IDEAL WATERBAG ELECTRON BUNCHES FROM AN RF PHOTOGUN

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Abstract

The use of femtosecond photoemission laser pulses in high-gradient RF photoguns enables the production of electron bunches whose rest-frame bunch length is much smaller than the bunch radius (so-called 'pancake' bunches) during a significant part of the acceleration path. Recently, we have shown for a constant and uniform acceleration field that by proper radial shaping of the photoemission laser pulses, a pancake bunch can be created that will evolve automatically into a uniformly filled 3D ellipsoid, i.e. into the ideal bunch. In this paper we show that the same holds for a realistic, non-uniform and time-dependent, RF acceleration field with magnetic focussing.

INTRODUCTION

With the implementation of fs mode-locked Ti:Sapphire lasers in high-gradient RF photoguns [1, 2], a new charged particle acceleration regime has emerged, the so-called 'pancake' regime. Pancake bunches have by definition a restframe bunch length much smaller than the bunch radius. This geometry allows a relatively simple, but effective analytical description of the space-charge dominated, critical initial part of the acceleration trajectory [3]. In high-gradient RF photoguns the pancake regime can be relevant up to several MeV.

The general opinion is that extremely short bunches should be avoided during the initial stages of the acceleration process, because high space charge densities are always detrimental to the final beam quality. This is not necessarily true: shorter bunches may even lead to better beams. In fact, we have shown recently [4] that the combination of acceleration in the pancake regime and proper radial shaping of the photoemission laser pulse enables the production of hard-edged, uniformly filled, 3D ellipsoidal electron bunches, so-called 'waterbags'.

The waterbag is characterized by perfectly linear behavior: it is the only charged particle distribution whose internal space charge force field is a linear function of position. A linear force field acting on a uniformly filled ellipsoid will lead to expansion and, unless it is perfectly spherical, deformation of the bunch, but it will remain a uniform ellipsoid. The bunch velocity field induced by a linear force field will also be linear. If one takes care that the external forces (due to the acceleration field and charged particle optics) acting on the bunch are also linear functions of position, then the dynamical behavior of the bunch becomes particularly simple. The evolution of the bunch can then be calculated very easily and accurately. Even more importantly, the waterbag bunch enables exquisite control as phase space may be manipulated with high precision. The ideal character of this distribution is expressed by zero emittance growth: in any linear accelerator transport system both the longitudinal and the transverse normalized emittances remain at their initial, 'thermal' values.

In Ref. [4] we derived the conditions required for a pancake bunch to evolve into a waterbag. The idea was tested by particle tracking simulations in a constant and uniform acceleration field, using the General Particle Tracer (GPT) code [5]. In this paper we go one step further by simulations of a waterbag bunch in a realistic, i.e. non-uniform and time-dependent, acceleration field. In the simulations we use the RF field, calculated with SUPERFISH, of the rotationally symmetric 1.5 cell S-band RF photogun currently under development in our group.

FROM PANCAKES TO WATERBAGS

The way to realize a uniformly filled, 3D ellipsoidal bunch in an RF photogun is by starting out with a surface charge density on the cathode surface given by:

$$\rho(r,z) = \sigma_0\sqrt{1-(r/R)^2}\,\delta(z), \tag{1}$$

where $\sigma_0 = 3Ne/(2\pi R^2)$ is the surface charge density at the center, and N the number of electrons. This corresponds to a spherical charge distribution with radius R, which has been compressed to zero thickness on the cathode surface. Such a flat distribution can be approximately realized by photoemission from copper with a radially shaped femtosecond UV laser pulse. In Ref. [4] we showed that if an acceleration field E_0 is applied, such that

$$\frac{eE_0\tau_l}{mc} \ll \frac{\sigma_0}{\varepsilon_0 E_0} \ll 1, \tag{2}$$

where τ_l is the duration of the photoemission process, i.e. approximately the laser pulse length, then the pancake bunch, which is accelerated outward, should automatically evolve into a full-fledged, 3D waterbag distribution.

For the realistic and relevant values $\tau_l = 30\,\mathrm{fs}$, $E_0 = 100\,\mathrm{MV/m}$, $Ne = 100\,\mathrm{pC}$, and $R = 1\,\mathrm{mm}$, we find $eE_0\tau_l/mc \approx 0.002$ and $\sigma_0/\varepsilon_0 E_0 \approx 0.05$, which fulfills condition (2) quite reasonably. In Ref. [4] we showed by GPT simulations, using a constant and uniform acceleration field, that such a bunch will indeed evolve into a 3D waterbag distribution, with perfectly linear momentum-position phase space correlations. The linear character of the phase space distribution was dramatically manifested in zero RMS normalized emittance growth over the entire acceleration trajectory.

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In principle the same should hold for non-uniform acceleration fields, as long as the fields are linear functions of position. In practice, however, there are always finite non-linear field dependencies which may distort the phase space distribution and thus lead to emittance growth. In the following this will be investigated for the particular case of our 1.5 cell S-band RF photogun, currently under development.

GENERATION OF WATERBAG ELECTRON BUNCHES WITH THE TU/E RF PHOTOGUN

The 1.5 cell TU/e RF photogun

The 1.5 cell S-band TU/e RF photogun is the next step in the development started with the 2.6 cell TU/e RF photogun, described in detail in Ref. [1, 2]. Just like its predecessor, it features perfect rotational symmetry, which is made possible by a coaxial RF input coupler (instead of side coupling) and the absence of tuning plungers (see Fig. 1).

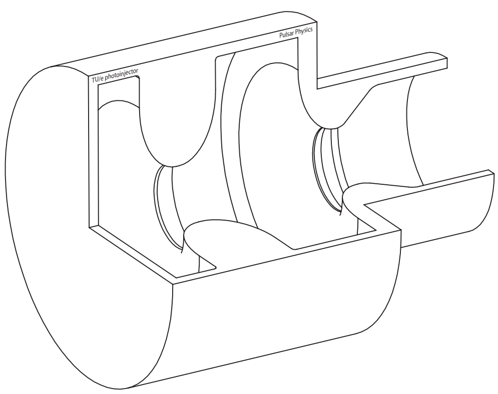

Figure 1: The 1.5 cell TU/e RF photogun.

The absence of tuning plungers requires very precise design and machining: less than 5% field imbalance between the cells implies that their widths and radii should not deviate more than 1 μm from the design values. With the first gun we demonstrated that this is possible with current technology.

Several improvements have been implemented with respect to the first TU/e gun. First, on the basis of constructional considerations of a practical nature it was decided to sacrifice one acceleration cell. Consequently, the maximum attainable electron energy is somewhat lower than in the 2.6 cell gun, but a higher degree of control over the field balance is now possible. Second, the length of the first half cell has been changed from 0.625 to 0.5, to enable the maximum electric field strength on the cathode at initiation, which is crucial for acceleration in the pancake regime [3]. In addition, on crest initiation of the femtosecond bunches enables much more accurate synchronization, due to strongly reduced arrival time variations (see Ref. [1], pp. 56-59). Third, following a suggestion by the Strathclyde University group, the irises in the 1.5 cell gun have been given an elliptical shape, so as to minimize the field strength on the surface of the irises for a given on-axis field strength. Since in our experience RF breakdown mainly occurs at the irises, this should facilitate higher acceleration field strengths.

The cavity design has been optimized using SUPERFISH. For an RF input power of 8.5 MW, a maximum electric field strength of 110 MV/m is realized on the cathode surface, with a maximum field strength on the irises of 100 MV/m.

Waterbag bunch simulations with the 1.5 cell TU/e RF photogun

We have performed GPT simulations, using the calculated RF acceleration field of the 1.5 cell RF photogun, combined with solenoidal focussing. The electrons are initiated with a radial distribution given by Eq. (1), with $R = 1$ mm, in a field at the cathode of $E_0 = 92\,\mathrm{MV/m}$. The bunch charge is $Ne = 100\,\mathrm{pC}$, represented by 2×10^5 sample particles. In the simulations the electrons are ejected isotropically from the cathode surface with an energy of 0.4 eV. The finite duration of the photoemission process is taken into account by initiating the particles sequentially in time, using a Gaussian temporal profile $\sim \exp(-t^2/2\sigma_t^2)$, with a full-width-at-half-maximum duration of $2.355\,\sigma_t = 30\,\mathrm{fs}$. The influence of image charges is also taken into account.

Figure 2 shows the projection in the $x - z$ plane of the resulting particle distribution 3 ns after initiation, corresponding to a centroid position $z_c \approx 0.9\,\mathrm{m}$, well outside the cavity. The centroid electron energy is approximately 4.4 MeV.

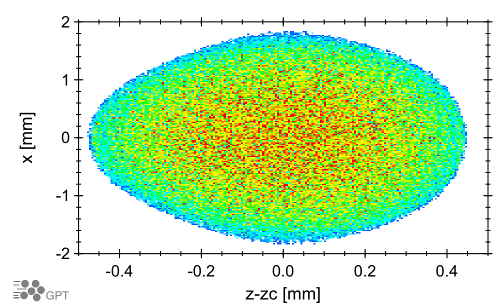

Figure 2: The projection in the $x - z$ plane of the electron bunch, 3 ns after initiation, corresponding to a centroid position $z_c \approx 0.9\,\mathrm{m}$.

Clearly the distribution has evolved into a nice uniform distribution, that is close to the desired ellipsoidal shape. Figure 3 shows the outer radius R of the bunch as a function of longitudinal position z: immediately after initiation the bunch expands rapidly due to space charge forces. Subsequently, the radial size oscillates under the influence of the RF field, until it is finally focussed magnetically to a waist at a distance of approximately 0.5 m from the cathode surface.

Figure 2 shows that under the influence of the RF

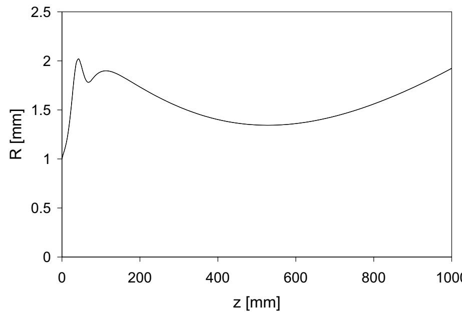

Figure 3: Outer radius R of the bunch as a function of longitudinal position z.

acceleration field and the magnetic field of the focussing solenoid, the bunch has become slightly 'egg-shaped', which raises the question whether the phase space momentum-position correlations are still sufficiently linear. The most stringent test of the supposedly linear character of its 6D phase space distribution is obtained by investigating the behavior of the RMS normalized transverse emittance, which is shown in Fig. 4.

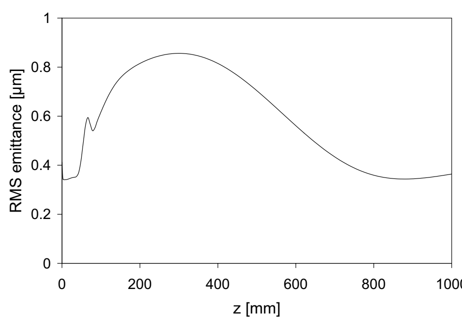

Figure 4: RMS normalized transverse emittance of the bunch as a function of longitudinal position z.

Initially, during the rapid space charge expansion the emittance remains fixed at its initial, 'thermal' value of approximately 0.35 μm. Subsequently, under the combined influence of the RF acceleration field and the magnetic field of the focussing solenoid, the emittance increases to a maximal value, which is however still well below 1 μm, after which it decreases again to its value at initiation. This implies that, in the end, the linearity in transverse phase space has fully recovered. The slight deformation visible in Fig. 2 is apparently not sufficient to disturb the desired behavior.

Figure 5 shows the current profile and the distribution in longitudinal phase space of the bunch of Fig. 2, i.e. 3 ns after initiation, corresponding to a centroid position $z_c \approx 0.9\,\mathrm{m}$. The current profile at 0.9 m is close to the parabolic shape expected for a uniform ellipsoidal distribution. The peak current is approximately 50 A. The distribution in longitudinal phase space is characterized by perfectly linear behavior. This suggests highly efficient α-magnet bunch compression. Multi-kA electron beams with sub-μm RMS emittance may thus be created, suited for the most demanding high-brightness applications.

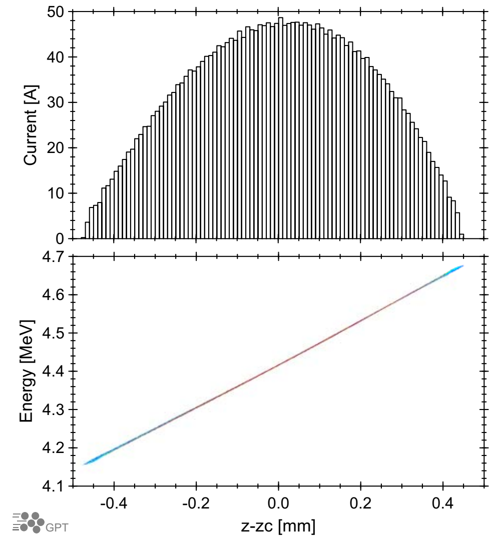

Figure 5: Current profile and the distribution in longitudinal phase space of the bunch 3 ns after initiation, corresponding to a centroid position $z_c \approx 0.9\,\mathrm{m}$.

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