THE DEPENDENCE OF LONGITUDINAL EMITTANCE UPON SURFACE CHARGE DENSITY IN A RF PHOTOINJECTOR

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Abstract
This paper describes the analysis of experimental energy spectra and pulse shapes to determine the electron distribution in longitudinal phase space produced by a RF photocathode gun for microbunch charges below space charge limited emission. It is found that the longitudinal phase space distribution cannot be represented by a simple ellipse, and requires the use of an ad hoc model in which the usual beam ellipse is distorted to fit the data and extract the emittance. The physical origins of these distortions are space charge forces at the cathode, wakefields and curvature due to the RF waveform. These effects increase the emittance by introducing correlations in the distribution, which in some situations can be corrected. In the absence of these correlations, the area of the undistorted ellipse gives the uncorrelated emittance of the photocathode gun. In this work, the uncorrelated longitudinal emittance is found to scale linearly with the surface charge density up to the space charge limit. In this experiment the increase in emittance is principally due to growth in energy spread instead of pulse length elongation. The implications these results have upon the limits of pulse compression at high charge are discussed.

1 INTRODUCTION

This paper summarizes a portion of the experimental results described in a series of papers on the longitudinal emittance from RF photocathode guns[1-4]. This work explores the high charge regime of RF guns, and attempts to document the dependence of the longitudinal emittance and its distortion upon space charge forces at the photocathode. The data show that not only is the phase space distribution distorted but is also observed to breakup longitudinally. The current paper describes the dependence of the longitudinal emittance upon surface charge density at the photocathode below space charge limited emission.

Due to the complex features of the longitudinal phase space, we have sought to develop a model-dependent analysis for fitting the data and extracting the phase space parameters. This model is used to fit both the single microbunch data and the multi-bunch case. Only the single microbunch analysis is described here. Tomographic techniques can also be used to obtain model-independent phase space distributions[5].

The paper begins by reviewing the experimental technique, followed by a description of the data analysis. The results section summarizes the emittance and phase space parameters as a function of surface charge density. Only the analysis for data below space charge limited emission are presented in this paper. (The space charge limit occurs when the planar-diode space charge field exceeds the RF field at the photocathode surface.) The paper ends by estimating the limits of microbunch compression due to the longitudinal emittance.

2 THE EXPERIMENTAL TECHNIQUE

The details of the experimental configuration are described elsewhere[1,6] and therefore are only briefly given here. The ELSA (Etude d'un LaSer Accordable) free electron laser (fel) facility in Bruyeres-le-Chatel, France consists of a 144 MHz, one cell RF photocathode gun followed by three additional 433 MHz accelerator sections. The beam energy after the gun is 1.8 MeV and the final energy is 17.5 MeV. Following the accelerator is a three dipole, non-isochronous 180 degree bend (called the demi-tour) which in the fel experiments is used to compress the microbunch before injecting it into the wiggler. The beam energy spectrum is obtained at the center dipole of the demi-tour where the beam is dispersed, and the pulse shape is measured with a streak camera after the bend. Optical transition radiation view screens are used to image the beam.

The experiment consists of measurements of the beam energy spectra and pulse shapes at the full beam energy of 17.5 MeV for microbunch charges of 0.5, 1.0 and 2.0 nC over a range of the main, 433 MHz accelerator RF phases in order to deduce the electron distribution in longitudinal phase space at the exit of the RF gun.

3 THE DATA ANALYSIS

The data is analyzed by assuming the electron distribution in longitudinal phase space lies within an ellipse whose is distorted by quadratic and cubic terms[2,4],

$$\Delta E = \pm\sqrt{\left(\frac{\tau_{12}}{\tau_{11}}\Delta t\right)^2 - \frac{\tau_{22}\Delta t^2 - \frac{\varepsilon_l^2}{\pi}}{\tau_{11}}} + \frac{\tau_{12}}{\tau_{11}}\Delta t + a\Delta t^2 + b\Delta t^3 \qquad [1]$$

Here Δt and ΔE are the phase space variables of the time and energy difference with respect to the reference particle. The quantities, τ_{11}, τ_{12} and τ_{22}, are the elements of the longitudinal beam matrix and are related to the longitudinal emittance, ε_l, by

$$\pi\varepsilon_l = \pi\sqrt{\det\tau} = \pi\sqrt{\tau_{11}\tau_{22} - \tau_{12}^2} \qquad [2]$$

The longitudinal phase space distribution is nearly identical to the transverse beam matrix[7], except for the quadratic and cubic distortions whose strengths are given by the coeficients, a and b. The effect these terms have upon the phase space ellipse is shown in Figure 1.

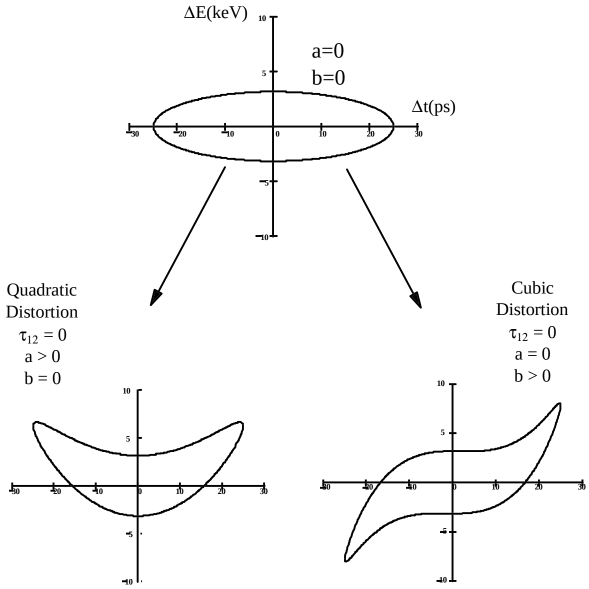

Figure 1. Distortions of the longitudinal phase space ellipse.

The analysis assumes the electron distribution is established inside the RF gun, after which it obeys simple transformation relations. The transformation of each macroparticle's energy and time coordinate, relative to the central ray, from the exit of the 144 MHz RF gun (Δt_0,ΔE_0), to the entrance of the demi-tour, (Δt_1,ΔE_1), (see References 1,4) is given by

$$\Delta E_1 = \Delta E_0 + E_{433}(\cos(\phi_{433} + 2\pi f_{433}\Delta t_0) - \cos(\phi_{433}))$$
$$\Delta t_1 = \Delta t_0$$

E_{433} is the maximum energy gain a macroparticle can achieve when on the crest of the rf wave form, ϕ_{433} is the phase of the central ray relative to the rf crest and f_{433} is the RF frequency. These relations assume the beam is relativistic, and no velocity bunching or debunching is possible. This is valid since the electrons are relativistic after leaving the injector cavity. Similarly the transport around the demi-tour is given in terms of its non-isochronicity, δ,

$$\Delta E_2 = \Delta E_1, \quad \Delta t_2 = \Delta t_1 + \delta \Delta E_1$$

These simple relations are used to propagate the phase space distribution from the exit of the RF gun through the 433 MHz accelerator and around the demi-tour. The interior of the distorted ellipse is first uniformly populated with a gaussian electron distribution of typically 1000 to 3000 macroparticles. The macroparticles are then individually transformed through the accelerator and the bend to obtain the distributions at the locations measurements are made. Projections of the transformed phase space distribution are performed to obtain the computed energy spectra and pulse shapes for comparison with the data. The initial phase space parameters are then varied to best fit the observed energy spectra and pulse shapes for each micropulse charge.

4 RESULTS OF THE ANALYSIS

Typical fits to the data are shown in Figure 2. The data is for a microbunch charge of 1.0 nC and the 433 MHz RF phase adjusted for minimum energy spread. The corresponding phase space distributions are given in Figure 3. The phase space labeled 'After Bend' is the final distribution at 17.5 MeV whose projections are plotted with the data in Figure 2. The upper distribution, labeled 'Exit of Gun', is the deduced 1.8 MeV microbunch phase space at the RF gun exit. Comparing Figure 3 with Figure 1 shows the dominant distortion is cubic with a zero quadratic term. Similar distributions are obtained for the data analyses at 0.5 and 2.0 nC.

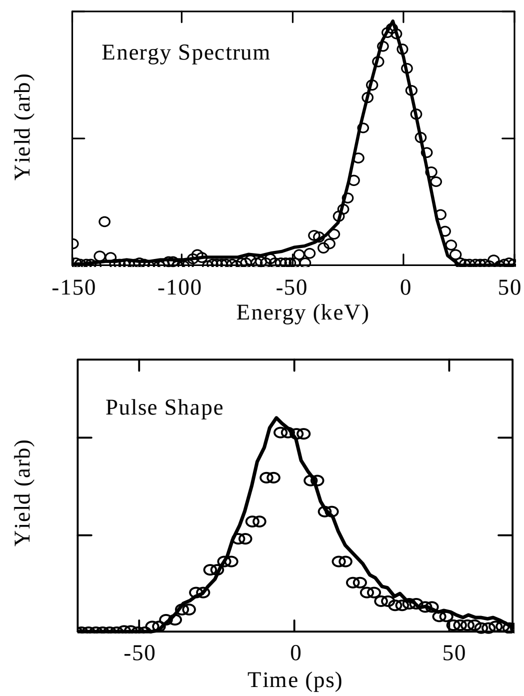

Figure 2. Fits of the 17.5 MeV energy spectrum (in the middle of the demi-tour) and pulse shape (after the demi-tour) for a microbunch charge of 1 nC. The rf is adjusted for minimum energy spread. The data is plotted as circles and the solid curves are the projections of the phase space distribution shown as 'After Bend' in Figure 3.

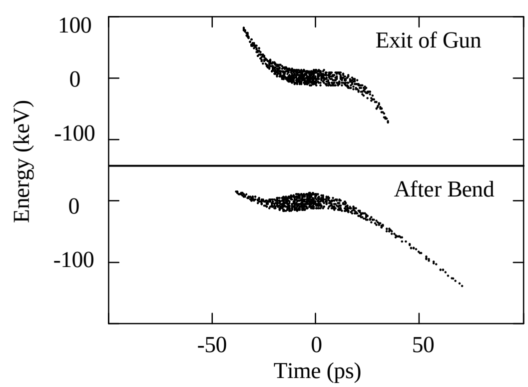

Figure 3. Longitudinal phase space distributions obtained from fitting the data in Figure2.

Ignoring the distortion terms and applying Equation 2 allows us to obtain the experimental, uncorrelated longitudinal emittance as a function of the surface charge density. Since the space charge electric field scales linearly with the surface charge density, this is used as the independent variable in the following figures. Figure 4 shows that the emittance varies linearly with the surface charge density.

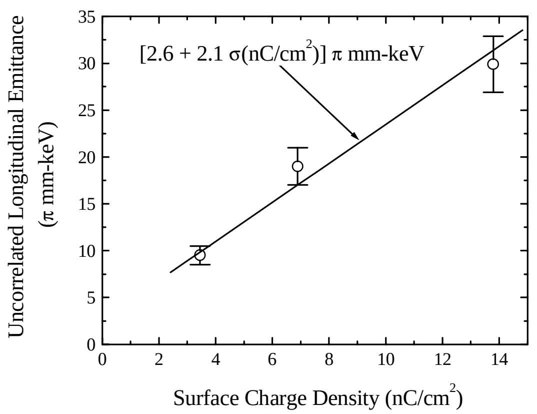

Figure 4. The uncorrelated, rms longitudinal emittance as a function of the surface charge density.

The analysis also shows the growth in longitudinal emittance results primarily from an increase in the uncorrelated energy spread, as shown in Figure 5, with negligible pulse length elongation. This occurs because, as the starting point for all the measurements, the launch phase of the electron microbunch from the photocathode is adjusted in concert with the 433 MHz RF phase for a

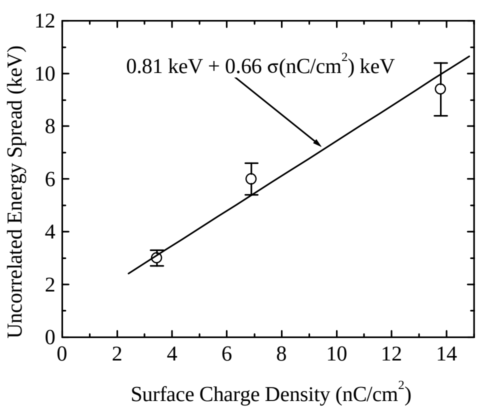

Figure 5. The uncorrelated, rms energy spread vs the surface charge density at the exit of the RF gun.

beam with minimum energy spread. This tuning algorithm tends to minimize any space charge driven pulse elongation by ballistically bunching the microbunch in the RF gun. Therefore we deduce a nearly constant width (11ps, rms) electron pulse at 0.5, 1.0 and 2.0 nC per microbunch. This is approximately the same length as that of the drive laser micropulse.

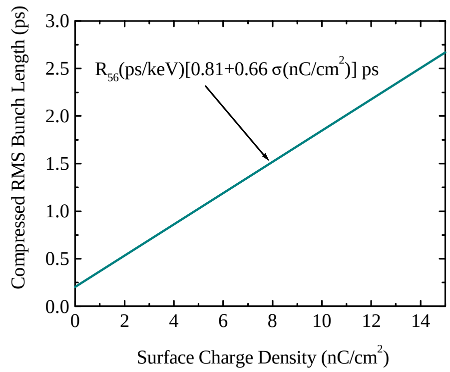

Figure 6. The compressed microbunch length acheived using the longitudinal data shown in Figures 4 and 5. The compressor R_{56} is 0.25 ps/keV.

Given these results for the longitudinal emittance it is straightforward to estimate the compressed microbunch length in a magnetic buncher. As an example, consider the demi-tour used in this experiment which has a rather aggressive non-isochronicity of 0.25 ps/keV. In this case, one finds the minimum microbunch lengths shown in Figure 6. These results include only the uncorrelated emttance, and in general any correlations will increase this microbunch length.

5 CONCLUSIONS

Space charge limited emission for this RF gun occurs near a surface charge density of 20 nC/cm^2 at an electric field of 22 MV/m. One could expect that doubling the applied RF field from 25 to 50 MV/m would reduce the slope of the emittance growth from 2.1 to 1 π mm-keV, as should be the case for higher gradient guns.

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