A HIGH TRANSFORMER RATIO PLASMA WAKEFIELD ACCELERATOR SCHEME FOR FACET*

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Abstract

The ideal drive beam current profile for the plasma wakefield accelerator (PWFA) has been predicted by 1D and 2D simulations to be characterized by a triangular ramp that rises linearly from head to tail, followed by a sharp drop. A technique for generating such bunches experimentally was recently demonstrated. We present here an adaptation of this scheme to generate ramped bunches using the 23 GeV electron beam produced in the first two-thirds of the SLAC linac, and discuss plans to implement this scheme for high transformer ratio demonstration experiments at the FACET plasma wakefield accelerator facility.

INTRODUCTION

A drive bunch having a ramped (i.e. triangular) current profile that rises gradually from head to tail, followed by a sharp drop, approximates the "doorstep" profile which linear plasma theory [1] and recent 2D simulations [2] predict to be the ideal shape for the current profile of the beam used to drive the accelerating wake fields in a PWFA. This type of drive beam maximizes the energy transfer from the drive beam to the trailing witness bunch (a process quantified in terms of a parameter called the transformer ratio, defined by $R = E_+/E_-$ where E_+ is the peak accelerating field behind the bunch and E_- is the peak decelerating field within the bunch). One of the experimental objectives of FACET program at SLAC will be to generate and demonstrate acceleration in a plasma with high transformer ratios ($R > 2$) by using a drive beam characterized by an asymmetric current profile that rises linearly from head to tail and then drops abruptly to zero. A technique for generating linearly ramped single-bunch current profiles has been experimentally demonstrated [3], and another technique has been recently proposed [4]. In the following sections, we use particle tracking and particle-in-cell (PIC) simulations to explore the application of a modified version of the technique in Ref. [3] to create high transformer ratio drive bunches for the PWFA experiment at FACET.

PIC SIMULATION RESULTS

The technique demonstrated in Ref. [3] requires injecting an electron bunch with a positive energy chirp (i.e. particles at the head of the bunch are at higher energy) into

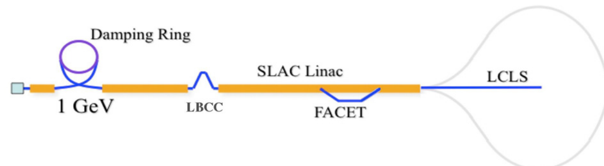

Figure 1: Schematic of the FACET beamline (not to scale).

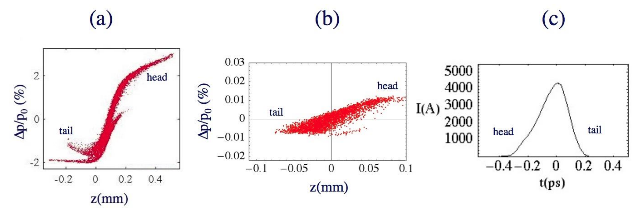

Figure 2: Particle tracking simulations of the FACET beamline showing longitudinal phase space (a) at entrance of FACET chicane and (b) after collimation with the $R_{56} = 0$ chicane optics, with (c) final ramped current profile corresponding to the distribution in (b).

a dispersive beamline, which serves as a bunch compressor. The nonlinear curvature imposed upon the longitudinal phase space distribution by the sinusoidal variation of the accelerating fields, combined with the negative longitudinal dispersion (or R_{56}) in the compressor, results in a hook-shaped distribution in longitudinal phase space, the projection of which onto the z-axis gives a ramped current density.

In adapting this technique to the FACET experiment, we observe that the second and third compression stages in the FACET beamline (marked as "LBCC" and "FACET" in Fig. 1) both operate with a negative R_{56}. The canonical optics configuration for these compressors is designed to produce a fully compressed (14 μm sigma, 23 kA) approximately Gaussian drive bunch at the interaction point. However, in the region between the LBCC and FACET compressors, the shape of the phase space distribution is close to what is desired for ramped bunches, as seen in Fig. 2(a), which shows a LiTrack simulation of the longitudinal phase space. A simple option for approximating the technique of Ref. [3] is therefore to reduce the compression, and use the FACET collimators to eliminate the low-energy tail seen in Fig. 2(a). An optical configuration for accomplishing this was recently proposed in Ref. [5].

An ELEGANT simulation of the longitudinal phase space of the SLAC beam after transport through the mod-

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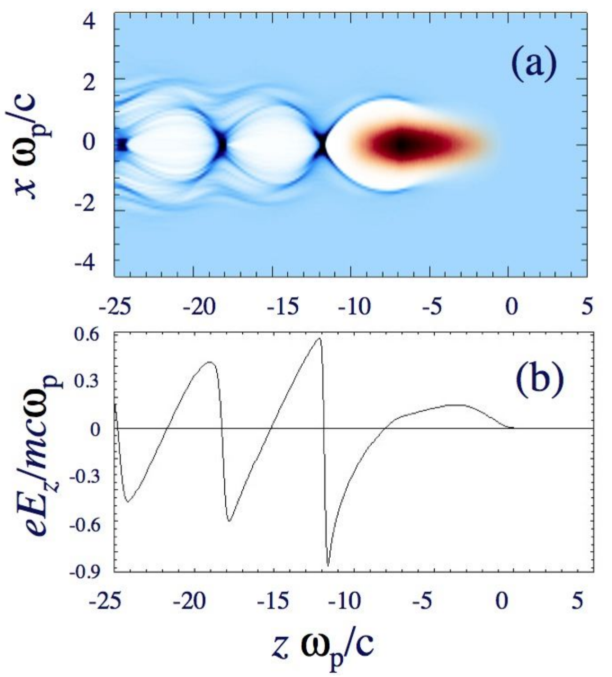

Figure 3: Particle-in-cell simulation of the ramped bunch of Fig. 2(c) in a pre-ionized plasma of density $n_0 = 1.2 \times 10^{17}\text{cm}^{-3}$ showing (a) drive beam and plasma electron density (in orange and blue respectively) and (b) axial electric field as functions of z normalized to the plasma skin depth.

ified optics is shown in Fig. 2(b). Collimation has been used to remove the high and low-energy tails, resulting in a 63 % loss in total charge (from 3 nC to 1.1 nC). The resulting current profile is shown in Fig. 2(c). A particle-in-cell simulation using the UCLA-based code QUICKPIC of the current profile from Fig. 2(c) propagating in a pre-ionized plasma of density $n_0 = 1.2 \times 10^{17}\text{cm}^{-3}$ is shown in Fig. 3. The color contour plot in Fig. 3(a) shows drive bunch electron density in orange (propagating to the right) and plasma electron density in blue. The strong radial electric field of the drive bunch expels plasma electrons from its path, producing a set of rarified ion bubbles (shown in white) characteristic of the plasma wake in the so-called blowout regime, where the drive bunch density n_b is much larger than the plasma density n_0. For the case of Fig. 3, $n_b/n_0 = 23$. From the linear theory for a triangular current profile of length L, the transformer ratio is approximately $R \approx k_p L/2 = 5$. This is surprisingly consistent with the value obtained by dividing the peak accelerating field by the peak decelerating field from the longitudinal electric field profile in Fig. 3(b), $R = E_+/E_- \approx 6$, even though the simulated case is highly nonlinear.

IMPROVED OPTICS

We note that the isochronous optical configuration of the prior section was derived independently of the canonical

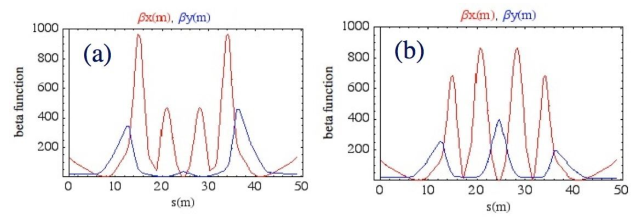

Figure 4: Symmetric beta functions in the FACET chicane for (a) R_{56} = 4 mm and (b) R_{56} = 0 cases with same input/output Twiss parameters, obtained using alternate lattice configuration.

lattice configuration for generation of high peak current single and double bunches described in Ref. [5], and thus requires very different matching conditions at the chicane entrance. Ideally one would like to be able to switch between the various experimental modes of operation without having to retune the upstream matching optics. To derive an isochronous configuration compatible with this scheme, the chicane lattice was re-optimized via a matching algorithm using the beam optics code MAD8. A set of chicane quadrupole current values was thereby derived which allows for continuous adjustment of the longitudinal dispersion (R_{56}) from -10 mm to 0 without modification of the upstream or downstream optics. This constitutes an extension of previously obtained canonical optics designed to allow such variation between -10 mm and -4 mm in order to switch between the single and double bunch (drive + witness) scenarios [6]. ELEGANT simulations of the resulting beta functions for the R_{56} = 4 mm (high peak current single bunch) and R_{56} = 0 (ramped bunch) cases are shown respectively in Fig. 4(a) and (b). The current profile and expected transformer ratio for the R_{56} = 0 case with this configuration were found to be equivalent to those of Fig. 2(c).

In developing a continuous knob to vary the R_{56} of the chicane, the question naturally arises whether an isochronous configuration is optimal for maximizing the transformer ratio. By extending the R_{56} to positive values, and thereby decompressing the bunch, one could produce a longer ramp, with higher transformer ratio, but at the expense of decreased peak current. In addition, sextupoles magnets in the existing design could potentially be used to impose a quadratic transformation on the longitudinal phase space (via the second order longitudinal dispersion, or T_{566}) to enhance the triangular shape of the bunch. To serve as a metric for the triangularity of the bunch, the current profile was fitted to a function consisting of two Gaussians of equal amplitude, joined at their peaks but with different fitted sigmas (σ_1 for the head and σ_2 for the tail of the bunch).

The canonical input phase space distribution at the FACET chicane entrance was then artificially manipulated via a first and second order matrix transformation using Mathematica. The values of the R_{56} and T_{566} were then scanned over a range of values (-3 mm to $+3$ mm and

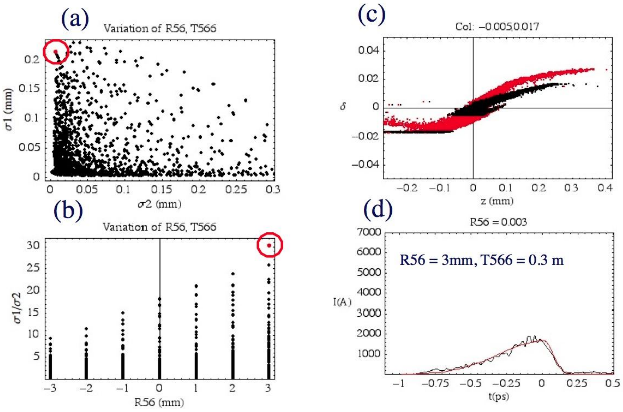

Figure 5: Parameter scan of longitudinal phase space transformation showing (a) front vs. back-of-bunch sigma values, (b) approximate transformer ratio vs. R_56, (c) initial (red) and final (black) longitudinal phase space for the parameter points highlighted in red in (a) and (b), and (d) the current profile corresponding to the phase space density in (c).

-0.3 m to $+0.3$ m respectively). The collimation was approximated by a pair of energy filters which were independently varied by $\pm$ 3 to 0.5%. The results of this parameter scan in terms of the resulting σ_1, σ_2 values and their ratio are shown respectively in Fig. 5(a) and (b). Since the tail of the bunch must lie within the accelerating region ($\sigma_2 < k_p^- 1$), and since the transformer ratio scales approximately as $R = k_p L/2$, the ratio of the two sigma values is a metric for the maximum transformer ratio ($\sigma_1/\sigma_2 \approx 2R$). Predictably, the highest σ_1/σ_2 value [highlighted in red in Fig. 5(a), (b)] within the scan range occurs at maximum decompression (R_{56} = +3 mm). Less obvious is that the corresponding T_{566} value is 0.3 m, or three times larger than the value for the canonical lattice configuration. The initial and transformed phase spaces are shown in red and black respectively in Fig. 5(c), with the resulting current profile and fitted bi-gaussian function shown in (d) in black and red respectively. The maximal value of σ_1/σ_2 = 30 would correspond roughly with a transformer ratio of 15. However, the peak current I_p is reduced from the isochronous case of Fig. 2 by a factor of 2. Since the accelerating gradient for a triangular bunch in the blowout regime scales with square root of peak current, this would correspond to a $\sqrt{2}$ reduction in gradient.

It should be emphasized that the results in Fig. 5 are an artificially imposed phase space transformation, and not the result of particle tracking in a realistic lattice. The ability to match the FACET chicane optics to the longitudinal dispersion values corresponding to Fig. 5(d) appears to be largely limited by the lack of sufficiently many independent sextupoles to simultaneously increase the T_{566} and minimize chromatic emittance growth in the beam line. It is also of interest to generate a witness bunch behind the drive beam to selectively sample the peak accelerating phase of the wake. The present technique does not appear well suited to this goal, as the required decompression of the bunch does not allow for a clean separation of drive and witness bunch within the span of a single plasma skin depth. One alternative is to allow the tail of the bunch to extend sufficiently far into the first accelerating bucket to sample the high gradient portion of the wake. These will be subjects of continuing study.

CONCLUSIONS

We have proposed a scheme for generating high transformer ratio drive bunches for the FACET plasma wakefield experiment using an isochronous chicane configuration and energy collimation. The optics have been designed to allow for changing the longitudinal dispersion of the chicane in order to accommodate the requirements of this and other planned plasma wakefield experiments without the need to significantly retune the upstream matching optics or linac parameters. Particle-in-cell simulations of the resultant bunches propagating in a pre-ionized plasma of density 1.2×10^{17} cm^{-3} predict a transformer ratio of 6, which exceeds the limit for symmetric drive bunches by a factor of 3. A parameter scan of the first and second order longitudinal phase space transformation suggests that higher transformer ratios may be possible with this approach by linearly decompressing the bunch and imposing a second order quadratic energy correlation, but at the expense of a reduction in peak current and peak accelerating gradient.

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