A High Charge and Short Pulse RF Photocathode Gun for Wakefield Acceleration

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Abstract:

In this paper we present a design report on 1-1/2 cell, L-Band RF photocathode gun which is capable of generating and accelerating electron beams with peak currents > 10 kA. We address several critical issues of high current RF photoinjectors such as longitudinal space charge effect, and transverse emittance growth. Unlike conventional short electron pulse generation, this design does not require magnetic pulse compression. Based on numerical simulations using SUPERFISH and PARMELA, this design will produce 100 nC beam at 18 MeV with rms bunch length 1.25 mm and normalized transverse emittance 108 mm mrad. Applications of this source beam for wake field acceleration are also discussed.

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1. **Introduction**:

High current short electron beams have recently been a subject of intensive studies [1]. One of the particular demands for this type of beam is for wake field acceleration applications. As in the case of the proposed plasma wake field acceleration scheme discussed in this workshop[2], the excited wake field amplitude not only depends on the drive beam charge but is also sensitive to the pulse length. This is particularly important for the case of nonlinear plasma wake field in the blow out regime, because the plasma wave breaking limit is proportional to plasma density. In general, the drive pulse length (FWHM) should not exceed 1/3 of the excited wake field wavelength for optimal coupling of the beam energy to the wake field. Also dielectric structure based wakefield acceleration research has been concentrated on structures in the 10 - 20 GHz range, but in order to study high gradient wakefield acceleration in 30 GHz structures, high charge (> 20 nC) and < 10 ps (FWHM) electron beam is required.

High current (kA) short electron beam generation and acceleration did not materialize until the invention of RF photoinjector technology[3]. Although most of the RF photocathode work has been concentrated on high brightness low charge applications such as free electron laser injectors, there have been several relatively high charge rf photocathode based electron sources built and operated[4,5,6]. In general, there are two approaches to attaining high peak current. One approach is to generate an initially long electron bunch with a linear head-tail energy variation which is subsequently compressed using magnetic pulse compression. The advantage of magnetic compression is that it is a well known technology and can produce sub-pico-second bunch lengths. Due to the strong longitudinal space charge and wake field effects at higher charge, this technology is limited to approximately 10 nC charge bunches. There have been designs and operations of relatively high charge L-band guns at APEX[5] and TTF[6].

Another approach is to directly generate short intense electron bunches at the photocathode and then accelerate them to relativistic energies rapidly using high peak axial electric fields in the gun [4]. The advantage of this approach is that it can deliver very high charges, for example, 100 nC if one uses an L-band gun. This would satisfy the requirements of most electron driven wakefield experiments for both plasma and dielectric structures if the pulse length is short enough (< 10 ps FWHM). So far, the Argonne Wakefield Accelerator (AWA) has demonstrated the capability of producing 100 nC, 25 — 35 ps (FWHM) electron beams at 14 MeV. This unprecedented performance was obtained using a half cell photocathode gun cavity and two standing wave iris-loaded linac sections [7]. The AWA machine has reached its design goal and has been used for dielectric wakefield [8] and plasma [9] experiments. The initial results are encouraging. Achieving higher gradients in wakefield experiments would require the drive electron pulse to be even shorter and have a lower emittance. In this paper, we discuss a new design for the RF photocathode gun with the capabilities to produce 10 - 100 nC with 2 - 5 ps (rms) pulse lengths.

2. Design Approaches:

The physics of high current beam is very complicated and some analytical work has been performed[10, 11]. In general pulse lengthening is due to space charge effects, particularly in the high charge case. One can simply estimate the longitudinal space charge force of a 100 nC beam with 1 cm radius in the rest frame as 27 MV/m. Another effect is the transverse rf focusing and defocusing of the electron beam passing through the accelerating cavity, which causes both pulse lengthening and transverse emittance growth. Thus, in this new design we took a brute force approach: 1) the electron beam is born in a strong axial electric field; 2) the beam is continuously accelerated with a gradient as high as possible, therefore preventing the bunch lengthening and emittance growth. 3) Adjusting the external focusing solenoid to minimize the emittance, eventually approaching the so called " emittance compensated" beam.

The choice for our new gun design is a Brookhaven type [12] 1— 1/2 cell cavity scaled up to L band operation as shown in Figure 1. Although in general the beam will have lower emittance if one chooses a multi-cell gun cavity, RF power requirements will be excessive. In this study, the updated standard computer codes SUPERFISH and PARMELA [13] are used to model cavity fields and beam dynamics, respectively.

Figure 1 shows a schematic diagram of the new gun and a section of the Linac. The linac section used here is an existing section from the current AWA linac. The drift distance between the gun and the linac is 32.3 cm designed to permit laser input and beam diagnostics.

The following table summarizes the parameters used in our simulation of the new rf gun.

Table 1 The gun design parameters as calculated using SUPERFISH

Inner Radius of the Cell, b (cm)	9.03
Radius of the iris, a (cm)	2.75
Width of the iris, d (cm)	1.5
Aperture of the exit (cm)	2.5
Operating frequency (GHz)	1.3
Initial bunch length (ps)	8.5
Initial beam radius (cm)	1
Quality factor, Q	26008
Shunt impedance (MΩ/m)	36.47

3. Numerical simulation results:

In the following sections, we describe the simulation results using the rf gun cavity parameters in table 1. We assume 1 cm laser radius at the photocathode with a uniform transverse distribution. The laser pulse length in all simulations is 8.5 ps also assuming a longitudinal flat top distribution. 5000 macro particles were used in each simulation. The simulation parameters were varied systematically to optimize the final bunch length and emittance. We scan through the total charge (10 - 110 nC), solenoid field strength and rf injection phase and field strength at cathode (50 -110 MV/m). Our criteria for selecting the operating point is shortest pulse and lowest emittance.

We have studied two modes of operation. First, the peak symmetric or field balanced case, where the electric field is the same in both the full cell and the half cell. A problem associated with the symmetric case is that it consumes high rf power, particularly if one wants to establish a high axial electric field. This could be problematic if there are rf power constraints such as at the existing AWA facility.. One way to get around this problem is to detune the full cell or half cell slightly to induce a field in-balance between the cells. Although the field in the full cell is lowered, the half cell field is the same as in the symmetric case. This reduces the rf power requirement as discussed in section 3b.

3a) Symmetric case

In Figure 2, we show the effect of the peak electric field in the gun on the rms bunch length and emittance for 100 nC beam. The gradient and injection phase in the linac section are kept constant in all the simulations. Both emittance and pulse length decrease as the electric field increases. At 100 MV/m surface field along with axial solenoid magnetic field of 3 kG and rf injection phase of 33°, one can achieve σ_Z = 1.2 mm (4 ps) and normalized emittance ε_N = 108 mm mrad at end of the linac with no beam losses in gun or linac. This is a very interesting result because it approaches the ~ 1 mm mrad/ nC attainable in the so called “emittance compensated” scheme. This is a significant improvement over the existing AWA gun design (σ_z = 3 mm, and ε_N=800 mm mrad).   Figure 3 shows the beam’s energy dependence on the cathode fields with energy range from 5 MeV - 11 MeV and energy spread of typically < 3 %. However, because PARMELA does not include wakefield or beam loading in its calculations, the energy spread can be much higher, particularly in the high charge cases. Typically it adds another 5% for AWA gun at 100 nC[14].

Figure 4 shows the dependence of the emittance and pulse length on the charge. We have scanned the charge from 10 nC to 110 nC. The solenoid current is also adjusted accordingly to compensate the different space charge forces as the charge changes. The pulse length and emittance is almost directly proportional to the charge. One interesting and surprising result is that in the low charge (10 nC) case, the rms pulse length can be as short as 0.7 mm which is essentially the same as the laser pulse length and the emittance can be as low as 14 mm mrad.

We have also calculated the rms pulse length and emittance evolution along the gun and linac. The results are shown in both Figure 5 and Figure 6. Figure 7 shows the ray-tracing of selected macro particles in the r - z plane, Langmuir beam flow is seen.

Figure 8 shows dependence of the rms emittance vs the axial magnetic field of the gun solenoid. In this calculation, 100 nC charge with 100 MV/m surface field on the cathode were used. We swept the magnetic field in the range of 2 - 4 kG. The emittance gradually decreases as the magnetic field increases. However, further increase the magnetic field strength would result in a much higher emittance due to over focusing effect.

3b) Non-symmetrical case.

As discussed the above, in order to support high field in the gun at 100 MV/m in the symmetric case, 16 MW of RF power is required. This will greatly affect the rf budget of the current AWA facility (25 MW available). One way to solve this problem is to detune the full cell slightly to reduce the peak field in the full cell, therefore reducing the power demand. This can be achieved by adjusting the outer radius of both half cell and full cell numerically. This is commonly known as asymmetric operation of the rf gun and should be avoided if sufficient RF power is available. As previously demonstrated by using either the cathode in the half cell or a plunger in the full cell as a tuner, one can operate a similar 1-1/2 cell gun in both modes [15].

We simulated a case where the rf peak field in the full cell is 60 MV/m and half cell peak field is maintained at 100 MV/m. The rf power consumption is only 10 MW in comparison to 16 MW in the symmetric case. The energy of the beam is lowered by to 8 MeV from 10 MeV. Other parameters such as pulse length and emittance show the same trend as in the symmetric case. We have also done systematic study as in the symmetric case, in general the beam quality (both pulse length and emittance) degraded by about 20%.

4. Discussion and Summary

In the last section we showed that the 1 - 1/2 cell rf photocathode gun plus a section of the current AWA linac would produce a very low emittance short electron beam. For a 20 nC electron beam, rms pulse length of 0.7mm is observed and 22 mm mrad normalized emittance with energy of 18 MeV. If this beam is used as a plasma wakefield accelerator driver, it can excite gradient in excess of 1 GeV/m with a plasma density of $\sim 10^{14}$ /cm^3 [16].

In applications to dielectric wakefield acceleration, this beam would also provide improvement over presently attainable gradients. One can use this beam to directly demonstrate collinear wakefield acceleration gradients in excess of 50MV/m, corresponding to 300 MW of rf power generated in 30 GHz dielectric structures.

We have designed an rf photocathode gun for high current applications. The numerical simulation results indicate that 10 kA peak current can be obtained. This beam will enable us to study high gradient wakefield acceleration in both plasma and dielectric wake field accelerator..

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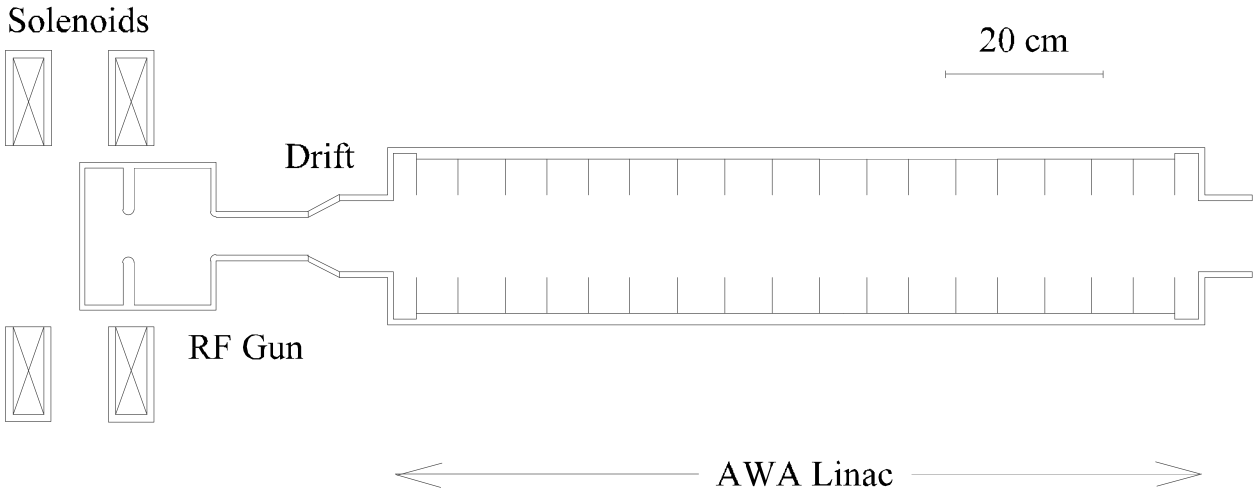

Figure 1. Schematic layout of the 1-1/2 Cell gun and an AWA linac section as a high charge short pulse electron sources.

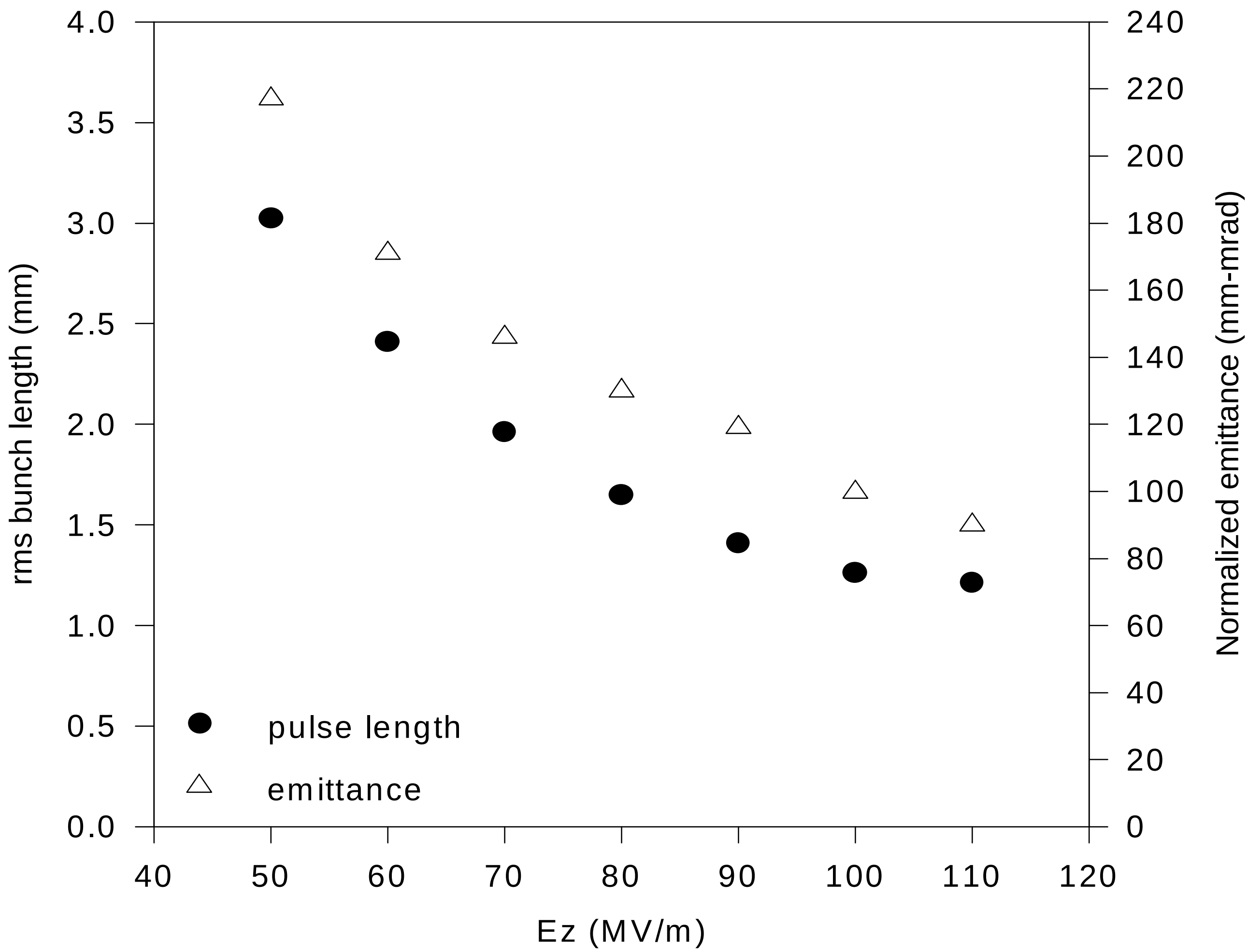

Figure 5. Simulation of the electron pulse length and emittance dependence on the peak electric field on the photocathdoe. The simulation uses 100 nC charge, with injection rf phase of 33°.

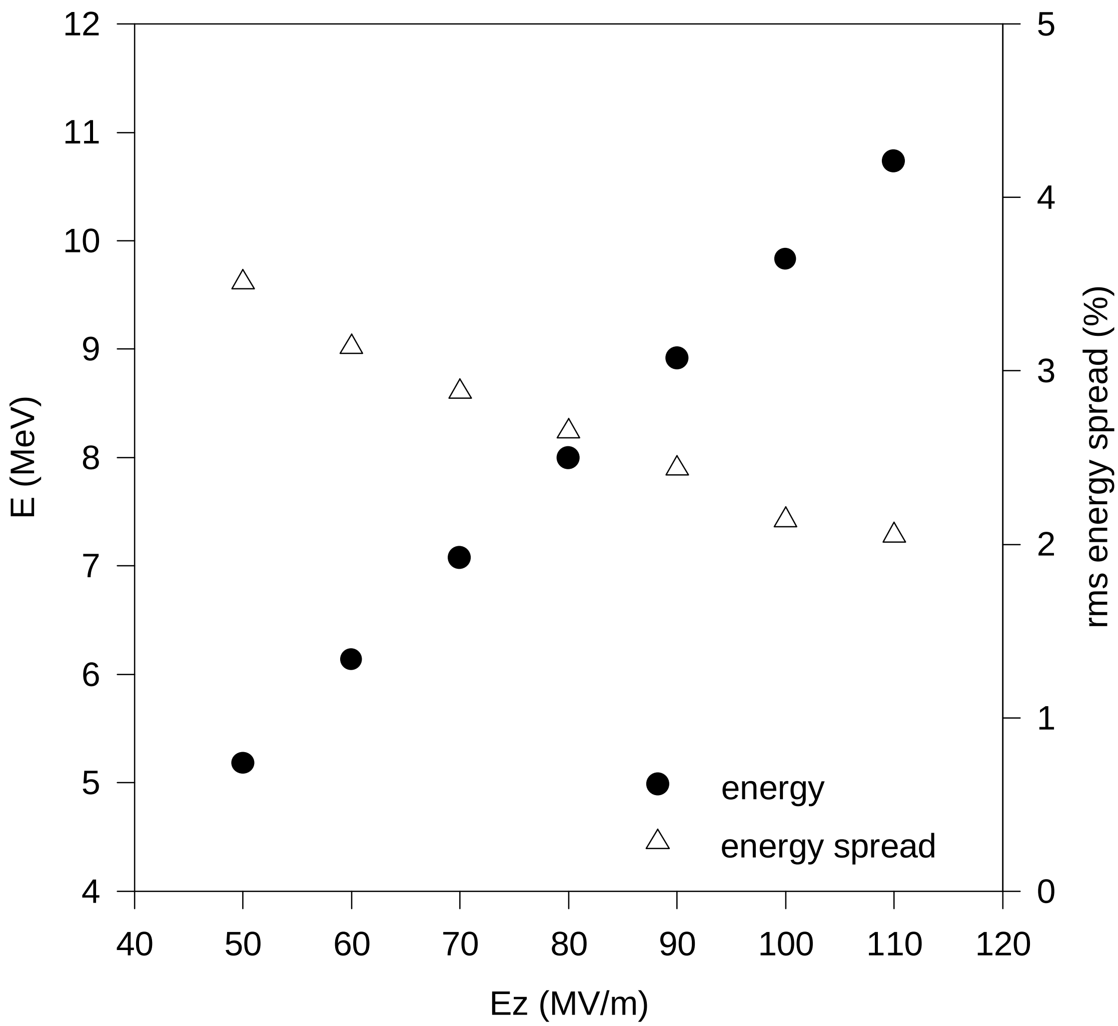

Figure 3. Energy and energy spread of a 100 nC beam at end of the gun. It shows the trend that higher field on the cathode not only improves the pules length and emittance but also reduces the energy spread.

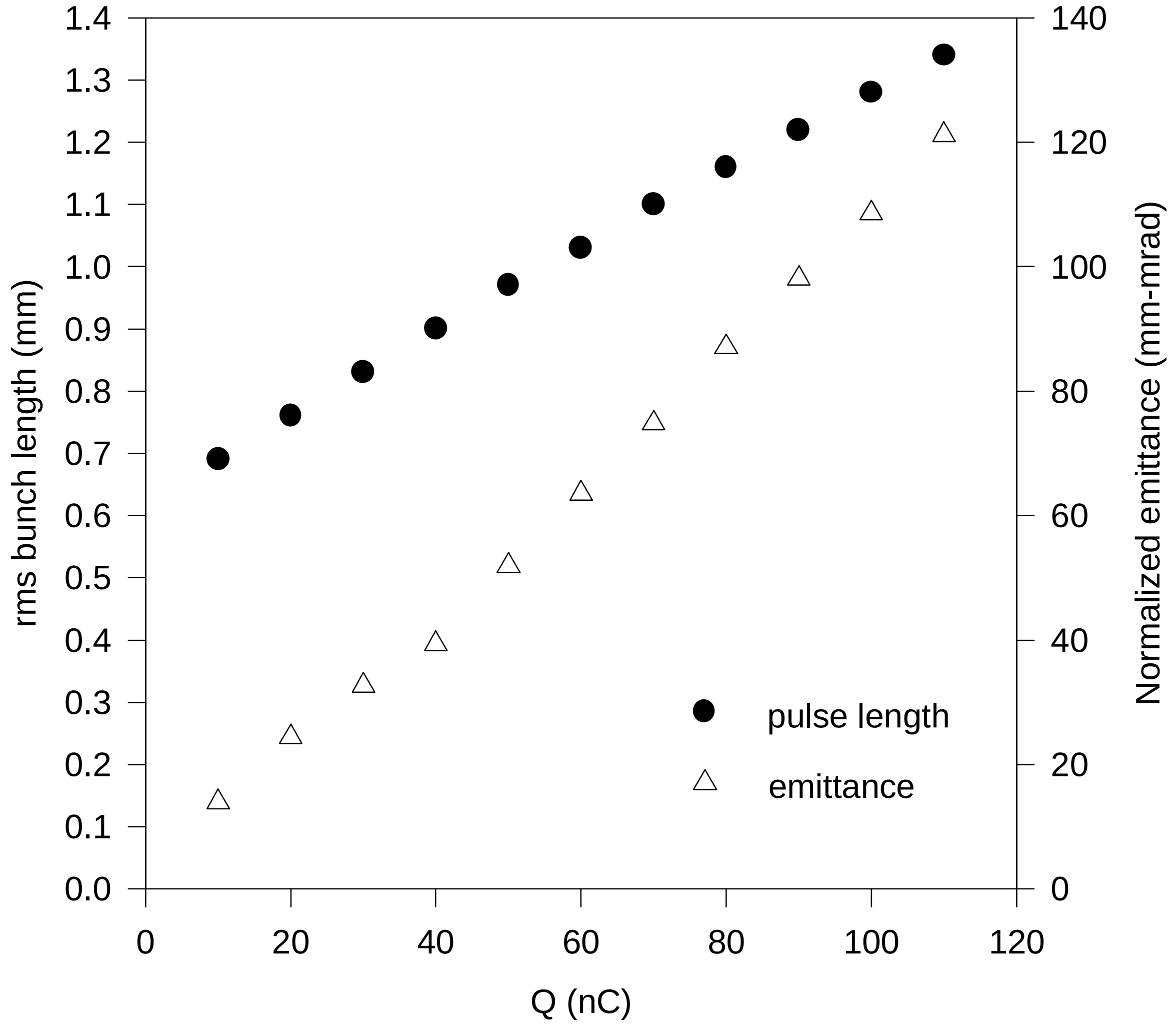

Figure 4. Electron pulse length and emittance dependence on the charge produced at the cathode. The rf injection phase and solenoid field were adjusted to optimize the pulse length and emittance for the different charges.

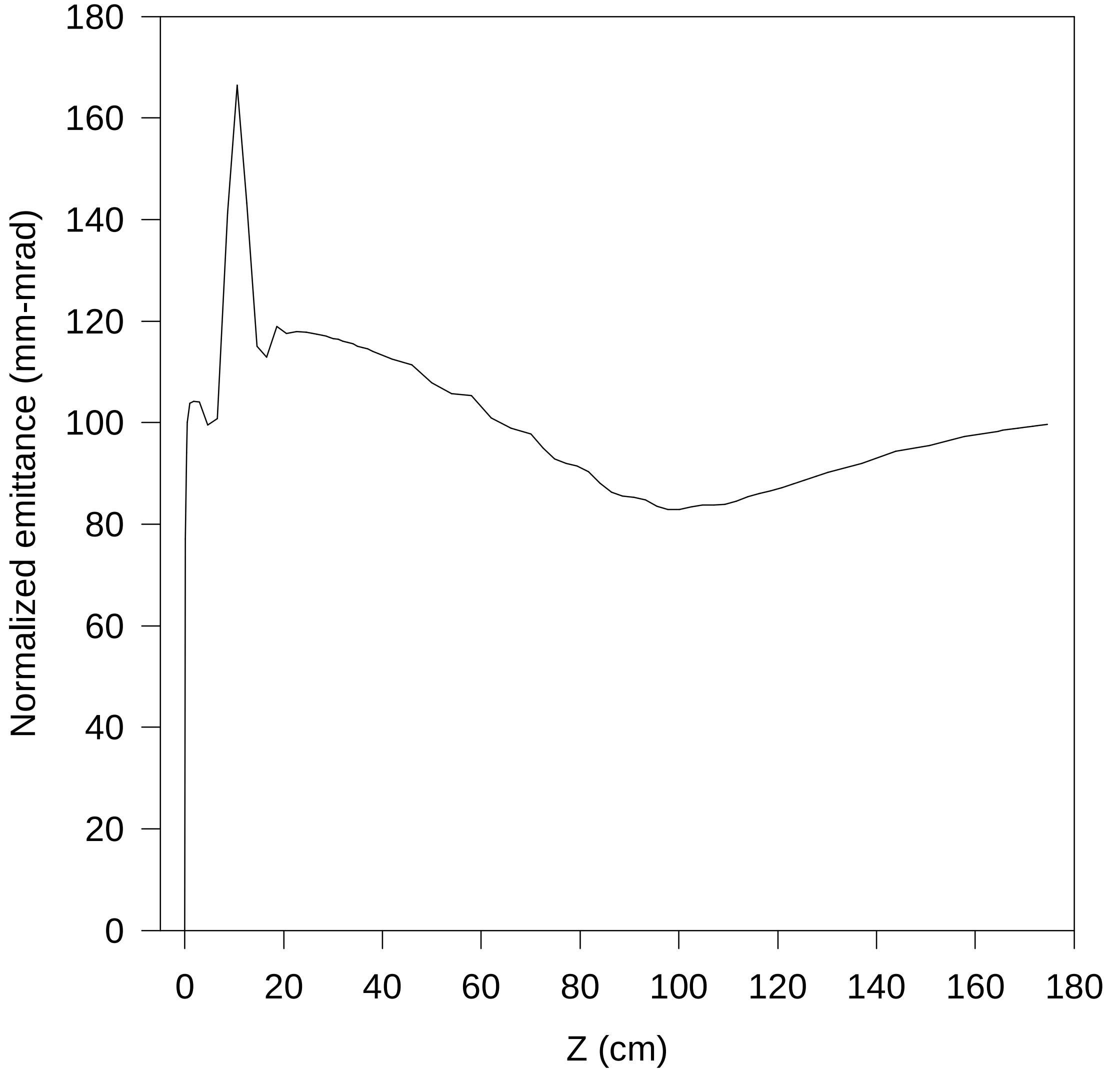

Figure 5. Evolution of the normalized transverse emittance for the 100 nC beam along the z-axis.

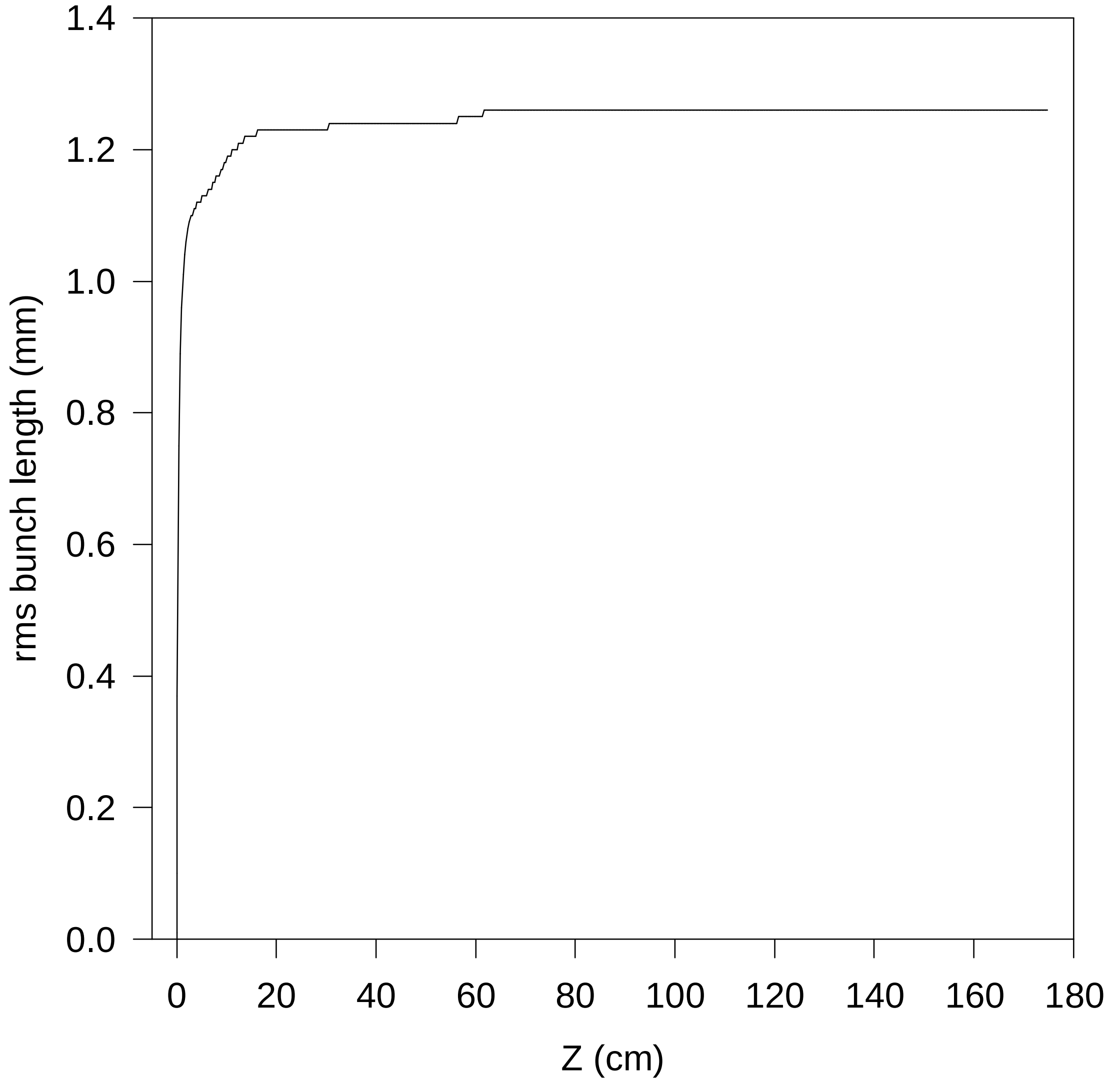

Figure 6. Evolution of the rms pulse length for the 100 nC beam with E_z =100 MV/m along the z-axis.

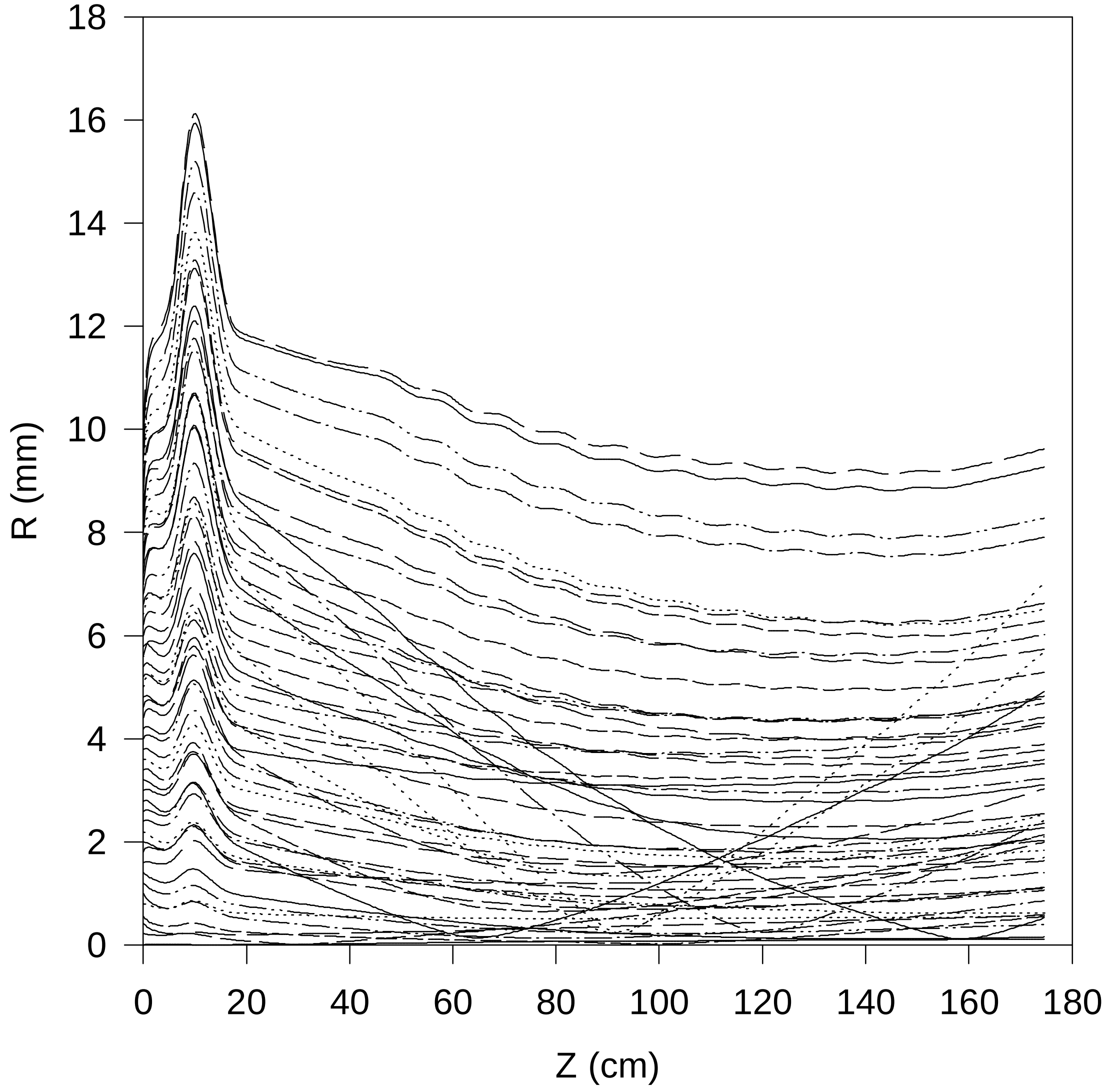

Figure 7. r-z traces of selected macro-particles in the both gun and linac for the 100 nC beam.

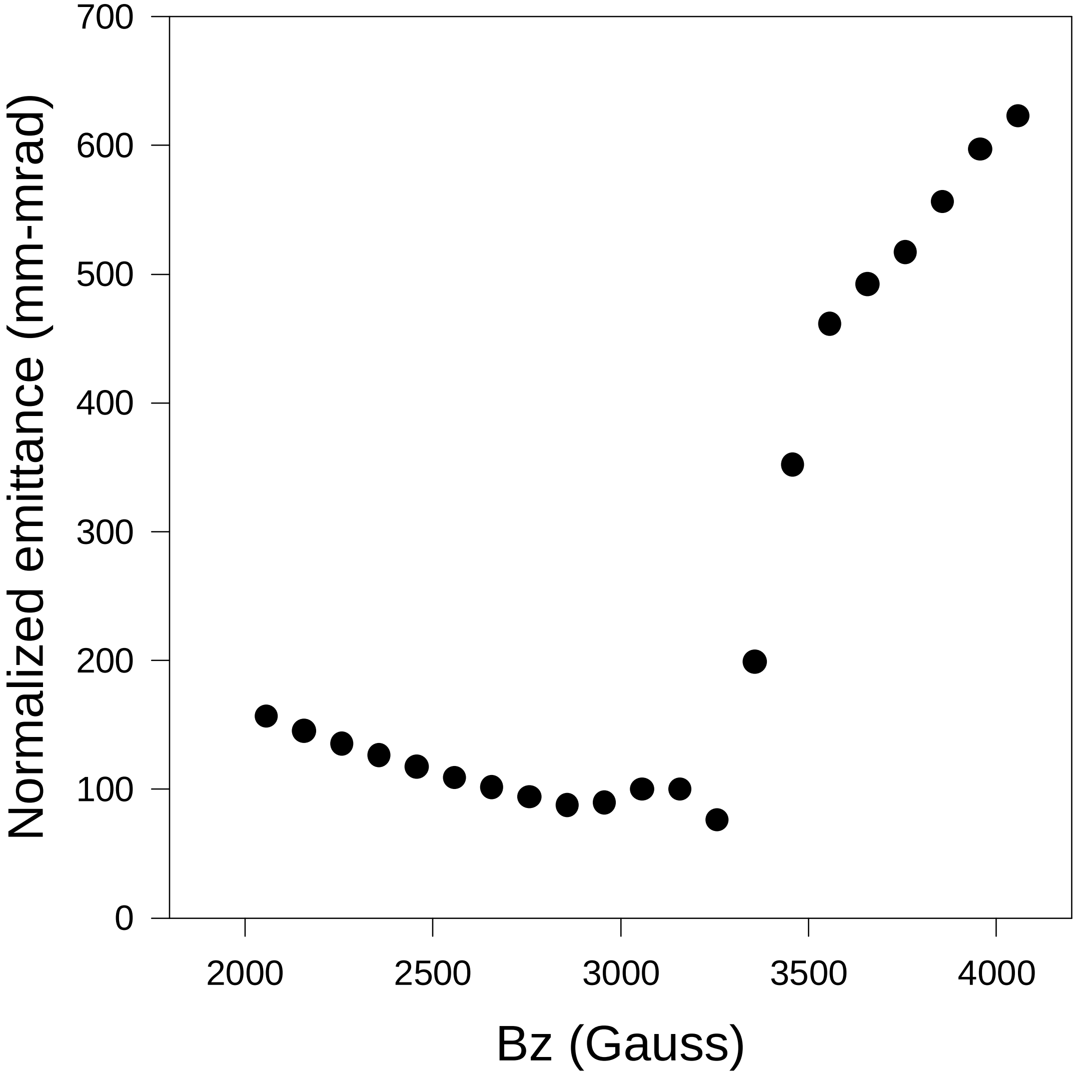

Figure 8. The rms emittance dependence on the gun solenoid axial magnetic field. The charge is 100 nC with cathode surface field of 100 MV/m.