

SIMULATIONS AND EXPERIMENTS OF ELECTRON BEAMS PRE-MODULATED AT THE PHOTOCATHODE*

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Abstract

The University of Maryland and the Source Development Laboratory at Brookhaven National Laboratory have been collaborating on a project that explores the use of electron beam pre-modulation at the cathode to control the longitudinal structure of the electron beam. This technique could be applied to creating deliberate modulations which can lead to the generation of terahertz radiation, or creating a smooth profile in order to suppress radiation. This paper focuses on simulations that explore some of the pre-modulated cases achieved experimentally.

INTRODUCTION

In this work, a laser pulse train consisting of several sub-picosecond pulses was used to illuminate a photocathode in an RF accelerator. This pulse train created a similar electron bunch train at the cathode. The intent of the work was to study both electron beam dynamics and terahertz radiation generated by such a pre-modulated electron beam.

Any electron beam modulation has a strong effect on the radiation that could be generated by the beam. Specifically, the energy of radiation generated is given by

$$W_{tot}(\omega) = W_1(\omega)(N_e + N_e(N_e - 1)f(\omega)) \quad (1)$$

where W_1 is the energy generated by 1 electron, N_e is the number of electrons in the bunch, and $f(\omega)$ is the form factor. The form factor is a number between 0 and 1, and is related to the geometry of the electron beam. The form factor is given by

$$f(\omega) = \left| \int d\vec{r} S(\vec{r}) e^{i\frac{\omega}{c} \hat{n} \cdot \vec{r}} \right|^2 \quad (2)$$

If the beam is tightly bunched such that the separation between the bunches in a train is on the order of wavelength λ , then the form factor approaches 1 at that wavelength. If the beam is not bunched compared to that wavelength, the form factor approaches zero. In this way, the form factor provides a useful description of the beam bunching. Fig.1 shows examples of two electron beam

envelopes; one is a longer pulse, while the other is broken into smaller pulses that form a bunch train. Figure 2 shows the form factor for each of these

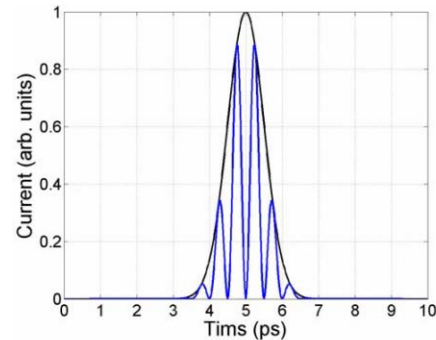


Figure 1: Examples of (black) Long electron beam pulse and (blue) a bunch train of electron pulses

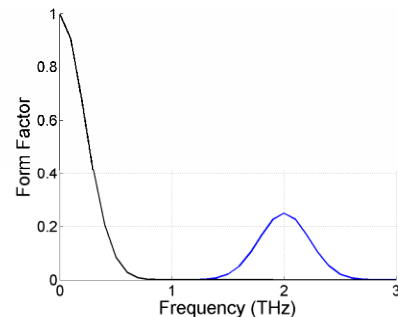


Figure 2: Form factor for (black) long electron beam pulse and (blue) pulsed bunch train.

The effect of the geometry on the form factor is clear in Figures 1 and 2. In this work, the simulation code PARMELA [1] is used to model electron beams that are pre-bunched at the photocathode, and the bunched nature of the beam is described with the form factor.

FACILITY DESCRIPTION

The Source Development Laboratory at Brookhaven National Laboratory houses the Deep Ultraviolet Free Electron Laser (DUV-FEL) facility. Experiments with pre-bunched electron beams were conducted at the DUV-FEL, and the simulations are based on a model of this facility. The photocathode system is driven by a Ti:sapphire laser pulse that is frequency tripled to 266 nm. The laser profile was measured with a scanning cross-correlator [2], and an example of a modulated laser pulse is shown in Fig. 3. The electron emission at the photocathode was assumed to be prompt [3], and so the

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input profile for the simulation was assumed to be identical to the laser profile.

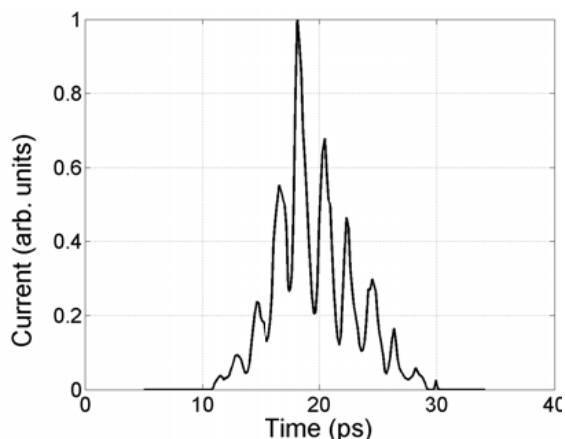


Figure 3: Laser input profile used to generate initial electron distribution in PARMELA.

The simulation consisted of a model of the RF gun, which accelerated the beam to approximately 4 MeV. The simulation continued through a single accelerating section, where the final energy of the beam was 34 MeV. In the experiment, the beam was accelerated through another section to 73 MeV, and was intercepted by a mirror. Transition radiation was measured experimentally, but no radiative effects were included in the simulation.

SIMULATION RESULTS

The simulations show that space charge has a strong effect on the final geometry of the electron beam. Fig. 4 shows the longitudinal density profile of the electron beam after it has been accelerated to 34 MeV in the simulation.

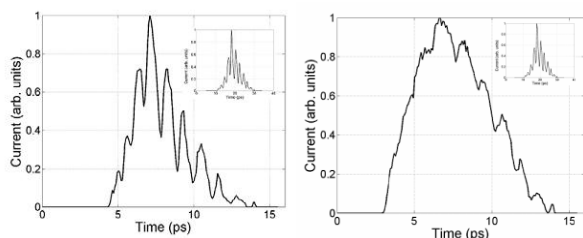


Figure 4: Electron beam longitudinal density after acceleration to 34 MeV for (left) 20 pC and (right) 200 pC.

Fig. 4 shows that as the charge increases, the density modulation in the longitudinal dimension initially imposed by the photocathode drive laser appears to wash out. It is useful to look at the longitudinal component of the form factor to see how the geometry of the beam changes with charge.

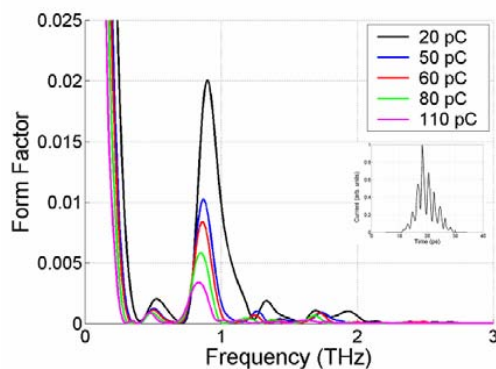


Figure 5: Variation of form factor with charge for pre-modulated electron beams accelerated to 34 MeV in the PARMELA simulation.

Fig. 5 shows the form factor for the simulated pre-modulated beam at 34 MeV for various amounts of total charge in the bunch train. The local maximum of the form factor near 1 terahertz drops as a function of charge, as does the frequency at which this maximum occurs. In Fig. 6, the peak of the form factor is plotted for three different bunch charges as a function of distance along the accelerator.

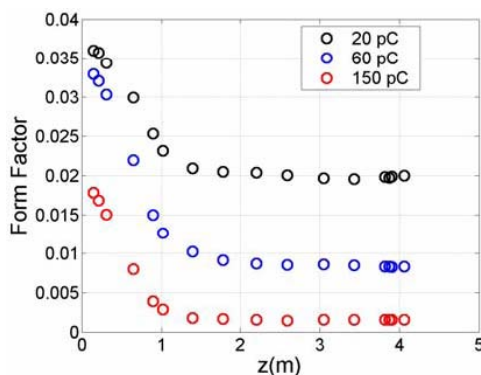


Figure 6: Peak form factor as a function of z .

In Fig. 6, the form factor drops steadily during the initial stages of acceleration, and stabilizes after reaching approximately 9 MeV. It should be noted that there is a drift section between the RF gun and the first accelerating section.

Longitudinal profile measurements were also taken experimentally at the DUV-FEL facility. The measurements were made by projecting phase space diagrams that were recreated using a tomographic reconstruction technique onto the longitudinal axis [4]. For comparison, some longitudinal profiles generated by the PARMELA simulations are compared with experimental results in Fig. 7.

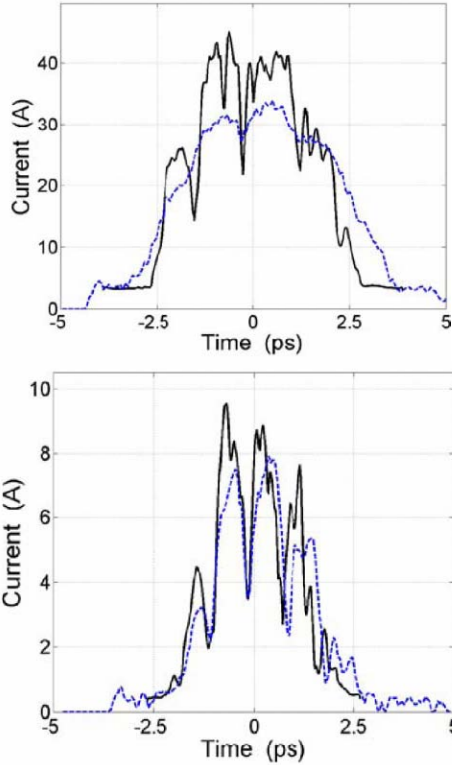


Figure 7: Longitudinal profile measurements (solid black) compared with simulations (dashed blue) for a 160 pC beam (top) and a 20 pC beam (bottom).

In Figure 7, there appears to be better agreement between the simulation and experimental data at lower charge. However, both experiment and simulation indicate that the density modulation is affected by space charge, and as expected, these effects are greater at higher charge.

The simulations also allowed the exploration of a parameter domain that was not available experimentally. For example, it was impossible to measure less than 20 pC experimentally. However, simulations can reveal information about cases at very low levels of charge. Fig. 8 is a plot of the peak value of the form factor over a wide range of charge levels determined through the use of the simulation.

In Fig. 8, the peak form factor is relatively stable at low levels of charge. The form factor begins to decay at charge levels near 3 pC. In the experimentally achievable range between 20 pC and 160 pC, the form factor falls rapidly, indicating that space charge forces are causing washout in density modulation.

Although the density modulation washes out, information from the modulated laser can still be seen in the phase space diagram, and it may be possible to recover density modulation using a dispersive section. Fig. 9 shows a sample phase space diagram from PARMELA at 20 pC.

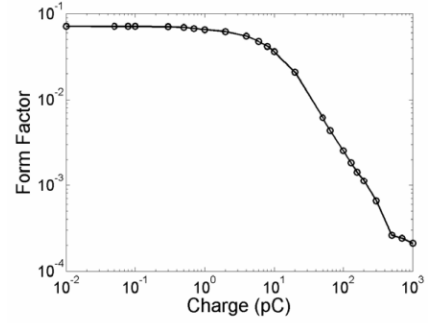


Figure 8: Form factor as a function of charge.

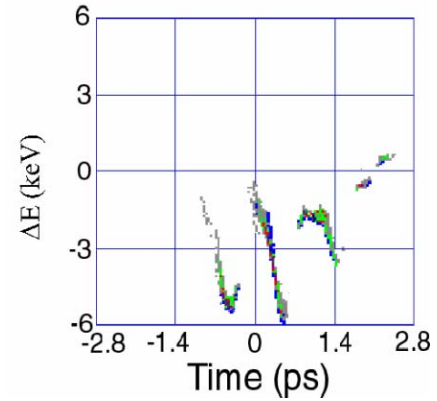


Figure 9: Longitudinal phase space plot for a 20 pC pre-bunched electron beam.

CONCLUSION

PARMELA simulations were useful for examining the bunch form factor for an electron beam that is pre-bunched at the photocathode in an RF accelerator by a sub-picosecond pulse train generated on the drive laser. Space charge strongly affects the modulation depth of the electron beam, although the modulation is still visible in phase space even if the density modulation is reduced. At extremely low charge levels (~ 3 pC and below), the density modulation is unaffected, as evidenced by the stability of the form factor as a function of charge.

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