

THE EFFECTS OF FIELD CURVATURE ON BUNCH FORMATION IN RF ELECTRON GUNS

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Abstract

For many years it has been speculated that uniformly filled ellipsoidal electron bunches, with their linear fields, would be ideal to produce high charge density with low emittance beams. This may be particularly advantageous with bunch compression schemes required for operation of a Free Electron Laser (FEL). In earlier studies a constant, DC electric field has been assumed in the production of ellipsoidal bunch distributions using “blow-out” mode. In this paper we look at the effects of a time varying, non-constant electric field on the development of the electron bunches as they are emitted from the photocathode and travel through an accelerating RF cavity. We present the effects of frequency in the cavity, field strength of the cavity, as well as the phase of the electron bunch. These three variables change the spatial curvature and the temporal slope of the electric field as observed by the electron bunch. This results in changes in bunch development and formation.

INTRODUCTION

Free Electron Lasers (FELs) are the next generation of light sources. One can film chemical reactions, map the atomic details of molecules, and capture 3D images of the nanoparticles. FELs make light when photon bunches overlap electron bunches in an undulator to produce a modulation in the electron bunch. The modulation emits photons which give gain to the photon bunch, resulting in coherence and a high flux density. The end result is an amplified, coherent light beam that is produced by modulating the electron bunch. Current light sources produce an incoherent light output because each electron radiates independently. Seeded FELs, like the Wisconsin FEL facility (WiFEL), use an external seed laser to energy modulate the electron bunch in the undulators. Subsequently the energy modulation is converted to a density modulation along the bunch which emits photons in a second undulator. It produces uniform photon energy spectra and temporal power distribution and it can produce harmonics of the seed laser through the up-conversion process (Fig. 1). This process may be “cascaded” in multiple steps to produce frequencies many times that of the seed laser while essentially preserving the seed laser’s desired spectral profile.

To make the seeded FEL work, though, requires a very high quality electron bunch. That electron bunch must pack many electrons into a very small, dense volume.

However, due the effects of space charge the electrons want to repel each other which reduces the density. We need to get up to the speed of light quickly, since particles close to the speed of the light become more massive and space charge effects lessen. The particles become more massive because of the theory of special relativity and its gamma factor. The other factor in having bright, dense, bunches is the phase space quality of the bunch. It was previously assumed that cylindrical shaped electron bunches, so called “beer can” shape, would be best for emittance compensation. This shape, though, produces space charge fields near the beam head and tail that are nonlinear due to the abrupt truncation of charge. They result in irreversible transverse and longitudinal emittance growth [1]. Three dimensional ellipsoidal distributions have space charge fields that are linear in all dimensions, and have better emittance compensation properties.

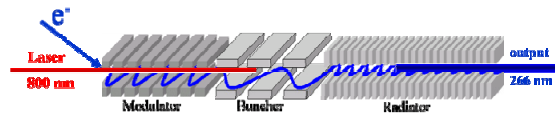


Figure 1: Up-conversion process.

PHYSICS OF PRODUCING ELLIPSOIDAL BEAM

To meet the requirements of the seeded FEL, we need to produce electron bunches with uniform ellipsoidal distributions. There are two ways to produce uniform ellipsoidal distributions (fig 2b) according to P. Musumeci, et al. [1, 2] One can temporally and spatially shape the laser pulse illuminating the cathode; however this greatly increases the complexity of the required laser system. Alternatively one can use an ultrashort laser pulse on the photo cathode and produce a “blow-out” mode bunch. [2] With “blow-out” mode bunches, the electrons are allowed to repel each other as they are emitted from the photocathode to expand to the desired ellipsoidal shape and distribution. In describing this technique, Luiten assumes a constant electric field E_z along the direction of acceleration. [2] In all real world cases this assumption is invalid to some degree; the E_z fields are time varying and non-constant spatially. Bas van der Geer [3] has calculated the correlation between the E_z , electric field strength, and the charge of the electron bunch to produce “blow-out” mode or “water

bag” bunches. It shows how large the E_z field strength must be to produce “blow-out” mode bunches with a given total charge.

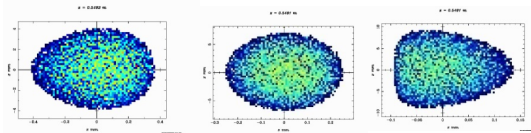


Figure 2: Final bunch distributions at $z = 55$ cm. a) “egg” shaped (left), 100 pC bunch in 1.3 GHz cavity, b) $E_0 = 63$ MV/m, ellipsoidal shape (middle). c) 100 pC bunch in 2.6 GHz cavity, $E_0 = 125$ MV/m, “bullet” shape (right).

There is field curvature produced by spatially varying fields. The field lines curve following the shape of the cavity. This field curvature causes focusing of the electron bunch and its formation can change from an ellipsoidal shape to a “bullet” shaped (fig 2c) formation. The focusing term may also compensate for the effects of space charge. An “egg” shaped (fig 2a) formation is observed due to the effects of space charge. When the two effects are balanced it is possible to obtain a uniformly filled ellipsoidal electron bunch with greater total charge than indicated in van der Geer’s [3] calculations.

METHODS

This paper describes a study of how field curvature effects bunch formation in an RF structure. Due to the high cost of physically running the experiment we are creating computer models of RF cavities which can be used in particle simulations calculating electron bunch development from emission at the photo cathode through the accelerating cavity.

The three variables in our experiment are the frequency inside the cavity, the field strength of the cavity, and the phase of the electron bunch, with respect to the RF wave. We ran simulations of a DC channel, 1.3 GHz cavity, 2.6 GHz cavity, and a 3.9 GHz cavity to see how frequency affects the bunch formation. The presence of a time varying gradient changes the observed electric field curvature and consequent focusing in the accelerating cavity. Peak cavity gradients are scaled to give a constant final particle energy for all simulations. The time varying gradient cases also have twice the peak field as the DC case for the same length. To avoid field curvature at the end of the DC channel cases, an artificial 3D field map for the cavity was generated which ruled out curvature at the end of the DC cavity. The phase, a measure of how far off crest the electron bunch is compared to the accelerating RF wave, is being varied because it affects the slope of the electric field and focusing of the electron bunch. The electron bunches can be behind, on top, or in front of the crest of the accelerating wave.

We performed simulations on 100 pC, 50 pC, and 25 pC charged bunches. To generate the initial “charge

pancakes” used in the simulations, the program Generator [5] is used to generate the particle distribution file. Superfish [4] is the program that is used to calculate the radio-frequency electromagnetic fields in chosen cavities. The cavity that we are using is a one and a half cell, super conducting structure. The cavity is designed to match a $\beta=1$ electron so that the electron bunches are accelerated close to the speed of light. The cavity length decreases as the frequency increases. As the frequency of the cavity increases the field strength must also increase to maintain the same final momentum. The program Astra [5] is used to track the particles through the defined fields taking in to account the space charge field of the particle cloud.

To quantify our results, the term $A=b/a$ [1] is used to quantify the quality of the ellipse. A is the measure of the asymmetry of the bunch along the z axis. The variables a and b are the distance longitudinally from the statistical median of the electron bunch. When $A=b/a=1$ the bunch is a perfectly uniform ellipse.

RESULTS

Field curvature and space charge repulsion are unavoidable effects in the presence of temporally and spatially non-constant electric fields. However, when the two effects are balanced it is possible to produce a uniformly filled ellipsoidal electron bunch.

In the DC channel the electric field is constant, 30 MV/m. The only way to change the quality of the ellipse generated, decreasing the A value so that it is closer to one, is to decrease the total charge of the electron bunch. In this accelerating field the final distributions for the 100 pC, 50 pC, and 25 pC electron bunches have an A value greater than one and are “egg” shaped because of space charge effects. The field strength is not high enough, nor are there curvature effects to compensate for the effects of space charge. The A value is constant for the different charges because there is no slope, curvature, in the electric fields. Without curvature you cannot change the phase to change the quality of the electron bunch.

The spatially varying field in the RF cavity, which produces focusing along the bunch, acts as a tuning knob. The focusing of the RF cavity decreases the A value (Fig. 3). In Fig. 3 the A value decreases significantly in the 1.3 GHz cavity, which is the same length as the DC channel. As the frequency of the cavity is increased to 2.6 GHz, the field strength is increased as well to 125 MV/m to keep the final momentum constant, and the focusing term increases. As the focusing term of the cavity increase it decreases the A value significantly lower than the desired value of one. The curvature effects and space charge effects are no longer balanced. The curvature effects greatly outweigh the space charge effects.

In the 3.9 GHz cavity there were some interesting effects. Instead of the A value decreasing further as

predicted because the focusing term increases, the A value actually increases. This is due to the fact that the cavity length is so short and the electron bunches are allowed to drift for a longer period of time. While the electron bunches are drifting to the z stop position the space charge is counteracting the focusing effects that were placed upon the bunch in the accelerating RF cavity.

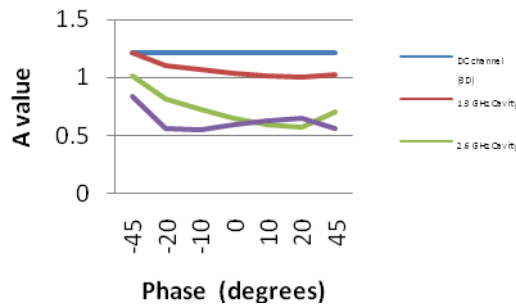


Figure 3: A vs. Φ of 50 pC electron bunches.

The phase acts as a fine tuning knob on the fields (Fig. 3). One can change the A value by changing how far off crest the bunch is compared to the accelerating wave and whether the electron bunch is in front of or behind the accelerating wave. The electron bunch produced can have a greater total charge than indicated on the “Water bag Existence Regime” graph if the effects are carefully balanced. After the electron bunches exit the accelerating RF cavity space charge starts to compensate for the effects of focusing, as well as increasing the rms bunch length.

We have observed three types of distributions thus far; an “egg”, a “bullet”, and an ellipse (Fig. 4). The “egg” shape is observed when the E_z field strength is too weak and the space charge of the electron bunch is allowed to repel the electrons away from each other, $A > 1$. The “bullet” shape is observed when the E_z field strength is too high and magnetic focusing deforms the electron

bunch, $A < 1$. The ellipse shape is our desired result and it is produced when the effects of space charge and field curvature balance each other, $A = 1$.

DISCUSSION

This paper describes how field curvature effects bunch formation in an RF structure. It is clear from our results that the temporally and spatially varying electric fields have a great impact on bunch development and formation. The tenability offered by phase control allows operation at higher bunch charges while still producing ellipsoidal electron bunches than would be possible in the constant field case. However, there were limitations to our study. We only observed 100 pC, 50 pC, and 25 pC charge bunches. The electric field strengths were scaled for each cavity so that all the runs had the same final momentum. Only the longitudinal bunch development was observed. Future works may include looking at other factors of electron bunch development, such as momentum variations and charge density of the bunches.

ACKNOWLEDGEMENTS

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