Lee Teng Internship

July 25, 2008

Design Optimization of a High-Intensity SC Ion Linac Injector

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ABSTRACT: An ion injector is a critical part of a high-intensity super conducting linear accelerator. This paper covers the concepts as well as the studies done to explore and optimize an ion injector for implementation in a future ion accelerator. The focus is to design and optimize a RFQ to be used in the injector and further compare and optimize the design with and without a MHB (Multi Harmonic Buncher) to achieve the highest quality and intensity beam. The design and optimization procedure for the RFQ was performed using the design codes PARMTEQ and DESRFQ, while using the beam dynamics code TRACK to simulate and further optimize the injector and the linac.

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1. Brief Description of the Project

An ion injector is a critical part of a high-intensity super-conducting linear accelerator (linac). Usually, such an injector consists of an ion source, a low-energy beam transport (LEBT), a radio frequency quadrupole (RFQ) and a medium-energy transport (MEBT). While it is not always required, a component called multi-harmonic buncher (MHB) could be inserted in front of the RFQ to perform preliminary bunching of the beam. This could significantly reduce the longitudinal emittance of the beam but with an efficiency of about 80%. The purpose of this project is to use the RFQ design codes PARMTEQ and DESRFQ along with the particle tracking code TRACK in order to study the effect of the different design parameters on the beam. The goal is to develop an optimized injector design with and without a MHB in order to decide on the best performing option for implementation.

2. Introduction to the RFQ

The most important and most critical part of a linac injector is the RFQ. The function of the RFQ is multipurpose; the RFQ uses quadropole electric fields to focus the particles in the transverse direction. The use of an electric field rather then the more common quadropole magnetic field that are seen in practically all accelerating structure is due the very low velocity of the ion beam (traveling at a small fraction of the speed of light). The force generated on the particles by an electric field unlike that of a magnetic field does not depend on the particles velocity and thus with low energy particles, the force seen by an electric field is greater then that due to a magnetic field.

The RFQ has also the ability to accelerate particles by using an RF voltage gradient generated by modulations (surface variations) in the four vanes or rods that make up the RFQ's quadropole feature. A RF voltage is applied to the RFQ vanes and these modulations will allow for some acceleration, the greater the modulation in the RFQ's vanes/rods the more accelerating voltage the particles will see. The RF feature of the RFQ allows for the particles to receive a varying amount of acceleration with respect to a reference charge in the "middle" of the particle bunch with the slower particles receiving a larger acceleration and the faster receiving less, the end effect is bunching in the longitudinal direction as the bunch accelerates. The RFQ is usually sub-divided into the following sections with the gentle buncher portion of the RFQ being the majority of the RFQ's length.

Input radial matcher,
Prebuncher,

Gentle buncher,
Full acceleration region,
&
Output radial matcher.

The input radial matcher is to match the beam size to the main portion of the RFQ while the output radial matcher should match the beam to the MEBT and the linac. The prebuncher and gentle buncher accelerate the beam bunches slowly with the main focus being bunching the beam longitudinally and focusing it transversely to minimize the beam emittances in all planes. The short full acceleration region brings the well bunched beam up the correct input energy for the MEBT.

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3. RFQ Design and Optimization: Study of Parameters Effects

Before using, the design codes PARMTEQ and DESRFQ to design a RFQ for use in the injector, it was important to become familiar with how a RFQ works and the parameters used in its design. A deal of time was spent becoming more familiar with the design codes listed above and how to take advantage of each code in providing the optimal results with some set of parameters. The process that seemed to yield the best overall results will be the focus of the further explanation.

In the process of understanding how to use the two RFQ design codes PARMTEQ and DESRFQ, I attempted to create a similar quality design as the final FNAL Proton Driver by using both codes in conjunction with the RFQ's published parameters.

	Parameter	Value
1	Input Energy, keV	50
2	Output Energy, MeV	2.5
3	Accelerated beam current, mA	40
4	Peak surface field, kV/cm	≤330
5	Total length of the vanes, m	~3
6	Acceleration efficiency, %	>95
7	Input rms transverse emittance, normalized, π mm mrad	0.25
8	Transverse rms emittance growth factor	<1.1
9	Longitudinal rms emittance, π keV·deg	≤150
10	Axial-symmetric output beam	yes

Table 1. Initial specifications for the RFQ design.

3.1 PARMTEQ Study

Knowing the desired initial parameters such as the beam energy and current, the aperture size and frequency of the RFQ it is possible to go through the steps of the PARMTEQ code and trying to get the optimum results in the transmission of the beam while staying within these set parameters including a certain length restriction on the RFQ. If the general parameters are fixed with the RFQ the main changes that can be made to create a better performing RFQ (at least in simulation) is to edit both the acceleration efficiency and the beam energy at end of the gentle buncher while of course keeping the length of the RFQ within the acceptable limits.

- While mocking the FNAL-PD RFQ design, an optimum was found at an acceleration efficiency near 0.41 and beam energy at the end of the gentle buncher of about 0.48 MeV.

In addition, it is possible to change the modulation start point and the size of the modulation increase steps to control the beams acceleration and bunching further. Overall, with these changes it is possible to get over 90% transmission in the PARMTEQ code where then we can look at the Parmteq and Pari outputs and use its beam parameters of beta (relative velocity), modulation, and phase to further optimize the design in the DESRFQ design code. One thing important to note is that PARMTEQ will change your aperture to another value than the one you entered. This change in aperture size (R_0) seems to have no consistency so step-by-step variation was needed to get to the desired value.

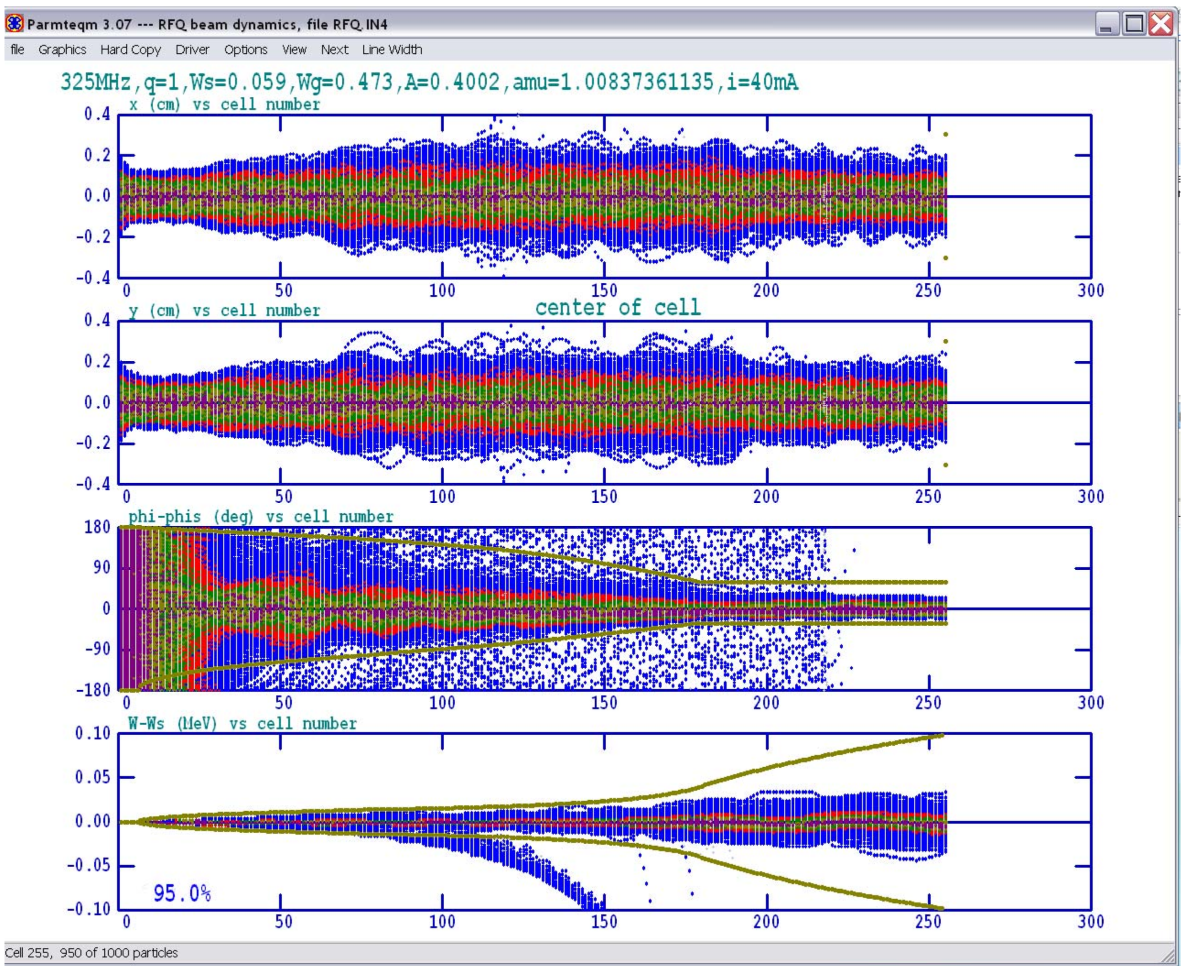


Figure 1: A Parmteq output showing FNAL Proton Driver RFQ recreation, this will then be put into the DESRFQ design code for further optimization.

3.2 DESRFQ Study

From the PARMTEQ the user will make an input file for the DESRFQ code that is in the following structure:

First line: # of cells in RFQ Aperture Size (cm) Vane Voltage (MeV)

Rest of lines: Beta Value (fraction of c) modulation Phase

This file will be loaded when user selects the user-defined option for the gentle puncher of the RFQ. The first page of initial parameters can either be filled out to be fed into the program as well as a file, this can be done simply by saving your values after the first time you input them, making multiple tests easier. Once these steps are done, the optimization inside DESRFQ takes place in the Gentle Buncher settings where the user can adjust the modulation and phase parameters of the RFQ to create a smooth phase variation along the RFQ. As well as choosing modulations that allows for good bunching and fast enough acceleration such that the RFQ need not be too long to reach the specified output energy. In the attempts made at optimization, comparing to the final FNAL-PD I found that a smooth modulation and phase change is the best option. With phase I found the best results when the seperatrix phase width is kept near or higher then the bunch phase width on its way to an end phase of -30 degrees. However, the phase may need to undergo some “oscillations” to help ensure that particles in the bunch are kept within the boundaries of the seperatrix to avoid beam loss but at the same time have an overall phase variation move smoothly towards the -30 degree output value. The modulation is best to start near one and only increase slowly in order to bunch the beam nicely and near the end of the RFQ should the modulation increase quickly in the final part of the RFQ intended for full acceleration.

Once this is done, it is possible to run the Profile Generation for the RFQ and save an output file for the TRACK code. In Track, it is important to edit the track.dat and sclinac.dat files to set the input parameters such that it matches the RFQ you are testing. The twiss parameters can be taken from PARMTEQ or DESRFQ outputs for the RFQ. The twiss parameters describe the beam size and shape and the values matching the beam to the entrance of the RFQ must be entered into TRACK to get a simulation with acceptable and realistic results. Figure 2 shows the beam in the (x,x') transverse phase space with the parameters defined by the beam ellipse.

Plots of the tracking of multiple attempts in the optimization can be seen below, as you can note when compared to the labeled finished FNAL-PD transmission you see that the optimization I have done closely matches the quality of transmission and the transverse emittance as the FNAL-PD has without looking at its settings until after the optimization was complete.

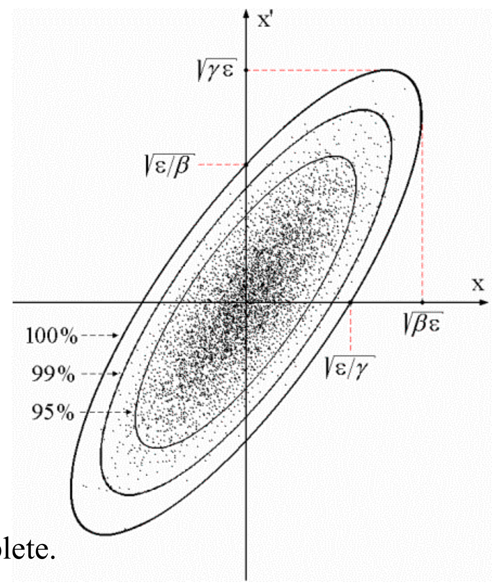


Figure 2

3.3 TRACK Study

In the TRACK beam dynamics code it is possible to study how the particles will act inside the RFQ that was constructed with the design codes described above. TRACK is initially used to find the best optimized RFQ from all the constructed RFQ files with slight variations. For the FNAL Proton Driver, multiple tests were performed and compared to original TRACK results, where the best result will have the most desirable combination of a low beam emittance and minimal particle loss. Figures 3 and 4 below show the TRACK code simulation of both cases in order to compare the two. The image shows beam ellipses in all three phase spaces, parameters on the top right, and the two plots show transverse emittance (x and y direction, rms and peak) and the phase advance.

Figure 3: Original FNAL PD-Linac TRACK results that tests were compared

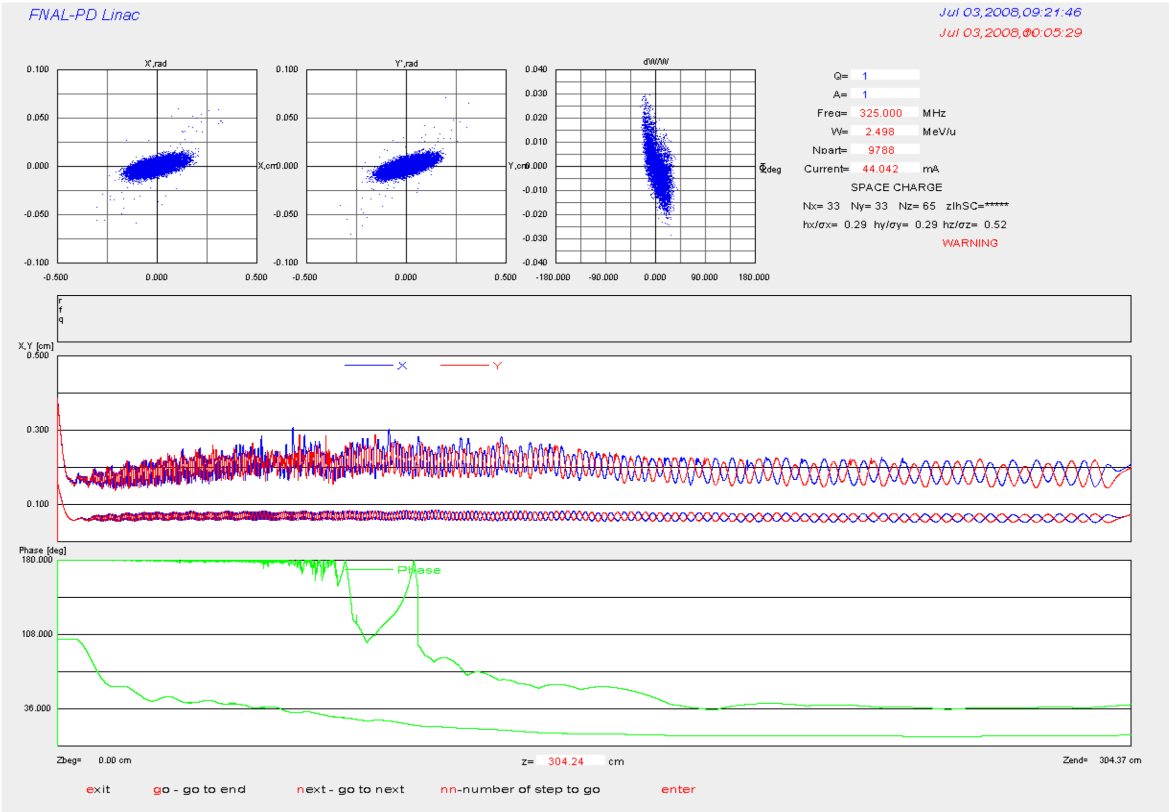
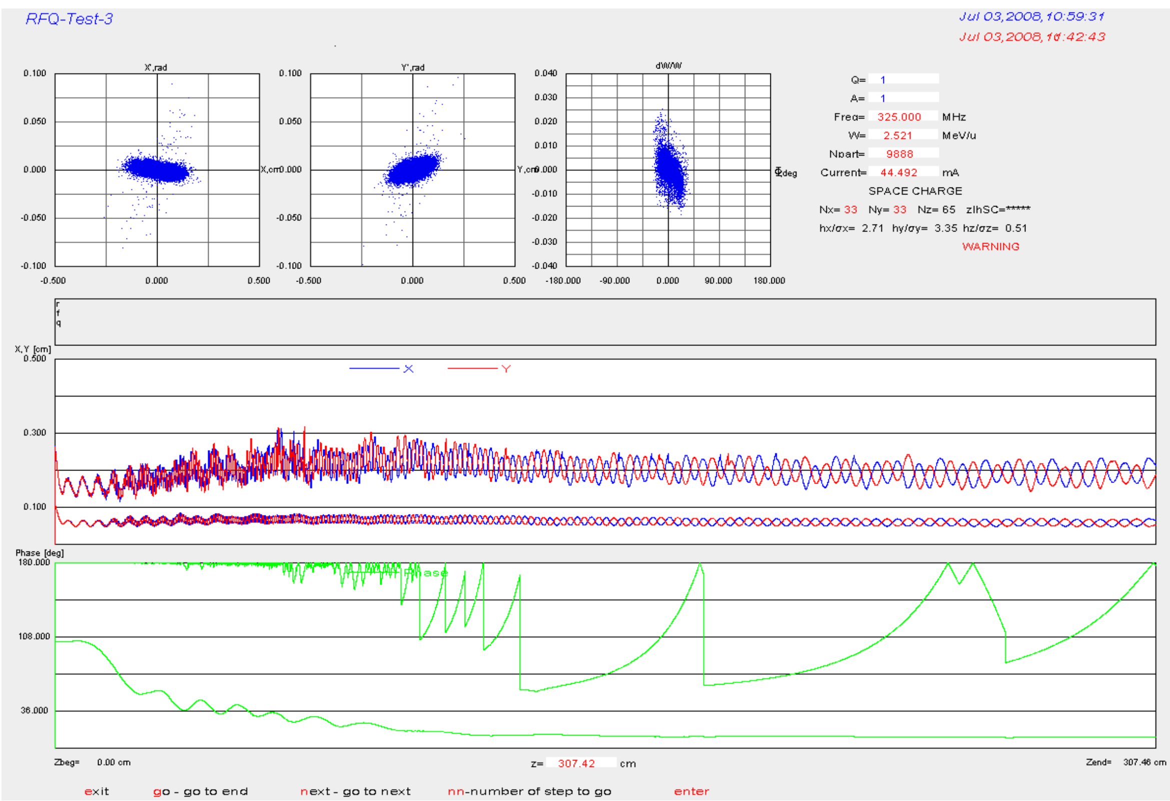


Figure 4: Shows the final RFQ design intended to closely match the quality seen in the original FNAL-PD Linac. It is slightly longer in length but also shows better transmission and comparable transverse emittance.



In TRACK it is also possible to implement a number of things to compare possible designs for an RFQ or entire injector; such things include adding a filter at the end to the RFQ or component tested to see how well bunched the packet is in the longitudinal direction. This ability and many others in TRACK were essential in the high-intensity ion linac study.

4. Ion Linac Studies and Optimization

The understanding of the RFQ design codes and the beam dynamics code TRACK gained by reproducing the RFQ design for the FNAL proton driver provides a solid foundation to finally explore, optimize, and compare possible design options for a high-intensity SC ion linac injector. The two studied cases are with and without a bunching component that is placed before the RFQ, this component known as Multi Harmonic Buncher (MHB) reduces the longitudinal emittance substantially but at the cost of losing about 20% of the beam. The question is a design without a MHB able to provide more beam intensity with acceptable emittance or is a design with a MHB the best option?

	Parameter	Value
1	Input Energy	14 keV/u
2	Output Energy	300 keV/u
3	Vane Voltage	87 kV
4	RF Frequency	57.5 MHz
5	Reference Charge	33.5
6	Actual Charge States	33, 34
7	Reference Particle Mass	238
8	Beam Current	0.4 - 0.5 mA
9	Aperture Radius	0.6 cm

Table 2: Shows basic design parameters for the Ion Linac (AEBL) RFQ.

The possibility of an injector design without the use of a Multi Harmonic Buncher component has the capability with good design to provide a larger beam intensity injecting into the linac. However, due to the greatly larger longitudinal emittance the possible beam loss in the linac could exceed the 20% beam loss seen when applying the MHB. The optimization process applied to this design without the MHB is to test and see if it is possible to retain enough of the beam intensity in the linac to make this design a possibility for implementation. The initial design of the injector RFQ was made using the design codes DESRFQ, by varying the parameters of modulation and the synchronous phase of the RFQ and then running a TRACK simulation with DESRFQ's output it is possible to select an optimum design.

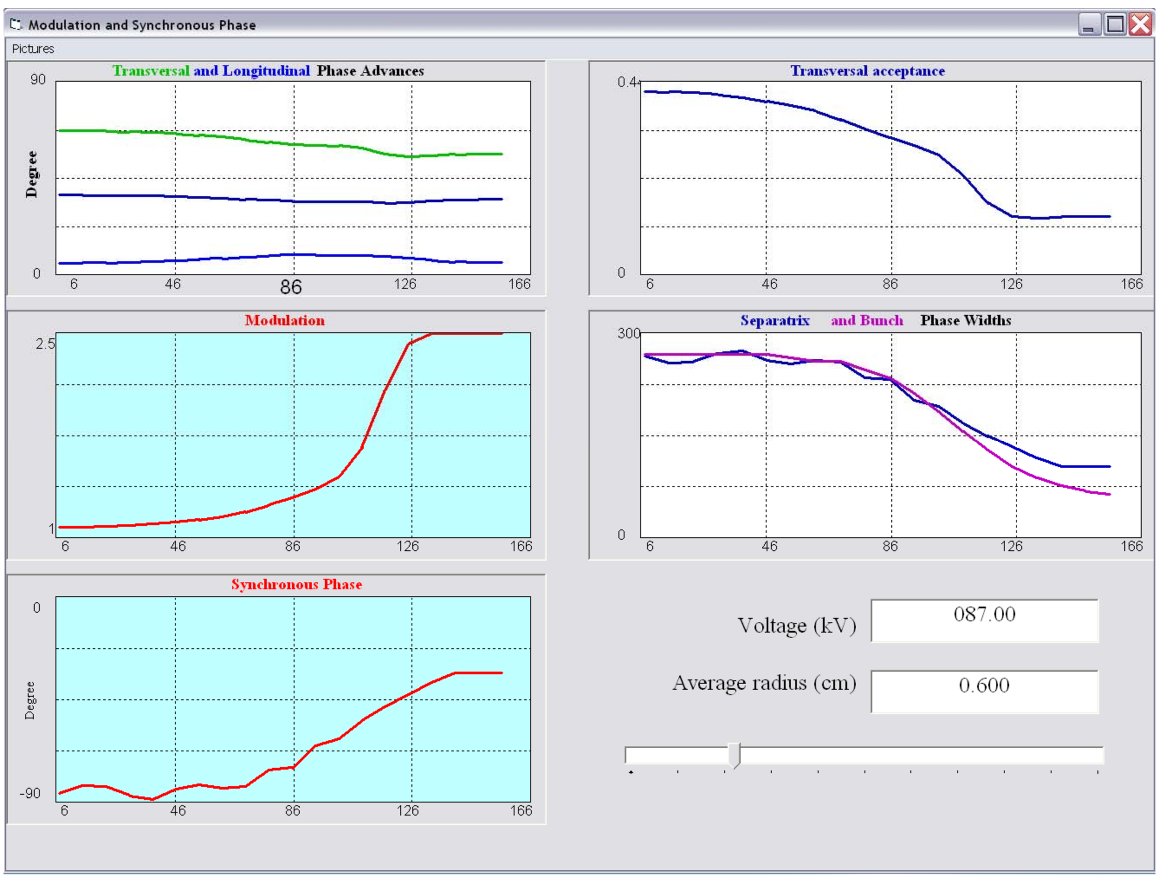


Figure 5: Shows the DESRFQ modulation and synchronous phase variations for the best possible configuration found for the Ion Injector RFQ.

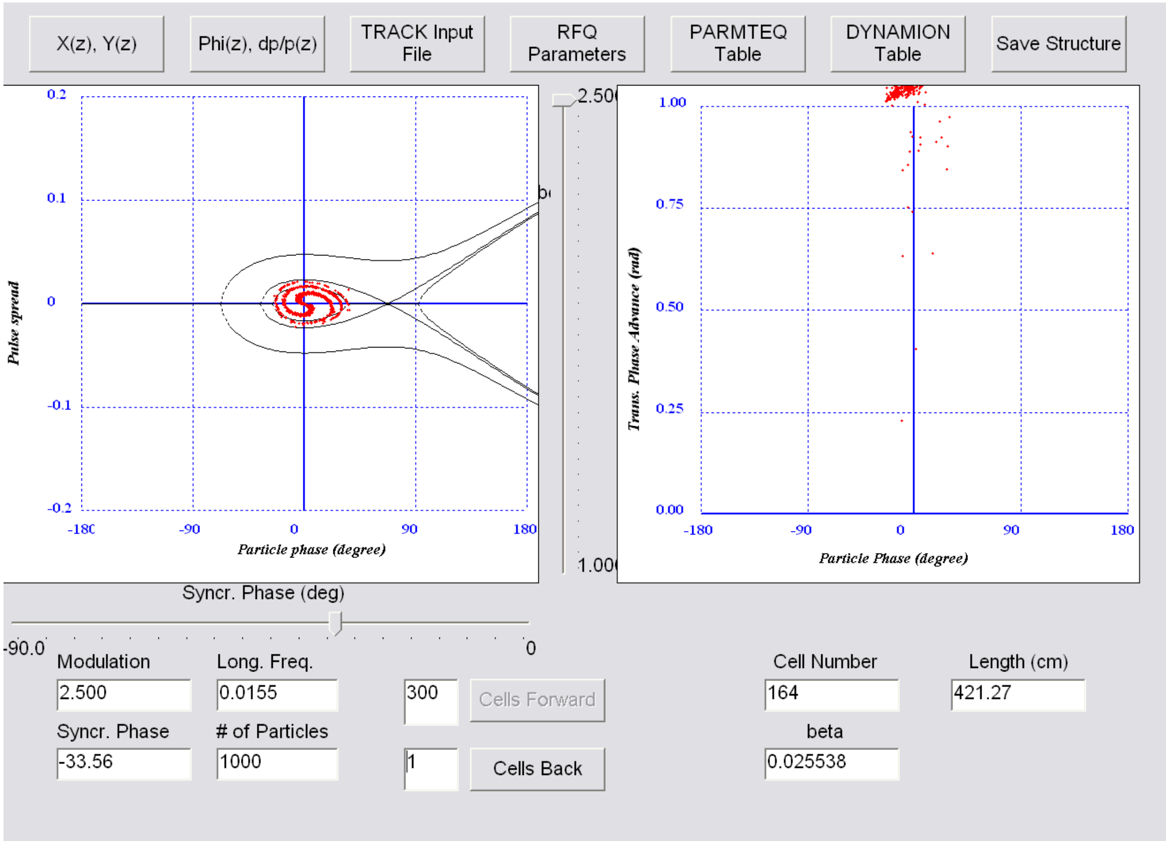


Figure 6: Shows two diagrams. One presents particle distribution in ψ - $\Delta p/p$ phase space and set of phase trajectories corresponding to the different values of Hamiltonian potential function:
$$V(\psi) = qE\beta c\left[\sin(\psi + \varphi_s) - \psi\cos(\phi_s)\right],$$
where q – ion charge, E – accelerating field, $\psi = \varphi - \varphi_s$, $\Delta p/p$ – pulse spread.

In figure 6, the phase trajectories shown correspond to almost linear oscillation, to the border of stability region (separatrix) and unstable longitudinal motion. Once the RFQ for the Ion injector was designed using DESRFQ, it was then possible to add on other important components of the injector. The main components added on to the RFQ were input and output matchers. With these matchers in place the beam coming into the RFQ becomes better matched for high transmission. At the end of the RFQ there is also a similar matcher that is in place to match the output beam from the RFQ to the first part of the main linac. Without proper matching the beam emittance was seen to be much higher and more unstable in both the transverse and longitudinal directions, resulting in the loss of a substantial amount of particles. The matchers are simply added in as special sections at the beginning and end of the RFQ input file pointing to another file that contains the matcher's parameters.

Once the beam goes through the RFQ and is matched properly to the low energy section of the linac further optimization is still required. Since the linac is optimized for the beam using the Multi Harmonic Buncher it will need to be re-optimized for the larger beam from the injector without the use of a MHB. The effect a MHB has on the longitudinal emittance of the beam is very noticeable. Even with the well constructed RFQ which has a percent transmission of over 99.9% it still has a rms longitudinal emittance (ε_z) from 15-17 keV/u*ns where the case with the MHB saw the emittance in the longitudinal plane of less than 0.5 keV/u*ns. The emittance

$\varepsilon_z = \sqrt{\overline{\Delta t^2}\ \overline{(dW/W)^2} - \overline{\Delta t(dW/W)}^2}$ is the normalized rms emittance in the longitudinal phase plane ($\Delta t = t - t_{RP}$, $\Delta W/W = (W - W_{RP})/W_{RP}$). t_{RP} and W_{RP} is time of flight and kinetic energy of the reference particle.

The challenge is to transmit almost 100% of the beam through the linac with the only acceptable place to lose particles outside the RFQ is the chicane region of the linac. In this region, the beam passes through a stripper that explodes the beam emittance and changes the two charge states to multiple higher charge states. The beam then passes through slits and bending magnets to the high-energy section of the linac. Even after countless hours of optimizing the injector and the actual linac to accommodate this larger beam there is still a minimal loss of particles within the low and high energy accelerating parts of the linac even before introducing errors into the simulations.

The challenge is to transmit this almost 100% of the beam through the linac with the only acceptable place to lose particles outside the RFQ is the chicane region of the linac. In this region, the beam passes through a stripper that explodes the emittance of the beam and changes the two charge state beam into multiple higher charge states and then is sent through slits and bending magnets on the beams way to the high energy section of the linac. Even after countless hours of optimizing the injector and the actual linac to accommodate this larger beam there is still a minimal loss of particles within the low and high energy accelerating parts of the linac even before introducing errors into the simulations. In simulating with a starting amount of 200,002 particles in the TRACK particle tracking code each section of the linac was simulated and anyalzed to see how many particles were lost and where. Without including errors, 6 particles in the low energy section of the linac, 3 lost in the high energy section, and the majority of the loss is where it should have been, in the chicane region of the linac. In this region, 7738 particles lost while the beam is passed through a series of slits.

The slits used in the chicane region were altered so that they are approximately 20% larger then they were for the already optimized case using the MHB in the injection due to the larger beam size. The slits act as a way to clean up the beam before it enters the high-energy section of the linac, shedding off the particles on the edges that would otherwise be lost later on in the high-energy portion of the linac. The loss of 7747 particles through all components equates to a loss of approximately 3.8% of the total beam adding that to the 5% lost in the RFQ and a net loss of 9-10% of the beam is documented. The three figures to follow show the beam without errors in each of the three sections separately: low energy, chicane, and high-energy, these were done separately to better analyze the beam parameters in each section individually.

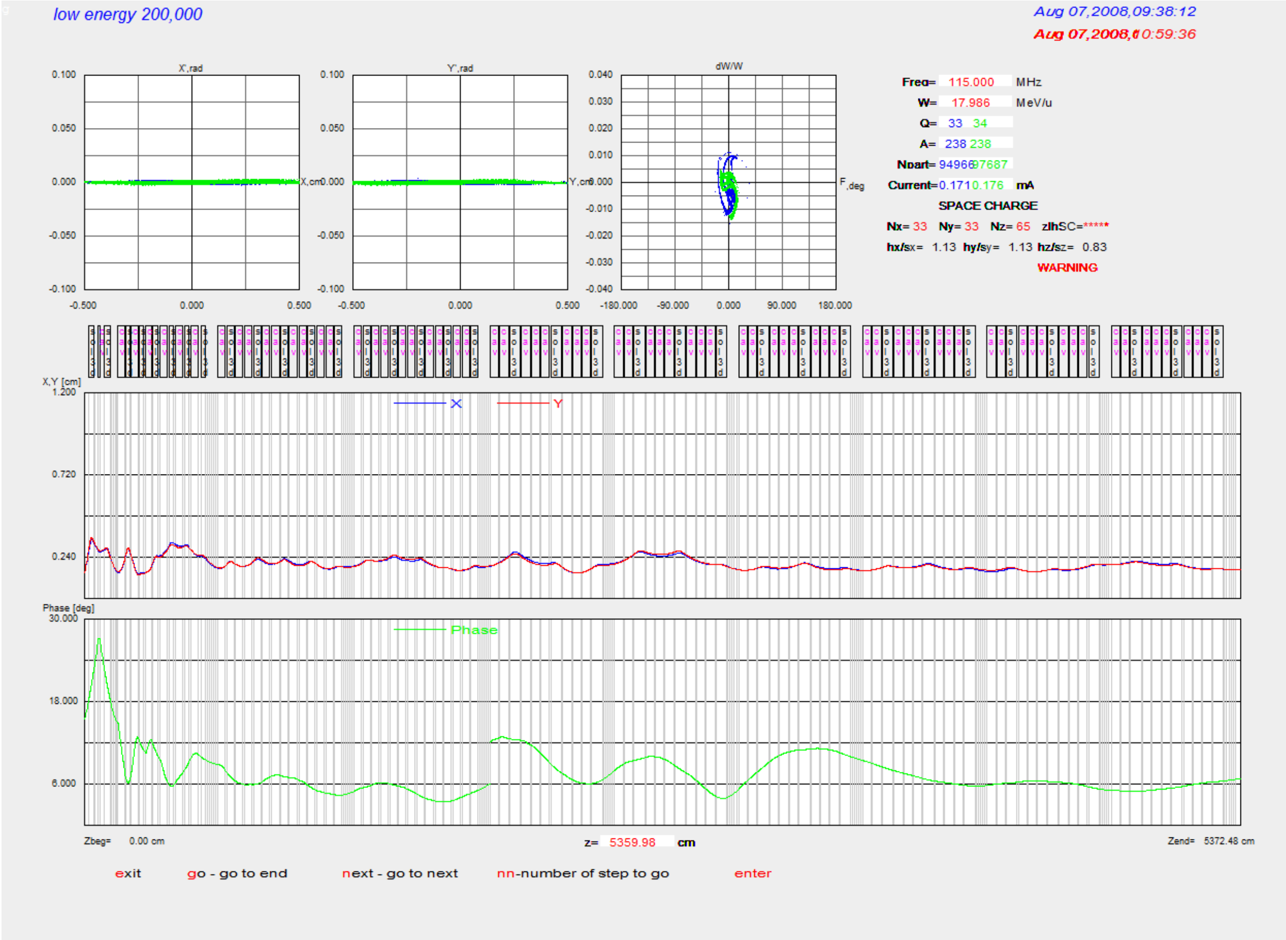
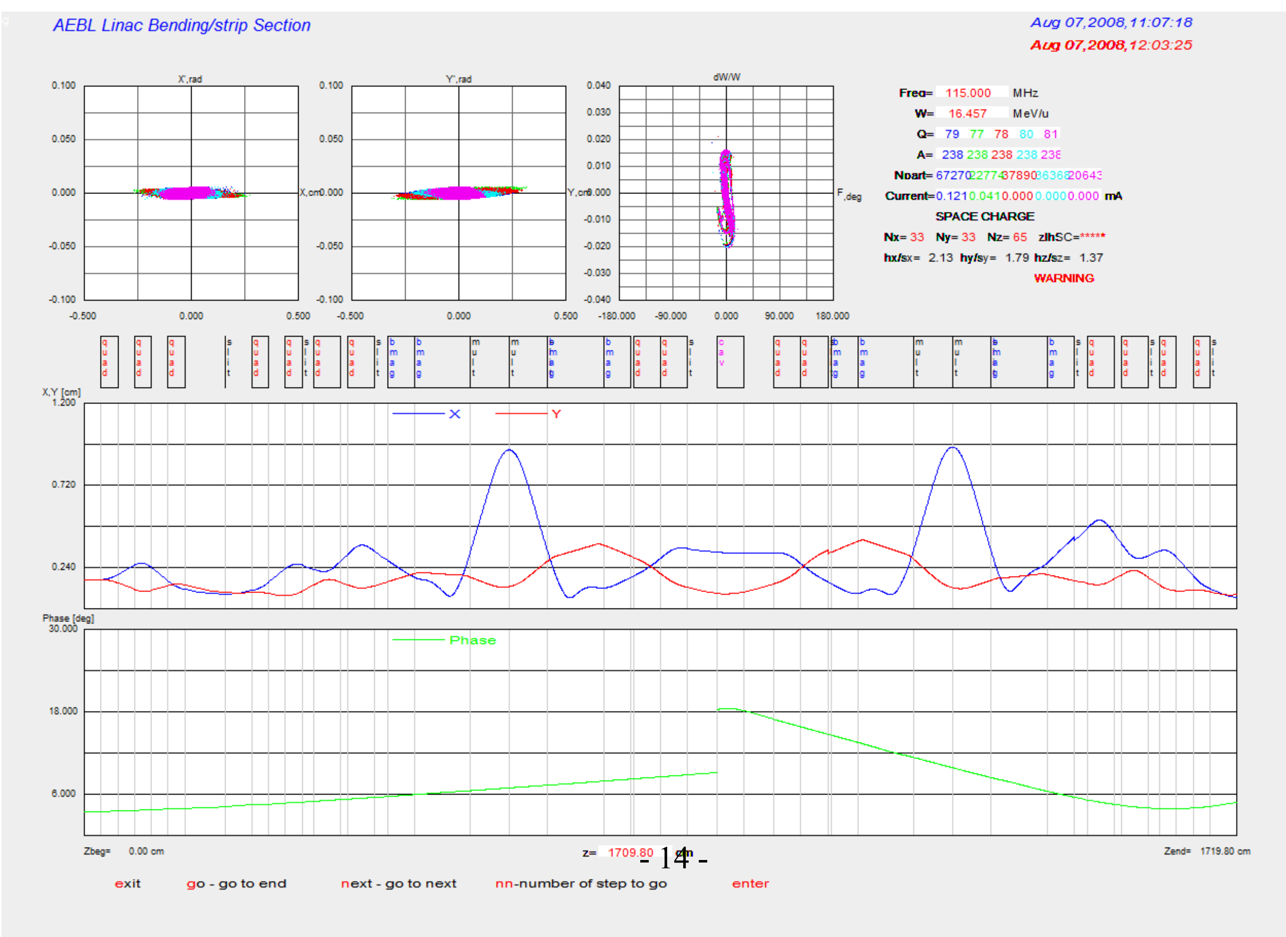


Figure 6: (above) Shows the first part of the linac from the RFQ, the low energy accelerating portion

Figure 7: (below) Shows the chicane section of the linac where the beam is converted to 5 higher chargestates by s stripper, is cleaned up by a series of slits, and is bent by bending magnets on its way to the high energy section of the linac.



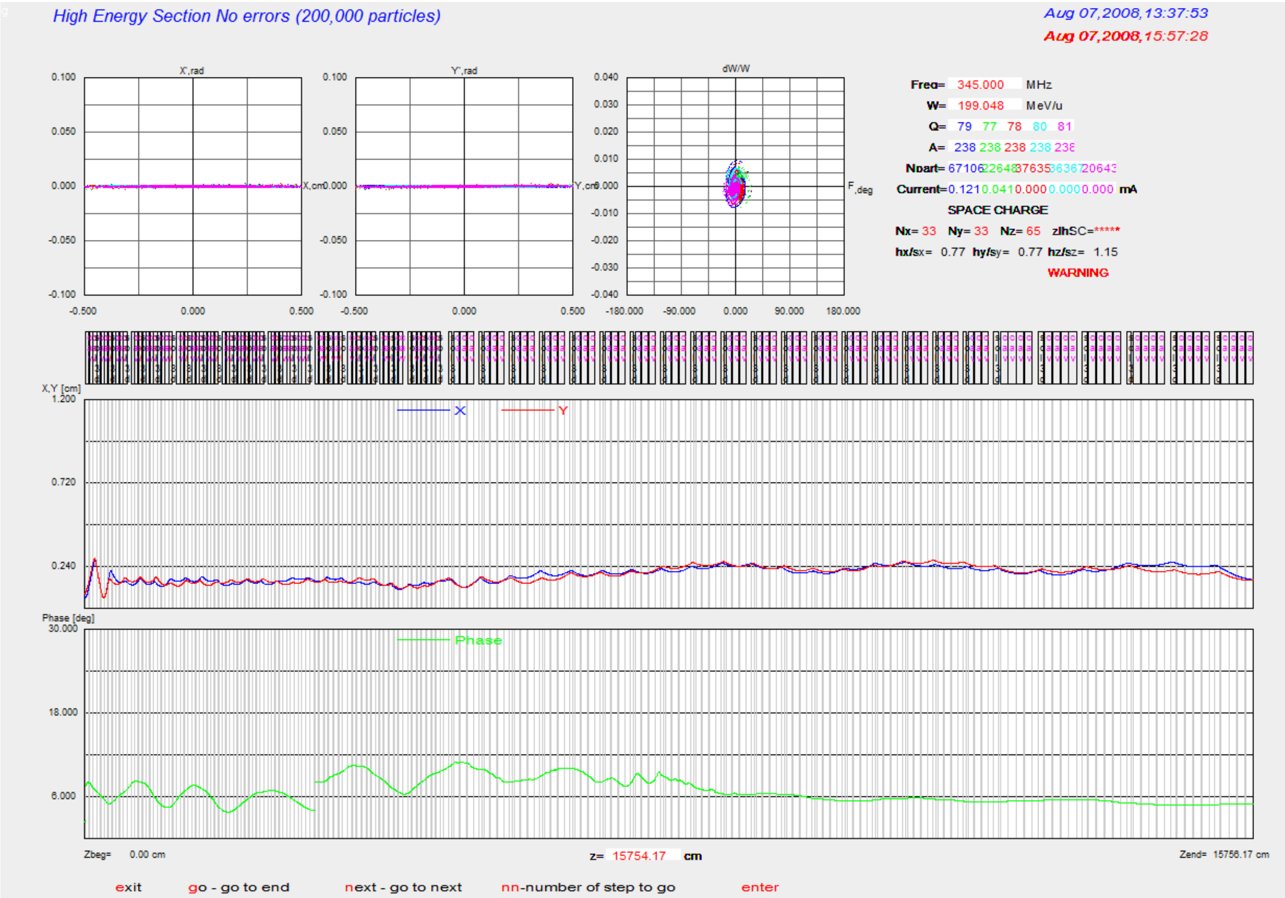


Figure 8: Shows the last section of the linac where the beam is accelerated heavily to an energy of 200MeV/u.

Inside the TRACK simulation code, errors that are implemented can be either of three types: A Misalignment error is a displacement of the device as a rigid body, a field error is the field amplitude of the device, or an error of the rf field phase. Inside the track.dat file and sclinac.dat files errors were added to this simulation for the entire linac. As a rigid body, six independent variables are needed to describe the displacement of the beam. Using a Cartesian coordinate system that is fixed in the rigid body and the body motion is defined by three shifts x, y, z of the CSC origin and three angles φx, φy, φz which specify the rotation axes about the initial axes. For each of the components of the linac there are two equivalent set of coordinates, the entrance coordinates and the exit coordinates. Figure 9 below shows such a displacement described by transformation from the entrance coordinates to the exit coordinates.

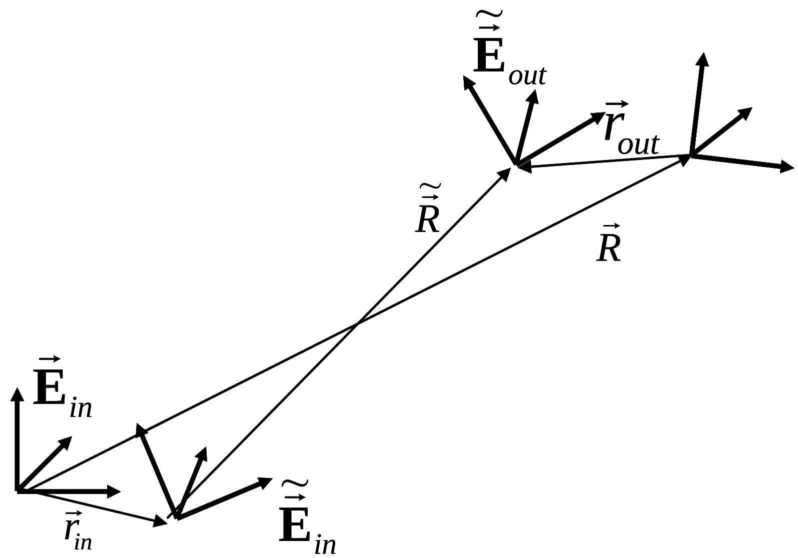


Figure 9: Shows the transformation from the entrance Cartesian coordinates to the exit coordinates for a device in the accelerator.

It was not possible however to finish the analysis of the linac injector design with errors implemented fully the results seem to show initially that a design without a MHB could be a possibility. It was possible to run the low energy section with errors implemented and saw no substantial particle loss so far with the simulations that have run successfully.

5. Conclusion

As of right now the possibility for a well designed injector for a High-Intensity SC Ion Linac Injector seems possible both with and without the presence of a MHB. Without the MHB however as a result of the high beam emittance in the longitudinal phase space, the beam is less stable and will be more difficult to design then if a MHB is used, but this design also as seen in the results listed in this paper, allows for a larger beam intensity. Throughout the design and optimization process it becomes apparent that the benefits gained by pre-bunching before the RFQ by a MHB is well worth the loss is beam intensity due to the high quality low emittance and much more easily controlled beam it in the end produces. Still the results from this report show that other options are possible but at this present time a design that includes a MHB appears the best choice in providing a well behaved and well bunched beam that is needed for a high intensity superconducting ion linac as was studied at Argonne National Laboratory.

Acknowledgements

I would like to first thank the Lee Teng selection committee and all those involved with the Lee Teng internship for giving me this great opportunity to both learn and better prepare myself for a future in physics. As well, I would like to thank Argonne National Lab, especially the Physics Division, the Accelerator R&D group, and my mentor Brahim Mustapha who helped me get the most out of this experience. Finally, I would like to thank all the other interns for helping throughout the process of the internship and especially the time spent at the USPAS in Annapolis Maryland.

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