# RAMPING LONGITUDINAL DISTRIBUTION STUDIES FOR THE FERMI@ELETTRA INJECTOR

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*Abstract*

In the FERMI Linac optimization studies it comes out the request to have at the exit of the photoinjector a linear ramp in the current distribution along the bunch as alternative option with respect to the flat-top. This requirement is translated in the photoinjector optimization in a big issue. In fact the longitudinal bunch profile at the exit of the photoinjector is affected by the strong non linearity of the space charge fields at the cathode and in the drift between the gun and the first booster. The knowledge of the space charge fields at the cathode plays in important role in finding the optimum driven laser pulse shape. At this purpose an analytical description of the space charge fields produced by a bunch with an arbitrary current distribution at the cathode is provided. Space charge codes (GPT [1] and ASTRA [2]) have been used to evaluate the evolution of several ramping profiles from the cathode to the entrance of the first booster and the results are presented in this paper.

## INTRODUCTION

In the optimization of the high brightness RF photoinjector a great effort is usually spent to produce an electron bunch as much as possible uniformly charged distributed. This is a precise requirement coming from the optimization of the emittance compensation in the injector and in the bunch transport through the linac, especially in presence of bunch compressors. By the other hand it has been demonstrated that the strong non-linearity of the linac sections longitudinal wakefields can be compensated by providing at the exit of the photoinjector a linear ramping electrons distribution instead of a flat top [3]. This requirement translates to the photoinjector optimization as a large perturbation due to the strong nonlinearity of the space charge fields at the cathode and in the drift between the gun and the first booster. To produce a ramped current bunch, a special initial profile has to be found that evolves along the injector to produce the final desired shape.

## LONGITUDINAL SPACE CHARGE FIELD ON AXIS

In order to solve this problem, the longitudinal space charge fields on axis at the cathode was investigated, since it is mainly responsible for blowing out the particles, especially in case of high peak current. In case of a uniformly charged bunch the longitudinal space charge field on axis, inside and outside the bunch, at a distance $z$ from the bunch tail is given by the following equation [4]:

$$E_z^{SC}(z) = \frac{Q}{2\pi\epsilon_0 R^2} H(z) \tag{1}$$

where H(z) is

$$H(z) = \sqrt{\left(1-\frac{z}{L}\right)^2 + \left(\frac{R}{\gamma L}\right)^2} - \sqrt{\left(\frac{z}{L}\right)^2 + \left(\frac{R}{\gamma L}\right)^2} - \left|1-\frac{z}{L}\right| + \left|\frac{z}{L}\right| \tag{2}$$

and Q is the total bunch charge, L the bunch length, R the bunch radius. For simplicity $\gamma = 1$ is assumed.
As example the figure 1 shows the field $E_z^{SC}(z)$ versus z (normalized with respect to the bunch length L) for a nominal 1nC bunch, with a radius of 1mm and a bunch length of 3mm. The flat-top current distribution at the cathode is

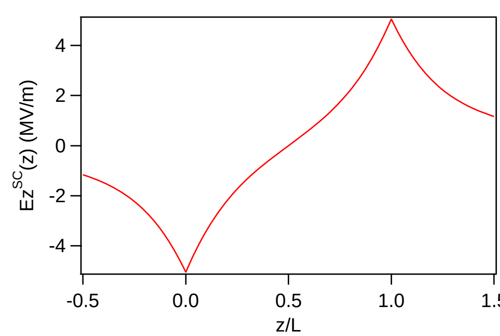


Figure 1: Longitudinal space charge field on axis of a bunch just extracted from the cathode; Q=1nC, R=1mm, L=3mm

deformed by this space charge field into a parabolic distribution after several centimeters, suggesting that a linear current distribution would suffer a strong degradation before entering into the relativistic regime. Thus the drive laser pulse should be shaped according to a non-linear distribution pattern. Eq.(1) has been generalized for an arbitrary longitudinal current density distribution $\rho(z)$ at the cathode [5], obtaining:

$$E_z^{SC}(z) = \int_0^L dz' \frac{\rho(z')}{2\epsilon_0} \left[ \frac{z'-z}{\sqrt{(z'-z)^2+R^2}} - \frac{|z'-z|}{z'-z} \right] \tag{3}$$

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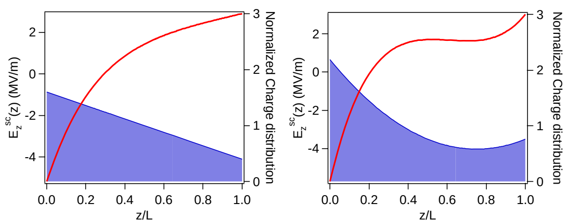
Eq.(3) represents a useful analytical instrument to quickly predict the evolution and distortion of an arbitrary current profile. For example figure 2 shows the longitudinal space charge field on axis inside a bunch with respectively a linear and a quadratic ramping in the current distribution (image charge not included). Electrons in the high charge density region are pushed backwards during the bunch propagation because of the strong repulsive electric field and this modifies the starting bunch profile.




(a) (b)

Figure 2: Longitudinal space charge field on axis of a linear (a) and parabolic (b) ramping charged bunch just extracted from the cathode having different radius; Q=1nC, L=3mm. Cathode plate is in z=0.

Figure 2a shows that a linear ramp charge distribution samples an almost quadratic longitudinal space charge field (Figure 2a). Thus one can easily expect a large deterioration of the initial ramping current profile while propagating through the injector. Multiparticles codes trackings of linear ramp profiles similar to figure 2a have confirmed the expectation and figure 3 shows the bunch current profile at the exit of the injector: the initial linear ramp has been destroyed and the bunch presents a parabolic-like charge distribution.

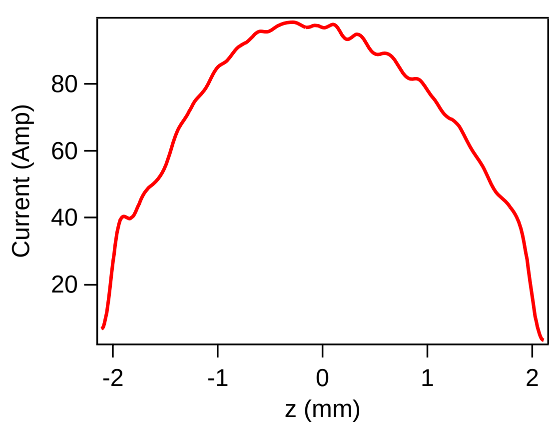



Figure 3: Resulting profile at the exit of the injector in case of an 800pC-bunch with a linear ramp at the cathode.

Also a quadratic ramp, like Figure 2b, is strongly modified during the transport between the cathode and the first booster section, but the linearity of the space charge field at least in the middle of the bunch helps in preserving the linear ramp in about 70% of the bunch (see Figure 4).

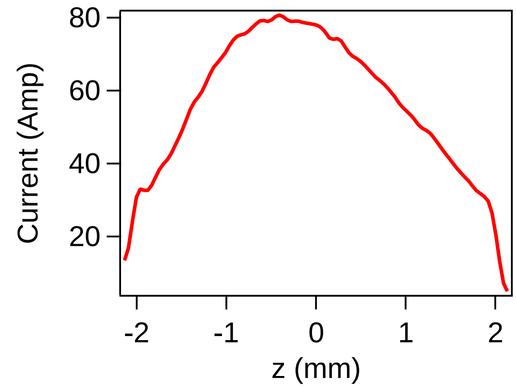
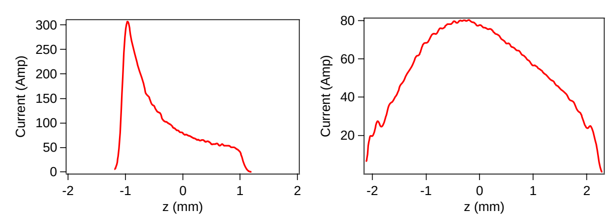



Figure 4: Resulting profile at the exit of the injector in case of an 800pC-bunch with a quadratic ramp at the cathode as Figure 2b.

Several initial current distributions have been studied in order to find the best one which linearizes as much as possible the space charge field experienced by electrons within the bunch and which evolves into the desired longitudinal profile. A fourth-degree polynomial distribution (see Figure 5) has been found to be an interesting solution that offers flexibility in compensating the high orders contributions of the space charge field and that increases the bunch fraction sampling a linear space charge field.




(a) (b)

Figure 5: A fourth-degree polynomial distribution at the cathode (a) and at the end of the photoinjector (b).

The current distribution plotted in Figure 5a has been considered as the baseline ramping distribution for the medium bunch case assuming a large efficiency in the laser pulse shaping process [6]. However in a conservative scenario even a quadratic distribution could be used without severe drawbacks.

A large charge density close to the cathode surface increases the image charge field and this should be considered in the generation of a ramping charge distribution. The effect of the image charge at the cathode can be easily included by adding the field $E_z^{SC}(-z)$ to the formula 3.
As example the space charge field with and without the image charges effects in case of a parabolic ramping charged bunch is shown in figure 6: the electrons close to the cathode sample a space charge field two times the value obtained without considering the image charges. In the optimization process and in the multiparticles trackings the

image charge effects have been included.

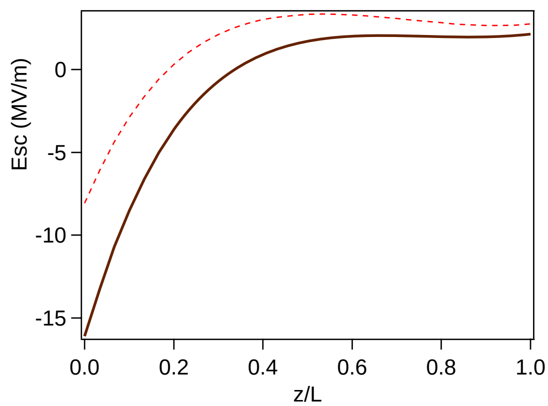



Figure 6: Comparison between the Longitudinal space charge field on axis with (continuous line) and without (dashed line) the image charges effects; Q=1nC, L=3mm

## EMITTANCE COMPENSATION AND OPTICS MATCHING ISSUES

Because of the non-uniform charge distribution of the ramping regime, it is very difficult to find an injector parameter set-up that completely satisfies the invariant envelope equation, performing perfect emittance compensation for all slices. Since each slice contains a different amount of charge, each slice evolves in a particular and unique way in the gun-booster drift when the injector parameters are fixed. In order to minimize the projected emittance at the end of the injector an average parameters setting should be found, taking in account also the slice parameters behavior along the bunch. Studies were carried on by tracking several initial laser shapes with GPT and ASTRA. A crucial role has been played by the coefficients of the quadratic ramp chosen at the cathode. For example an attractive solution is to consider a quadratic profile with “double peaks”, as showed in figure 7a. The small peak electrons are pushed forwards by the space charge field and this partially compensates the backwards spreading of the high peak electrons, increasing the linearity and the width of the ramping fraction of the bunch (figure 7b). In addition the head of the bunch presents a hard edge, instead of a smoothing falling edge. By the other hand, finding the optimum focusing condition is an issue in this case. In fact in order to compensate the emittance contribution of the high charge fraction of the bunch, the solenoid strength has been increased, leading to an overfocusing of the bunch core and head, as showed in the top view of figure 8.

Figure 9 shows the slice analysis concerning the emittance and the Twiss parameters for this case. The overfocused electrons in the middle of the bunch have even a higher slice emittance, around 1.4mm mrad. This ovefocusing has consequences also in the optics parameters: Twiss parameters suffer a very large oscillation slice by

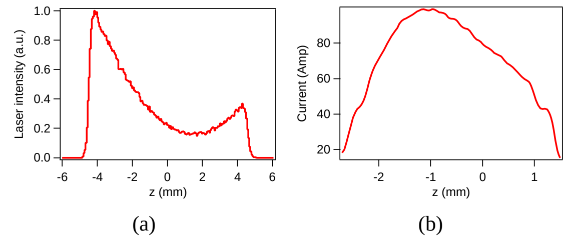



Figure 7: The “double peaks” charge distribution at the cathode (a) and at the end of the potoinjector (b).

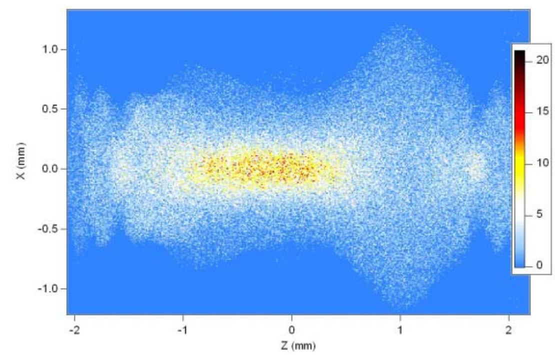



Figure 8: Top view of the evolved “double peaks” option. The initial charge distribution is translated into a transversal charge density.

slice. These modulations in $\alpha$ and $\beta$ affect not only the matching with the linac optics, but they can be even sources of microbunching instabilities when the bunch propagates through the chicanes, leading finally to enlarge the bandwidth of the FEL output radiation [7]. A different result is

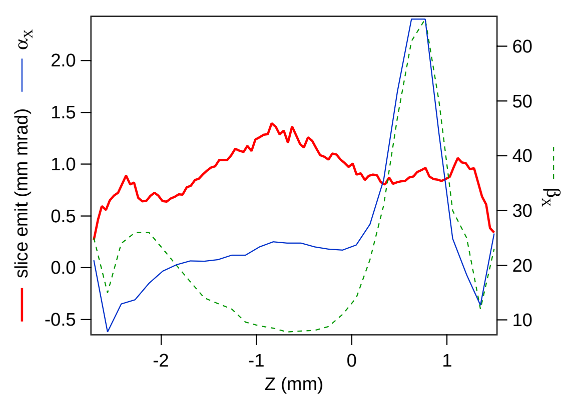



Figure 9: Slice analysis of the emittance, $\alpha_X$ and $\beta_X$ parameters for the double peaks solution.

obtained starting with a profile similar to figure 5a, which presents at the end of the injector a trasversal distribution showed in figure 10. The slice analysis have been performed as well and the results are reported in figure 11. In this case the slice emittance has a ramping behavior very similar to the ramp in the charge distribution, and no bunch

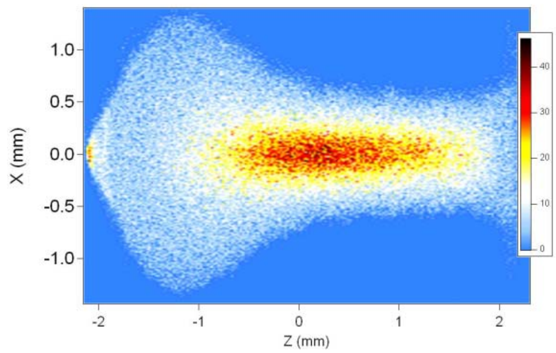



Figure 10: Top view of the evolved profile of figure 5a.

fraction is overfocused. By the way in correspondence of the high charge density the space charge field leads to increase the transversal dimension, as showed in the plot inside of figure 11. Also the slice $\beta$ and $\alpha$ functions are very high in correspondence to the high charge density, but they are quite constant in the remainder bunch fraction and this constitutes a great improvement for the linac matching

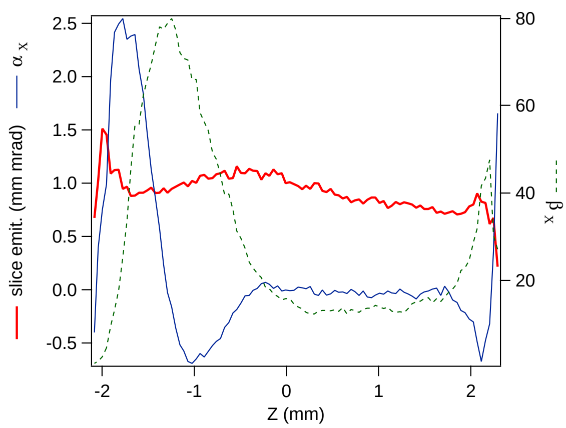



Figure 11: Slice analysis of the emittance, $\alpha_X$ and $\beta_X$ parameters for the propagated bunch of figure 5a.

## CONCLUSION

The linac requirement to have a bunch with a linear current ramp at the injector exit has been translated in studying the best current distribution at the cathode that evolves in the desired profile. An analytical description of the longitudinal space charge field on axis helps in predicting the evolution of an arbitrary current ramp before running the multiparticles space-charge codes. A quadratic current ramp at the cathode constitutes a good option to have at the end of the injector a reasonable large ramping bunch fraction.
Emittance compensation scheme has been showed to be an issue since each slice evolves in an unique way. Optimization of the injector parameters has to aim not only to minimize the projected emittance, but also to avoid overfocusing and slice emittance blowing-up, paying attention also to the behavior of the slice optics parameters. In fact tracking results have revealed that large modulation of the slice $\alpha$ and $\beta$ functions can be an issue in the bunch propagation through the linac chicanes. Finally great attention has to be paid in the choice of the coefficients of the quadratic ramp, in order to reach the best compromise between the achievement of the linear ramp at the end of the injector and emittance and optics functions slice behavior.

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