ENERGY-SPREAD COMPENSATION OF A THERMIONIC-CATHODE RF GUN*

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Abstract

The Advanced Photon Source (APS) ballistic bunch compression (BBC) gun was designed as a prototype injector to explore the technique of drift-space compression of a high-brightness beam [1]. It is constructed from three independently powered S-band rf cells, one cathode half-cell, and two full cells, and is designed to operate with both thermionic cathodes and photocathodes; this flexibility allows the gun to be operated in modes other than for ballistic compression.

In particular, appropriate choices of rf power and phase can be used to reduce the energy spread of the beam produced by the gun. With a thermionic cathode, simulations indicate that a 1% FWFM energy spread can contain at least 90% of the emitted beam charge. This operating mode demonstrates many of the capabilities required for ballistic bunch compression, but allows verification of the basic gun performance via a much easier measurement. Also, such a beam is of interest as a source for other experiments, e.g., low-cost, compact, free-electron lasers.

INTRODUCTION

The APS ballistic bunch compression (BBC) gun was built to demonstrate the principle of ballistic compression for high-brightness beams. This is accomplished by placing a positive chirp on the electron beam as it transits the gun, thereby inducing the beam to self-compress in the drift space between the gun and a capture linac section. An analogy would be the operation of a highly relativistic klystron with no output coupler.

To allow full exploration of the parameter space, the rf field gradient and phase is independently adjustable in each cell of the gun. This allows the gun to be readily operated in modes other than ballistic compression.

The BBC gun was designed to operate with either a thermionic cathode or a photocathode [2]. The thermionic cathode offers the advantages of simplicity, robustness, and high average beam currents. Disadvantages typically include beams with large energy spreads and lower per-bunch charge than is possible with a photocathode. The remainder of this paper assumes a thermionic cathode.

When operating with a thermionic cathode, the energy-compression mode is of particular interest. The BBC gun can generate a beam with most of the beam in a very narrow relative energy spread, making the gun more efficient as a driver for devices such as compact, far-infrared free-electron lasers. Also, as the performance of the gun in this mode is easily measured with a simple electron spectrometer, it provides a ready check of the operation of the gun.

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PRINCIPLES OF OPERATION

Beams from thermionic-cathode rf guns typically suffer the disadvantage of very large energy spreads [3]. Even given that charge is concentrated at the head of the bunch, typically no more than 10 – 20% of the beam charge is within a 1% FWFM energy spread. Figure 1 shows the simulated momentum spectrum of the BBC gun running in π-mode, thereby mimicking the operation of a conventional thermionic-cathode rf gun.

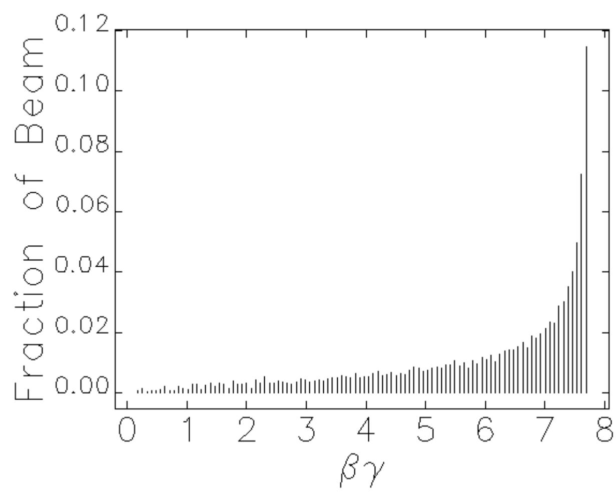

Figure 1: Momentum spectrum of BBC gun operating in π-mode. Bin widths are 1% of the maximum momentum.

A somewhat greater fraction of the bunch charge can be moved into the uppermost 1% of beam energy by increasing the gradient in the gun, specifically the cathode cell. This is not an especially desirable mode of operation for several reasons, including the possibility of gun damage and the requirement for running at relatively high beam energies.

The ballistic compression gun offers an alternative mode of operation. By appropriate selection of the gradient and phase in the full cells, a much greater amount of the beam charge can be compressed into the uppermost 1% beam energy. This method has been proposed before [4] but not yet physically demonstrated.

One-Dimensional Model System

The model system for energy compression consists of a thermionic-cathode source in a cathode cell, followed by full cells. The length of the full cells is taken to be ½ of the free-space wavelength corresponding to the resonant frequency of the gun–in other words, a typical gun design.

To a reasonable approximation, the energy of the beam as a function of the time it exits the cathode cell can be represented by a quadratic equation, i.e.,

$$P_0(t) = a + b \cdot t + d \cdot t^2 , \tag{1}$$

where $P_0(t)$ is the normalized momentum ($\beta\gamma$) as a function of time; t extends over a range of typically -20/+40 ps; and a, b, and d are constants depending on the particular gun in question. For the BBC gun with a typical gradient of 50 MV/m in the cathode cell, a = 1.529, b = $-1.68 \cdot 10^{10}$ sec^{-1}, and d = $-5.95 \cdot 10^{19}$ sec^{-2}.

The beam is, at the exit of the cathode cell, not fully relativistic and has a large velocity spread as well as a large energy spread. Treating the full cells as true pillbox cavities and ignoring the change in particle velocity while within the cell, the normalized momentum at the end of the n^{th} full cell can be approximated as

$$P_n(t_i) = P_{n-1}(t_i) + \Delta P_n \cdot \cos\left(\pi \frac{\sqrt{1 + P_{n-1}^2(t_i)}}{P_{n-1}(t_i)} + \omega t_i + \phi_n \right), \tag{2}$$

where t_i is the time the i^{th} particle leaves the cathode cell, ΔP_n is the maximum momentum gain through the n^{th} full cell for a relativistic particle, ω is the angular frequency of the cavity, and ϕ_n is the phase of the field in the n^{th} cavity. Finally, a weighting function $\rho(t_i)$ can be defined as the normalized longitudinal charge density at the exit of the cathode cell. This explicitly takes into account the bunching that naturally occurs in the cathode cell of most rf guns; in effect, it places more emphasis upon the head of the bunch.

Figure 2 shows the momentum at the exit of the cathode and full cells as a function of cathode cell exit time relative to a reference particle, generated using Eqs. (1) and (2). For this plot, $\omega = 2\pi \cdot 2856$ MHz, ΔP_1 = 1.9, ΔP_2 = 3.0, ϕ_1 = 230 deg, and ϕ_2 = 135 deg. The weighting function $\rho(t_i)$ is shown in Figure 3 and was derived from a simulation of the beam at the exit of the BBC gun cathode cell. In this calculation, 46% of the beam was within 1% of the maximum beam momentum.

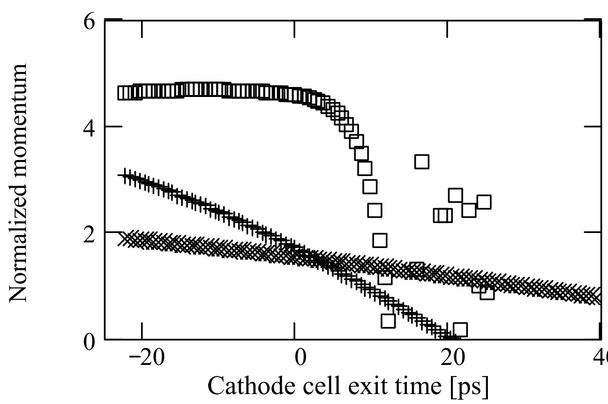

Figure 2: Momentum spectra at the exit of the cathode cell ("X"), first full cell ("+"), and second full cell ("□").

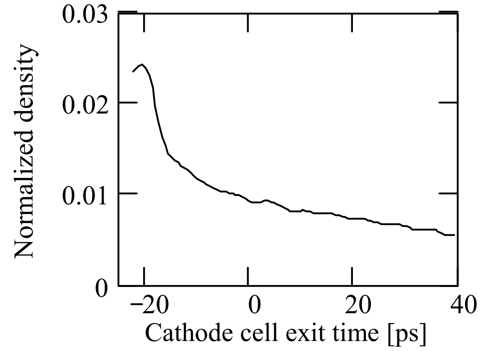

Figure 3: Normalized longitudinal beam density at the exit of the cathode cell. The exit time is relative to the PARMELA reference particle exit time.

THREE-DIMENSIONAL SIMULATION

The computer code PARMELA [5] was used to simulate the energy-compression process using the actual BBC gun field profiles, assuming a 3-mm-radius thermionic cathode and small bunch charge (e.g., the built-in space-charge routines were not used).

A downhill simplex optimizer was used to automatically vary the phase and field gradient in the full cells; the number of beam particles within 1% of the peak beam energy served as the figure-of-merit for the optimization process.

The optimized beam momentum spectrum is shown in Figure 4. Approximately 96% of the particles are within 1% of the maximum momentum, and the great majority of the beam is within the top 3%. (Compare this result to Figure 1, the same gun running in a π-mode.) Figure 5 shows the longitudinal phase space at the exit of the BBC gun for π-mode and ballistic compression as well as energy compression settings.

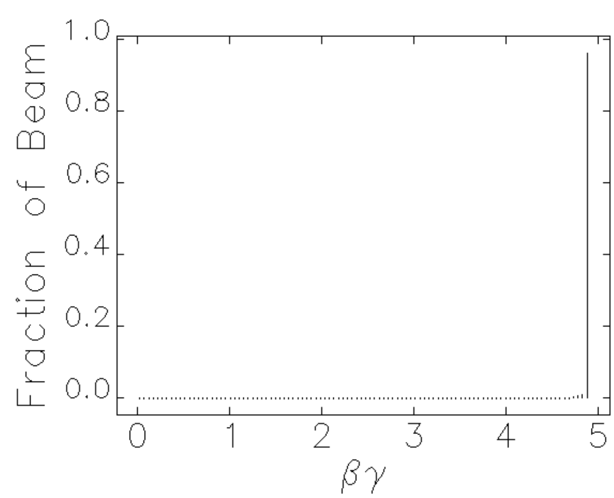

Figure 4: Momentum spectrum of the BBC gun operating in energy-compression mode. Bin widths are 1% of the maximum momentum.

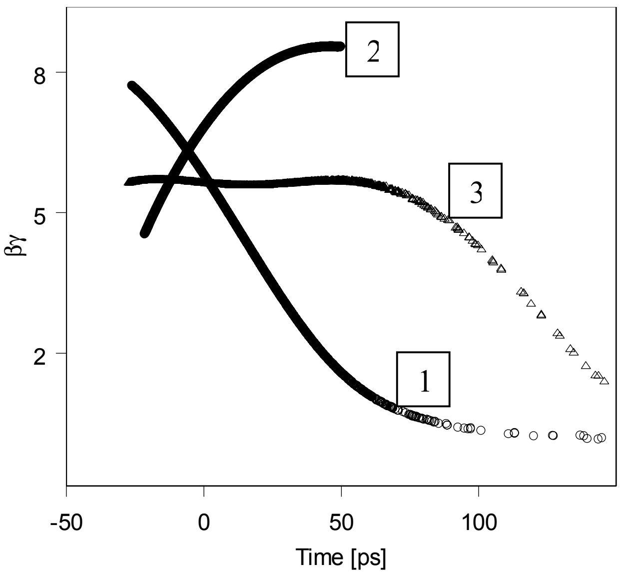

Figure 5: Longitudinal phase space for various operating modes. π-mode is Curve 1, ballistic compression is Curve 2, and energy compression is Curve 3.

The maximum beam energy in the simulation is somewhat lower than for the π-mode; this is an expected result, as one can think of the gradient in the full cells being used more to rotate the longitudinal phase space than to raise its mean value. The simulation's much better result, as compared to the analytic expression, is due to several factors. First, there are fewer approximations made in terms of the particle transport through the full cells. Second, the simulation is a 3-d calculation, and particles with very low beam energies tend to be lost on walls or cell nosecones. This has the result of automatically winnowing some low-energy particles from the beam before they can exit the gun and be included in the analysis. If the lost particles are also counted, the result is in better agreement with the analytic calculation.

The calculated transverse normalized emittance for this simulated beam, excluding particles outside of a 1% FWFM energy window and including only particles which exit the gun, was 35 μm. While not a spectacular emittance, in itself this would be a suitable beam for devices with modest emittance requirements, such as far-infrared free-electron lasers [6]. If the beam is divided longitudinally into 10-ps-long slices, the leading three slices–all consisting of particles within a 1% FWFM momentum spread–contain 66% of the beam and have an average emittance of about 1.5 μm. The emittance grows towards the tail of the beam, where the particle density becomes much lower and the energy spread begins to increase.

RESULTS AND DISCUSSION

Both the one-dimensional analytic approximation and the three-dimensional simulation demonstrate that the APS ballistic compression rf gun can operate in an energy-compression mode, generating a beam with very low energy spread from a thermionic cathode. Operating in such a mode will verify the basic beam dynamics of the gun via an easily measured quantity, the fraction of the beam charge within a small energy spread. This will prove to be an important step towards operation of the gun in the ballistic-compression mode.

The projected emittance of the low-energy-spread beam as a whole indicates that the gun should be suitable as the sole-source driver for devices such as far-infrared free-electron lasers, which often have modest beam quality and energy requirements. The slice emittance at the head of the beam is considerably better than the projected whole-beam emittance.

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