SIMULATIONS OF FIELD EMITTED DARK CURRENT DYNAMICS IN DC PHOTOINJECTORS

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Abstract

Field emission is a concern in injectors with DC photoelectron guns because of the constant generation of dark current, which is accelerated down the beam line and can deteriorate the photoemitted bunch quality and lead to hardware damage. Simulations were carried out on the co-propagation of a field emitted, dark current halo and a photoemitted bunch in a typical 350 kV gun as used in an ERL or FEL injector, followed by a single cell buncher cavity. The photoemitted bunch repelled the halo longitudinally, leaving the area in the centre of the bunch with very low dark current, surrounded by two peaks of relatively high current at the front and back of the bunch. The peaks in current occur at all levels of dark current and were about 3.5 times the amplitude of the undisturbed dark current. The buncher caused the dark current to overcompress, forming a "ghost" pulse an order of magnitude larger than the initial level of dark current, in front of the photoemitted bunch.

INTRODUCTION

Photocathode DC guns have become popular as electron sources for Energy Recovery Linacs (ERLs) [1-3] and proposed high repetition rate Free Electron Lasers (FELs) [4] because of the high brightness and high average current beams they can produce. Beam quality may deteriorate because of space charge effects, which decrease at higher beam energy, therefore it is favourable to operate the injection system at the maximum voltage; which typically is in the range 300 – 500 kV [1-3]. The high gradient in the gun causes field emission at the cathode surface, as described by the well known Fowler-Nordheim equation [5]

$$J_{FN} = \frac{1.54\cdot 10^{-6}\cdot 10^{4.52\phi^{-0.5}}\cdot(\beta E)^2}{\phi}\cdot exp\left(\frac{-6.53\cdot 10^9 \phi^{1.5}}{\beta E}\right) \qquad (1)$$

where: J_{FN} – current density in A/m^2, ϕ - work function of the material in eV, E – electric field strength in V/m, and β - field enhancement factor, which is a dimensionless value commonly used as a measure to compare the field emission from different surfaces. In the simulations, it was assumed an antimonide photocathode with a 1.9 eV work function was used.

The field emitted electrons are collectively known as dark current and in a DC field all dark current is accelerated down the beam line. This can cause problems because the dark current can interact with the photoemitted bunch in the beam line, or collide with equipment and damage it.

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The initial results are shown for simulations of a photoemitted electron bunch moving through a DC electron gun and buncher cavity, typical of any ERL or FEL injector, whilst surrounded by a uniformly distributed dark current halo.

SIMULATIONS

Description of Simulated System

Simulations were performed in ASTRA [6] of a 20 ps long electron bunch being emitted from the photocathode of a laser driven, DC-photoelectron gun, surrounded by a 1 ns long, field emitted, dark current halo. The peak, on axis gradient in the gun was 8.4 MV/m with a final particle energy of 350 keV. A bunch charge of 100 pC was used, typical of a FEL or ERL. A focussing solenoid was placed 0.2 m after the photocathode to provide a constant beam size up to 2 m from the photocathode. Figure 1 shows typical behaviour of the transverse profile of the photoemitted bunch and dark current in the simulations. As the level of dark current was much lower than the current of the photoemitted bunch, this was independent of the level of dark current in the system.

The initial transverse distribution of the photoemitted bunch and dark current were 2 mm and 4 mm flat top radii respectively; the typical sizes of an ideal laser spot size and photocathode. All dark current was assumed to be due to field emission from the photocathode and was varied between 1 nA – 10 mA, which from Eq. 1 gives a range of β between 45 - 75. A large range was used to investigate how the interaction between the photoemitted bunch and dark current was affected by the initial level of dark current. The larger values of dark current used in these simulations could occur in a real machine if other emission sources were considered, such as halo generated by the laser and field emission from a larger area of the cathode surface and from the gun electrodes. Two distributions were made in the same input file to create the photoemitted bunch and dark current with different

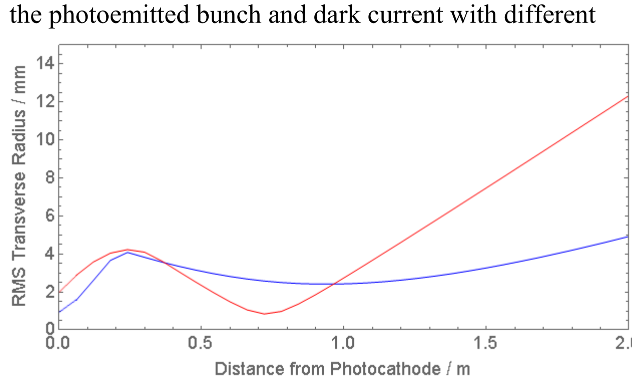

Figure 1: RMS transverse radius of photoemitted bunch (blue) and dark current (red) along the beam line.

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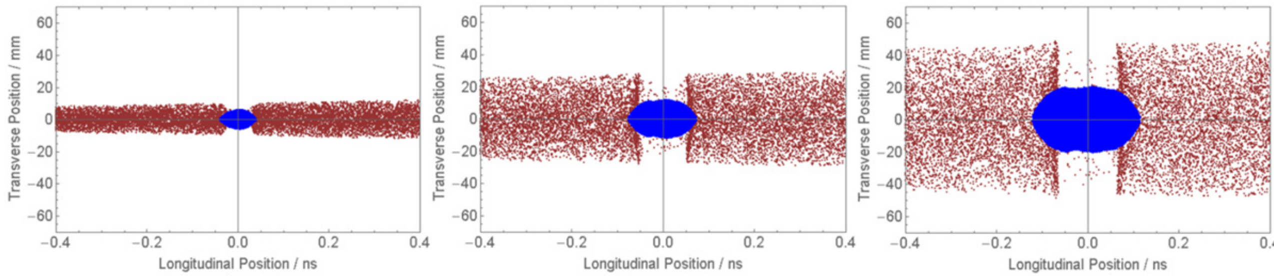

Figure 2: Longitudinal particle distribution for the simulation with 10 mA dark current, shown at different positions in the beam line. From left to right: 1.2 m, 2.07 m and 3.0 m from the photocathode. The macroparticles for the photoemitted bunch (blue) and dark current (red) are shown.

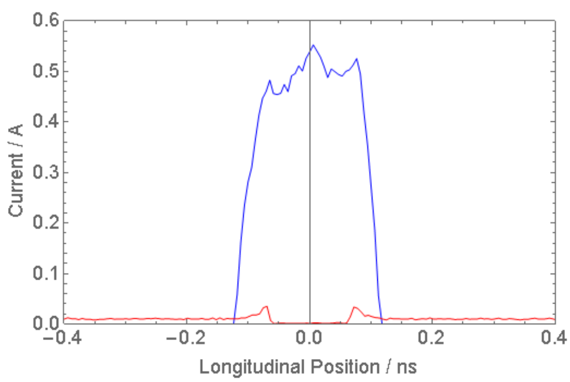

Figure 3: Current profile of photoemitted bunch with 10 mA dark current at 3 m from the cathode, the dark current (red), the photoemitted bunch (blue) are shown.

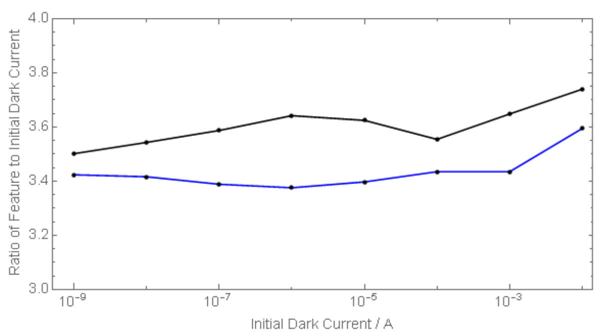

Figure 4: Ratio between the front (blue) and back (black) peaks in dark current and the initial level of dark current, results were taken at 3 m from the photocathode.

properties. The charge of the dark current macroparticles was varied to simulate the large range in dark current and keep the number of macroparticles below one million. The charge of the photoemitted bunch macroparticles was kept constant. This kept the computation time of a single ASTRA run under 24 hours.

Results Without the Buncher

Figure 2 shows the longitudinal particle distribution of the data with 10 mA dark current. A region of very low dark current density in the area within the photoemitted bunch developed down the beam line. Also, at the leading and trailing edges of the bunch there were two regions of relatively high dark current, which are clearly shown in the current profile (Fig. 3). This was caused by the larger space charge of the photoemitted bunch repelling the central dark current, causing it to blow out longitudinally. The position of the dark current peaks were consistently within the photoemitted bunch, implying the rate of peaks separation slowed to below the rate of the photoemitted bunch expansion. This occurred because the space charge in the photoemitted bunch decreased as it became larger.

10 mA dark current is shown as an example to clearly demonstrate the effects. Figure 4 shows that the amplitude of the dark current peaks were consistently about 3.5 times the level of undisturbed dark current, implying the peaks in current also form at lower levels of dark current.

Effects of the Buncher Cavity

The simulations were repeated with the addition of a single cell, 1.3 GHz buncher cavity positioned 1.3 m from the photocathode, the size of each RF bucket in the buncher was approximately 0.769 ns. With the field in the buncher at 2.7 MV/m, the photoemitted bunch reached its minimum length at 3 m (Fig. 5). At this position in a machine, the bunch would enter into a booster cavity, after which the beam properties would be effectively frozen. Figure 6 shows the particle distributions and current profiles of a filled and empty RF bucket with 10 mA dark current; at maximal compression of the dark current in both an empty and filled RF bucket and at maximal compression of the photoemitted bunch. The peaks in dark current reached maximal compression around 2 m, therefore when the bunch reached 3 m, the dark current peaks had overcompressed. A peak in dark current formed in front of the photoemitted bunch, referred to as a “ghost pulse”, followed by a plateau of higher dark current surrounding the bunch. The streaking seen in the dark current was an artefact of the simulation.

Simulations without the photoemitted bunch, representing empty RF buckets, show the dark current

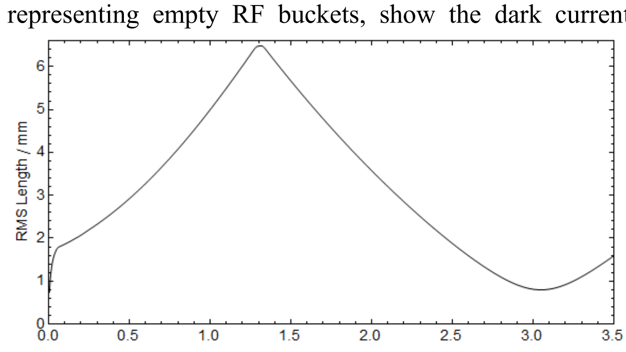

Figure 5: RMS length of photoemitted bunch.

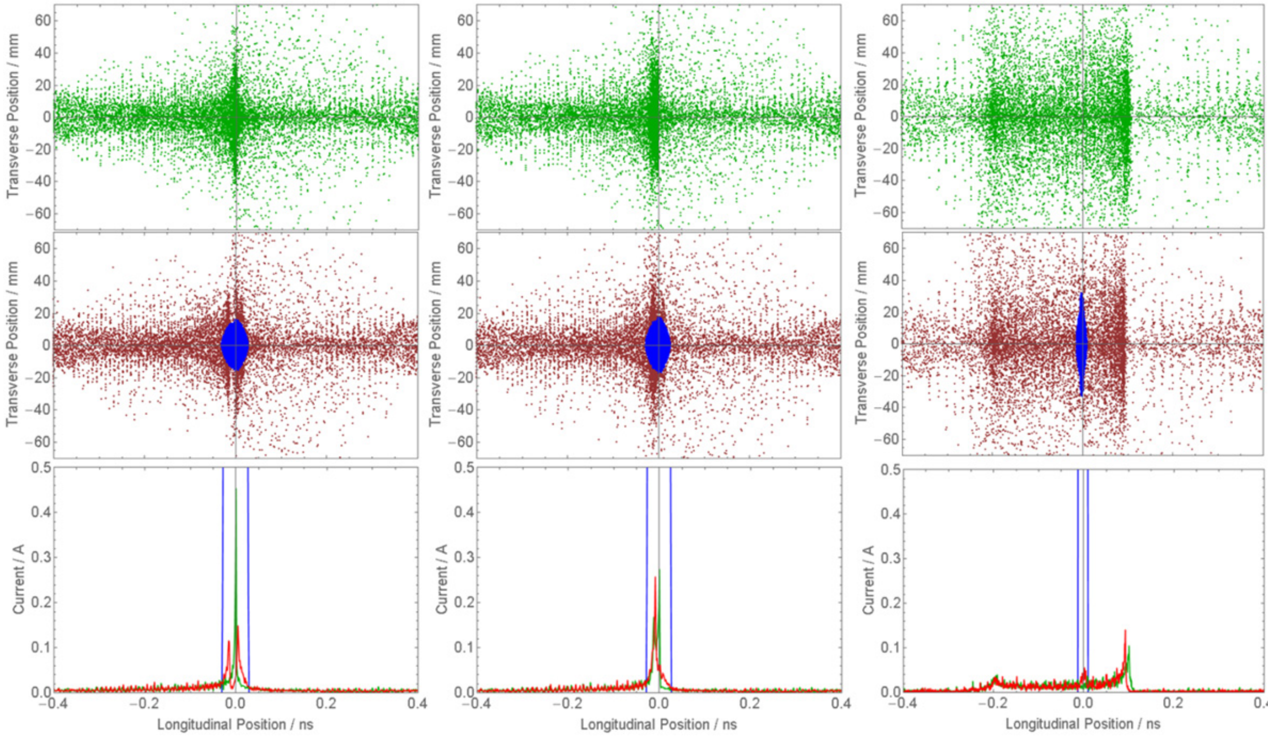

Figure 6: Particle distributions for an empty (top) and filled (middle) RF bucket and current profiles (bottom) with 10 mA dark current, at positions: from left to right; 1.98 m – maximal compression of dark current in empty RF bucket, 2.07 m – maximal compression of dark current in filled RF bucket and 3 m – maximal compression of photoemitted bunch. The photoemitted bunch (blue), dark current (red) and dark current in the empty RF bucket (green) are shown.

compressed quicker but had a similar distribution at 3 m; except the peak amplitude of the "ghost pulse" was around 40 % lower than the filled RF bucket (Fig. 7).

The dark current plateau was measured by finding the mean dark current between -0.05 and -0.15 ns and was identical in the empty and filled RF buckets; about 40 % larger than the initial dark current level (Fig. 7). The peak amplitude of the "ghost pulse" was more than an order of magnitude larger than the initial dark current level. However, the peak "ghost pulse" amplitude was significantly smaller than the photoemitted bunch current; less than 1 % with 10 mA dark current.

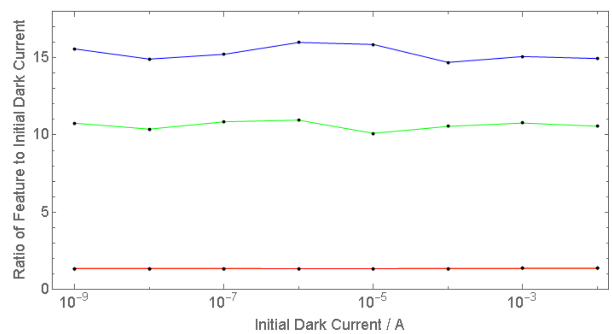

Figure 7: Ratios between the amplitude of the ghost pulse for a filled (blue) and empty (green) RF bucket, and the dark current plateau around the photoemitted bunch for both RF buckets (red), compared to the initial level of dark current. Measured at 3 m from the photocathode.

SUMMARY

Simulations of the interaction between a photoemitted bunch and a field emitted, dark current halo showed that the bunch repelled the surrounding halo and formed two peaks in dark current at the head and tail of the bunch. The amplitude of the peaks scaled linearly with the initial level of dark current. When passed through a buncher cavity, the dark current had overcompressed. This formed a plateau around the photoemitted bunch 1.4 times higher than the initial level of dark current. A "ghost pulse" formed in front of the bunch, with an amplitude 15 times higher than the initial dark current level. The "ghost pulse" also formed in an empty RF bucket, although at a lower peak amplitude – 11 times higher than the initial dark current level, suggesting that the buncher cavity has a greater effect on the dark current distribution than the space charge from the photoemitted bunch.

FUTURE WORK

To determine how the current peaks form under different conditions, further simulations will be carried out varying system parameters, such as the bunch charge, solenoid strength and gun gradient. The slice emittance and phase space of the photoemitted bunch and dark current will be investigated to compare the effects of dark current on the beam quality in DC photoinjectors. More components will be added to the simulated system, such as a booster cavity and apertures, to investigate the co-propagation of the dark current and photoemitted bunch further down the beam line in a more realistic model.

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