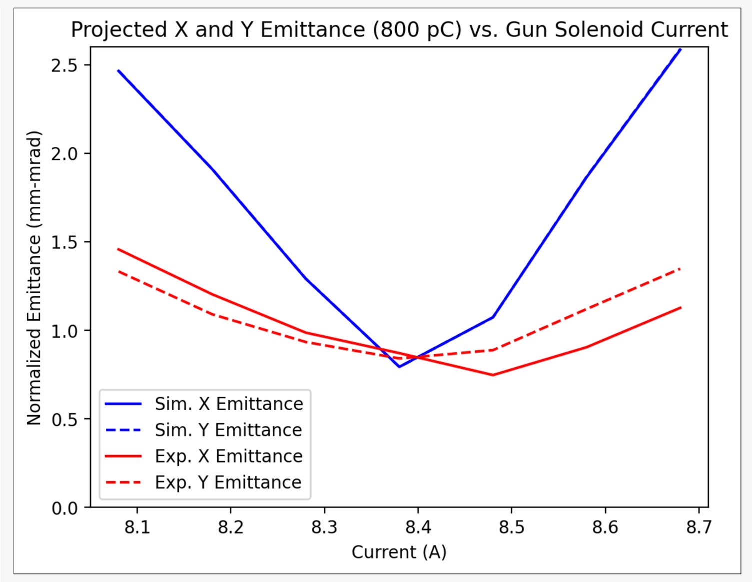

Figure 9: 800 pC simulation comparison.

The deviation from simulations could be caused by:

- Non-uniform beam charge density
- Incorrect photocathode recess measurement affecting electric field strength and focusing in the SRF cavity

Conclusion

After making corrections to the beamline setup, we gained more accurate simulations and found optimal LEBT1 and SRF gun solenoid currents of around ±4.5 A and 8.6 A, respectively. The experimental width measurements aligned with our expectations. The optimal LEBT1 and SRF gun solenoid currents for minimized emittance are still unclear given the large mismatch between simulations and experimental data.

Further work includes generating new electromagnetic field maps for IMPACT-T to account for the new photocathode recess. Another simulation software may also be used to test 0 pC bunches, as IMPACT-T is better suited for space-charge-dominated beams.

References and Acknowledgments

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