OPTIMIZATION OF FOCUSING AT THE ERL GUN CATHODE*†

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Abstract

This is a continued study of optimization for the design of a high brightness, high current photoinjector being developed at Cornell University. Previous optimization studies of the injector do not include an investigation of cathode focusing; a property that has been integrated into the design of the injector's dc photoemission electron gun. In this research we vary the focusing angle of the electron gun's electrode cathode/anode in an attempt to investigate its effect on the emittance of the injector. Using multi-objective genetic algorithms alongside parallel computation and a shortened beamline we were able to determine that the application of a focusing angle has a significant effect on the emittance of the injector, where greater focusing angles provide better emittance. Future work will help decide on a final angle to be used in the design of the electron gun.

INTRODUCTION

The Development of an Energy Recovery Linac (ERL) at Cornell University has potential for many different applications. One significant use includes the production of high brightness, short pulse synchrotron radiation x-ray beams. Of course for this to be possible the development of a high current, high brightness injector is required, with average currents nearing an ampere and emittances that are considerably better than any present machine.

The study of the ERL injector is extremely important, since it is the creation point for the beam that will be used to produce useful science. Generating a beam of low quality will without doubt produce poor results from the ERL. The quantity emittance is what determines beam quality, which can be defined simply as a measure of the parallelism of the beam, or mathematically defined as beam size multiplied by beam divergence at the location of the beam waist. Lower values of emittance are sought for producing better emittance than higher values, since having a small beam size and very low divergence is highly desirable.

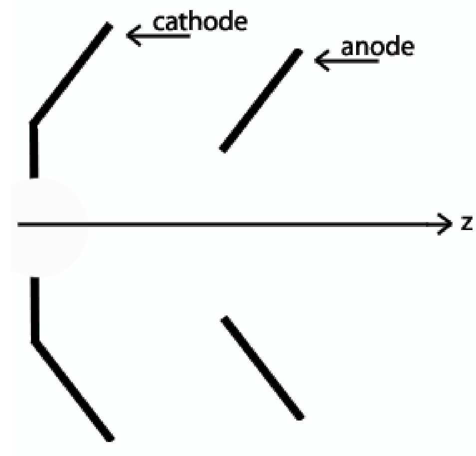

Figure 1: Rough diagram of injector gun

Previous research on the ERL injector includes a multivariate optimization used to determine the physical properties (i.e. injector component distances, field strengths, etc...) of the injector that will create a beam w/ good emittance [1]. However in this research one property was not explored, that is the how the focusing angle of the gun affects emittance. The term focusing angle refers to the fact that the cathode electrode and anode are not flat, but rather bent at a certain angle (see fig. 1). This focusing angle ensures an overall focusing effect for the gun, despite a defocusing effect present at the anode. In the previous optimization study the focusing angle was fixed at an arbitrary 25°. We would like to know whether or not we can squeeze better emittance out of our injector by varying this focusing angle.

A known benefit to this focusing can be seen when looking at the trajectory of a particle that is

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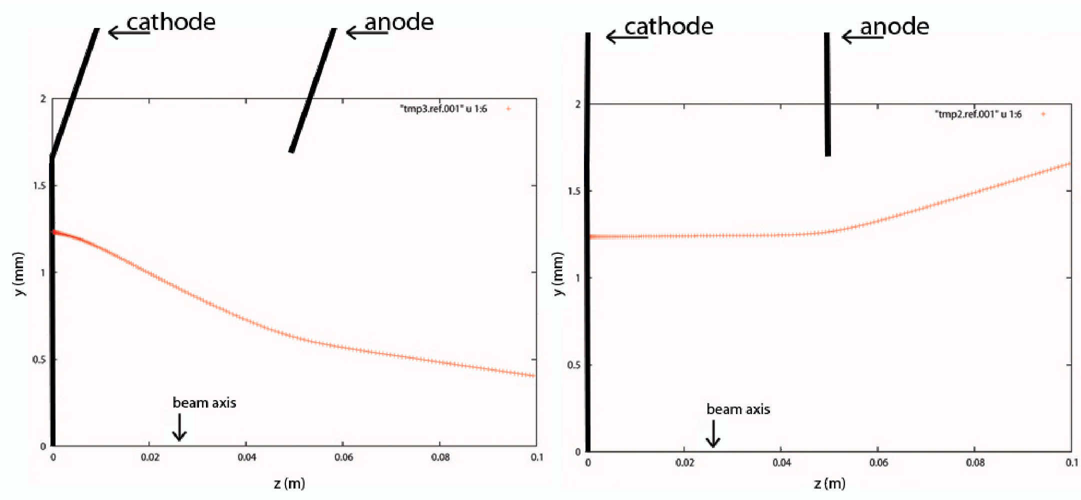

Figure 2: Off axis emission of particle in focused and non-focused gun environment. In the focused case the particle is pushed towards the beam axis in contrast to the non-focused case, where only the defocusing effect is present. (note: Only half of the gun is superimposed on the plot. The gun is axially symmetric around the beam axis.)

emitted off axis (see fig. 2). As can be seen in the case where the gun has a focusing angle the particle is pushed towards the beam axis. Near the anode the trajectory of the particle is not as steep as it once was; this is due to the defocusing effect of the anode. In the case where there is no focusing angle present the particle is only affected by the defocusing effect, which deflects the particle away from the beam axis.

In this research we will determine how the focusing angle affects the emittance of the injector, if it affects emittance at all. This requires field mapping for the major injector elements, and space charge tracking for the 8 meter injector beamline using the code ASTRA [2]. Computationally this is a very tedious process. In order to reduce computation time we shortened the injector beamline from the 9 major elements (1 gun, 2 solenoids, 1 buncher, 5 RF cavities) to just the first two elements, i.e. the gun and the first solenoid. This drastically reduces the length of the beamline. With the solenoid sitting only .3 m from the gun we inserted a 1 m gap immediately after. Final emittances were taken from the end of this gap 1.3 m downstream from the gun.

OPTIMIZATION

Field Maps

The ASTRA code requires field maps for each of the injector elements in order to perform space charge tracking correctly. Field maps for various gun angles (with gun voltage set at 500KV) and the solenoid were produced using POISSON [3], a field mapping finite element analysis-code solver of magneto-electro static problems. The field maps consist of a tabular listing of the

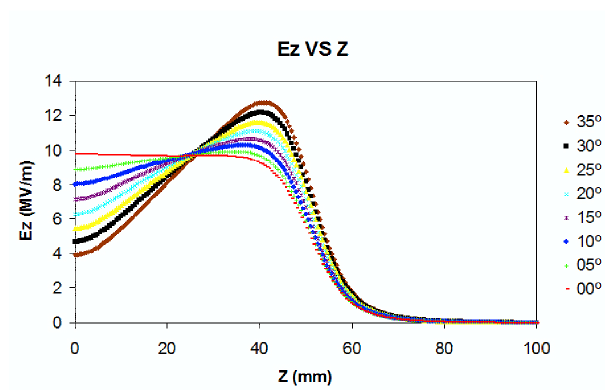

Figure 3: Field plot for angles 0-35°

longitudnal component field strength (Ez) VS. distance (z) along the path that the particle beam travels (in this case the distance along the beam axis). For the gun we produced field maps for seven different gun geometries with angles varying from 0° to 35° in 5° increments In total 7 field maps for the gun were created. (see fig. 3)

POISSON was also used for finding the peak field strength on the cathode. Figure 4 shows how this peak field changes with cathode angle. We used this data to scale the voltage for each angle, so that the peak field at all angles would be equal to the peak field present with the 30° geometry.

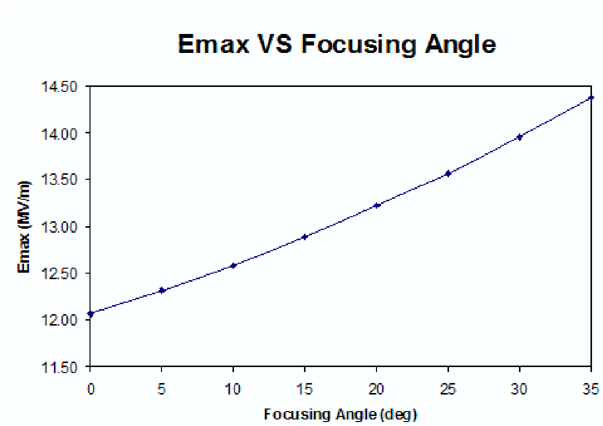

Figure 4: Plot of E_{max} VS focusing angle used for scaling voltages.

Genetic Algorithm

Multi-objective genetic algorithms serve as very useful tool in optimization problems. They have the ability to handle problems with large amounts of variables and many conflicting objectives (for example in this situation minimizing emittance and minimizing gun voltage). In our case we are using parallel computing techniques with a slightly modified version of the genetic optimizer SPEA2 (Strength Pareto Evolutionary Algorithm 2). The genetic algorithm is used to find an optimal set of solutions for our problem which will allow us to see the optimal trade offs between emittance and gun voltage. No point within this optimal set (known as a pareto-optimal set) dominates any other solution, i.e. no solution within the set is better than any other solution. For more information on technicalities and specifics of genetic algorithm the reader is referred to [1, 4].

Problem Setup

As mentioned the beam line that was used in the optimization was shortened dramatically, leaving just the gun and the first solenoid as shown in figure 5. The parameters varied in the optimization include spotsize, solenoid field

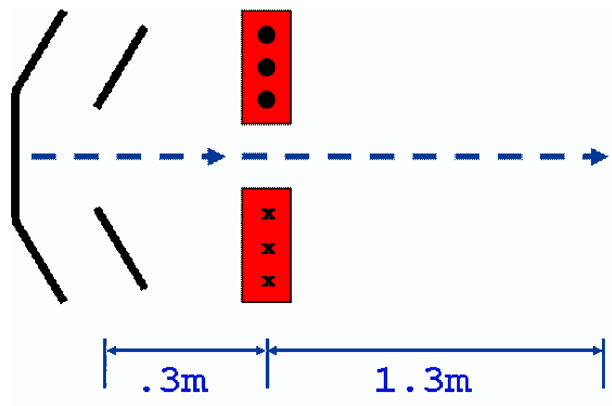

Figure 5: Description of beamline used in optimization

strength, and gun voltage. Throughout all optimizations XYrms (spotsize) was varied between the values of 0 mm and 7 mm. The solenoid field strength was also varied between 0.04 T and 0.15 T for all optimizations. However, the values that the gun voltage was varied between changed depending on the focusing angle of the gun. We always chose the minimum gun voltages as 100 KV less than the scaled voltage found (as mentioned earlier) and the maximum value as 100 KV more than the scaled voltage (see table 1 for variations).

The optimization was done twice for each of the seven angles used. One optimization uses a low charge per bunch (80 pC) and the second uses high charge per bunch (800 pC). The only other parameter that was changed between low and high charge per bunch situations was bunch duration. The low charge per bunch case had a duration of 12 ps rms and the high charge per bunch case used 14 ps rms.

In total there were two initial particle distributions used for the space charge tracking code. Both consist of a uniform “beer can” distribution using 1,000 and 20,000 particles. The 1,000 particle distribution optimization was run first for

Table 1: Margin specifications

Angle (°)	Scaled Voltage (KV)	Min. Voltage (KV)	Max. Voltage (KV)
0	578.6	478.6	678.6
5	566.7	466.7	666.7
10	554.8	454.8	654.8
15	542.0	442.0	642.0
20	528.0	428.0	628.0
25	514.6	414.6	614.6
30	500.0	400.0	600.0
35	485.2	485.2	685.2

the sake of speed to make sure that the optimization would run correctly and we were getting expected results. The results obtained from the 1,000 particle optimization were then used to jumpstart the full optimization using the 20,000 uniform "beer can" particle distribution. The mesh sizes used for each of these distributions is shown in table 2.

Table 2: Mesh sizes used

# of particles	Nrad	Nlong_in
1,000	7	14
20,000	30	63

The objectives we used in our optimizations were set to minimize emittance and minimize gun voltage, so that we may see the trade offs between the two quantities for the different focusing angles.

RESULTS

Here we present our results from our two sets of optimization low and high charge per bunch.

Low Charge Per Bunch

In figure 6 we see our pareto-optimal fronts for our optimizations, showing the trade offs between emittance and gun voltage. It is easy to see from this plot that as the focusing angle becomes stronger emittance becomes better. However, the focusing angle becomes less effective in producing better emittance as the focusing angle becomes large. E.g. we see a large change in emittance when moving from the 0° to 5° focusing angle, but hardly any change at all when shifting from 30° to 35° focusing angles.

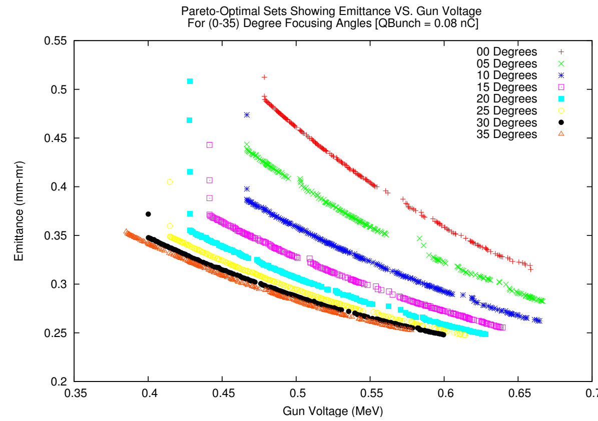

Figure 6: Pareto-optimal fronts for various focusing angles low charge per bunch

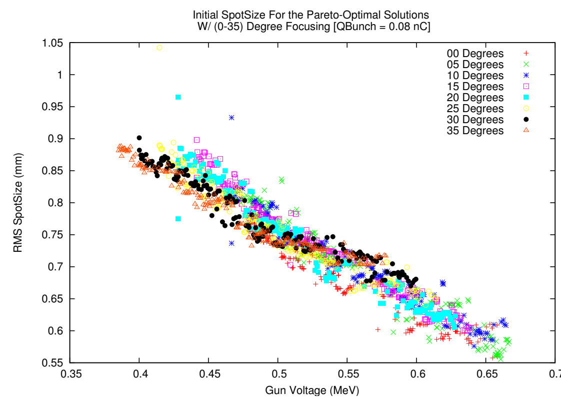

Figure 7: Initial spot sizes for pareto-optimal solutions low charge per bunch

From figures 7-9 the initial spotsizes, solenoid field strengths, and final spotsizes can be seen for the pareto-optimal solutions. It is interesting to note from figure 8 that the solenoid field strength does not depend on the focusing angle of the gun. Also note that there is a trade off in final spotsize with stronger focusing angles. Small focusing angles have a much smaller spotsize than cases where the focusing angle is large.

Using the solutions from the pareto-optimal fronts in figure 6 we looked at an individual solution with a gun voltage of 500 KV from each

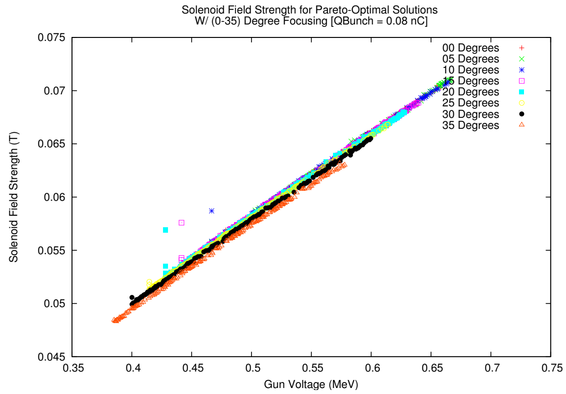

Figure 8: Solenoid field strength for pareto-optimal solutions low charge per bunch

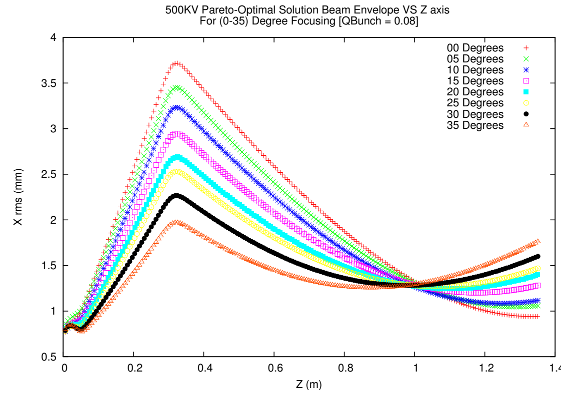

Figure 10: Beam envelope for 500 KV solutions low charge per bunch

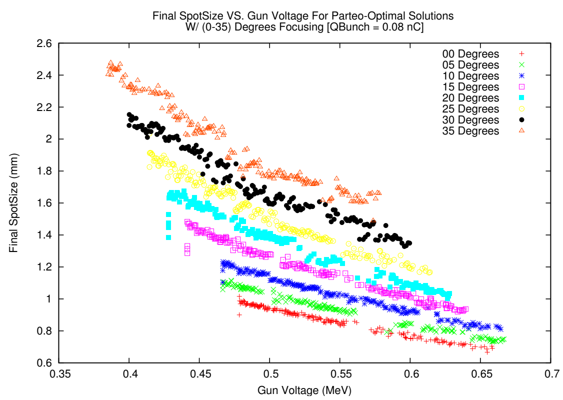

Figure 9: Final spotsize for pareto optimal solutions low charge per bunch

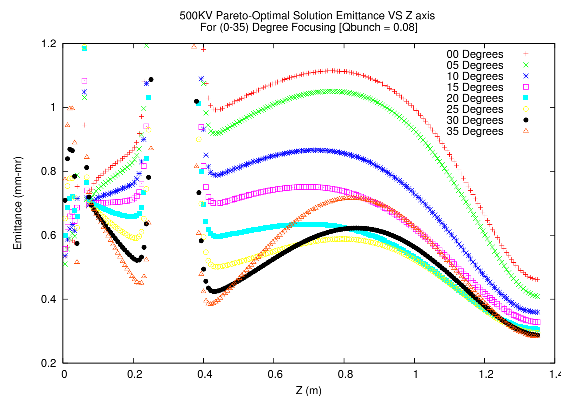

Figure 11: Emittances along beamline for 500 KV solutions low charge per bunch

pareto-optimal front. The specific variables that define the solution at the 500 KV point for each curve (i.e. initial spotsizes and field strengths) were used individually in ASTRA to look at the space charge tracking properties for that particular solution; figures 10 and 11 show the beam envelope, and emittances VS distance along the beamline for each focusing angle.

In Figure **??** we see what we would expect (for the most part) from the emittances. Along the beamline final emittances become better as the focusing angle gets stronger. However, looking prematurely at the beamline, e.g. in the 0.8 m region we see that emittances are worse for very large angles, such as 30° and 35°.

High Charge Per Bunch

The results from the high charge per bunch case, where bunch charge was set to 800 pC, turned out to be quite interesting, and many of the strange things seen in the plots are not well understood. Overall the pareto-optimal fronts for the high charge per bunch case (see fig. 12) obey the same relation as the low charge per bunch case, i.e. as the focusing angle becomes stronger emittance becomes better. This holds true for all curves except the 35° case, which appears to have a worse emittance than both the 25° and 30° cases. This phenomenon is not understood.

Figures 13-15 show the initial spotsizes, solenoid field strengths, and final spotsizes for the pareto-optimal solutions. It is quite strange to see from figure 14 that the 0° focusing angle's solenoid strengths does not match up with

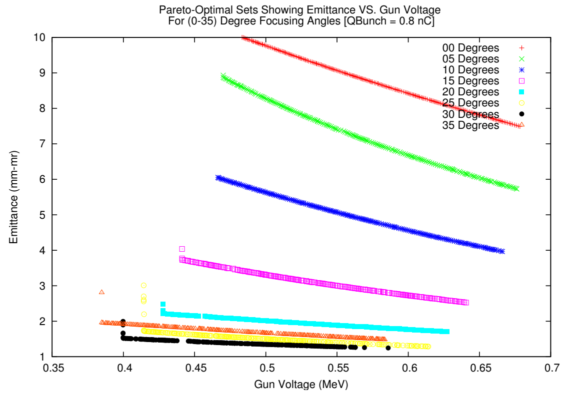

Figure 12: pareto-optimal fronts for various focusing angles high charge per bunch

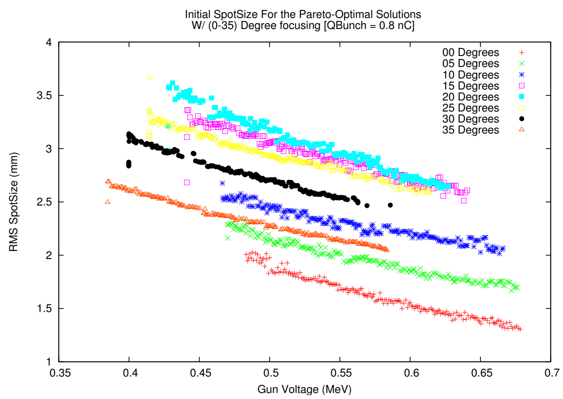

Figure 13: Initial spot sizes for pareto-optimal solutions high charge per bunch

the other angle's values, like we would expect. It can also be argued that the 5° and 10° angles are also off from where we would expect them on the solenoid plot. Also in figure 15 we can see that the final spot size for the 0° focusing case is more than 3 times greater than all other angles.

As with the low bunch charge case we also looked at the 500 KV pareto-optimal solutions for each of the focusing angles in ASTRA. The beam envelope and emittance VS beam axis distance can be seen in figures 16 and 17. From figure 16 it is quite obvious that the solenoid strength is too small for certain angles, since it does not correctly focus the 0°, 5°, 10° cases through the beam waist. The optimization code was checked and double checked for optimization setup faults in the high charge per bunch case, but no problems could be found. So we are

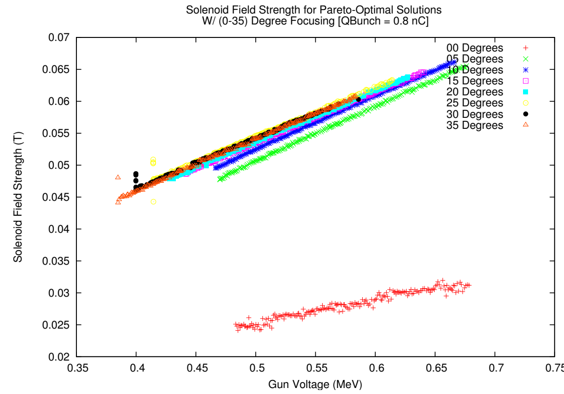

Figure 14: Solenoid field strength for pareto-optimal solutions high charge per bunch

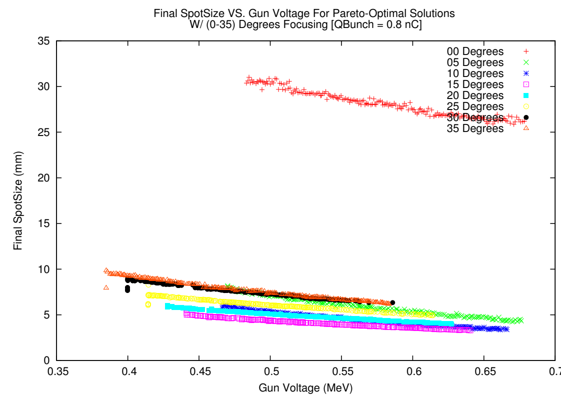

Figure 15: Final spotsize for pareto optimal solutions high charge per bunch

currently uncertain as to why we are seeing funny results in the cases of small focusing angles.

DISCUSSION

Overall our optimizations show the focusing angle present at the guns cathode electrode does play a significant role in determining the final emittance along the beamline; The greater the focusing the better the emittance. Also data shows that solenoid strength seems to be focusing independent, excluding the seemingly faulty data output from small focusing in the high bunch charge case. In the end the focusing angle used in the previous optimization of the ERL injector [1] may not be exactly optimal, but we can conclude that the 25° focusing angle is not far off from being optimal

In regards to the problems faced in the high

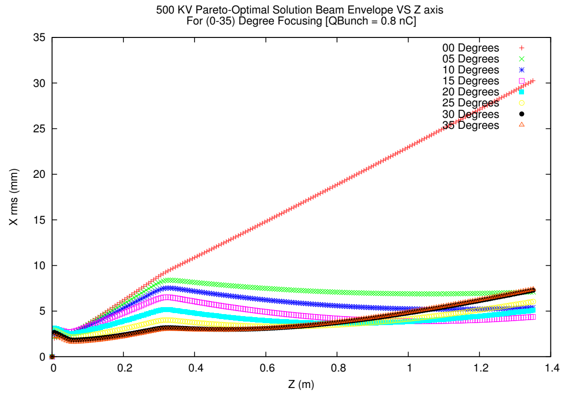

Figure 16: Beam envelope for 500 KV solutions high charge per bunch

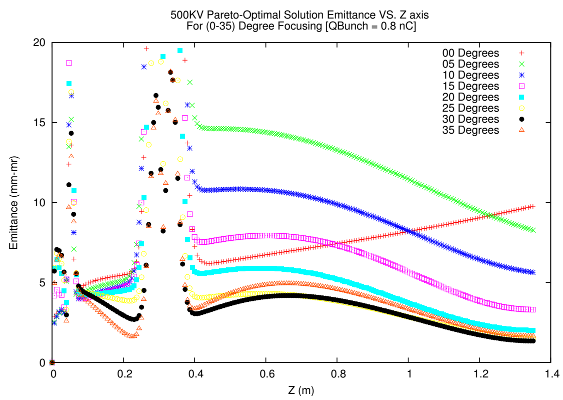

Figure 17: Emittances along beamline for 500 KV solutions high charge per bunch

charge per bunch, small focusing case, we are sure that the ERL injector gun will be built to have some sort of focusing much greater than 0° and therefore the situation encountered in the simulations will not be relevant.

ACKNOWLEDGMENTS

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