# SIMULTANEOUS GENERATION OF DRIVE AND WITNESS BEAM FOR COLLINEAR WAKEFIELD ACCELERATION

Gwanghui Ha, Pohang Accelerator Laboratory, Pohang, Gyeongbuk 790-784, KOREA
John Gorham Power, Manoel Conde, Darrell Scott Doran, and Wei Gai, Argonne National Laboratory, Argonne, IL 60439, USA

*Abstract*

Generating the drive and witness bunch for collinear wakefield acceleration (CWFA) requires precise control of the longitudinal bunch shape for each bunch as well as the controlling their separation. The emittance exchange (EEX) beamline and a transverse mask can be used to achieve all of these requirements. First, this EEX-based method can independently control the longitudinal bunch shape of each bunches so that the drive bunch is shaped to generate a high transformer ratio while witness bunch is shaped to suppress its energy spread. Second, the timing jitter between the drive and witness bunch poses a serious limitation to the CWFA scheme but the EEX-based method eliminates this since both bunches are generated at the same time and share the exactly same beamline so there are no relative errors. In this paper, we confirm the feasibility of this EEX-based method for simultaneous generation with simulation for CWFA in a dielectric structure.

## INTRODUCTION

Generation of the drive and witness bunch for collinear wakefield acceleration (CWFA) requires precise control of the longitudinal profile of each bunch and control of their separation. The longitudinal bunch shape of the drive bunch needs to be controlled to generate a high transformer ratio [1] and the witness bunch must be shaped to suppress its energy spread for efficient acceleration [2]. Timing jitter between the drive and witness bunch in CWFA poses a serious limitation to the scheme. This is because a jitter in the high frequency CWFA scheme can significantly change the energy gain of the witness bunch.

All three of these requirements can be met with an emittance exchange (EEX) based method [3] that simultaneously generates the drive and witness bunch. The method uses a transverse mask in the EEX beamline to independently control the longitudinal distribution of each bunch [4,5] as well as controlling the separation between the bunches. This method uses a single mask, but with two shapes, to carve a single input beam into two beamlets with different transverse profiles.These beamlets pass through the EEX beamline which exchanges the properties of the transverse and longitudinal phase spaces. Therefore, the two transverse beamlets that enter the EEX beamline become two longitudinally separated bunches (i.e. drive and witness bunches). This method allows control over temporal profiles of both bunches via the shapes on the mask. Further, control over the final bunch lengths and their separation can be controlled from a combination of the separation of the shapes on the mask and the quadrupoles in front of EEX beamline [5]. Finally, this method eliminates the timing jitter between the bunches since they were carved out of the same bunch and propagate through the same beamline so that the bunches experience the same jitters along the beamline.

In summary, the EEX-based method provides distinct advantages for CWFA.

- High transformer ratio from drive beam shaping
- High efficiency from witness beam shaping
- Controlled drive-witness separation
- Relative jitter free acceleration

In this paper, we explored the simultaneous generation and shaping of drive and witness bunches. Also, bunches travel through a rectangular CWFA structure to demonstrate a high transformer ratio and an efficient acceleration. Particle tracking code GPT [6] is used for the simulation. This code includes 3D space charge effect and coherent synchrotron radiation.

## GENERATION AND TAILORING OF DRIVE AND WITNESS BEAMS

The simulation is performed with a double EEX beamline (Fig. 1) and 6D Gaussian beam artificially generated at the entrance to the beamline. The bending angle of the dogleg is 15°, and the spacing between the dipoles is 1.5 m. This angle is too large to transport a high charge beam without significant emittance growth from CSR but we used 15° in order to install the experiment in the space available at the Argonne Wakefield Accelerator facility [5]. The dispersion from the dogleg is 0.5 m, and the corresponding transverse deflecting cavity (TDC) kick strength is $\kappa = 2\ m^{-1}$. The input beam parameters are given in Table 1. Quadrupoles in the middle of the beamline are set to satisfy the transverse parameters (with the subscript 2) in Table 1. The mask is located in between the last quadrupole in the middle and the first dipole of the second EEX beamline. The shape of the mask is determined from Eq. 2 in Ref. [7].

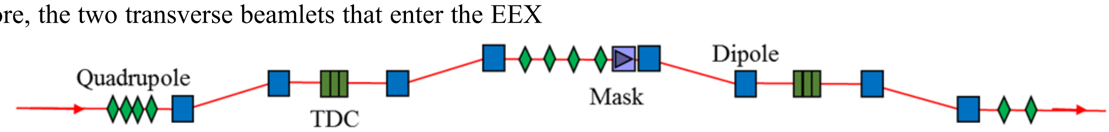


Figure 1: Configuration of a double EEX beamline. The Beam is moving from the left to the right in this figure.




ISBN 978-3-95450-182-3

Table 1: Beam parameters for 6D Gaussian input. Subscript 1 and 2 stands for the entrance to the first and second EEX beamline respectively.

| Input beam parameters | Value | Unit |
|---|---|---|
| Energy | 40 | MeV |
| Charge | 12 | nC |
| $\sigma_{x1}, \sigma_{y1}, \sigma_{z1}$ | 5.0, 3.0, 1.5 | mm |
| $S_{x1}, S_{y1}, S_{z1}$ | -0.2, 0.0, 1.0 | $m^{-1}$ |
| $\sigma_{x2}, \sigma_{y2}$ | 8.0, 3.0 | mm |
| $S_{x2}, S_{y2}$ | 0.0, 0.0 | $m^{-1}$ |

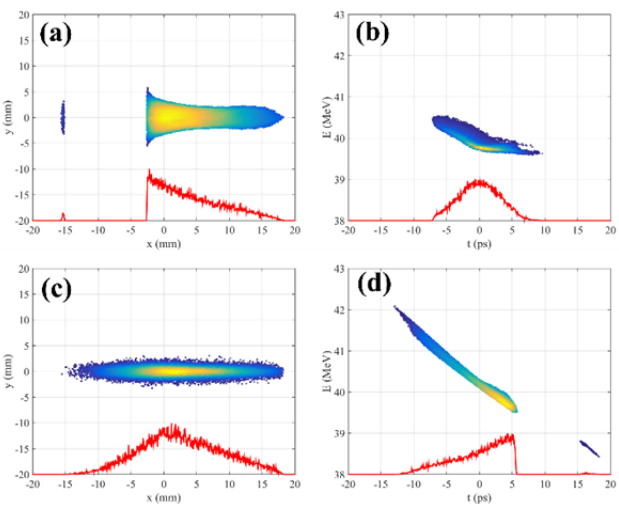


Figure 2: (a) x-y projection and (b) longitudinal phase space after the mask. (c) x-y projection and (d) longitudinal phase space after the second EEX beamline. Red curves are projections to the x-axis (i.e. horizontal profile or temporal profile).

Figure 2 shows the transverse projection and the longitudinal phase space of the beam before and after the second EEX. The mask separates 12 nC beam to two beamlets whose charges are 4.14 nC (drive) and 22.5 pC (witness). The mask size is designed to make the drive bunch length 2λ, the witness bunch length 10° of λ, and the separation 5/4 λ, where λ is the wavelength of the wakefield. Since the R51 of the second EEX is ~0.25, the dimensions on the mask are 20 mm, 0.3 mm, and 13 mm, respectively (Fig. 2a). Separation and bunch length control are accomplished by adjusting the horizontal mask or changing R51 of the EEX beamline with the quadrupoles in front of the second EEX beamline.

Horizontally shaped profiles of the beamlets become a single horizontally symmetric profile after the second EEX beamline (Fig. 2c). Similarly, the initially symmetric longitudinal profile (Fig. 2b) becomes two beamlets (Fig. 2d) at the end. The drive beam has a clear triangle profile and its bunch length is ~17 ps which is close to 2λ. Unfortunately, the profile of the witness beam is collapsed. The ideal bunch length is 0.23 ps, but the result is ~2 ps. The lengthening occurs due to the thick-lens effect (dominant) and second order effects [3]. The thick-lens effect term, $\frac{L_c}{4}\kappa^2\xi$, is 0.06, so an initial rms bunch length of 1.5 mm becomes at least 1.1 ps long. This can be overcome by introducing a fundamental mode cavity to the beamline to suppress the thick-lens effect [8].

## WAKEFIELD ACCELERATION WITH LONGITUDINALLY TAILORED BEAMS

To simulate the wakefield acceleration, we used CST to generate the wake function of a 120 GHz rectangular CWFA structure [9]. Since the horizontal beam size easily blows up due to CSR along this beamline (due to its large bending angle), rectangular structures are preferred. Dimensions in Table 2 were chosen to generate a measurable energy loss on the drive and energy gain (~ 1 MeV) on the witness beam during the planned experiment.

Since the structure is only 50 cm long, three quadrupoles are used to focus the beam to minimize its size near the center of the structure. Horizontal and vertical beam envelops along the beamline are shown in Fig. 3. All particles pass through the structure without any loss.

The wakefield generated by the drive bunch in the structure is calculated by taking the convolution of the wake function and the current profile (Fig. 2). Fig. 4 shows the temporal profiles of the drive and the witness bunches and the corresponding wakefield. Two oscillations of the wakefield inside the drive bunch show that the bunch length is 2λ. Although the witness bunch is lengthened by the second order and thick-lens effects, the separation is well-controlled. The witness beam is ~5/4 λ away from the end of drive beam where the accelerating wakefield becomes maximum.

The ideal transformer ratio due to a bunch length of 2λ is 6.3 [10]. The simulated transformer ratio, however, is 4.5 which is 71% of the ideal due to the curvature in the triangle shape. This curvature creates an imbalance between the two peaks of the wakefield inside the drive bunch. It results in a higher second peak (1.12 MV/m), so the ratio of maximum accelerating wakefield (5 MV/m) to the maximum decelerating wakefield (1.12 MV/m) is lower than the ideal value. This curvature originates from the initial horizontal profile (Fig. 2a) (i.e. initial horizontal profile is not a perfect triangle).

Table 2: Dimensions of the CWFA structure generating a wakefield. The shape of the structure is a rectangle.

| Dimensions | Value | Unit |
|---|---|---|
| Height (vacuum) | 3 | mm |
| Width (vacuum) | 18 | Mm |
| Length | 500 | Mm |
| Thickness | 130 | Mm |

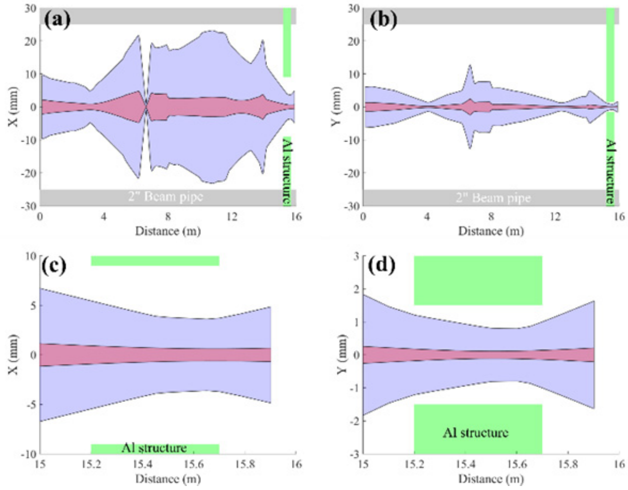


Figure 3: Horizontal (a) and vertical beam (b) envelope along the double EEX beamline. The red envelopes show the sigma for x and y, and the blue envelopes shows the full size of the beam for x and y. (c) and (d) shows the beam envelopes near the structure.

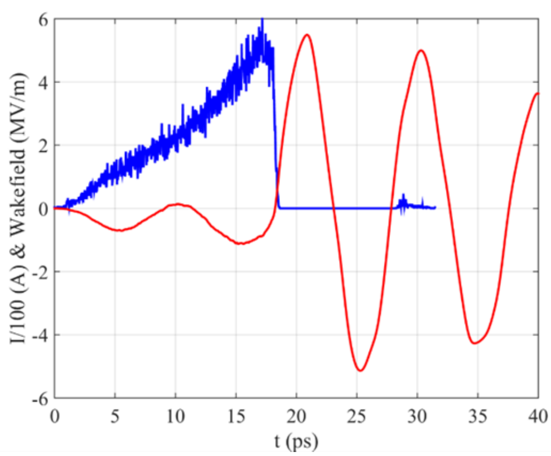


Figure 4: Current profiles at the entrance to the structure (blue). Wakefield calculated by the convolution of the current profile and the wake function (red).

Figure 5 shows the particle tracking simulation results. A homemade wake module in GPT calculates the wakefield by convoluting the wake function and the current profile. The module also calculates the effect of the wake function on the bunch.

Figure 5a shows the longitudinal phase space before the CWFA structure and 5b shows it after. The longitudinal phase space of the drive beam also has an oscillating shape due to the oscillating decelerating wakefield (Fig. 4) while the witness beam shows a typical RF curvature with an acceleration. The maximum energy loss of the drive beam is about 0.4 MeV (39.5→39.1 MeV), and the maximum energy gain of the witness beam is about 2.5 MeV (38.5→41.0 MeV). Therefore the transformer ratio should be in between 4 and 6 which is larger than 2 (transformer ratio limit for symmetric bunches) [11]. This result agrees with the estimated number.

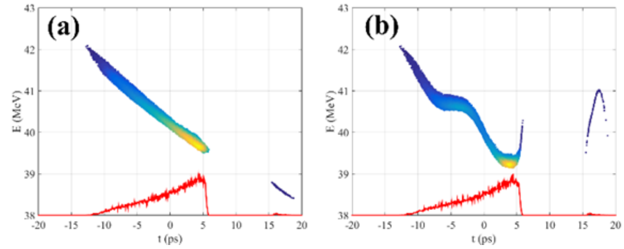


Figure 5: Longitudinal phase space before (a) and after (b) the CWFA structure. Red curves are temporal profiles.

## CSR AND EMITTANCE GROWTH

Although the shaping and a high transformer ratio is feasible, one of the major limitation of present EEX method is the emittance growth from CSR. This method uses eight dipole magnets which makes the beam has more chances to interact with CSR. Also, it requires a high charge beam due to the low transmission (~30-40%). When the 12 nC beam passes through the first EEX, the four dipoles contribute CSR that dilutes the emittance significantly (30→200 μm). More seriously, CSR directly changes both the initial horizontal and longitudinal phase spaces due to the exchange process. This effect increases both projected and slice emittances. We are still investigating methods for suppressing CSR and its effect on the emittance in double EEX beamline.

## REFERENCES

[1] B. Jiang, C. Jing, P. Schoessow, J. Power, and W. Gai, *Phys. Rev. Accel. Beams* 15, 011301 (2012).
[2] A. Zholents *et al., Nucl. Instrum. Methods Phys. Res.*, Sect. A 829, 190 (2016).
[3] P. Emma, Z. Huang, K. –J. Kim, and P. Piot, *Phys. Rev. Accel. Beams* 9, 100702 (2006).
[4] Y.-E Sun, P. Piot, A. Johnson, A. H. Lumpkin, T. J. Maxwell, J. Ruan, and R. Thurman-Keup, *Phys. Rev. Lett.* 105, 234801 (2010).
[5] G. Ha *et al., Phys. Rev. Lett.* 118, 104801 (2017).
[6] www.pulsar.nl/gpt.
[7] J. G. Power, A. Zholents, K. –J. Kim, M. Conde, C. Jing, M. H. Cho, W. Namkung, and G. Ha, in *Proc. IPAC'14*, Dresden, Germany, 2014 (JACoW, Geneva, 2014), p. 1506.
[8] A. A. Zholents and M. S. Zolotorev, "A New Type of Bunch Compressor and Seeding of a Short Wave Length Coherent Radiation", Report No. ANL-APS-LS-327, 2011.
[9] From Ben Barber.
[10] F. Lemery and P. Piot, *Phys. Rev. Accel. Beams* 18, 081301 (2015).
[11] K. L. F. Bane, P. Chen, and P. B. Wilson, SLAC-PUB-3602 (1985).




ISBN 978-3-95450-182-3