PART 2: INITIAL BEAM DYNAMICS RESULTS OF AN INTEGRATED AND COMPACT 1.3 GHZ SUPERCONDUCTING RADIO FREQUENCY (SRF) ELECTRON SOURCE

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Abstract

This paper is the continuation of a technical paper which is called "Detailed Electromagnetic Design of an Integrated and Compact 1.3 GHz Superconducting Radio Frequency (SRF) Electron Source" [1]. In the previous paper, we examined if a promising RF electromagnetic design of the gun and cathode region could be achieved. Further, we examined if this gun region could be fully integrated, in terms of the electromagnetic RF design, with the rest of the accelerator, keeping in mind the overall goal of compactness and reduction of duplicative infrastructure commonly associated with separated function electron guns and structures. While we convinced ourselves thus far that the RF electromagnetic design of our concept is feasible, we also needed to perform particle tracking to assess the beam properties through the entire system, understand and remediate any beam loss. For this step, we examined the cathode region and analyzed the gating process of the thermionic cathode, as losses would most likely be attributed to releasing electrons into the accelerating structure during an unfavorable phase window.

This material is based upon work supported in part by the Visiting Scholars Program of the Universities Research Association (URA). Fermilab is Operated by the Fermi Research Alliance, LLC under Contract No. De-AC02-07CH11359 with the United States Department of Energy.

This manuscript has been authored by Fermi Research Alliance, LLC under Contract No. DE-AC02-07CH11359 with the U.S. Department of Energy, Office of Science, Office of High Energy Physics.

BEAM DYNAMICS SIMULATIONS FOR THE INTEGRATED SRF ELECTRON SOURCE

The overall solid model of the gun's geometry, illustrating only the first two 1.3-GHz cells and the cathode region (resonant at 2.6 GHz), is shown in Figure 1. Also shown is a cutaway of the cathode region to illustrate the detail. The RF choke blocks RF leakage of the 1.3 GHz into the adjacent region cathode region and the 70 K shield prevents thermal leakage into the 4K area.

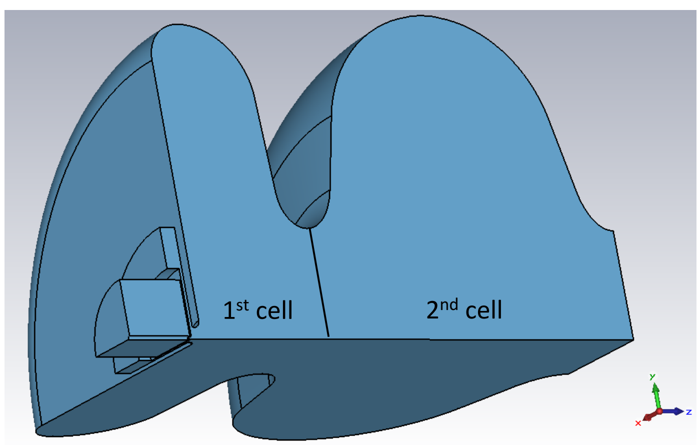


Figure 1: The solid model of the RF Gun and the cavity region as modeled in CST MWS.

For the particle tracking, as in the case of the RF electromagnetic design, we used multiple accelerator codes to examine our system through particle tracking include SMASON, ASTRA and SPIFFE which will be described herein.

Simulation Results using SMASON

SMASON is capable of simultaneously simulating multiple RF frequencies and their nearly arbitrary field distributions as well as DC fields. In addition it is capable of tracking particles through these fields. It includes space charge effects making it ideal for simulating the complexity near the cathode of our design. It uses the Finite Element Method for the field calculation in the electron guns and the Particle-in-Cell Method for the numerical simulation of the electron emission and space charge within the applied RF and DC voltages. It is a spatially 2D program with the macro-particles described by the infinitely thin rings with uniform charge distribution [2,3].

We used SMASON for more realistic initial particle tracking simulations of the combined (cathode assembly and gun) structure. We transferred the cathode and gun cell (30% of regular cell length) geometry into SMASON (Figure 2).

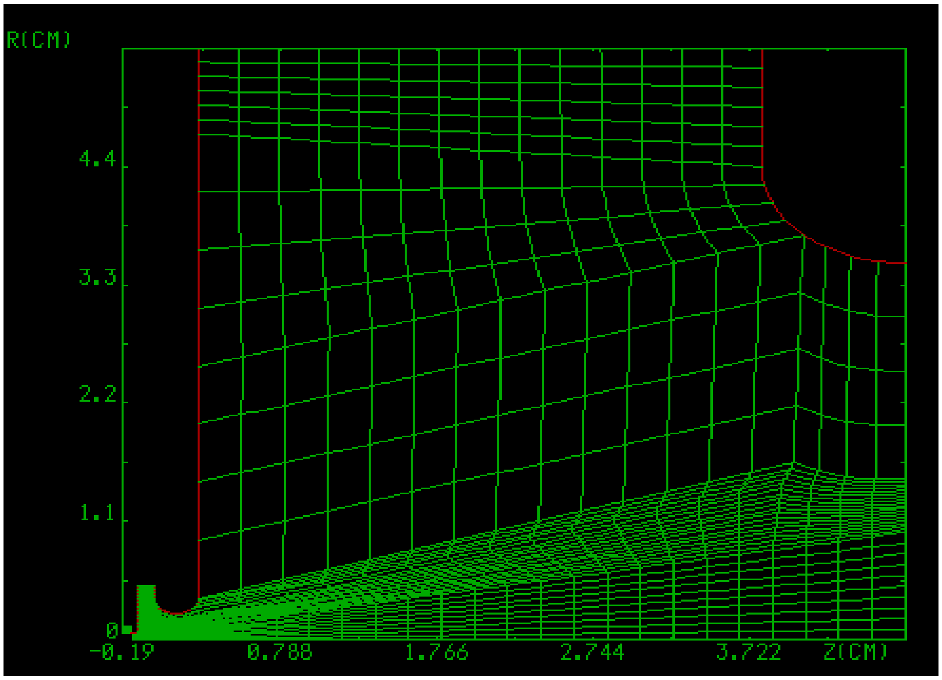


Figure 2: The mesh view of the combined geometry of the cathode assembly and the first cell in SMASON.

SMASON is used to track the electrons from the cathode up to the plane of the iris between the 1^{st} and 2^{nd} 1.3-GHz cells. The voltage from the cathode and into the 1^{st} cell has time and spatial dependence [4].

Our optimization goal was to limit the beam losses to the cavity walls to less than ~0.5 W (of a total of 5 W, so therefore 10%) while delivering a 10-MeV, 2-mA beam of electrons. A cathode area of 0.78 mm^2 was assumed. The longitudinal profiles of the DC, the fundamental RF, and the second harmonic RF (phase differences included) were summed together linearly with their amplitudes set by the optimization routine. The optimization process also varied the relative phase between the fundamental and 2^{nd} harmonic.

A series of SMASON simulations were performed without space charge to find the conditions of optimal performance, as defined by minimizing the beam loss through the system. These parameters are provided in Table 4.

Table 1: The optimized beam parameters at the end of first cell as simulated by SMASON.

Beam Parameters	Values
Bias Voltage	2 kV
RF Voltage	2.72 kV
Average Gradient of fundamental Frequency (1.3 GHz)	~8 MV/m
Average Gradient of Second Harmonic Frequency (2.6 GHz)	~5.4 MV/m
Phase	-15°
Energy (end of the 1st cell)	0.335 MeV
Energy Spread	5.9 %
Average Current	2 mA
rms Phase Size (rms Bunch Length)	~ 7.3° (15.6 ps at 1.3 GHz)

In Figures 3, the some outputs of SMASON are shown for the bunch length and energy spread at the end of the first cell as a function of the relative phase between the fundamental and 2nd harmonic. According to these results to achieve the smallest bunch length and energy spread at the same time one should operate at a phase difference of -15 degrees.

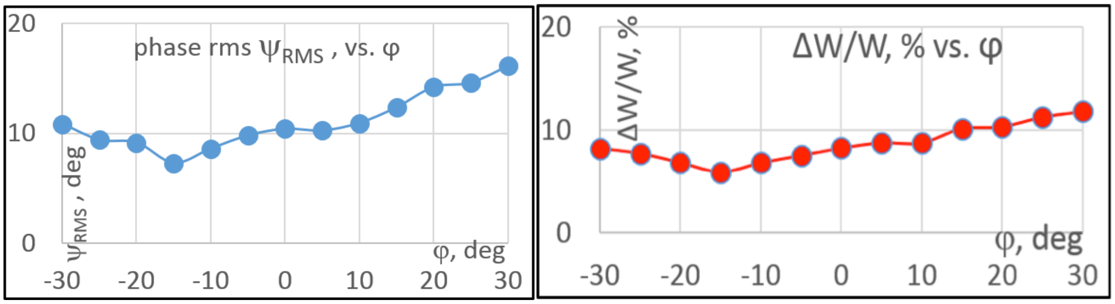


Figure 3: The bunch length vs. relative phase (left) and the bunch rms energy spread vs. phase for the SMASON simulations without space charge.

The results from SMASON represent a start; however, more sophisticated, capable codes are required to really explore some of the fine details.

Beam Dynamics Simulations using ASTRA

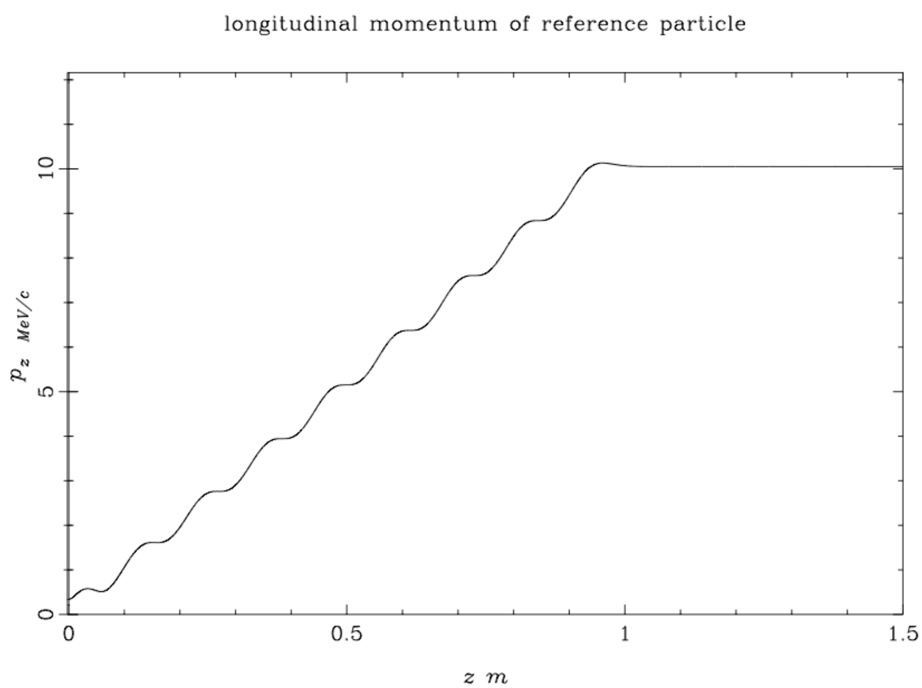
The freely available particle tracking simulation code known as ASTRA (A Space Charge Tracking Algorithm) [5] allow us to more fully simulate a thermionic cathode and RF acceleration system of particles. This code has been used before in many design studies and also validated against their actual performance [6].

ASTRA allows us to analyze the electron beam properties in detail not only until the second cell of the structure but also the fully integrated (cathode assembly and the 9-cell structure) system.

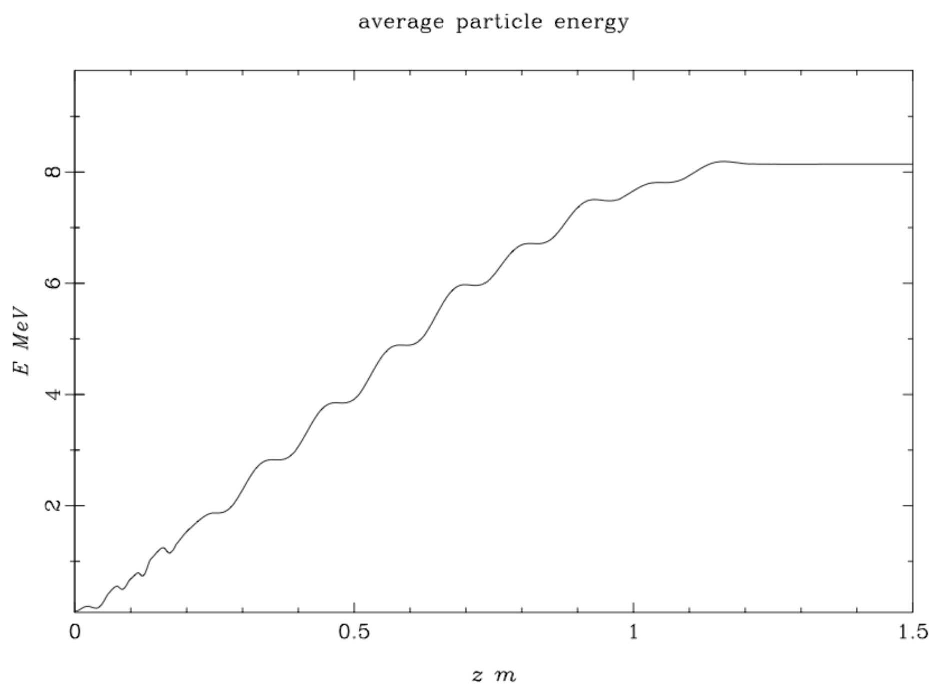
We first defined a long bunch length (769ps = 1/1.3 GHz) in ASTRA in order to see how an un-gated thermionic cathode might perform in our design.

This code also uses external field distributions in order to track particles. Therefore, the field maps for both the cathode assembly region and the 8.3-cell structure was generated and imported into ASTRA [3]. The DC bias was turned off for this part of the study.

Then, we defined the cathode emission details and start to track the particles generated from the cathode. The optimum phases of the RF fields were found to be 268 degrees and 221 degrees, respectively. Although these numbers look rather odd at first they are readily understood in terms of how ASTRA handles zero phase. ASTRA starts with a sine-like time profile and so at zero phase the field is zero. It reaches a maximum positive gradient at 90 degrees and a maximum negative field at 270 degree. Negative fields accelerate electrons and since one wants as much energy as possible it make sense that the optimal fundamental phase is near 270 degrees. During this process, the reference particle is first tracked through the beam line to check the settings and then it is tracked again starting with a small radial offset. Figure 4.4 (a) shows the reference particle’s longitudinal momentum through the full structure. Particle emission was then setup to allow emission at any phase. Figure 4.4 (b) shows the average energy of the particles that are generated from the cathode and manage to get accelerated through to the end of the 8.3-cell accelerating structure. Even though the reference particle reaches roughly 10 MeV energy at the end of 9^{th} cell, the average particle energy at the end of the accelerating structure is only 8.14 MeV. The reason for this is that we did not at this time gate the electrons as in the SMASON simulations. The electrons were emitted from the cathode and propagated, if possible and not lost, through the accelerating structure. There is a significant amount of particle loss in the system and a very large energy spread.

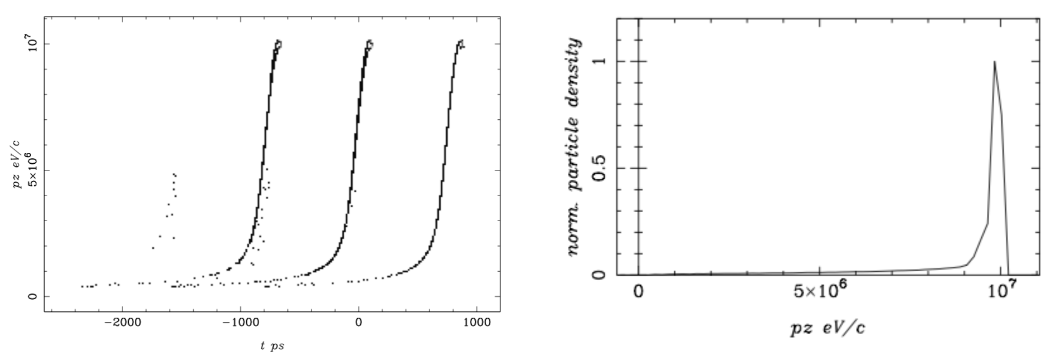


(a)



(b)

Figure 4.4 a) The momentum of the reference particle along the z-axis. The final energy is 10 MeV at the end of 9th cell and b) The average energy of the beam along the z-axis. The final energy is 8.14 MeV at the end of the 9th cell.



(a) (b)

Figure 4.5. a) The longitudinal phase space of the bunches at z = 1.5m, b) projection of the 1st bunch's phase space in Figure 4.7 (a)

Figure 4.5 shows the longitudinal phase space of a number of sequential bunches emitted off the cathode (z = 1.5 meters). As the particle moves the reference particle move but the convention is to refer its position (or time) to as zero. The plot shows the results at z = 1.50 which is actually the laboratory position of the reference particle. So $t = 0$ on the plot shows to 1.5 m from the cathode position. These bunches have a maximum ~10 MeV energy, however, with a very large energy spread.

Clearly even though there is energy gain at the end of the structure, the field still needed to gate to prevent the large particle loss and large energy spread. Therefore, as a next step in our simulations, we studied gating the field inside the structure as we did in SMASON. The results are given in Figure 4.6 and 4.7.

Figure 4.6 shows the average energy of the particles that are generated from the cathode and accelerated through the 8.3-cell accelerating structure with space charge turned on but this time with gating. Since we gate the field before the particles go through the accelerating structure, the average energy is now 9.49 MeV with virtually no particle loss.

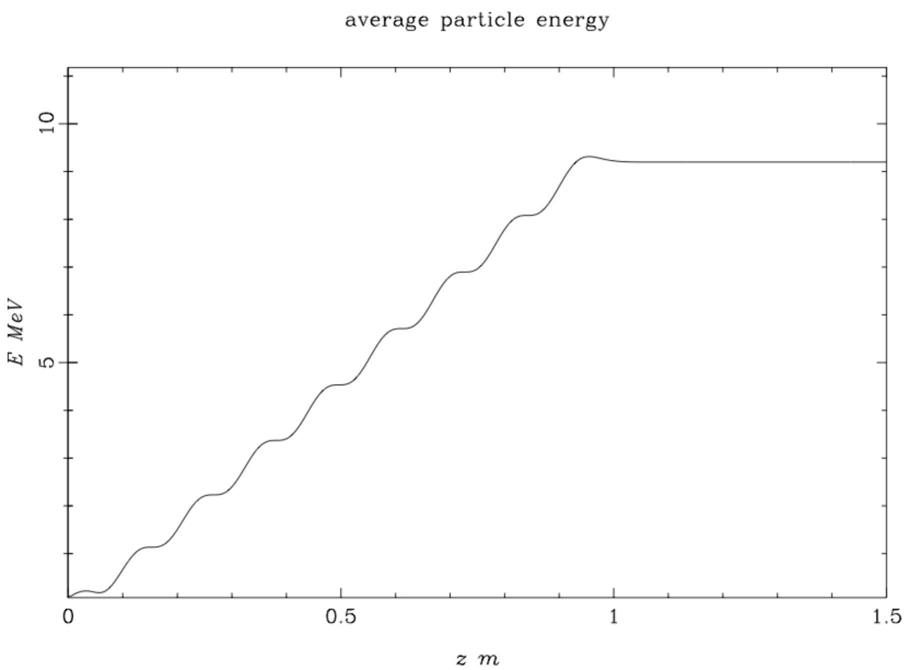
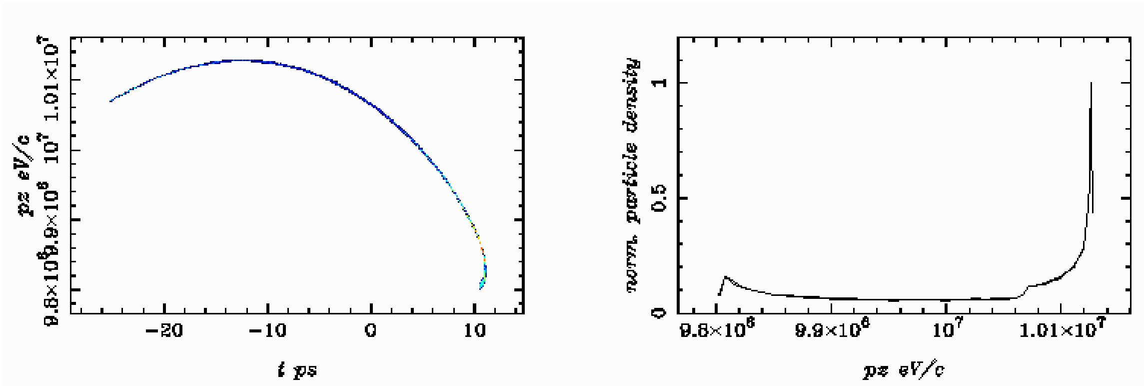


Figure 4.6. The average energy of the beam along the z-axis. The final energy is 9.49 MeV at the end of 9th cell.

Figure 4.7 shows the longitudinal characteristics of the bunches at the end of the accelerator but this time when we gate the fields and have space charge turned on. These bunches reach ~10 MeV energy (as can be seen in Figure 4.7 (b)) with a very small energy spread. As can be seen, when we gate the field, we can achieve higher average energies than without gating as the energy spread is a significantly smaller, and there appears to be no particle loss.



(a) (b)

Figure 4.7. a) The longitudinal phase space of the bunches, b) projection of the longitudinal momentum of Figure 4.7 (a).

SUMMARY

In this paper, we have performed charged-particle tracking simulations using SMASON and ASTRA (and SPIFFE) to assess the beam properties through the entire designed system [1] with a design goal of generating an electron beam power of at least 3 kW and up to 10-MeV beam energy. We are confident from the results that our design has merit and shows potential for operation. The gating method shows promise and space charge effects appear to be minor and controllable.

Overall, this fully–integrated system (thermionic cathode and accelerator section – 8.3-cell ILC/XFEL cavity) is contained within a footprint smaller than classical designs as it eliminates certain infrastructure by capitalizing on new innovations.

Acknowledgement

This material is based upon work supported in part by the Visiting Scholars Program of the Universities Research Association (URA). Fermilab is Operated by the Fermi Research Alliance, LLC under Contract No. De-AC02-07CH11359 with the United States Department of Energy.

I would like to express my thanks to my Fermilab URA advisor, Vyacheslav Yakovlev and also Robert Kephart, Timergali Khabiboulline and Nikolay Solyak for their support during this work.

I also want to thank to Phillipe Piot and Michael Borland for their continuous help and technical feedbacks during my beam dynamics simulations.

I would like to give special thanks to Ivan Gonin for his support and endless help in every step of my work.

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APPENDIX

Beam Dynamics Simulations using SPIFFE

In addition to the initial SMASON and ASTRA results, we also study with another charged-particle tracking code called SPIFFE [7] for the more detailed beam dynamics simulations for the fully integrated (cathode assembly and the 9-cell structure) system. SPIFFE is short for **SP**ace Charge and **I**ntegration of **F**orces **F**or **E**lectrons. It is also a well-known simulation code especially for analyzing the space charge effects and the beam behaviors close to the electron gun area. This code has been previously bench-marked in several studies [8], therefore we reassured it for our simulations.

In order to perform particle tracking with SPIFFE, we first transferred field distribution into SPIFFE. Then, the next step was loading particles. Since we have the design of the cathode system and would like to analyze the results of a realistic cathode geometry couple to the 8.3-cell accelerating structure, we defined a thermionic cathode with the current density, 100 kA/m^2 with a cathode area of 0.78 mm^2. We then looked at two cases: one with no gating and one when the gating is functional.

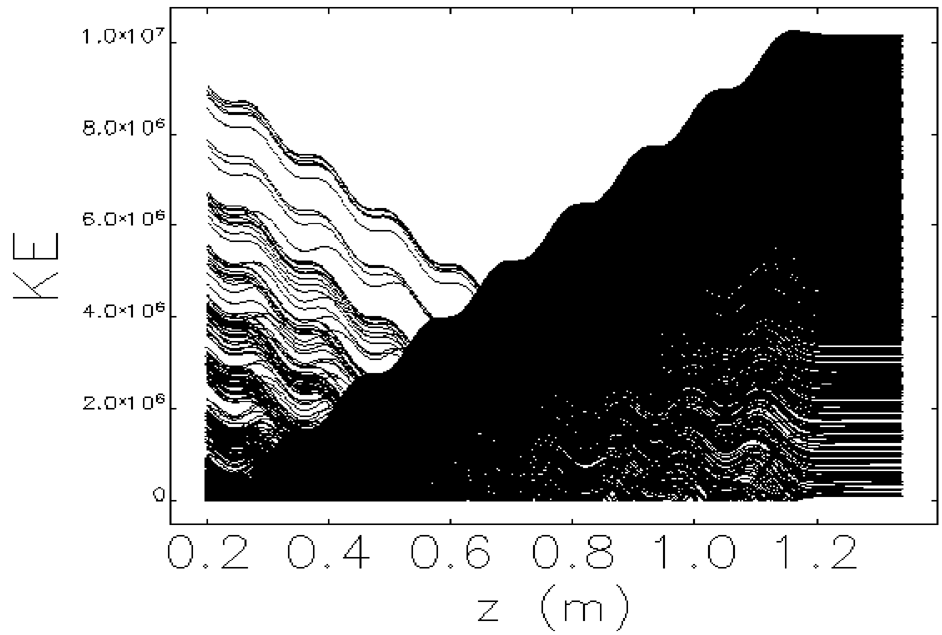

Figure 4: Kinetic energy of all particles in one bunch through the combined structure (cathode and 8.3-cell geometry)

Figure 5 shows the kinetic energy plot of all particles in a bunch that are emitted from the cathode without gating. Even though the some proportion of the particles in the bunch travel though the end of the cavity, their final energies are different and most of them have less than 10 MeV. Moreover, there are also undesired particles some of which oscillate in the fields and eventually propagate backward and are lost. Here, we have intentionally not gated the electrons that entered the structure to illustrate this undesirable effect. This is highly undesirable since the particles can strike the surfaces of the SRF cavities and cause detrimental issues such as quenching as well as back bombardment and thermal runaway of the cathode. Figure 6 shows the time evolution of the number of sequential particles in one bunch emitted off the cathode. The odd behavior is due to many particles emitted from the cathode at too late a phase to get fully accelerated. Even though the some particles are not at the optimum phase, they can be accelerated through the structure but then they get lost into the cavity. The others are trapped in subsequent RF cycles leading to the peculiar and unwanted phase space distribution.

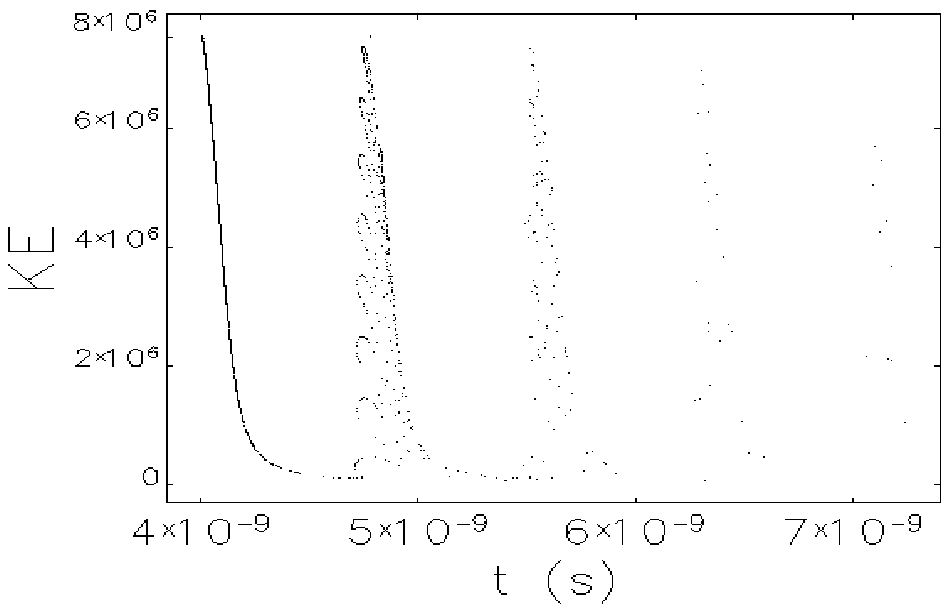

Figure 5: Longitudinal phase space in time for the particles in one bunch without gating

Next, we simulated the gating that we intend to implement in our system. Figures 7 and 8 show the kinetic energy through the full structure and longitudinal phase space in time with gating, respectively. In Figure 7, snap shots of the bunch are spaced by 50 ps. This time, the average kinetic energy of the particles is 9.4 MeV at the end of structure. This means that by gating we avoid the large energy spread and capture all particles without loss.

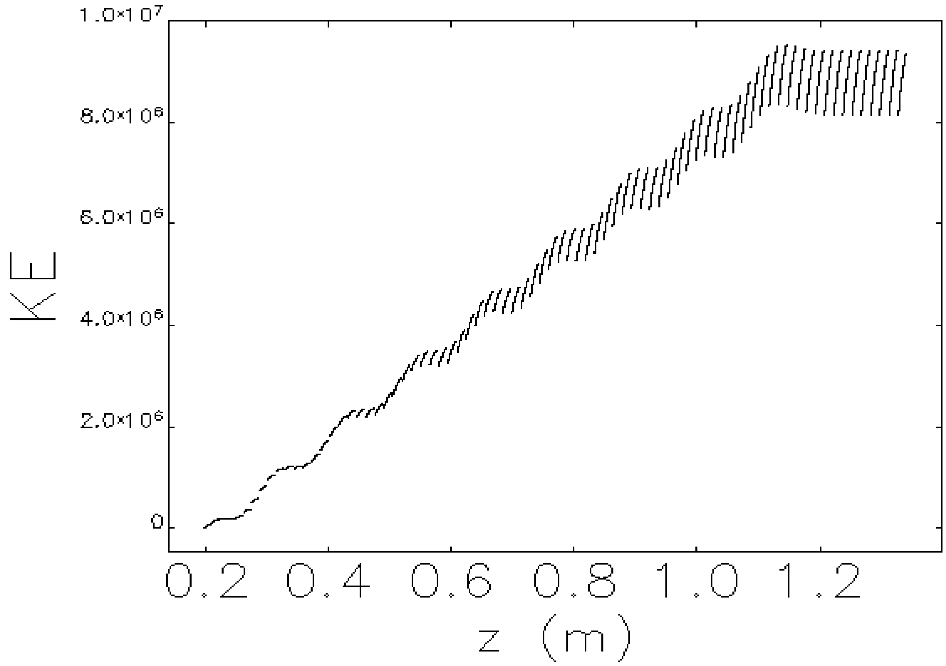

Figure 6: The kinetic energy of a bunch through the combined structure (cathode and 8.3-cell geometry)

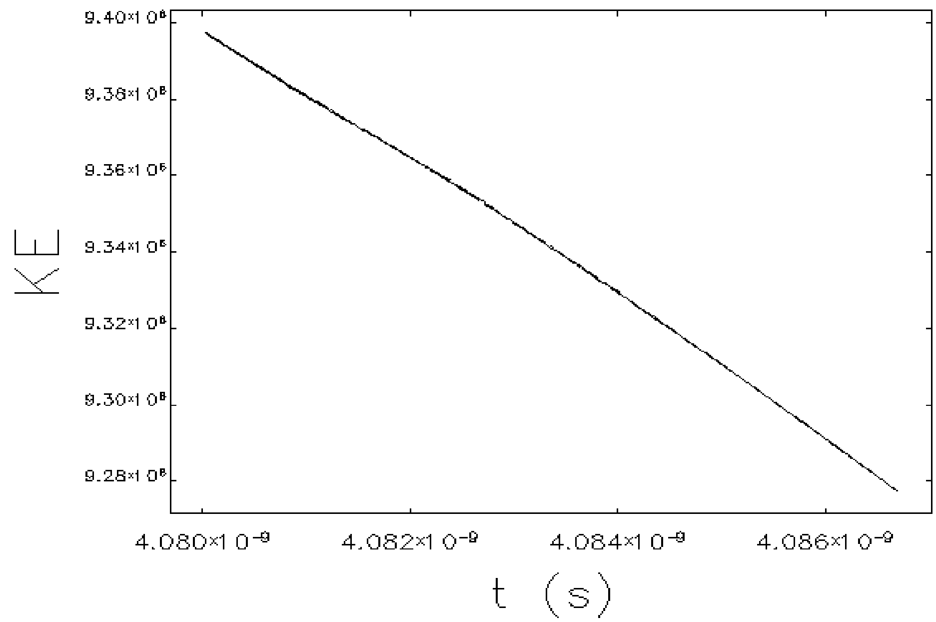

Figure 7: The longitudinal phase space in time for the particles in one bunch with gating