COMPUTATIONAL STUDIES OF THE ELECTRON INJECTOR FOR THE ERL AND COMPARISON BETWEEN OPTIMIZED PERFORMANCES OF DC AND RF GUN BASED INJECTORS

Bijoyananda Adhikary
Department of Physics, Wayne State University, Detroit, MI, 48202

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A DC gun based injector having one buncher and five SRF cavities and two solenoids was studied with fixed settings for various bunch charges. The charge was varied from 1.2 to 77pC in a geometric fashion. Total number of macro particles in the initial particle distribution was 10000. Then a comparison between DC and RF gun based injectors was made. The DC gun based injector was studied having 50000 macro particles. The number of macro particles used for the RF gun based injector was 25000. Two quadrupoles were used in addition to the solenoids in the RF gun based injector. The bunch charge for the DC gun based injector was specified to be .8 nC while for the RF gun based injector it was 1 nC. The simulations were done using a program called ASTRA which tracks particles including the effects of space charge through the injector.

I. INTRODUCTION

The production of high energy, coherent X-rays is desirable by experimental physicists. The proposed injector for Cornell's Energy Recovery Linac is expected to provide low emittance and bright beam for that purpose. We have a choice between the kinds of gun we would use in the ERL. The gun delivers a bunched electron beam for subsequent acceleration. Comparisons were made between DC and RF gun. A DC gun has a cathode from which electrons are emitted when it is hit by laser pulses and then accelerated because of a DC field. In a RF gun the electrons are emitted the same way, but when they leave the cathode they see a RF accelerating field rather than seeing a DC field. When describing beam qualities the term emittance is a very descriptive word that can tell us about the quality of the beam. Emittance is closely related to the product of the spot size and the divergence angle and it is equal to the area of the ellipse that encompasses a bunch going through the six-dimensional phase space. The phase space vector has six components to it.

$$r = (x, y, z, p_x, p_y, p_z) \tag{1}$$

But working with a six dimensional co-ordinate system can be avoided if we can split that in three two dimensional systems and still can predict beam behavior with desirable accuracy. The evolution of the beam in the three two dimensional phase space are not completely independent of each other but assuming them to be decoupled gives us good approximations. So we can express the coordinates of a point in phase space as:

$$r_x = (x, p_x), \qquad r_y = (y, p_y), \qquad r_z = (z, p_z) \tag{2}$$

But in the transverse case we can further simplify the problem by taking the angle that the momentum vectors make with the $x - z$ plane in case of x-emittance and the $y - z$ plane in case of y-emittance. If we denote these angles by x' and y' then the coordinates can be expressed as:

$$r_x = (x, x'), \qquad r_y = (y, y'), \qquad r_z = (z, z') \tag{3}$$

Then the emittance can be expressed (in case of x) as:

$$\epsilon_{rms} = \sqrt{< x^2 >< x'^2 > - < xx' >^2} \tag{4}$$

When a bunch is accelerated its transverse momentum doesn't change while the longitudinal momentum increases. Thus transverse angles decrease in value resulting in a decreased total emittance. To take this effect into account we use an expression called *normalized emittance* and can be expressed as:

$$\epsilon_{norm,x} = \gamma\beta\epsilon_x \tag{5}$$

Adding to this, when we have ultra-relativistic electron beam, magnetic forces induced by the moving electrons in the beam can counteract the defocusing of space charge.

But in an injector the velocity is not great enough to cause equilibrium between space charge defocusing and intrinsic magnetic focusing of the beam.

This is why we have to use the computer program ASTRA which stands for “A Space Charge Tracking Algorithm”. This program allows us to run many simulations varying a wide range of parameters such as spot size and initial thermal emittance, bunch charge, solenoid field strengths, cavity field strengths and angles. Also the initial particle distribution at the cathode can be varied through this program. Variation of parameters in a multidimensional parameter space to achieve desirable emittance was done by Peter Battaglino last year. The bunch charge in the optimized version of the DC gun based injector was varied to address beam turn on process. In addition to that,the inside of the beam pipe is not a perfect vacuum, as a result the electron beam knocks off electrons of the atoms of the residual gas creating positive ions. Those positive ions then get attracted towards the negatively charge electron beam, creating the possibility of beam defocusing. This problem can be addressed by having gaps in the beam flow by turning off the beam for a few moments so that the ions see only each other rather than the electrons and repel away from each other. For that we need to have current settings in a way such that we can afford the turning on and off capability of injector while gradually incrementing current. For that we need to know the qualitative and quantitative characteristics of the beam as we vary the charge from small value to our desirable amount. Also a comparison can be done between already existing optimized designs of RF gun based injectors and DC gun based injectors.

II. VARYING THE BUNCH CHARGES

Incrementing the current gradually can be done by increasing the frequency of the laser pulses or by increasing the amplitude. But it's not very convenient to increase the frequency of the laser pulses. Also increasing the frequency induces a chance of matching the resonant frequency of the higher order modes of the SRF cavities. But it's fairly easy to increase the amplitude of the pulses and it doesn't create additional problems. Charge per bunch increases as the amplitude is increased. That is why the charge was varied to see whether we can have a beam if we start from a low charge and work our way up gradually.

TABLE I: Parameters of the cavities are given below

	Rf field frequency in GHz	Rf field amplitude in MV/m	Rf field phase in degrees	Cavity position m
Gun	0	-10	0	0
Buncher	1.3	2.875	-91	.86
Cavity 1	1.3	13.5	-5	1.79
Cavity 2	1.3	25.25	-1	2.626
Cavity 3	1.3	25.25	-1	3.302
Cavity 4	1.3	25.25	-1	4.138
Cavity 5	1.3	25.25	-1	4.814

A spot size of 2mm was used to generate bunches having an initial emittance of .2617μm. A uniform longitudinal and a radial transverse particle distribution were used.

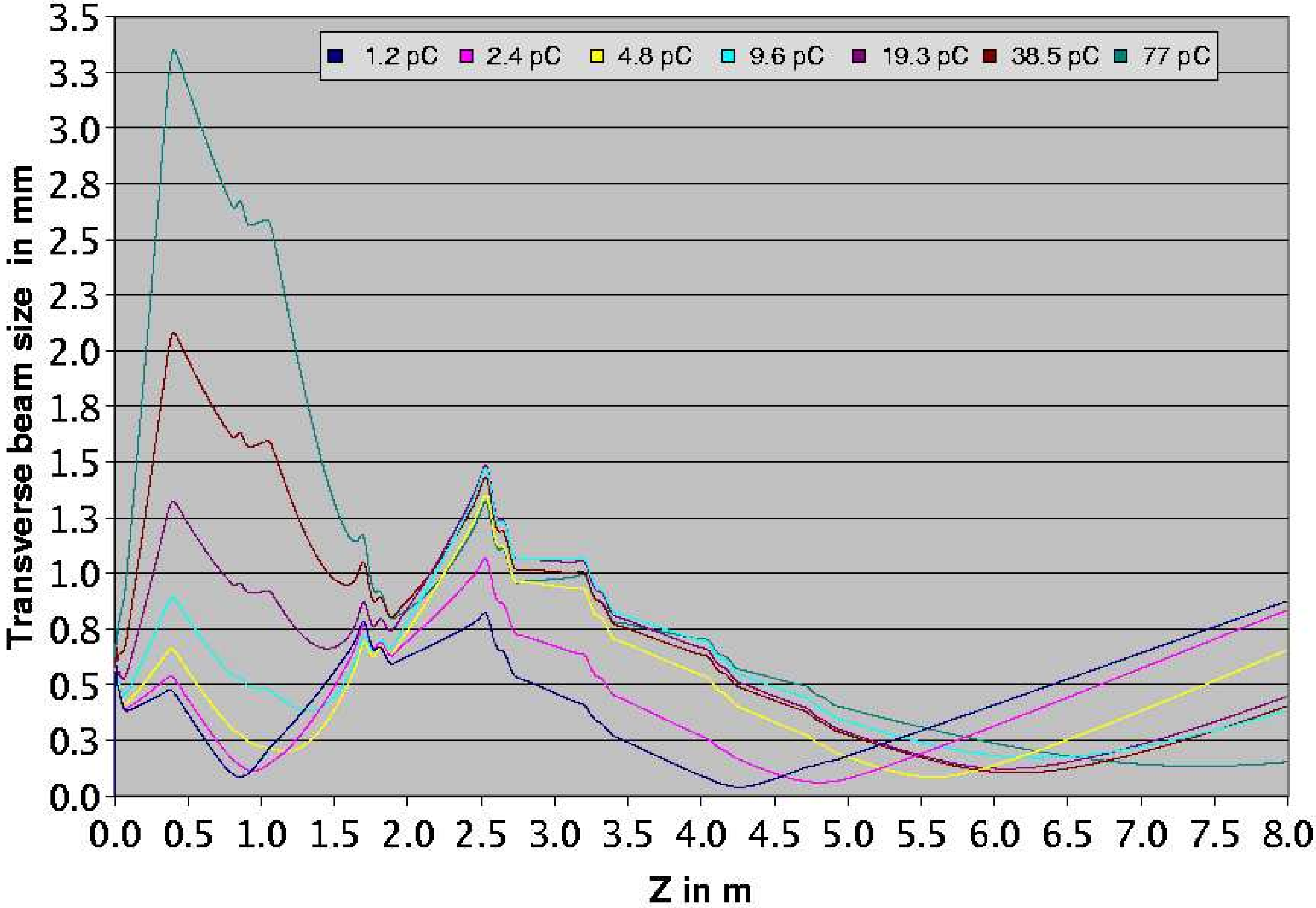

FIG. 1: Change in transverse beam size as the charge per bunch is varied

Transverse momentum distributions in the horizontal and vertical directions for the initial

TABLE II: Parameters of the solenoids are given below

	Maximum field value of the solenoid field in T	Solenoid position in m
Solenoid 1	0.0583	0.39
Solenoid 2	0.0417	1.06

particle distribution were uniform. Also a uniform longitudinal energy and momentum distribution for the initial particle distribution was used.

In figure 1 we can see the change in the evolution of the transverse beam size as it goes through the whole length of the injector as the charge is varied from 1.2pC to 77pC in a geometric fashion.

In figure 1 the transverse beam size tends to fluctuate a lot but in the end of the injector the size tend to be well below 1 mm which is tolerable. The length of the injector was 8.00 meters.

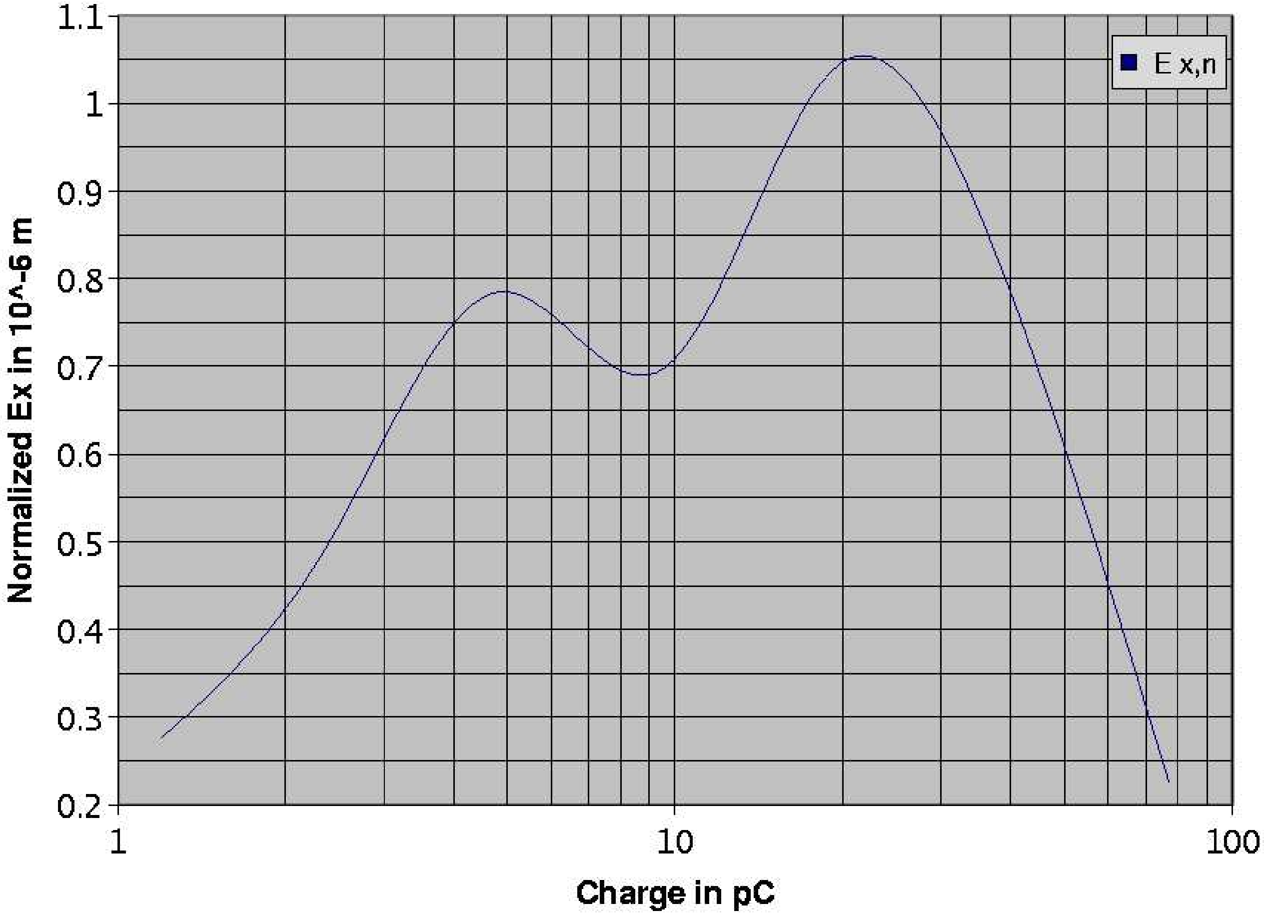

FIG. 2: Change in emittance as the charge per bunch is varied on a log scale

In fig 2 the emittance fluctuates, but the fluctuation is not enough to cause trouble. And in fig 3 the β function is plotted against the charge. The electrons in the bunches see each other and the coulomb repulsion tends to spread them out in six dimensional phase space.

This is known as space charge. At the same time the solenoids provide focusing just to counteract that effect. The β function gives us a measure of that balance. When the bunch charge is lowered and the solenoid strength is kept the same, the beta function tend to rise as it is expressed as:

$$\beta_x = \frac{(x_{rms})^2}{\epsilon_x} \tag{6}$$

And

$$\epsilon_x = \frac{\epsilon_{n,x}}{\beta\gamma} \tag{7}$$

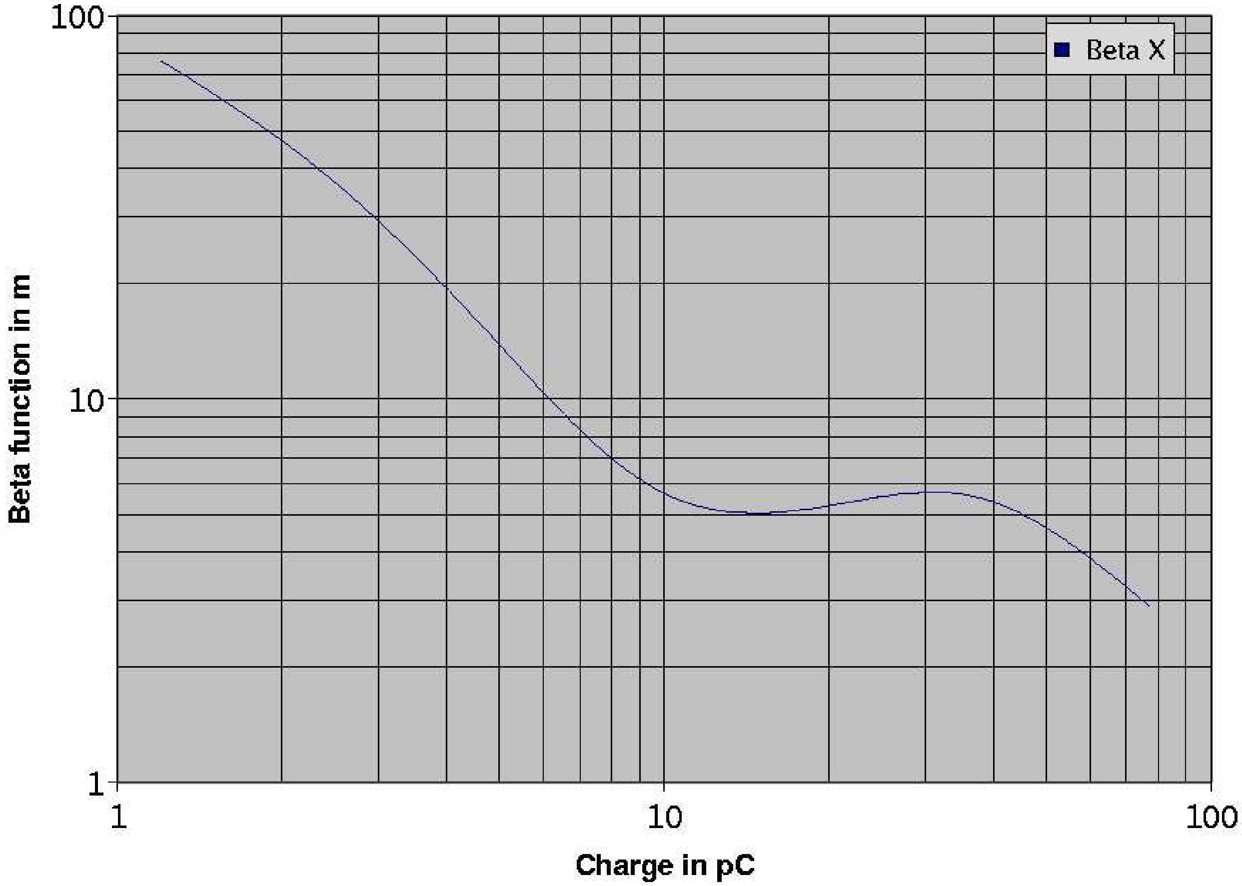

FIG. 3: Change in β function as the charge per bunch is varied on a log scale

III. COMPARISON BETWEEN DC AND RF GUN BASED INJECTORS

An injector having a DC gun, a buncher and five SRF cavities was compared with an injector having a RF gun and six SRF cavities. The length of the DC gun based injector was 7.66 m while for the RF gun based one it was 18.7m. The bunch charge was .8 nC for the DC gun based injector and 1 nC for the RF gun based injector.

TABLE III: Parameters of the cavities for the DC gun based injector are given below

	Rf field frequency in GHz	Rf field amplitude in MV/m	Rf field phase in degrees	Cavity position m
Gun	0	-9.75	0	0
Buncher	1.3	5.275	-91	.825
Cavity 1	1.3	12.75	-25.625	1.46
Cavity 2	1.3	22	-13.4375	2.296
Cavity 3	1.3	22	-13.4375	2.972
Cavity 4	1.3	22	-13.4375	3.808
Cavity 5	1.3	22	-13.4375	4.484

TABLE IV: Parameters of the solenoids for the DC gun based injector are given below

	Maximum field value of the solenoid field in T	Solenoid position in m
Solenoid 1	0.053125	0.46
Solenoid 2	0.046875	1.025

A spot size of 10.35 mm was used to generate bunches having initial emittance of 1.354μm. A uniform longitudinal and a radial transverse initial particle distribution for the DC gun based injector was used. Transverse momentum distributions in the horizontal and vertical directions for the initial particle distribution were uniform. Also a uniform longitudinal energy and momentum distribution for the initial particle distribution was used.

TABLE V: Parameters of the cavities for the RF gun based injector are given below

	Rf field frequency in GHz	Rf field amplitude in MV/m	Rf filed phase in degrees	Cavity position m
Gun	1.3	40	-2.773	0
Cavity 1	1.3	38.124	-62.123	3.00
Cavity 2	1.3	38.124	40.523	4.385
Cavity 3	1.3	38.124	-62.123	5.770
Cavity 4	1.3	38.124	40.523	7.155
Cavity 5	1.3	38.124	-10.80	8.54
Cavity 6	3.9	22.50	-183	16.325

TABLE VI: Parameters of the solenoid for the RF gun based injector are given below

	Maximum field value of the solenoid field in T	Solenoid position in m
Solenoid 1	0.163	0.0

TABLE VII: Parameters of the quadrupoles for the RF gun based injector are given below

	Focusing strength of the quadrupole in $(m)^{-2}$	Effective length of the quadrupole in m	Quadrupole position in m
Quadrupole 1	0	0.15	13.667
Quadrupole2	-0	0.15	13.667

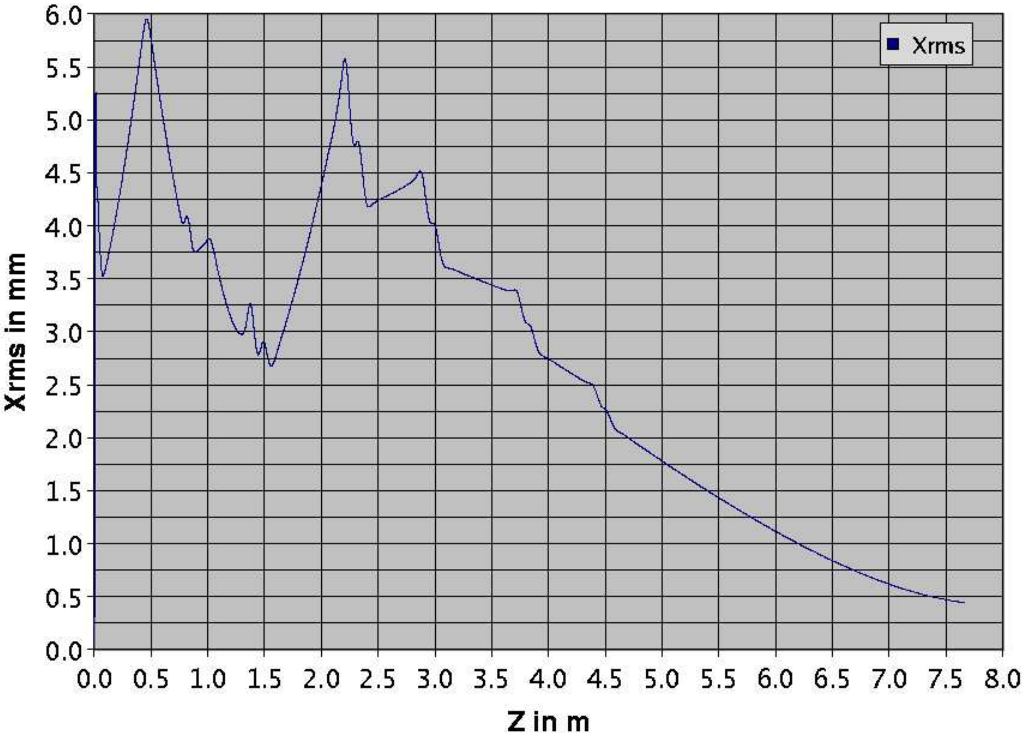

FIG. 4: Evolution of transverse beam size in the DC gun based injector

In case of the RF gun a spot size of 1.5 mm was used to generate bunches having initial emittance of .6352μm. A plateau longitudinal and a radially uniform transverse particle distribution were used. Transverse momentum distributions in the horizontal and vertical directions for the initial particle distribution were radially uniform. Also a plateau longitudinal energy and momentum distribution for the initial particle distribution was used.

In figure 4 and 5 we can see the difference in evolution of the transverse size of the beam. The fluctuations are different but in the end of the injector they seem to reach a desirable value.

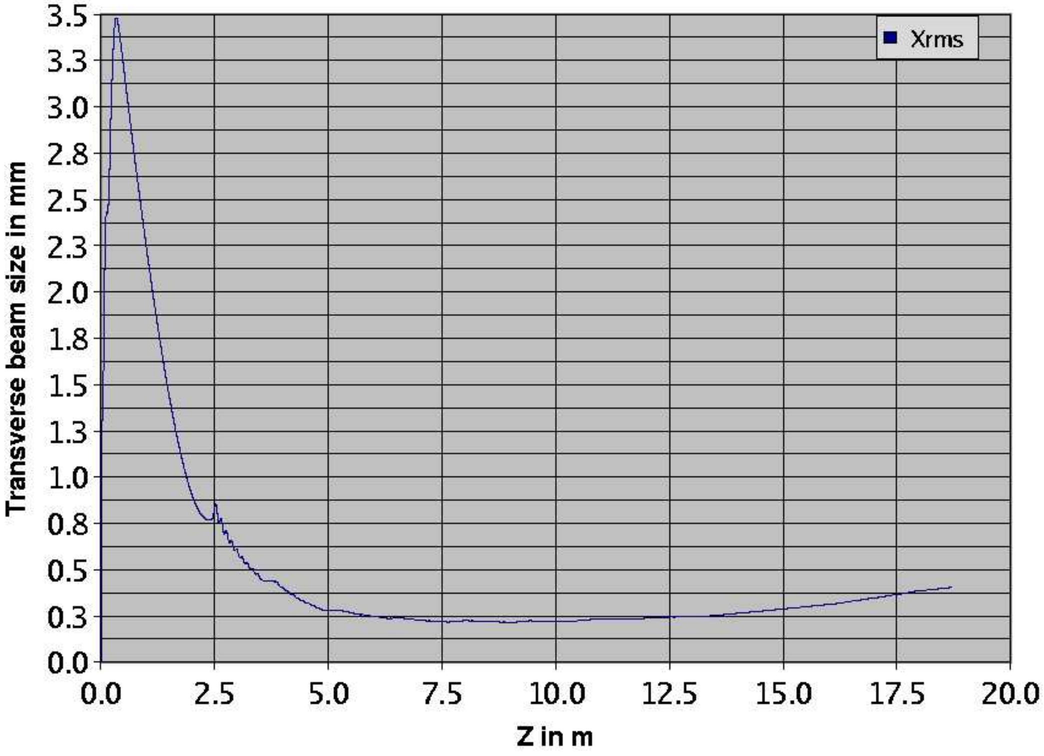

FIG. 5: Evolution of transverse beam size in the RF gun based injector

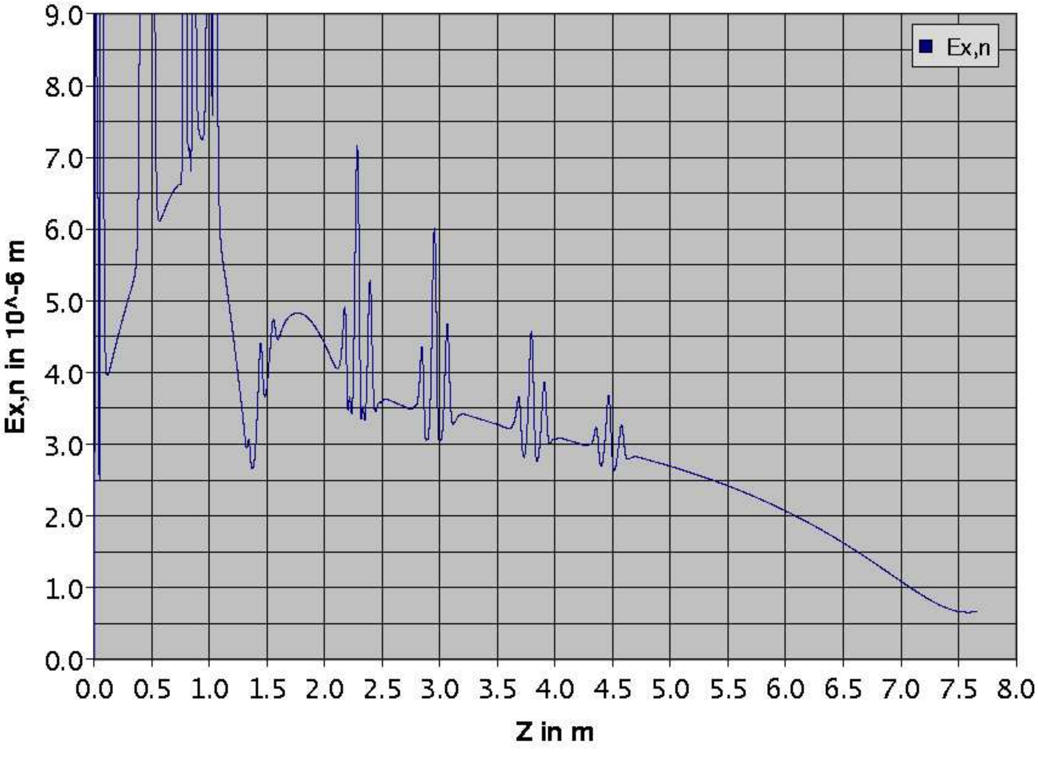

FIG. 6: Evolution of normalized emittance in the DC gun based injector

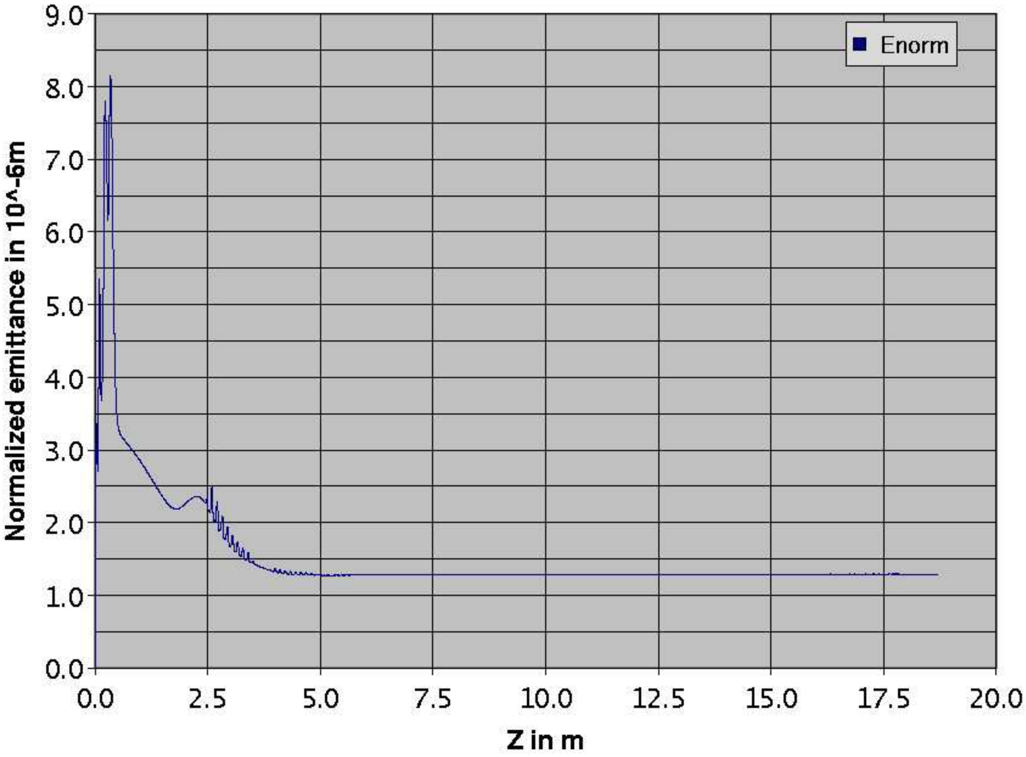

FIG. 7: Evolution of normalized emittance in the RF gun based injector

In figure 6 and 7 the emittances for both guns decrease to points which are close to each other vertically. After some length into the injector the stability of the emittance versus distant function indicates the beam traveling very close to the speed of light therefore the space charge force is cancelled by the intrinsic magnetic force of the traveling beam.

IV. RESULTS

When the charge was varied the normalized emittance stayed within 1.04μm, transverse beam size stayed within 1 mm and bunch length decreased. As for the β function it started to rise sharply after when the charge was lowered below 9.6 pC, but before that the increment wasn't big enough to cause problem.

The results of the comparison between DC and Rf gun based injectors are given below.

TABLE VIII: Results of the comparison are given below

	Normalized emittance in μm	**Transverse beam size in mm**	**Bunch length in mm**	**Kinetic energy in MeV**
RF gun based injector	1.285	.404	1.885	124.4
DC gun based injector	1.615	.445	.898	11.65

V. CONCLUSIONS

When charge was varied we saw that the parameters stay within a reasonable limit. In case of the β function, it does go a little out of hand, but it's tolerable. Or we can start gradual increment of the power from where the function starts to rise sharply.

Compared to the DC gun based injector RF gun based one has a better emittance and transverse beam size. As for bunch length the DC gun based injector has a better value. But since we already have a better value of emittance and transverse beam size for the RF gun based injector, we can vary the buncher cavity to come up with even better bunch length. In case of the energy RF gun has a better energy. But it's a parameter that can be manipulated to achieve a desirable value when enough power is used.

Also increasing the voltage allows us to have a smaller spot size therefore smaller thermal emittance which is an important contributor to the final emittance.

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[] Klaus Floettmann, *Users' Manual For Astra(A Spacecharge Tracking Algorithm)*; see: *http//www.desy.de/~mpyflo/Astra_dokumentation/manual_part1.pdf*