BNL-113852-2017-JA

*Generation of ramped current profiles in
relativistic electron beams using wakefields in
dielectric structures*

**G. Andonian^{1,2}, S. Barber¹, F. H. O'Shea², M. Fedurin³,
K. Kutsche³, C. Swinson³, J. B. Rosenzweig¹**

¹Department of Physics and Astronomy, UCLA, Los Angeles, CA 90095 USA

²RadiaBeam Technologies, Santa Monica, CA 90404 USA

³Accelerator Test Facility, Brookhaven National Laboratory,
Upton, NY 11973 USA

Submitted to Physical Review Letters

May 2017

Collider-Accelerator Department

Brookhaven National Laboratory

U.S. Department of Energy

Office of Science, Office of High Energy Physics

Notice: This manuscript has been co-authored by employees of Brookhaven Science Associates, LLC under Contract No. DE-SC0012704 with the U.S. Department of Energy. The publisher by accepting the manuscript for publication acknowledges that the United States Government retains a non-exclusive, paid-up, irrevocable, world-wide license to publish or reproduce the published form of this manuscript, or allow others to do so, for United States Government purposes.

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, nor any of their contractors, subcontractors, or their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or any third party's use or the results of such use of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof or its contractors or subcontractors. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

Generation of ramped current profiles in relativistic electron beams using wakefields in dielectric structures

G. Andonian^{1,2}, S. Barber¹, F. H. O'Shea², M. Fedurin³, K. Kusche³, C. Swinson³, J. B. Rosenzweig¹

¹*Department of Physics and Astronomy, UCLA, Los Angeles, California 90095, USA*

²*RadiaBeam Technologies, Santa Monica, California 90404, USA and*

³*Accelerator Test Facility, Brookhaven National Laboratory, Upton, New York 11973, USA*

(Dated: December 22, 2016)

Temporal pulse tailoring of charged-particle beams is essential to optimize efficiency in co-linear wakefield acceleration schemes. In this paper, we demonstrate a novel phase space manipulation method that employs a beam wakefield interaction in a dielectric structure, followed by bunch compression in a permanent magnet chicane, to longitudinally tailor the pulse shape of an electron beam. This compact, passive, approach was used to generate a nearly linearly-ramped current profile in a relativistic electron beam experiment carried out at the Brookhaven National Laboratory Accelerator Test Facility (BNL ATF). Here we report on these experimental results including beam and wakefield diagnostics and pulse profile reconstruction techniques.

The development of next-generation light-sources and colliders hinges on advances in high-energy, high-gradient field generation beyond conventional radio-frequency (RF) acceleration. Alternative acceleration techniques are required for deployment of high-brightness beams in a manageable footprint, and cost-effective manner. Charged particle beam-driven wakefield schemes, such as dielectric wakefield acceleration (DWA) or plasma wakefield acceleration (PWFA) are anticipated candidates to progress the field with the promise of multi-GV/m accelerating gradients [1–3]. However, the viability of co-linear, beam-driven wakefield schemes for such applications depends on demonstrated enhanced extracted energy efficiency, typically characterized by the transformer ratio ($\mathcal{R}$). The transformer ratio, for the collinear beam-driven wakefield accelerator, is defined as the ratio between the peak acceleration field behind the driving bunch and the peak decelerating field experienced by the bunch. For symmetric bunch profiles, $\mathcal{R} < 2$, however specially shaped asymmetric profiles, such as a longitudinally linearly ramped (i.e. triangular) shape, allow for greater $\mathcal{R}$ [4–6].

Existing robust methods to shape the longitudinal profile of the beam include higher-order magnetic compensation [7, 8] and notch collimation [9] in high-dispersion beamlines, direct drive laser pulse shaping [10], or transverse to longitudinal emittance exchange (EEX) techniques [11, 12]. In this paper we describe and demonstrate an alternative bunch shaping scheme that uses a beam wakefield interaction in a dielectric lined structure, followed by a compact chicane, to generate approximately linearly ramped distributions. The method is advantageous to other beam shaping techniques as it has a compact footprint, is passive (i.e. requires no external power source), can be placed close to the interaction region to alleviate profile preservation issues in transport [13], and does not reduce charge through masking techniques allowing for the utilization of the full beam charge. The approach is also scalable to higher energies.

In this concept, a charged particle bunch traverses through a dielectric lined structure producing a wakefield. For Gaussian beams with rms bunch length on the order of $\sim 1/4$ of the excited wakefield wavelength, an energy correlation is imparted onto the trailing distribution of the beam that samples only the leading, decelerating component of the wakefield. The energy-time correlation is then converted to a density modulation via a magnetic chicane compressor, whose strength is characterized by the longitudinal dispersion, given by the matrix element of the transport function corresponding to the beam energy-path length correlation, R_{56} . The resultant current profile of the bunch is a nearly linearly ramped, or triangular, distribution, with many parameters available for optimization (dielectric material, shape, size, chicane R_{56}) as depicted schematically in Fig. 1 [14]. This method follows similar lines of recent work on dielectric structures used for beam and radiation manipulations, such as sources for narrowband THz radiation, beam dechirpers, and microbunchers [15–17]. For example, in the opposite limit, where the driver beam bunch length is much longer than the wakefield wavelength, the dielectric wakefield interaction can be used to produce micro-bunched beamlet distributions [18].

For a charged bunch traveling through a dielectric lined waveguide, the wakefield is a convolution of its wake function with the longitudinal profile distribution [4],

$$W(z) = - \int_0^\infty \rho(z - z') w(z') dz, \quad (1)$$

where $\rho(z)$ is the normalized longitudinal bunch distribution, and $w(z)$ is the wake function, which for a single-mode, cylindrically symmetric, dielectric lined structure is given by

$$w(z) = \frac{Z_0 c}{\pi a^2} \cos kz, \quad (2)$$

with Z_0 is the impedance of free space, c is the speed of light in vacuum, a is the inner radius of the dielectric structure, and k is the wavenumber corresponding to

FIG. 1: Conceptual schematic for ramped bunch generation, with insets of longitudinal phase space and current profiles (not to scale). A dielectric wakefield "shaper" (DWS) imposes a partial sinusoidal energy correlation on the drive beam dependent on the frequency supported by the structure. The chicane converts this correlation into density space. The resultant profile is linearly ramped ready for injection into a e.g. dielectric wakefield accelerator (of different frequency) for enhanced efficiency with high $\mathcal{R}$.

the fundamental mode of the structure (e.g. TM_{01} for a cylindrical structure), which is calculated by solving the dispersion relation for a dielectric lined cylindrical waveguide. The energy change $\delta E = E - E_0$ of a given particle of energy E from initial energy E_0 , is proportional to the wakefield induced voltage for a given net charge of Nq_e , over an interaction distance of L_d , where N and q_e are the total number of electrons and electron charge respectively. For small fractional energy deviation, δE is given by [4],

$$\delta E(z) = q_e(Nq_e)W(z)L_d. \quad (3)$$

After passing through the dielectric structure, the linear coordinate transformation in phase space for a chicane of given R_{56} is simply $z = z_0 + R_{56} \frac{\delta E}{E_0}$. In practice, the dielectric structure is designed such that the fundamental wavelength supported by the structure is approximately 4 times the bunch length of the drive beam. Conceptually, this scaling is necessary so that the bulk of the beam experiences only the leading decelerating component of the wakefield that is generated as it passes through the structure. For appropriate values of fundamental frequency, the chicane, characterized by its R_{56} value, alters the longitudinal phase-space to generate a nearly-linear ramped current profile after passage through the transport.

An experiment to generate ramped bunch distributions using the described method was carried out at the Brookhaven National Laboratory Accelerator Test Facility (BNL ATF). The BNL ATF electron beam parameters used for this experiment are listed in Table I. The initial distribution is approximately Gaussian in longitudinal coordinate with a correlated energy chirp (Fig. 2 - left). The analytically calculated beam phase space distribution after interaction with the generated wakefield, using the transformation described by Eq. 3, is shown in

Fig. 2 - middle. The longitudinal phase space correlation shows that the particle distribution is partially sinusoidal in energy due to the wakefield interaction, however the current profile is still Gaussian. The chicane compressor transformation serves to shear the phase space, manifesting in a particle density correlation. The final distribution and current profiles are shown in Fig. 2-right where the current profile is approximately triangular.

Accurately satisfying the shaping criterion requires exact calculation of the fundamental frequency dependent on the dielectric structure parameters. The fundamental operating frequency of a cylindrically-symmetric, dielectric lined structure can be determined from the solution to the transcendental equation describing the generated wakefield, as in Ref. [19], where a/b , are the inner/outer radii of the dielectric cylinder, $(b - a)$ is the thickness of the dielectric, ϵ is the relative permittivity. The design rms bunch length of the BNL ATF experiment is $\sigma_z = 180 \mu\text{m}$ and the dielectric structure with frequency $f_{01} = 0.39 \text{ THz}$ ($\lambda_{01} = 765 \mu\text{m}$) was used.

The cylindrical dielectric structure is composed of SiO_2 ($\epsilon = 3.8$), with $a/b = 200/300 \mu\text{m}$ and a $25 \mu\text{m}$ thick copper coating, deposited with a multi-step process consisting of a thin titanium adhesion layer, followed by a thin copper transition layer, and a bulk electroplated deposition of copper. The structure is mounted on an in-situ aluminum holder and a multi-axis, remote control stage for final precision alignment. The chicane in this experiment is composed of four permanent magnet (NdFeB) dipoles, 10 cm long, with a 7.5 mm gap, and typical field on the order of 8 kG assembled on an aluminum strong-back. Aluminum spacers provide precision offset and the design R_{56} is tuned on a bench top while zeroing the effects of the first and second integrals of the magnetic field and using non-magnetic shims. The measured R_{56} for this chicane is 9.2 mm.

TABLE I: Measured experimental parameters for the electron beam and dielectric structure.

Beam Energy (E_0)	50 MeV
Energy Spread ($\delta E/E_0$)	1×10^{-4}
Total Charge (Nq_e)	80 pC
Norm. Transverse Emittance ($\epsilon_{nx} = \epsilon_{ny}$)	2 mm-mrad
Transverse Spot Size (σ_r)	60 μm
RMS Bunch length (σ_z)	180 μm
Dielectric Structure Inner/Outer Radius (a/b)	200/300 μm
Dielectric Structure Length (L_d)	5 cm
Dielectric Constant (ϵ)	3.8
Fundamental mode (f_{01})	0.39 THz
Chicane strength (R_{56})	9.2 mm

For these measurements, the BNL ATF produced an electron beam with bunch length, σ_z , variable in the range of $150 - 200 \mu\text{m}$, that was propagated to an interaction point in a dedicated experimental chamber which housed the dielectric structure and chicane compressor.

FIG. 2: Longitudinal phase space describing correlation with particle energy and longitudinal coordinate ($\xi = z - z_0$), in false color for initial Gaussian beam distribution (left), after interaction with wakefield in dielectric structure (middle) and after compression in chicane (right). The current profile for each distribution is superimposed on the intensity plot, with conversion to the desired approximately triangular distribution at the end of the transformation. The parameters used here correspond to the beam measurements from BNL ATF.

FIG. 3: Left: Predicted autocorrelation traces using the simulated current profiles of Fig. 2 for the unperturbed beam (blue) and the beam going through the dielectric wakefield shaper (red). Right: FFT of the corresponding autocorrelation curves.

The design rms bunch length was $\sigma_z = 180 \mu\text{m}$. The dielectric structure and chicane are aligned to the electron beam centroid trajectory as mapped on insertable transverse profile monitors, using a local visible alignment laser, focussed down to a $\sim 40 \mu\text{m}$ spot size at the interaction point. The beamline and diagnostic components have been described in detail in Refs. [18, 20, 21]. The beamline utilizes a doublet and triplet quadrupole configuration for electron beam final focus and collimation into the experimental chamber. The beam energy spectrum is diagnosed using a dipole and screen with a high-resolution CCD located at the beam dump. The beam charge is monitored using a Faraday cup, and the emittance is measured using a parameter fitting routine to transverse beam sizes along the transport measured with scintillating beam profile monitors. The beam spot size is measured using a 4-screen method at profile monitors position around the interaction region. The relevant measured beam parameters for this experiment are summarized in Table I.

The electron beam current profile distributions are measured using coherent transition radiation (CTR) interferometric methods for cases of the beam traversal

with and without the wakefield shaping device. CTR carries frequency information directly related to the longitudinal beam form factor and such methods are commonly used in accelerator facilities to determine beam bunch profiles [22]. In this study, the measurements are performed using CTR generated from the electron beam incident upon a 45 degree polished aluminum mirror located $\sim 10 \text{ cm}$ downstream of the chicane exit. The CTR is reflected to a Michelson-like THz-band interferometer and He-cooled Silicon bolometer detector, where the signal is autocorrelated. A typical autocorrelation scan consists of stepping the optical path length delay in $40 \mu\text{m}$ increments over a total length of 4 mm and averaging 4 shots per step.

Using the analytical profile distributions of Fig. 2, the predicted CTR autocorrelations of an unperturbed beam, and a beam interacting with the wakefield shaping components, are shown in Fig. 3. These results include effects of frequency cutoffs from the transport and detector. Some noticeable signatures are evident. First, in the case of the ramped beam, the central peak is slightly narrower with a higher peak value indicating a compression process. Second, the ramped beam shows additional higher frequency components, with longer roll-off, as indicated in the spectra when taking the FFT of the autocorrelation curves (Fig. 3-right).

The experimentally measured autocorrelations (Fig. 4 - left) and FFTs (Fig. 4 - center), both with and without passage through the DWS setup, reveal signatures that are predicted from the calculations shown in Fig. 3, namely, a narrower central peak with a greater amplitude, and longer high-frequency roll-off at $\sim 1 \text{ THz}$, that is consistent for the linear ramped case compared to the symmetric case. These features of the raw autocorrelations themselves represent necessary qualitative agreement of the linear current profiles, however, the full current profile distributions, with more detailed information,

are performed using a CTR interferometry reconstruction algorithm.

In principle, the longitudinal profile of a single electron beam can be reconstructed from the CTR emission intensity spectrum using the Kramers-Kronig relations and a minimal phase assumption, if the entire frequency spectrum is known [23]. In practice, however, experimental factors limit the ability to wholly measure the spectrum across the full range from zero to infinity. Hence, informed by other experimental measurements, the missing frequency components of the spectrum must be augmented for accurate bunch length reconstruction. The low-frequency cutoff is related to several factors such as detector sensitivity and diffraction through the quasi-optical collection transport. This systematic response, however, can be approximately calibrated in whole by analyzing the CTR emission response. The time domain autocorrelation of the CTR generated by a short bunch, as in the measurement described herein, exhibits characteristic dips on either side of the central peak which are due to the systematic low frequency cutoff. This cutoff is modeled with an analytic filter function, as motivated in Ref. [22], with the form $g(\omega) = 1 - e^{-\zeta^2 \omega^2}$, where ζ^{-1} is the characteristic cutoff frequency calculated from a fit to the measured CTR autocorrelation curve of the given bunch length. The subsequent spectral measurements are divided by this filter function, to effectively restore the low frequency spectral amplitude. For these experimental measurements, the cutoff frequency determined from the nonlinear regression (fit) to the CTR model is 108 GHz, with a standard deviation of 4 GHz and a 95% confidence interval of 100-115 GHz. Additionally, at high-frequency, the spectral amplitude of CTR generated by a short bunch rapidly drops to zero for wavelengths shorter than the bunch. In the measured spectra there is a white noise frequency response well above this coherent regime, which must be subtracted as background, to eliminate the influence of spurious artifacts in the reconstruction.

Once all frequencies are accounted, the Kramers-Kronig transform is used to inform on the complex phase term of the frequency dependent form factor. The longitudinal bunch distribution is then evaluated from the Fourier transform of the complex form factor following the analysis in Ref. [23]. The measured data sets, with the restored frequencies as described above, are shown in Fig. 4 (center), and used to calculate the phase factor. The spectra in Fig. 3 (right) show the difference in the expected spectral characteristics for the asymmetric ramped beam relative to the input beam. The relative frequency fall-off and higher frequency content expected near ~ 1 THz, manifests as an additional skewness to the final distribution, as seen in the data in Fig. 4 (center). The calculated frequency dependent phase term, which informs on the asymmetry of the bunch, and amplitude are then used to generate the longitudinal form factor

used in the profile reconstruction. Fig. 4 (right) shows the end result of the reconstruction algorithm for the two cases. The distribution for the shaped beam is shown to be nearly-linear ramped with a high level of skewness, relative to the initial bunch distribution, which is consistent with the analytical theory and predicted models from simulation results shown above.

At this point in the analysis, it is important to evaluate how possible errors in the assumptions used to augment the full frequency domain may propagate through the reconstruction algorithm and lead to different bunch profiles in the time domain for the given data sets. Figure 4 (left) shows the measured autocorrelation curves including error bars that denote the measurement ranges of maximum and minimum values for each time step during the autocorrelation scan. The average values for each curve are Fourier transformed to generate the spectra. The shading on the curves of Figure 4 (right) shows the results of the reconstruction algorithm run for >1000 cases in which the low frequency restoration is slowly changed by varying the characteristic ζ over a range within the confidence interval, and the noise subtraction is varied over a range informed by the RMS value of the measured noise amplitude. The results of this analysis demonstrate the algorithm robustness in terms of variations in the observed data and variations in the previously discussed assumptions required to perform the bunch shape reconstruction.

In summary, an experiment to tailor beam current profiles using a wakefield interaction in a dielectric structure was carried out at the BNL ATF. The results showed that nearly-linear ramped current profile generation of relativistic electron beams was measurable with existing diagnostics and robust reconstruction algorithms, in a compact, passive layout. Follow-on experiments to realize and measure the transformer ratio are presently underway and preliminary simulations show that using the shaped pulse from this experiment, followed by a dielectric wakefield accelerating structure of higher frequency will yield an enhanced $\mathcal{R}$ compared to the unperturbed beam. Further, measurements using a nascent transverse deflecting cavity for profile diagnosis [24], will allow for single-shot, real-time optimization of the ramped beam for injection into an accelerating module. Phase space manipulations using beam-driven dielectric wakefield structures, such as those presented here, show promise as real tools applicable in present-day and future accelerators. Such shaping schemes are adaptable and scalable for future high-energy colliders and next generation light sources based on advanced accelerator methods [25].

This work supported by DOE SBIR grant No. DE-SC0011271 and DOE HEP grant No. DE-SC0009914. The authors acknowledge useful discussions and contributions from P. Frigola, P. Hoang, A. Murokh, P. Musumeci, B. O'Shea, and O. Williams.

FIG. 4: Left: Autocorrelation measurements at the BNL ATF for the cases where the beam is unperturbed (blue curve) and when the beam traverses through the dielectric wakefield shaping (DWS) structures (yellow curve). Each step along the autocorrelation consists of 4 shots (range shown by error bars) and the average (line). Middle: Frequency spectra for the two cases using the average values of the autocorrelation plots. Right: Full pulse reconstructions of the unperturbed beam and the shaped beam, with shading showing >1000 different reconstructions with random cutoff frequency within confidence intervals.

-
- [1] M. Thompson, H. Badakov, A. Cook, J. Rosenzweig, R. Tikhoplav, G. Travish, I. Blumenfeld, M. Hogan, R. Ischebeck, N. Kirby, et al., *Physical Review Letters* **100**, 214801 (2008).
- [2] M. Litos, E. Adli, W. An, C. I. Clarke, C. E. Clayton, S. Corde, J. P. Delahaye, R. J. England, A. S. Fisher, J. Frederico, et al., *Nature* **515**, 92 (2015).
- [3] B. D. O'Shea, G. Andonian, S. K. Barber, K. L. Fitzmorris, S. Hakimi, J. Harrison, P. D. Hoang, M. J. Hogan, B. Naranjo, O. B. Williams, et al., *Nature Communications* **7**, 1 (2016).
- [4] K. L. F. Bane, P. Chen, and P. Wilson, SLAC-PUB pp. 1–3 (1985).
- [5] B. Jiang, J. Power, R. Lindberg, W. Liu, and W. Gai, *Physical Review Letters* **106** (2011).
- [6] F. Lemery and P. Piot, *Physical Review Special Topics - Accelerators and Beams* **18**, 081301 (2015).
- [7] R. J. England, J. B. Rosenzweig, G. Andonian, P. Musumeci, G. Travish, and R. Yoder, *Phys. Rev. ST Accel. Beams* **8**, 012801 (2005).
- [8] R. J. England, J. B. Rosenzweig, and G. Travish, *Phys. Rev. Lett.* **100**, 214802 (2008), URL <http://link.aps.org/doi/10.1103/PhysRevLett.100.214802>.
- [9] P. Muggli, V. Yakimenko, M. Babzien, E. Kallos, and K. P. Kusche, *Physical Review Letters* **101**, 054801 (2008).
- [10] G. Penco, M. Danailov, A. Demidovich, E. Allaria, G. De Nino, S. Di Mitri, W. M. Fawley, E. Ferrari, L. Giannessi, and M. Trovó, *Physical Review Letters* **112**, 044801 (2014).
- [11] P. Piot, C. Behrens, C. Gerth, M. Dohlus, F. Lemery, D. Mihalcea, P. Stoltz, and M. Vogt, *Physical Review Letters* **108**, 034801 (2012).
- [12] D. Xiang and A. Chao, *Physical Review Special Topics - Accelerators and Beams* **14** (2011).
- [13] D. Y. Shchegolkov and E. I. Simakov, *Physical Review Special Topics - Accelerators and Beams* **17**, 041301 (2014).
- [14] G. Andonian and et al., *Proceedings of AAC 2014* (in press) (2014).
- [15] G. Andonian, O. Williams, S. Barber, D. Bruhwiler, P. Favier, M. Fedurin, K. Fitzmorris, A. Fukasawa, P. Hoang, K. Kusche, et al., *Physical Review Letters* **113**, 264801 (2014).
- [16] F. Lemery and P. Piot, *Physical Review Special Topics - Accelerators and Beams* **17**, 112804 (2014).
- [17] S. Antipov, S. Baturin, C. Jing, M. Fedurin, A. Kanareykin, C. Swinson, P. Schoessow, W. Gai, and A. Zholents, *Physical Review Letters* **112**, 114801 (2014).
- [18] S. Antipov, C. Jing, M. Fedurin, W. Gai, A. Kanareykin, K. Kusche, P. Schoessow, V. Yakimenko, and A. Zholents, *Physical Review Letters* **108** (2012).
- [19] A. M. Cook, R. Tikhoplav, S. Y. Tochitsky, G. Travish, O. B. Williams, and J. B. Rosenzweig, *Phys. Rev. Lett.* **103**, 095003 (2009).
- [20] G. Andonian, O. Williams, X. Wei, P. Niknejadi, E. Hemsing, J. B. Rosenzweig, P. Muggli, M. Babzien, M. Fedurin, K. Kusche, et al., *Applied Physics Letters* **98**, 202901 (2011).
- [21] G. Andonian, D. Stratakis, M. Babzien, S. Barber, M. Fedurin, E. Hemsing, K. Kusche, B. O'Shea, X. Wei, O. Williams, et al., *Physical Review Letters* **108**, 244801 (2012).
- [22] A. Murokh, J. Rosenzweig, M. Hogan, H. Suk, G. Travish, and U. Happek, *Nuclear Instruments and Methods in Physics Research A* **410**, 452 (1998).
- [23] R. Lai and A. Sievers, *Physical Review E* **50**, R3342 (1994).
- [24] A. Murokh and et al., *Proceedings of EPAC'08*, Genoa, Italy **06**, 1215 (2008).
- [25] A. Zholents, W. Gai, R. Lindberg, J. G. Power, Y. Sun, C. Jing, A. Kanareykin, C. Li, C. X. Tang, D. Y. Shchegolkov, et al., *Proceedings of FEL2014* p. 993 (2014).