Formation of Electron Bunches with Tailored Current Profiles using Multi-Frequency Linacs

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Abstract. Tailoring an electron bunch with specific current profile can provide substantial enhancement of the transformer ratio in beam-driven acceleration methods. We present a method relying on the use of a linac with accelerating sections operating at different frequencies followed by a magnetic bunch compressor. The experimental verification of the technique in a two-frequency linac is presented. The compatibility of the proposed technique with the formation and acceleration of a drive and witness bunches is numerically demonstrated.

Keywords: beam dynamics, electron beams, phase-space manipulations, beam shaping

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INTRODUCTION

Recent advanced applications of electron-beam accelerators have increased the demand for precise phase-space control schemes. In particular, electron bunches with a well-defined temporal distribution are often desired. In beam-driven collinear acceleration methods, where a “drive” bunch excites wakefields in a high-impedance medium for acceleration of a subsequent “witness” bunch, shaping the drive-bunch current profile can result in dramatic improvements such as an enhanced transformer ratio \( R = |E_+ / E_-| \) defined as the ratio of peak accelerating field behind the drive bunch \( E_+ \) to the peak decelerating field within the bunch \( E_- \) [1]. High transformer ratios allow for longer interaction lengths, lower energy modulation through the drive bunch, increased efficiency and also relaxes requirements on the focusing system. To date there has been no direct attempt to increase the transformer ratio by shaping the current bunch due to the lack of method. To date, experiments on enhanced transformer ratio [2] in GHz dielectric-loaded structures were carried out using a bunch train with bunches having their charges linearly ramped; see Ref. [3]. The latter technique is challenging to scale to accelerating structures operating at THz wavelengths.

Recently, several methods have been proposed to produce ramped bunch. The use of sextupole magnets in a dispersive section can be used to impart nonlinear correlations in the longitudinal phase space (LPS) [4] which can lead to ramped current profiles [5]. This methodology has the disadvantage of introducing coupling between the transverse and longitudinal degrees of freedom which can impact the brightness of the witness bunch. Another recent development is the use of transverse-to-longitudinal phase space exchangers [6, 7] in conjunction with transverse shaping method to shape the current profile [8, 9, 10, 11]. These techniques have been shown to provide a very fine control over the bunch shape [12] at the cost of an increased complexity. Moreover, in this shaping technique the longitudinal emittance is exchanged with one of the transverse emittances thereby often resulting in a transversely-asymmetric beam which can impact the performance of cylindrical-symmetric acceleration method. In some circumstances, this latter feature might actually be taken advantage of, e.g., when the acceleration mechanism is based on a slab-type structure; see, e.g., Ref. [13].

It has long been recognized that linacs operating at multiple frequencies could be used to correct for LPS distortions and improve the final peak current [14, 15, 16]. In this paper we present a bunch tailoring technique that uses a linac with sections operating at different frequencies to impress nonlinear distortions in the longitudinal phase space. The distortions are controlled to tailor the bunch current profile. We show analytically how a two frequency linac could be operated to control over the current profile and present experimental data obtained at the Free-electron LAser in
Hamburg (FLASH) facility in DESY supporting the proposed method [17]. Finally we show that the technique is compatible with the generation and acceleration of a drive bunch followed by a witness bunch as required for collinear beam-driven acceleration methods.

**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 \((z, \delta)\) 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 an electron subject to an accelerating voltage in a rf linac with sections operating at frequencies \(f_1\) and \(f'\). The experienced accelerating voltage is

\[
V(z) = V_1 \cos(k_1 z + \varphi_1) + V’ \cos(k’ z + \varphi’),
\]

where \(V_1, V’\) and \(\varphi_1, \varphi’\) are respectively the accelerating voltages and operating phases of the two linac sections, and \([k_1, k’] \equiv 2\pi [f_1, f’]/c\). We refer \(f_1\) to as the fundamental frequency and \(f’\) is usually an harmonic frequency of \(f_1\).

The electron is subsequently transported through a bunch compressor characterized by the longitudinal linear \(R_{56} \equiv \partial z/\partial \delta\) and quadratic \(T_{566} \equiv \partial^2 z/\partial \delta^2\) dispersion functions. It can be shown that the final coordinates of the electron are given as functions of the initial coordinates following

\[
\begin{align*}
  z_f &= a_f z_0 + b_f z_0^2, \\
  \delta_f &= a_l z_0 + b_l z_0^2,
\end{align*}
\]

where \(a_f \equiv 1 + a_i R_{56}, b_f \equiv b_i R_{56} + a_i^2 T_{566},\) and \(a_l\) and \(b_l\) are parameters that depend on the linac settings [17].

**FIGURE 1.** Left: Current profiles analytically obtained from Eq. 4 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 for \(\sigma_u = 0.05\) (the head of the bunch is at \(z_f > 0\)). Right: Transformer ratio versus peak accelerating field for dielectric-wakefield acceleration for a Gaussian (blue), and linearly-ramped (green) profiles compared to the profile described by Eq. 4 “distorted LPS” (red). No appreciable performance loss is observed compared to the linearly-ramped current profile. The simulations are performed for a 1-\(\mu\)C electron bunch.

Taking the initial current to follow the Gaussian distribution \(I_0(z_0) = I_0 \exp[-z_0^2/(2\sigma_{z,0}^2)]\) (where \(I_0\) 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 \(\sigma_{\delta,0}^2\), the final current is given by

\[
I_f(z_f) = \int d\tilde{z} I_f^0(\tilde{z}_f) \exp[-(z_f - \tilde{z}_f)^2/2\sigma_{\delta}^2],
\]
where $\sigma_u \equiv R_{56}\sigma_{u,0}^u$ and

$$I_f(z_f) = \frac{I_0}{\Delta^{1/2}(z_f)} \exp\left[-\frac{(a_f + \Delta^{1/2}(z_f))^2}{8b_f^2\sigma_{z,0}^2}\right] \times \Theta[\Delta(z_f)].$$  

(4)

Here $\Delta(z_f) \equiv a_f^2 + 4b_fz_f$ 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 (left plot). These analytical predictions were also confirmed with particle tracking simulations including collective effects and higher-order effects.

Although the analytically-computed profiles are generally not perfect linear ramps, their performance compares well with the ideal linearly-ramped current profile as inferred from the peak-field vs transformer ratio trade-off curves displayed in Fig. 1 (right plot). These trade-off curves were generated for a cylindrically-symmetric dielectric-loaded waveguide without loss of generality. More generally, we find that these trade-off curves are not critically influenced by the precise shape of the bunch as long as it has a pronounced temporal asymmetry; see Ref. [19].

**EXPERIMENTAL DEMONSTRATION**

The experiment described in this paper was performed at the FLASH facility [18] diagrammed in Fig. 2. At FLASH the electron bunches are generated via photoemission from a cesium telluride photocathode located on the back plate of a 1+1/2 cell normal-conducting rf cavity operating at 1.3 GHz on the TM_{010} $\pi$-mode (rf gun). The bunch is then accelerated in a 1.3-GHz and 3.9-GHz superconducting accelerating modules (respectively ACC1 and ACC39) before passing through a bunch compressor (BC1). The ACC39 3rd-harmonic module was installed to nominally correct for nonlinear distortions in the LPS and enhance the final peak current of the electron bunch. Downstream of BC1, the bunch is accelerated in a second accelerating-module section (ACC2) and can be further compressed in BC2. A last acceleration stage (ACC3) brings the beam to its final energy (maximum of $\sim 1.2$ GeV but nominally set to $\sim 700$ MeV during our experiment). The beam’s direction is then horizontally translated using a dispersionless section referred to as dogleg beamline (DLB). Nominally, the beam is sent to a string of undulators to produce ultraviolet light via the self-amplified stimulated emission free-electron laser (FEL) process. For our experiment, the bunches will instead be vertically sheared by a 2.856-GHz transverse deflecting structure (TDS) operating on the TM_{110}-like mode and horizontally bent by a downstream spectrometer [20]; see Fig. 2. Consequently the transverse density measured on the downstream Cerium-doped Yttrium Aluminum Garnet (Ce:YAG) scintillating screen is representative of the LPS density distribution. The horizontal and vertical coordinates at the Ce:YAG screen are respectively $x_s \simeq \eta \delta_F$, where $\eta \simeq 0.75$ m is the horizontal dispersion function, and $y_s \simeq \kappa z_F$ where $\kappa \simeq 20$ is the vertical shearing factor and $(z_F, \delta_F)$ refers to the LPS coordinate upstream of the TDS.

Figure 3 provides examples of measured LPS and associated current profiles. These data were 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 sharp contrast with the typical (uncorrected) compression case at FLASH where the longitudinal phase space distortion usually leads to a low-charge trailing population. The produced ramped bunches have been shown to be
FIGURE 3. Measured LPS [(a), (c)] and associated current profile [(b), (d)] for the nominal compression [(a), (b)] and for linearly-ramped bunch generation [(c), (d)]. Plot (e) displays the different current profiles achieved during our experiment (obtained for different settings of ACC1 and ACC39 phase and amplitude). The head of the bunch corresponds to $z > 0$.

compatible of producing high-peak electric fields with transformer ratios significantly higher than 2 using a dielectric-loaded waveguide (DLW) structure [21].

COMPATIBILITY WITH WITNESS-BUNCH GENERATION

In order to demonstrate 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 and remain monoenergetic while the witness bunch would be adequately 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.

FIGURE 4. Numerical simulation of the formation of a quasi-linearly-ramped drive bunch followed by a witness bunch in a two-frequency linac using the FLASH setup. The sequence of plot shows the LPS downstream of the rf gun (a), of BC1 (b), and of ACC3 (c). The horizontal (resp. vertical) red traces are the associated current (resp. energy) profiles. For these simulations the drive and witness bunches charge are respectively set to 500 and 50 pC.

The witness bunch will be generated by temporally splitting the photocathode uv laser pulse with a birefringent
\(\alpha\)-BBO crystal [22, 23]. Such a method would provide two identical pulses with temporal separations given by

\[
\delta \tau = GL
\]

where \(L\) is the crystal thickness and \(G \simeq -0.96\) ps/mm is the group velocity mismatch. Considering the FLASH accelerator layout where the current laser system generate a \(\sigma_t = 6\)-ps long uv pulse, a 21-mm-thick crystal would be needed to provide a \(\delta \tau \simeq 20\) ps longer than the nominal laser pulse duration. Simulation of the beam dynamics throughout the rf gun carried with \textsc{astra} [24] confirms that a clear separation between the two electron bunches is obtained downstream of the gun; see Fig. 4 (a). In addition, the ratio of the drive- and witness-pulse intensities could be controlled by varying the angle between the optical axis of the \(\alpha\)-BBO crystal and the incoming laser polarization.

Simulations with \textsc{astra} and a 1D-1V model were performed to explore whether a shaped drive bunch followed by a witness bunch could be achieved downstream of \textsc{acc}3. The resulting LPS provides the needed shape as shown in Fig. 4 (b) and (c). In the simulations, the drive and witness bunches have a respective charge of 500 and 50 pC. The 500-pC drive-bunch charge is consistent with the experiment reported in the previous section. A 50-pC charge for the witness bunch is large enough to allow for further energy collimation and decrease the witness-bunch duration to an acceptable value to only sample accelerating field [the witness bunch shown in Fig. 4 (c) has a length comparable to the typical mode wavelength excited in a structure operating in the THz regime and would therefore be energy modulated rather that purely accelerated]. Such a collimation could be performed by locating a notch energy filter within \textsc{bc}1 to select the desired witness-bunch population [25]. Therefore, such a simple modification of the laser system would provide a drive bunch followed by a low-charge population consistent with the requirement of collinear beam driven acceleration.

**SUMMARY**

We have developed and experimentally demonstrated a new method for shaping electron bunches with ramped-current profiles. The method was also shown, via numerical simulations, to also be able to generate of a low-charge witness bunch behind the ramped bunch as needed in a collinear beam-driven accelerator. We are currently exploring the implementation of the method to investigate beam-driven dielectric-wakefield acceleration with enhanced transformer ratio at \textsc{flash}-\textsc{iii} at \textsc{desy} and at the Advanced Superconducting Test Accelerator (\textsc{asta}) at \textsc{fermilab} [28, 29].

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