GENERATION AND CHARACTERIZATION OF ELECTRON BUNCHES WITH RAMPED CURRENT PROFILE AT THE FLASH FACILITY*

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Abstract

We report on the successful generation of electron bunches with current profiles that have a quasi-linear dependency on the longitudinal coordinate. The technique relies on impressing nonlinear correlations in the longitudinal phase space using a linac operating at two frequencies (1.3 and 3.9 GHz) and a bunch compressor. Data taken for various accelerator settings demonstrate the versatility of the method. The produced bunches have parameters well matched to drive high-gradient accelerating field with enhanced transformer ratio in beam-driven accelerators based on sub-mm-sizes dielectric or plasma structures.

INTRODUCTION

Modern applications of particle accelerators often rely on phase space manipulations necessary to tailor the bunch distributions to match the requirements of the front-end applications. Usually, phase-space matching is done in a root-mean-square (rms) sense. However, there has been an increasing demand for more precise phase space control. In particular, electron bunches with tailored temporal distributions are often desired. For instance, novel accelerator concepts based on beam-driven acceleration mechanisms, e.g., plasma or dielectric wakefield-based acceleration [1, 2, 3, 4], would greatly benefit from asymmetric, ideally linearly-ramped, current profiles. These temporal distributions can significantly increase the transformer ratio $--$ the energy gain of the accelerated bunch over the energy loss of the driving bunch in beam-driven acceleration schemes [5]. Linearly-ramped current profiles can be produced by imparting nonlinear distortions in the longitudinal phase space [6, 7] or by performing intricate phase-space manipulation between the transverse and longitudinal degrees of freedom [8].

In this paper we show how a linear accelerator with accelerating sections operating at two different different frequencies followed by a bunch compressor could be used to impart nonlinear correlations in the longitudinal phase space which would enable the tailoring of the current profile. A comprehensive report of the analytical model and experiment is provided in Ref. [9].

* This work was sponsored by the DTRA award HDTRA1-10-1-0051 to Northern Illinois University, the German's Bundesministerium für Bildung und Forschung and by the DOE contract DE-AC02-07CH11359 to the Fermi research alliance LLC.

THEORETICAL BACKGROUND

In this section we briefly elaborate a 1D-1V model single-particle model of the longitudinal phase space dynamics and take an electron with coordinates (z, δ) where z refers to the longitudinal position of the electron with respect to the bunch barycenter (in our convention $z > 0$ corresponds to the head of the bunch) and $\delta \equiv p/\langle p\rangle - 1$ is the fractional momentum spread (p is the electron's momentum and $\langle p\rangle$ the average momentum of the bunch). We consider this electron is subject to an accelerating voltage in a rf linac with sections operating at frequencies f_1 and $f_n = nf_1$. The electron is subsequently transported through a bunch compressor characterize by the longitudinal linear $R_{56} \equiv \partial z/(\partial\delta)$ and quadratic $R_{56} \equiv \partial^2 z/(\partial\delta^2)$ dispersion functions. It can be shown that the final coordinates of the electron are given as functions of the initial coordinates following

$$\begin{cases} z_f = & a_f z_0 + b_f z_0^2, \\ \delta_f = & a_l z_0 + b_l z_0^2, \end{cases} \quad (1)$$

where $a_f \equiv 1 + a_l R_{56}$, $b_f \equiv b_l R_{56} + a_l^2 T_{566}$, and a_l and b_l are parameters that depend on the linac settings [9].

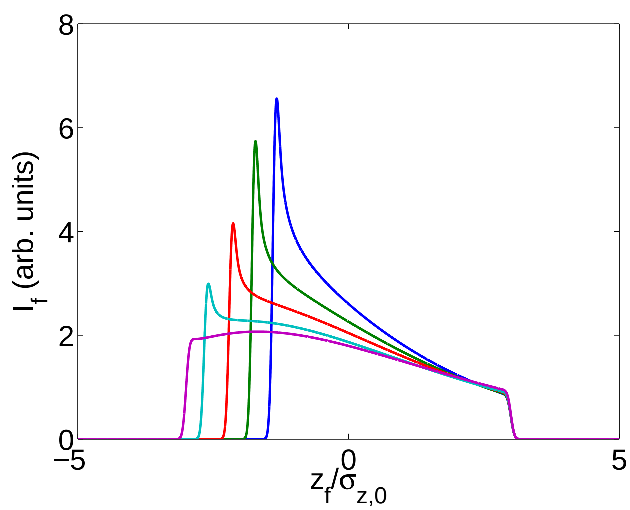

Figure 1: Current profiles analytically obtained from Eq. 3 for $b_f = 0.7$ and $a_f = 2.0$, 2.25, 2.5, 2.75, and 3.0 corresponding to decreasing current from blue to magenta traces (we took $\sigma_u = 0.05$).

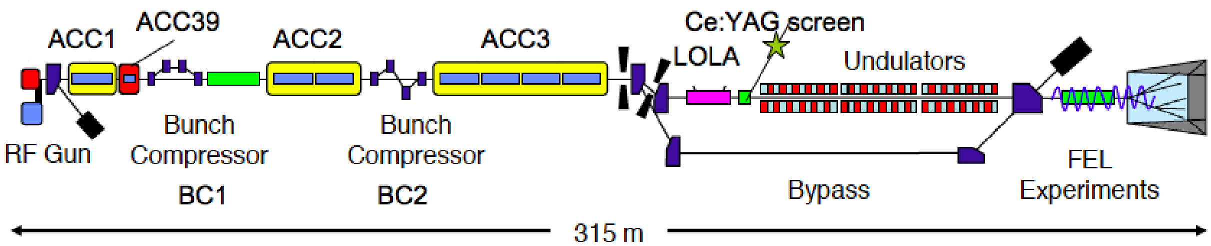

Figure 2: Overview of the FLASH facility. ACC1, ACC2, and ACC3 represents the three 1.3-GHz accelerating sections and ACC39 corresponds to the 3.9-GHz accelerating section.

Taking the initial current to follow the Gaussian distribution $I_0(z_0) = \hat{I}_0 \exp[-z_0^2/(2\sigma_{z,0}^2)]$ (where $\hat{I}_0$ is the initial peak current), and invoking the charge conservation $I_f(z_f)dz = I_0(z_0)dz_0$ and incorporating the effect of the initial uncorrelated fractional momentum spread $\sigma_{\delta,0}^u$, the final current is given by

$$I_f(z_f) = \int d\tilde{z_f} I_f^u(\tilde{z_f}) \exp[-\frac{(z_f - \tilde{z_f})^2}{2\sigma_u^2}], \tag{2}$$

where $\sigma_u \equiv R_{56}\sigma_{\delta,0}^u$ and

$$\begin{aligned} I_f^u(z_f) &= \frac{\hat{I}_0}{\Delta^{1/2}(z_f)} \exp[-\frac{(a_f + \Delta^{1/2}(z_f))^2}{8b_f^2\sigma_{z,0}^2}] \\ &\times \Theta[\Delta(z_f)]. \end{aligned} \tag{3}$$

Here $\Delta(z_f) \equiv a_f^2 + 4b_f z_f$ and $\Theta()$ is the Heaviside function. The final current shape is therefore controlled via the parameters a_f and b_f, and can be tailored to follow a linear ramp as demonstrated in Fig. 1. These analytical predictions were also confirmed with particle tracking simulations including collective effects.

We also note that the formalism developed in this section could easily be applied to the case of velocity bunching used to bunch non-ultrarelativistic electron bunches [10]. Such an implementation of a two-frequency version of the velocity bunching would also lead to shaped bunches while circumventing the use of the magnetic bunch compressor thereby being immune to coherent synchrotron radiation effects.

EXPERIMENT

A proof-of-principle experiment of the current-shaping technique described in the previous section was conducted at the Free-electron LASer in Hamburg (FLASH) facility [11]; see Fig. 2. In the FLASH accelerator, electron bunches are generated via photoemission from a CsTe photocathode located in the backplane of a 1+1/2 cell rf gun. The produced ~ 4-MeV bunches are then injected in 1.3-GHz section (ACC1) and accelerated to ~ 140 MeV. Downstream of ACC1, a 3.9-GHz third-harmonic accelerating section is nominally used to linearize the longitudinal phase space. Such a correction is needed to increase the peak current and improve the final performance of the front-end free-electron laser (FEL) [12, 13]. The bunches are then compressed in a chicane-type magnetic bunch compressor and further accelerated to ~ 400 MeV. After a second stage compression (BC2), the bunches are accelerated to their final energy (maximum of 1.2 GeV). Finally, the bunches pass through a collimation system located in a dogleg beamline and are sent to the undulators.

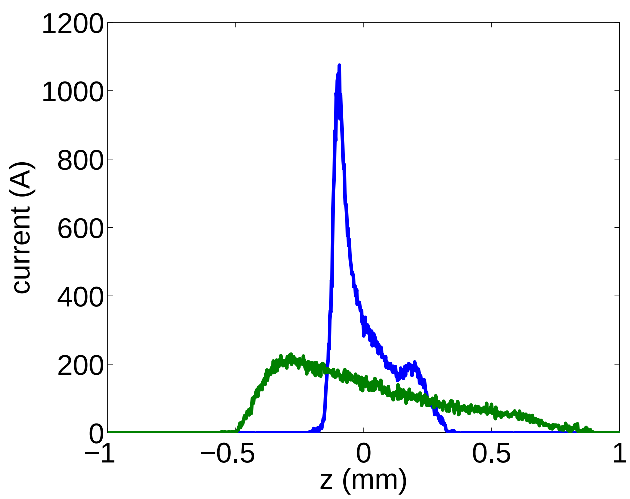

Figure 3: Measured current profiles at the Ce:YAG screen. The green and blue traces correspond to two settings of ACC1 and ACC39 amplitudes and phases. The head of the bunch correspond to $z > 0$.

During the experiment reported in this paper, the beam final energy was ~ 700 MeV as only part of the ACC3 section was powered. The second and third accelerating sections (ACC2 and ACC3) were operated on crest and the bending angles of BC2 dipoles were reduced. These settings ensured that the longitudinal dynamics was minimally affected by BC2 and the dogleg beamline. Downstream of the collimating section, the bunch was vertically sheared by a 2.856-GHz transverse deflecting structure (LOLA) and horizontally bent by a dipole magnet. The beam's transverse distribution is then observed on a downstream Cerium-doped Yttrium Aluminum Garnet (Ce:YAG) screen. Under proper optics tuning, the vertical and horizontal coordinates at the Ce:YAG screen are respectively dominated by the shearing factor $\kappa \simeq 20$ and dispersion $\eta \simeq 0.75$ m and the observed distribution supplies a single-shot measurement of the longitudinal phase space distribution upstream of the transverse-deflecting structure [14].

Figure 3 shows two examples of measured current profiles obtained for different settings of ACC1 and ACC39 amplitudes and phases. As expected, the observed current profiles are asymmetric and can be tailored to be ramped with the head of the bunch ($z > 0$) having less charge than the tail. The latter feature is in contrast with the nominal compression case at FLASH where the longitudinal phase space distortion usually leads to a low-charge trailing population.

OUTLOOK

The produce ramped bunch have been shown to be capable of producing high-peak electric field with transformer ratios significantly higher than 2 using a dielectric-loaded waveguide (DLW) structure [15]. In order to demonstrated the capability of the generated ramped bunch to support an enhanced transformer ratio, the wakefield would have to be driven by a high-charge (drive) bunch followed by a low-charge (witness) bunch. Ideally the drive bunch would only lose energy while the witness bunch would be delayed to only sample the accelerating portion of the wakefield. The latter would also imply that the witness bunch length should be shorter than the wavelengths of the excited wakefield modes. Unfortunately producing two bunches with controllable spacing and individual duration at the DLW experiment location is challenging in the current FLASH configuration. Therefore we are currently envisioning to produce the witness bunch by temporally splitting the photocathode laser with a birefringent α-BBO crystal [16, 17]. Such a method would results in two identical pulse with temporal separation given by $\Delta\tau = \mathcal{G}L$ where L is the crystal thickness and $\mathcal{G} \simeq -0.96$ ps/mm is the group velocity mismatch. A 15-mm thick crystal would therefore provide a $\Delta\tau = 14.5$ ps which is longer than the laser rms duration $\sigma_t = 6$ ps. In addition, the ratio of the drive- and witness-pulse intensities could be controlled by varying the angle between the optical axis of the crystal and the incoming laser polarization. Therefore such a simple modification of the laser system would provide a drive bunch followed by a low-charge population. Since this low-charge tail has a length larger than the excited wakefield modes, it will be energy-modulated by the drive-bunch wakefields.

ACKNOWLEDGMENTS

We are thankful to the FLASH team for the excellent technical support. We thank M. Dohlus, K. Flöttmann, T. Limberg, I. Zagorodnov, E. Vogel, S. Wesh, H. Edwards, B. Faatz, K. Honkavaara, and S. Schreiber for discussions and support.

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