Investigating Radio Frequency Photocathode Electron Sources

Supervisor
Dr. Steffen Doebert

Virtual CERN Summer Student
2021

Benjamin Appleyard

Home Institute
The University of Saskatchewan
Canada

1 Introduction

The goal of the virtual CERN summer student project was to learn about radio frequency electron sources. It was proposed to study an RF photocathode electron gun which could be used for the CLEAR or AWAKE experiments at CERN. This electron gun beam line is a 1.5 m long with a 3 GHz, 120 MV/m, 1.5 cell, standing wave cavity. The goal of the summer project is to learn about electron sources by investigating beam diagnostics of a simulated beam as it emerges from the electron gun cavity in order to predict measurable characteristics of the beam later on in further accelerating structures, as well as discover optimal conditions for operating the electron gun.

2 Investigations of the Electron Source

2.1 List of investigations proposed for project

1. Scan the phase of the electric field of the e-gun $\pm 30^\circ$ from the maximum accelerating phase in steps of 5°
2. Plot the minimum emittance, final energy spread, final beam energy, minimum beam size, and final bunch length as a function of the phase of the electric field
3. Change the electric field in the gun to 100 MV/m (the working point of the current electron source), and plot same five parameters as above
4. Change the magnitude of the magnetic field by $\pm 15\%$, observe same five parameters
5. Scan the laser spot size between 0.4-0.6 mm and observe the same five parameters
6. Change the laser distribution to be uniform and compare the above items to their Gaussian distribution counterparts
7. Observe key parameters, and longitudinal and transverse phase space along the beam line

2.2 Accelerating Voltage

The new electron source has a nominal accelerating voltage of 120 MV/m whereas the previous version had a gradient of 100 MV/m. Simulations were performed for the new electron source configuration. Comparison of these two gradients will provide a guideline for the difference between the two instruments. This test was done by changing the magnitude of the absolute maximum of the electric field, as well as adjusting the automatically calculated, absolute phase of the electric field seen by the particles, in the ASTRA input files. Figures of the five relevant beamline parameters are shown in Fig.1-5.

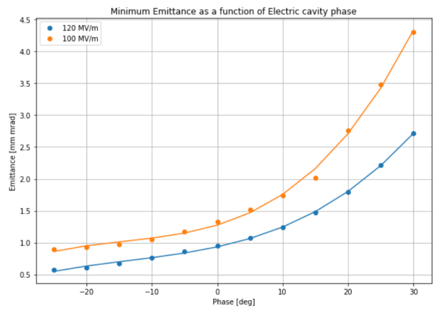

Figure 1: Emittance comparison between the 100 MV/m and the 120 MV/m accelerating gradients.

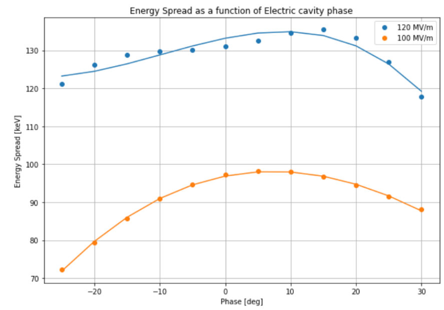

Figure 2: Comparison of the energy spread between the 100 MV/m and the 120 MV/m accelerating gradients.

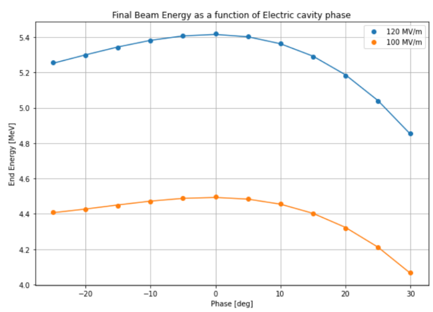

Figure 3: Comparison of the final beam energy between the 100 MV/m and the 120 MV/m accelerating gradients.

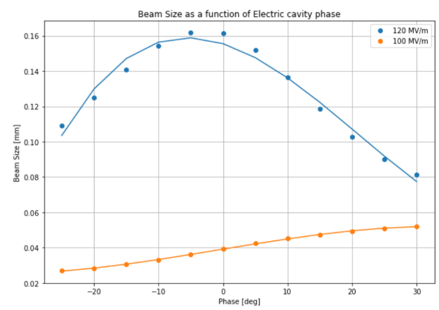

Figure 4: Beam size comparison between the 100 MV/m and the 120 MV/m accelerating gradients.

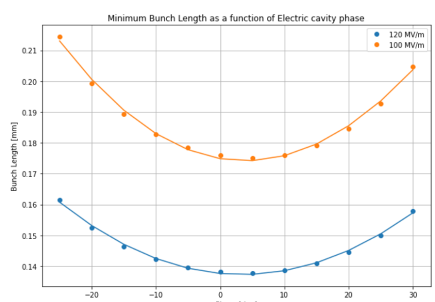

Figure 5: Bunch length comparison between the 100 MV/m and the 120 MV/m accelerating gradients.

We can observe that the higher accelerating gradient produces more advantageous emittance and bunch lengths, as well as higher beam energies. Asymmetrical patterns in the emittance about phase $\phi = 0$ are due to more of the bunch experiencing stronger acceleration at negative phases. Unsurprisingly, the stronger acceleration resulted in a higher final beam energy.

2.3 Electric Field Phase

The ASTRA program automatically calculates the phase of the electric field which will result in the bunch experiencing the maximum accelerating voltage. However, it may be advantageous to alter this phase in order to optimize certain aspects of the beam at the end of the accelerating cavity. This investigation was done by adjusting the automatically calculated, absolute phase of the electric field in the ASTRA input files. Figures of the five relevant beamline parameters are shown in Fig.6-10.

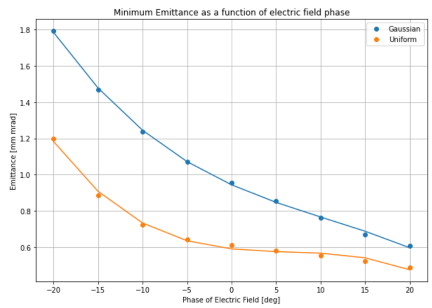

Figure 6: Emittance comparison between the Uniform and Gaussian laser distributions.

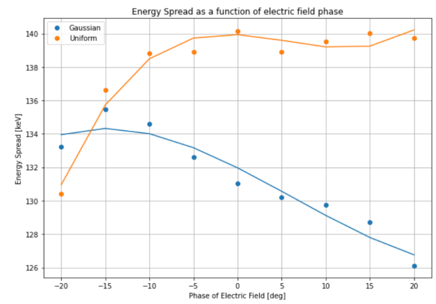

Figure 7: Comparison of the energy spread between the Uniform and Gaussian laser distributions.

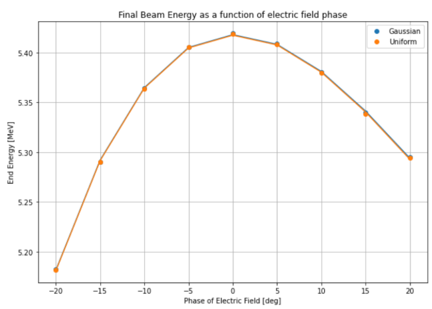

Figure 8: Comparison of the final beam energy between the Uniform and Gaussian laser distributions.

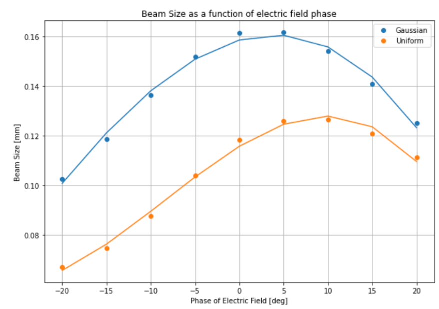

Figure 9: Beam size comparison between the Uniform and Gaussian laser distributions.

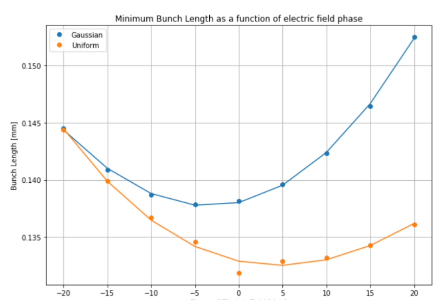

Figure 10: Bunch Length comparison between the Uniform and Gaussian laser distributions.

From this investigation we can conclude several things. The uniform distribution is more evenly distributed than the Gaussian distribution, this means that there is always a part of the beam that experiences the full acceleration and correct focusing. With the Gaussian distribution, it matters a lot more which part of the bunch is on phase with the accelerating gradient. The same follows for the beam size. The uniform distribution experiences space-charge forces in the same way across the entire bunch, but the Gaussian distribution has a varying charge density and so experiences stronger bunch length changes depending on particle position.

2.4 Magnetic Field Tune

Since the solenoid field is used for focusing the beam initially, it is responsible for ensuring that the emittance and beam size are favourable for injection downstream. This investigation was performed by changing the magnitude of the maximum value of the magnetic field in the ASTRA input files. Figures of the five relevant beamline parameters are shown in Fig.11-15.

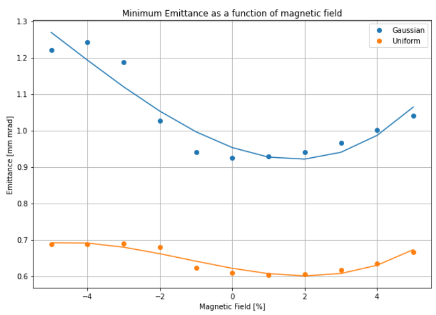

Figure 11: Emittance comparison between the Uniform and Gaussian laser distributions.

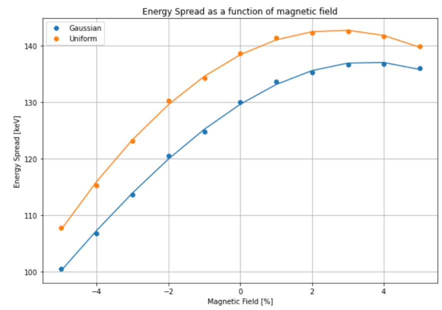

Figure 12: Comparison of the energy spread between the Uniform and Gaussian laser distributions.

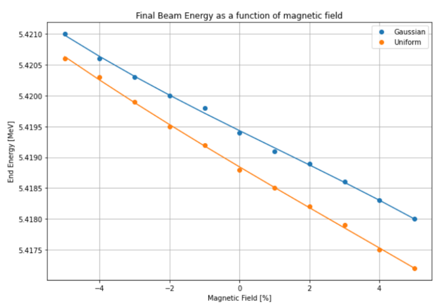

Figure 13: Comparison of the final beam energy between the Uniform and Gaussian laser distributions.

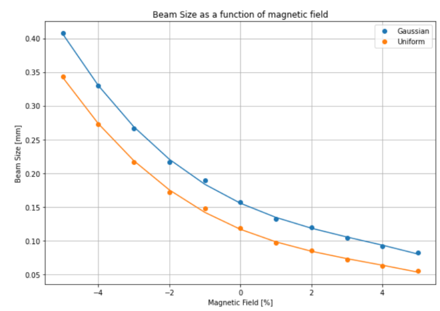

Figure 14: Beam size comparison between the Uniform and Gaussian laser distributions.

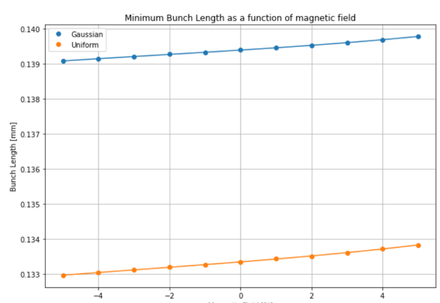

Figure 15: Bunch Length comparison between the Uniform and Gaussian laser distributions.

Again, the smaller emittance of the uniform distribution has a flatter curve due to the bunch distribution. There should theoretically be one correct magnetic field that properly focuses the beam, and with the uniform distribution, each longitudinal bunch slice contains the same charge and so that slice is more likely to be properly focused than a slice of the Gaussian beam.

2.5 Laser Radius

The intrinsic thermal emittance of the beam is related to the initial spot size. The laser radius is a reasonably simple parameter for the experimenters to control externally. A smaller laser radius is preferred, but at some point, the space-charge forces of the emitted beam will overcome the benefits of the smaller spot size. This simulation was done by changing the spot size of the laser in the ASTRA input files. Figures of the five relevant beamline parameters are shown in Fig.16-20.

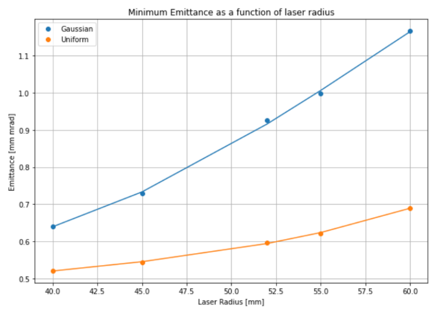

Figure 16: Emittance comparison between the Uniform and Gaussian laser distributions.

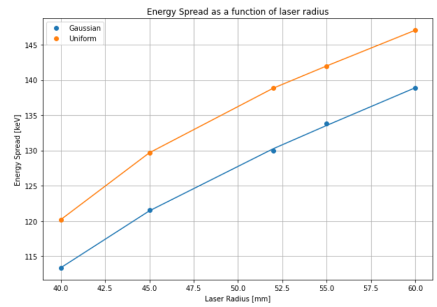

Figure 17: Comparison of the energy spread between the Uniform and Gaussian laser distributions.

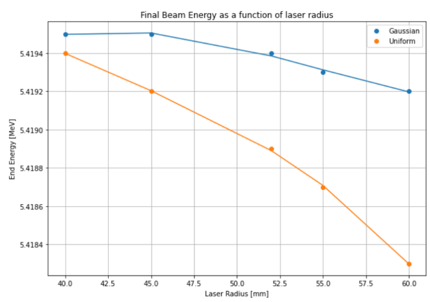

Figure 18: Comparison of the final beam energy between the Uniform and Gaussian laser distributions.

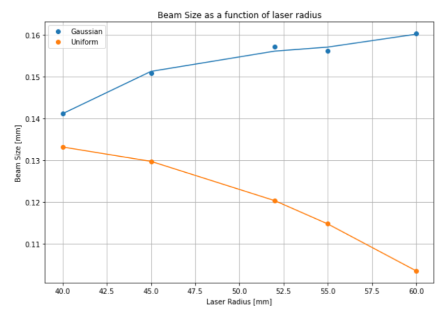

Figure 19: Beam size comparison between the Uniform and Gaussian laser distributions.

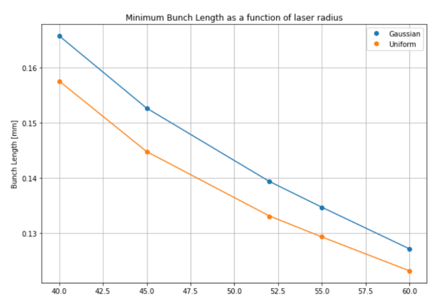

Figure 20: Bunch Length comparison between the Uniform and Gaussian laser distributions.

The energy spread of the beam is affected equally for both distributions which is expected since this factor depends more on the longitudinal parameters of the beam, and not its transverse radius. This is true also for the bunch length. An additional factor that contributes to the smaller bunch length of the uniform distribution, is that there are no trailing Gaussian tails that expand the RMS value of the bunch length. There is also less degradation of the beam due to space-charge forces, which results in a smaller beam size.

3 Discussion

From these investigations, we have obtained a data set which describes general trends which occur when various, easily changed variables are adjusted. This not only helps the experimental team understand the usage of the electron source, but also allows them to predict the downstream effects of changing the initial conditions of the gun.

Since these investigations have been performed as simulations using a space-charge tracking algorithm, the results of these tests are idealized and contain no attempts at quantifying their uncertainty. Repeating the simulations will yield no statistical variation.

The next area of interest for this project is to determine how to use the knowledge gained in these investigations in order to optimize the injection of the beam into a secondary accelerating structure. It will be important to inject the beam at a favourable location such that low emittance, low beam size, and low divergence are preserved through the secondary accelerating structure. This mean choosing optimal focusing and accelerating fields as well as choosing the location of the injection point.