

EUROFEL-Report-2007-DS2-085

EUROPEAN FEL Design Study



Deliverable N°: D 2.12

Deliverable Title: TREDI simulation of photo-injector designs - Spectral Analysis of Charge Emission Spatial Inhomogeneities and Emittance Dilution in RF Guns

Task: DS-2

Authors: see next page

Contract N°: 011935

**Project funded by the European Community
under the “Structuring the European Research Area” Specific Programme
Research Infrastructures action**

Spectral Analysis of Charge Emission Spatial Inhomogeneities and Emittance Dilution in RF Guns.

M. Quattromini, L. Giannessi and C. Ronsivalle
ENEA, C.R. Frascati, Via E. Fermi, 45
I - 00044 Frascati (Rome), Italy.

January 15, 2008

Abstract

In this report we present the analysis of the effects of transverse dis-homogeneities in cathode's quantum efficiency on the performances of a RF photo-injector. The layout (that of SPARC experiment) is aimed at minimizing the emittance growth due to space charge effects. The numerical code used for simulations is TREDI.

INTRODUCTION

In the last decade, laser driven photo-injectors have become essential devices in all applications requiring high brightness electron beams. In the case of FELs the role played by emittance becomes crucial at sub-nm wavelengths where the emittance is related to the transverse coherence of the output radiation. Most of the emittance growth affecting the beam at the undulator is produced at the injector in the first stages of the beam acceleration. The emittance optimization procedure rely on a well established linear theory[1] which has been verified both experimentally and numerically. The optimized working point is the result of a careful design based on the assumption of highly ideal conditions (e.g. flat time structure, steep boundaries of the optical pulse impinging onto the cathode, perfect axi-symmetry of both electron beam and fields, homogeneous transverse structure of the bunch, etc), which can at the best be only partially fulfilled in practise. Many of the sources of

emittance growth are genuinely three-dimensional effects, usually not accounted for by many of the available numerical codes. In this contribution we extend the analysis presented in Refs [2] and [3] where the role played by a non uniform electron emissivity was examined. That study was performed by using two different codes based on different algorithms: the Los Alamos version of PARMELA (PARMELA-LANL)[4] and TREDI[5]. It should be considered that while both codes are capable of genuine 3D description of space charge effects, lack of a parallel version of PARMELA makes its use prohibitive for a large number of 3D simulations. For this reason, the results presented here have been obtained only with the parallel version of TREDI code. As a last remark, it should be noted that while TREDI can take into account "retarded" effects (i.e. associated to finiteness of signal propagation within the bunch), the results discussed below were derived in "static" approximation, that is assuming that self-interaction within the bunch propagate instantaneously.

PROBLEM DESCRIPTION

In order to study the effect of charge in-homogeneities on scales smaller than the beam spot radius R at the cathode surface, transverse dimensions were decoupled and described in terms of a specific vector wave-number in the Fourier space. The layout considered is that of SPARC[6]experiment, with a standard S-Band (2856 MHz), 1.6 cells, BNL type photo-injector

configuration[8], and a focusing solenoid counter-acting space charge effects followed by a drift and TW cavities for further acceleration. In absence of linac sections, a characteristic emittance double minimum[10] is expected to occur at the end of the drift. Theory dictates that careful placement of first accelerating structure at the position of the local maximum between the minima is the optimal choice to postpone the second emittance minimum at the end of acceleration. The actual working point needs to be optimized by tuning accelerating gradient, extracted charge, extraction RF phase, beam spot size, focusing solenoid strength etc. A crucial point is the requirement that both transverse and longitudinal (time) charge profile be flat at extraction. In the case considered the charge extracted is -1.1nC , the longitudinal (time) pulse has a duration of $\approx 11.25\text{ps}$ (see fig. 1) and a spot radius $R = 1.13\text{mm}$. The extraction RF phase for the centre of the bunch is 32° . No thermal emittance is included. The layout parameters are resumed in table 1.

In order to mimic cathode's quantum efficiency transverse in-homogeneities the charge distribution extracted from the cathode was modelled as a perturbation with respect to the ideal case with the following functions at the centre of the spot ([2], [3]):

$$\rho_p(x, y) = \rho_0 [1 + \delta \cdot \cos(k_n x)] [1 + \delta \cdot \cos(k_n y)] \quad (1)$$

and

$$\rho_p(x, y) = \rho_0 [1 + \delta \cdot \sin(k_n x)] [1 + \delta \cdot \sin(k_n y)] \quad (2)$$

for

$$x^2 + y^2 \leq R^2 \quad \text{and} \quad k_n = n \frac{2\pi}{R}$$

Assuming that the values of δ and k_n are small, we may write in first approximation

$$\epsilon(k_n, \delta) = \epsilon_0 + \sum_n a_{n,j} \delta^j \quad (3)$$

where ϵ_0 is the value of the unperturbed emittance and the coefficients $a_{n,j}$ show the sensitivity of the emittance to charge in-homogeneities at the scale R/n .

In the study the code was run with quite a large number of macro-particles ($4 \cdot 10^5$). The cases examined assumed that the emissivity of the cathode could vary locally from zero (the ideal case) up to 40% ($\delta = \pm 0.4$) and that the scale parameter could vary from $n = 1/2$ (larger) up to $n = 4$ (smaller). The attention was focused at estimating the effect on the normalized rms emittance at the location of the first minimum.

A previous comparison between codes in the ideal configuration, i.e. at $\delta = 0$, has shown a good agreement[9].

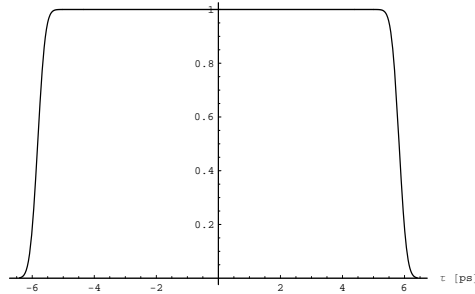


Figure 1: Longitudinal (time) profile of the laser pulse impinging onto the cathode. The distribution shown has been used for the generation of extraction times of the macro-particles from the cathode. The overall duration is 11.25 ps, with a rise/fall time of 1ps.

Table 1: Photo injector parameters.

Peak accelerating field	100-120 MV/m
Frequency	2.856 GHz
Phase (beam centre)	32°
Charge	-1.1 nC
Laser spot radius (homogeneous)	1.13 mm
Laser pulse length (flat-top)	11.2 ps
Focusing solenoid peak field	2.73 kG

RESULTS

The analysis of the results has shown that

- for all cases, quite expectedly, the best emittance achievable grows with δ ;
- the parity of the charge distribution plays an essential role on the minimal emittance achievable,
- for even-parity (“cos”-like) perturbed charge distributions, the worse cases are those with inhomogeneities occurring at the boundaries of the charge distribution, as for the case $n = 1$ shown in fig.2;

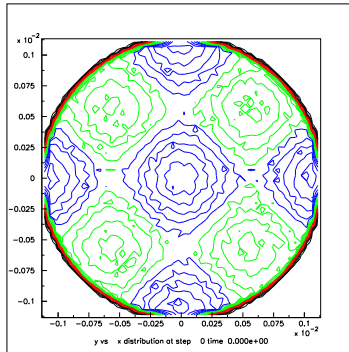


Figure 2: Transverse space for a profile described by eq. 1 with $\delta = 0.15, n = 1$.

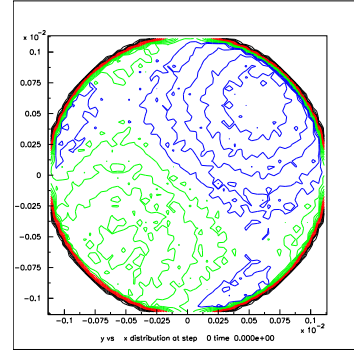


Figure 3: Transverse space for a profile described by eq. 2 with $\delta = 0.15, n = 0.5$.

- for odd-parity (“sin”-like) perturbed charge distributions, the worse case are those with large scale (i.e. small values of the wave-number k_n) inhomogeneities see fig.3;

The behaviour of the transverse emittance as a function of the longitudinal coordinate at $\delta = 20\%$, for different values of k_n is shown in figs. 4 and 5 for perturbed charge densities as of eqs. (1) and (2), respectively. The emittance undergoes a typical series of oscillations due to the changes in correlation between longitudinal slices along the bunch which are subject to different focusing as a function of the extraction phase. These oscillations exhibit the well known structure with a double minimum located at the places where the correlation is maximized. In this analysis the second minimum does not appear since it falls behind the final longitudinal coordinate.

could be related to the reduced transverse coupling of the beam with the RF photo-injector at the early stage of extraction[10].

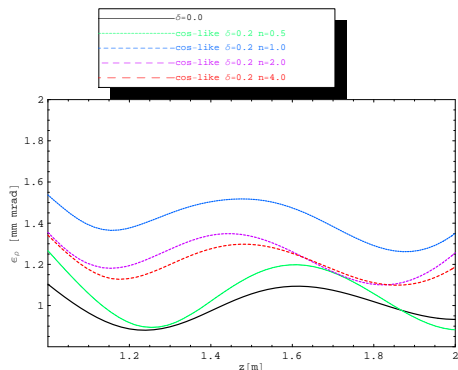


Figure 4: RMS transverse normalized emittance vs z for $\delta = 20\%$ and $n = 1/2, 1, 2, 4$ and perturbed density ρ as in eq. (1).

As an indication of the emittance growth we have considered the first minimum, whose position may depend on the in-homogeneity parameter δ especially at the lower perturbation frequencies k_n . The effect of the asymmetry in perturbed density (2) induces clearly a much larger emittance dilution at lower values of the transverse “scale” parameter k_n than for an even parity perturbation. As expected, at higher frequencies, for the same value of δ , the effect of different parity in charge distribution is negligible. This effect is clearly visible in figs 6 and 7, where the value of the normalized rms emittance divided by the value obtained with a completely uniform distribution ($\delta = 0$) is plotted as a function of n . Values of ϵ/ϵ_0 slightly lower than one are predicted unexpectedly for even parity, small δ ’s and $n = 0.5$. A possible explanation

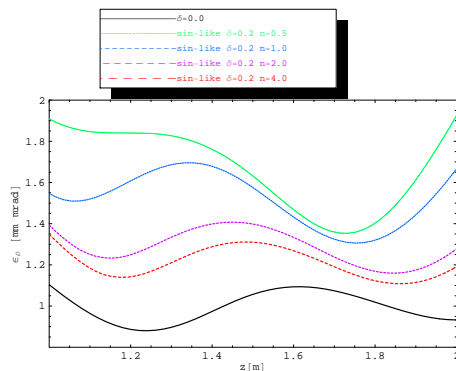


Figure 5: RMS transverse normalized emittance vs z for $\delta = 20\%$ and $n = 1/2, 1, 2, 4$ and perturbed density ρ as in eq. (2).

The emittance degradation increases with the modulation depth δ , as expected. An analysis of the data similar to that performed in Refs. [2] and [3] yielded the same scaling law at high values of k_n . In fig 8 the result of a fit of $\epsilon(\delta)/\epsilon_0$ for $n = 2$ is shown. Clearly the function $a_0 + a_3\delta^3$ fits the data better than $a_0 + a_2\delta^2$. By converse for $n = 1$ (see fig. 9) the quadratic law fits the data better than the cubic. This result is probably related to the asymmetry induced by the charge distribution (2) and is in agreement with the analysis developed in Ref. [11] where a quadratic scaling law was shown to reproduce well

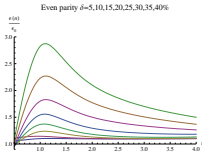


Figure 6: Emittance growth vs n for δ ranging from $\delta = 0.05$ to $\delta = 0.4$ at the position of the first minimum of the emittance for ρ as in eq. (1).

the emittance behaviour due to beam misalignments.

CONCLUSIONS

In this contribution we have extended the analysis of the emittance dilution as a function of the frequencies associated to a non axi-symmetric perturbation of the ideal transverse density extracted from the photocathode. A scaling law of this effect in function of the perturbation amplitude has been derived and some indications of the dependence of the effect with the transverse frequency have been obtained. At high k_n the results observed for a sine-like (odd) perturbation of the type (2) are similar to the predictions for a cos-like (even) perturbation like (1). At low n the results are substantially different since the parity of the initial charge distribution plays a significant rôle. Further refinement of the analysis should include cross-checks of the predictions and of scaling laws derived here against those from other numerical codes and actual quantum efficiency maps of real

cathodes. Such a task requires a significant computational effort since the number of macroparticles and the transverse mesh fineness for the evaluation of the fields grow non-linearly with the frequency associated to the transverse mode.

All the simulations described in this report were run on the parallel cluster set up with Eurofel funding at ENEA-Frascati Computer Center as one of the deliverable of DS2.

References

- [1] L. Serafini, J.B. Rosenzweig, "Envelope analysis of intense relativistic quasilaminar beams in RF photoinjectors: a theory of emittance compensation" Phys. Rev. E55 (1997) p.7565.
- [2] L. Giannessi, M. Quattromini and C. Ronsivalle, "Emittance dilution due to 3D perturbations in RF-photoinjectors", Proceedings of 9th European Particle Accelerator Conference, 5 to 9 July, 2004, Lucerne, to be published.
- [3] L. Giannessi, M. Quattromini and C. Ronsivalle, "Spectral Analysys of Charge Emission Spatial Inhomogeneities and Emittance Dilution in RF Guns", Proceedings of the 2004 FEL Conference, 27 August - 1 September, 2004, Trieste.
- [4] L. Young, J. Billen "PARMELA" LA-UR-96-1835.
- [5] L. Giannessi, M. Quattromini, "TREDI simulations for high-brilliance photoinjectors and magnetic chicanes", PRST-AB 6 120101 (2003), Web site: <http://www.tredi.enea.it>.
- [6] Sparc injector TDR, Sparc Collaboration, available at http://www.lnf.infn.it/acceleratori/sparc/SPARC_TDR.pdf
- [7] M. Ferrario et al, SLAC-PUB-8496 LCLS-TN-00-09, July 2000.
- [8] AA.VV., LCLS Design Report, SLAC-R-593, April 2002.

- [9] C. Limborg et al. "Code comparison for simulations of photo-injectors ", Proceedings PAC2003.
- [10] M. Ferrario, private communication.
- [11] F. Ciocci et al., Nucl. Instr. and Meth. A393, (1997), 434.

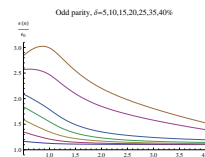


Figure 7: Emittance growth vs n for δ ranging from $\delta = 0.05$ to $\delta = 0.4$ at the position of the first minimum of the emittance for ρ as in eq. (2).

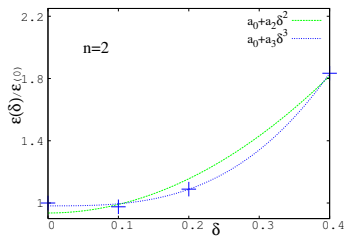


Figure 8: Emittance growth vs δ for $n = 2$ in the position of the first minimum of the emittance as computed by TREDI for ρ as in eq. (2).

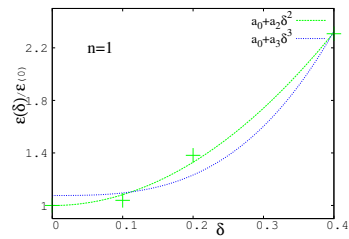


Figure 9: Emittance growth vs δ for $n = 1$ in the position of the first minimum of the emittance as computed by TREDI for ρ as in eq. (2).