SPECTRAL ANALYSIS OF CHARGE EMISSION SPATIAL INHOMOGENEITIES AND EMITTANCE DILUTION IN RF GUNS

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

Abstract

The effects of fluctuations in cathode's quantum efficiency and other sources of dis-homogeneities in the performances of a typical RF photo-injector have been investigated with PARMELA and TREDI numerical codes. The RF gun layout includes a focusing solenoid in a configuration aimed at minimizing the emittance growth due to space charge effects.

INTRODUCTION

Many applications from X-ray Free electron lasers to high energy colliders require high brightness beams produced by photo-injectors. The final performances of these devices are strictly linked to the beam quality produced by the electron source. 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 budget that characterizes the beam at the undulator is produced at the injector in the first stages of the beam acceleration. The emittance optimization procedure rely on the linear theory[1] which has been verified both experimentally and numerically. In this paper we extend the analysis presented in Ref.[2] where the role played by a non uniform electron emissivity was examined. This study has been performed by using two different codes based on different algorithms: the Los Alamos version of PARMELA (PARMELA-LANL)[3] and TREDI[4]. TREDI has been used in "static" mode, i.e. ignoring effects associated to the finite velocity propagation of signals within the bunch.

PROBLEM DESCRIPTION

The aim of this work is to study the effect of charge in-homogeneities at the cathode surface, by decoupling in a transverse Fourier space, the in-homogeneities occurring at a specific wave-number , on a scale of the beam spot radius R, and higher. We have considered a standard S-Band (2856 MHz). 1.6 cells, BNL type photo-injector configuration[5], in a set-up optimized at minimizing the emittance in terms of accelerating gradient, extraction phase, beam spot size, focusing solenoid strength. Space charge effects compensation is achieved assuming both transverse and longitudinal flat charge distribution at extraction. The gun starts at z=0 and the drifts ends at z=2 m. The peak electric field in the gun and the solenoid peak magnetic field have been set respectively to 120 MV/m and 2.73 kG. The longitudinal shape of the pulse is square with a length of 10 ps and the charge is 1 nC. The phase of the centre of the bunch is 35°. No thermal emittance is included. The beam spot radius R is 1 mm. In Ref.[2] the charge distribution extracted from the cathode was modelled as a perturbation with respect to the ideal case with the following cosine function showing a maximum on the centre of the spot:

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

for

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

In this contribution we analyze the effect of a sin-like (odd) perturbation of the type

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

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 in this injector configuration to the charge in-homogeneities at the frequency .

The study has been performed by varying the two parameters δ and n and estimating the effect on the normalized rms emittance at the location of the first minimum (fig.1). The parameter δ has been varied between 0 and 40% and n has been given the values $n = 1/2, 1, 2, 4$.

A previous comparison between codes in the ideal configuration, i.e. at $\delta = 0$, has shown a good agreement[6].

RESULTS

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. 1 and 2 for perturbed charge densities as of eqs. (1) and (2), respectively, as computed by TREDI. 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.

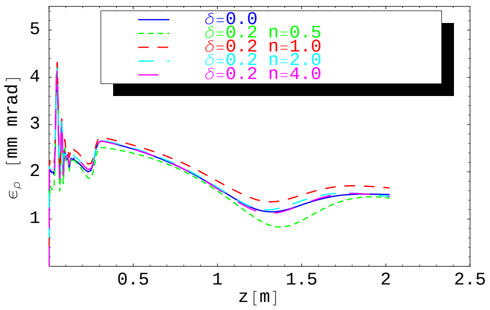

Figure 1: RMS transverse normalized emittance vs z for $\delta = 20\%$ and $n = 1/2, 1, 2, 4$ and perturbed density ρ as in eq. (1).

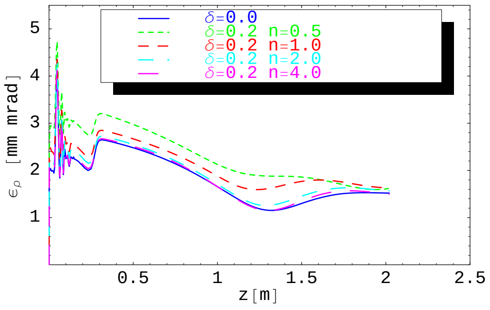

Figure 2: RMS transverse normalized emittance vs z for $\delta = 20\%$ and $n = 1/2, 1, 2, 4$ and perturbed density ρ as in eq. (2).

As an indication of the emittance of the beam 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 "frequency" k_n. As expected, at higher frequencies, for the same value of δ, the effect of different parity in charge distribution is negligible. In figure 3 the value computed by TREDI of the horizontal normalized rms emittance divided by the value obtained with a completely uniform distribution is plotted as a function of n. The data at $n = 4$ may be affected by some aliasing. The transverse mesh size used to describe the space-charge fields is 20×20 and could not be sufficient to resolve the fluctuations at $n = 4$. This may explain the slight emittance diminution observed in fig. 3. A more visible effect is predicted by TREDI for $n = 0.5$ and $\delta = 10\%$ (see fig. 4) for the charge distribution described by eq. (1). While this result is not evidenced by PARMELA, and require a further investigation, for $n \geq 1$ the two codes are in fairly good agreement and both give the maximum emittance increase for $n = 1$. A possible explanation could be related to the reduced transverse coupling of the beam with the RF photo-injector at the early stage of extraction[7].

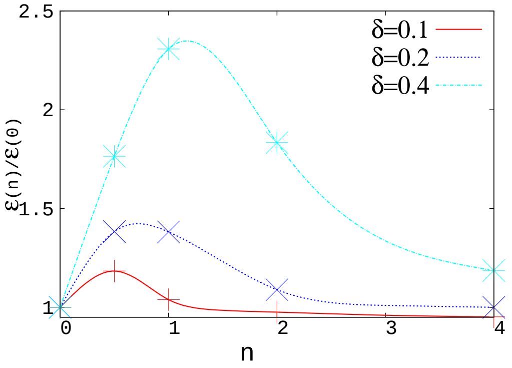

Figure 3: Emittance growth vs n in the position of the first minimum of the emittance as computed by TREDI for ρ as in eq. (2).

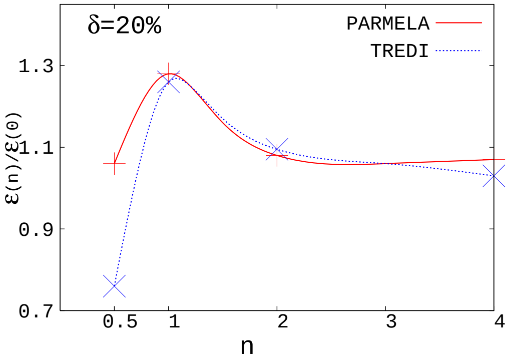

Figure 4: Emittance growth vs n in the first emittance minimum for $\delta = 20\%$ as computed by PARMELA and TREDI for ρ as in eq. (1).

This behaviour may be understood by looking at the x-y space shown in fig.5 in three longitudinal positions: at the cathode ($z = 0$), near the minimum of emittance ($z \approx 1.30\mathrm{m}$) and the local maximum of emittance ($z \approx 1.5\mathrm{m}$). The non-linear space charge forces induced by the non uniform transverse distribution at the cathode give a deformation of the beam shape. The distortion is stronger when the non-uniformities are more localized respect to the cases in which they are more diffused and tend to a partial re-compensation along the drift.

In fig 5 the action of the solenoid focusing is also visible as a rotation of the distribution around the axis.

The emittance degradation increases with the modulation depth δ, as expected. An analysis of the data similar to that performed in [2] yielded the same scaling law at high values of k_n . In fig 6 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

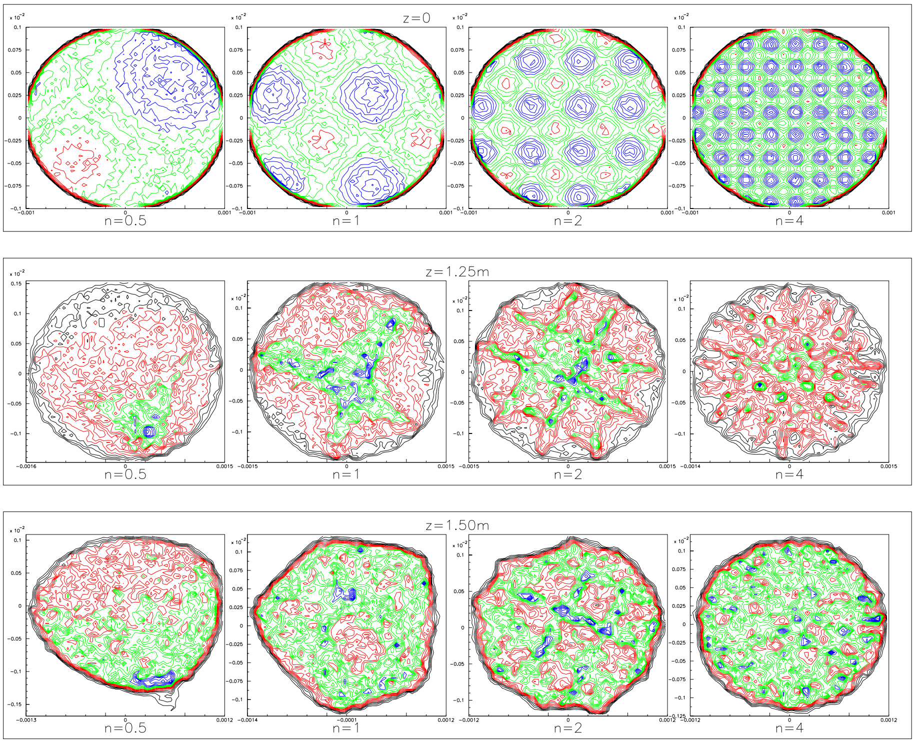

Figure 5: X-Y plots derived from TREDI computations for $\delta = 20\%$ in different longitudinal positions for ρ as in eq. (2).

data better than $a_0 + a_2\delta^2$. By converse for $n = 1$ (see fig 7) 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. [8] where a quadratic scaling law was shown to reproduce well the emittance behaviour due to beam misalignments.

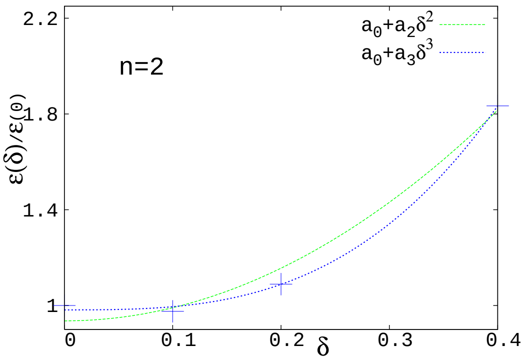

Figure 6: Emittance growth vs δ for $n = 2$ in the position of the first minimum of the emittance as computed by TREDI for ρ as in eq. (2).

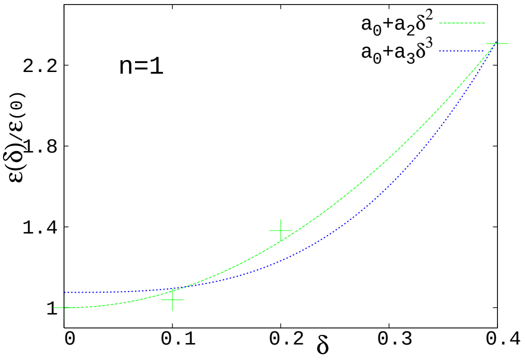

Figure 7: Emittance growth vs δ for $n = 1$ in the position of the first minimum of the emittance as computed by TREDI for ρ as in eq. (2).

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. In the future we plan to further refine this analysis and check the scaling laws derived here against the predictions from other numerical codes. 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 role. We plan to continue this study to the beam slice emittance, which is not affected by correlations between slices and is probably a better indicator of the influence of cathode inhomogeneities on the beam quality. This work will require 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.

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