TRANSFORMER RATIO ENHANCEMENT EXPERIMENT BASED ON EMITTANCE EXCHANGER IN ARGONNE WAKEFIELD ACCELERATOR

Qiang Gao[1,2,*], Chunguang Jing[3], Sergey P. Antipov[3], Jiaru Shi[1], Huaibi Chen[1], Wei Gai[1,2], John Goham Power[2], Manoel Conde[2], Charles Whiteford[2], Eric Edson Wisniewski[2], Wangming Liu[2], Darrell Scott Doran[2],
[1] Tsinghua University, Beijing 100084,China,
[2] Argonne National Laboratory, Lemont, IL 60439, USA,
[3] Euclid TechLabs, Solon, Ohio 44139, USA

Abstract

The transformer ratio is an important figure of merit in collinear wakefield acceleration, it indicates the efficiency of energy transferring from drive bunch to witness bunch. Higher transformer ratio will significantly reduce the length of accelerator thus reducing the cost of accelerator construction. However, for the gaussian bunch, this ratio has its limit of 2. To obtain higher transformer ratio, one possible method is to tailor the beam current profile to specific shapes. One method of beam shaping is based on emittance exchange, which has been demonstrated at the Argonne Wakefield Accelerator. Its principle is to tailor the beam transversely using a mask then exchange the beam's transverse profile and longitudinal profile. In this paper, we describe our efforts to optimize the beamline and mask in order to generate a triangular beam with quadratic head, which has a transformer ratio of 6.4. We also present our design of a dielectric slab based accelerating structure to measure the transformer ratio. Finally, we discuss an experiment for this high transformer ratio at Argonne Wakefield Accelerator Laboratory.

INTRODUCTION

Transformer ratio (TR) is an important figure of merit in the collinear wakefield acceleration. It is defined as the ratio of maximum energy gain by witness beam to the maximum energy loss by the drive beam. This ratio indicates the efficiency of energy transferring from drive bunch to witness bunch. The higher transformer ratio it is, the higher energy gain that witness bunch has when the drive bunch energy is fixed. However, it can be proved that TR is less than 2 for a drive beam with a symmetric longitudinal current profile, such as a gaussian[1]. Two main techniques have been explored by scientist to enhance the TR recent years. One of them is to utilize a ramped bunch train which had been demonstrated at Argonne to obtain TR as high as 3.4 [2] while another methods shape the drive bunch current profile. This can be done by tailoring the beam transversely then exchange its longitudinal profile with transverse profile. Recently an experiment has demonstrated that inserting a mask into one dogleg can obtain a triangle bunch which has TR as high as 3.5 [3]. Now we design and optimize an experiment to enhance the transformer ratio utilizing emittance exchange (EEX) beamline at Argonne Wakefield Accelerator Laboratory.

* *gaoq08thu@gmail.com

PRINCIPLE

The concept of EEX was first come up with in 2002 [4]. Then scientist found that it can be used for beam longitudinal shaping [5]. The crucial components of EEX are that two identical doglegs and one deflecting cavity which is inserted between the two doglegs. The linear transport matrix of EEX beamline can be expressed as following equation when taking the thin-lens assumption,

$$\begin{bmatrix} x_f \\ x'_f \\ z_f \\ \delta_f \end{bmatrix} = \begin{bmatrix} 0 & 0 & \kappa L/2 & \eta+\kappa\xi L/4 \\ 0 & 0 & \kappa & \kappa\xi/2 \\ \kappa\xi/2 & \eta+\kappa\xi L/4 & 0 & 0 \\ \kappa & \kappa L/2 & 0 & 0 \end{bmatrix} \begin{bmatrix} x_i \\ x'_i \\ z_i \\ \delta_i \end{bmatrix} \quad (1)$$

So the beam longitudinal profile after EEX is only determined by the initial transverse phase space. It means that we can obtain arbitrary longitudinal profile if we tailor the beam transversely with mask [6].

When a charged drive bunch traverses a dielectric waveguide it will excite the wakefiled inside and behind the bunch. The TR can be calculated as ratio of the maximum accelerating voltage behind the drive bunch to the maximum decelerating voltage inside the drive bunch. Figure 1 shows the current profile of a gaussian bunch and its wakefield.

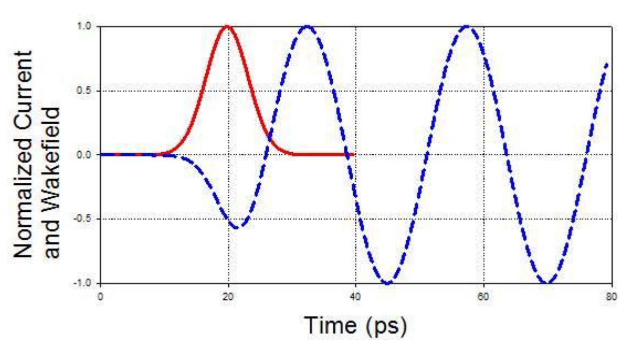

Figure.1: The current profile and wakefield of a gaussian bunch. The red solid line is the current profile and blue line is the wakefield.

From figure 1 we can see that the wakefield at some distance behind drive bunch shows a positive accelerating field which indicates the witness bunch gain energy at these specific phases. Also the wakefield inside bunch is a decelerating field, which means that the particle of the drive bunch will lose energy. The decelerating field inside the gaussian bunch is not uniform so that some particles will lose more energy than the others. Therefore, the maximum energy loss determines the efficiency of collinear wakefield acceleration. It can be derived that the more homogenized decelerating field inside drive bunch, the higher TR we can achieve. The recent theory shows that triangle profile has a much higher TR than gaussian case [5]. Furthermore, if there is a little bump in the head of the triangle, the decelerating field will be more uniform than other cases, for example, double triangle profile and quadratic head triangle profile [5][7].

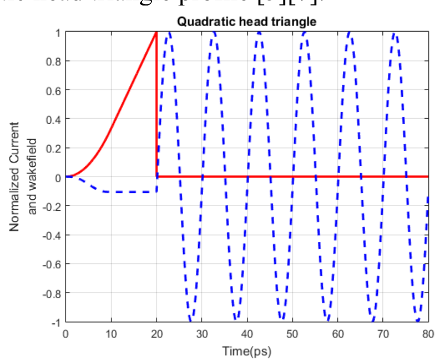

Figure 2: The quadratic head triangle current profile and wakefield.

Figure 2 shows that the decelerating field inside the quadratic head triangle bunch is much more uniform than the gaussian bunch, ideally the triangle bunch with quadratic head has a TR as high as 9.4. We design an experiment to generate a bunch with this longitudinal profile and to demonstrate the transformer ratio enhancement.

EXPERIMENT SETUP

Argonne Wakefield accelerator has a L-band emittance exchange beamline [8]. The beamline layout is shown in figure 3. We have designed quadratic head triangle mask and the witness bunch mask for this experiment. As shown in figure 4, the mask consists of two pieces of tungsten plate, their assembly can generate the drive bunch and a witness bunch with adjustable phase.

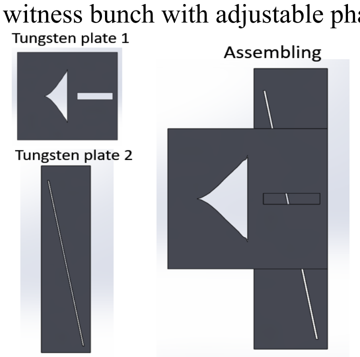

Figure 4: The mask for TR enhancement experiment.

The quadratic triangle cut open of the first tungsten plate is calculated numertically according to the beam profile in the mask position. The length of the triangle is determined by the frequency of dielectric waveguide whose function is to generate the wakefield. When assembling the first plate and second plate with each other, a small parallelogram cut open can be used for generating the witness bunch. If moving the second plate up and down, we can adjust the speration between drive bunch and witness bunch which means that we can scan the accelearting phase.

The dielectric waveguide is also a crucial component for this experiment. A trade-off between high R over Q and large dynamic aperature should be taken into consideration. The R over Q reflects the dielectric waveguide intrinsic accelerating ability, the energy gain of the witness bunch is proportional to the R over Q value when the charge and current profile of drive and witness bunch have been fixed. Higher energy gain means that it is easier to measure the energy change using spectrometer. However, higher R over Q requires a small beam dynamic aperature of the dielectric waveguide. Besides the relationshipd with R over Q, the energy gain is also proportional to the drive bunch charge if any other conditions are fixed. In this case, the large beam dynamic aperature which allows more particles to traverse through the structure should be selected. We have optimized the R over Q and beam dynamic aperature for the dielectric waveguide in which can the witness bunch can obtain more than 0.5 MeV energy gain. Figure 5 shows the slab dielectric waveguide for this experiment.

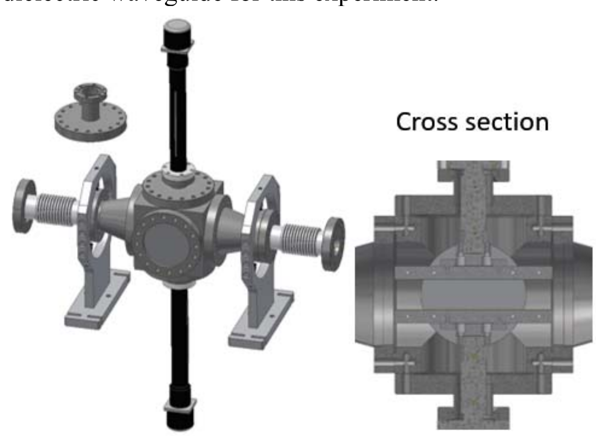

Figure 5: The slab dielectric waveguide assembly.

The size of slab is 15 cm long and 1.3 cm wide. Two motorized actuators moving up and down to change the gap between two dielectric slab from 1 mm to 3 mm, corresponding the frequency from 170 GHz to 130 GHz and R over Q ranging from 12.44 kOhm/m to 3 kOhm/m. The advantage benefited from slab waveguide can be concluded in two points, one is to fit for the asymmetric projection emittance of x and y direction at the end of EEX, the other one is to reduce the dipole kick from high order mode wakefield so that the beam break up (BBU) inside the dielectric waveguide can be suppressed.

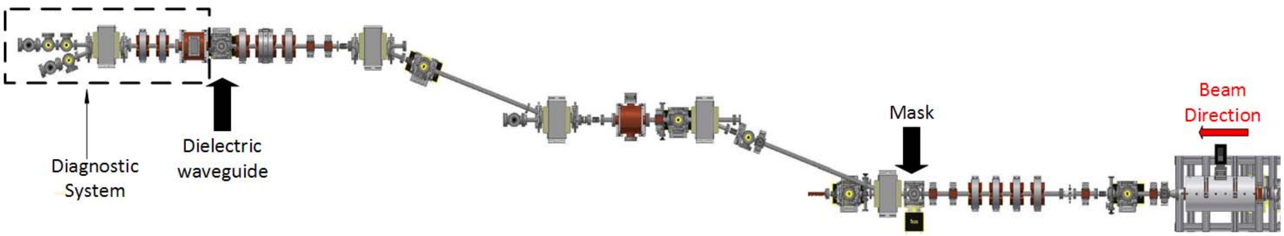

Figure 3: layout for transformer ratio enhancement experiment based on emittance exchange beamline.

BEAM DYNAMIC SIMULATION

We have finished the preliminary full beamline simulation for 130.9GHz working frequency case using quadratic triangle mask. We select the charge as 13 nC before the mask and the beam energy is 45 MeV.

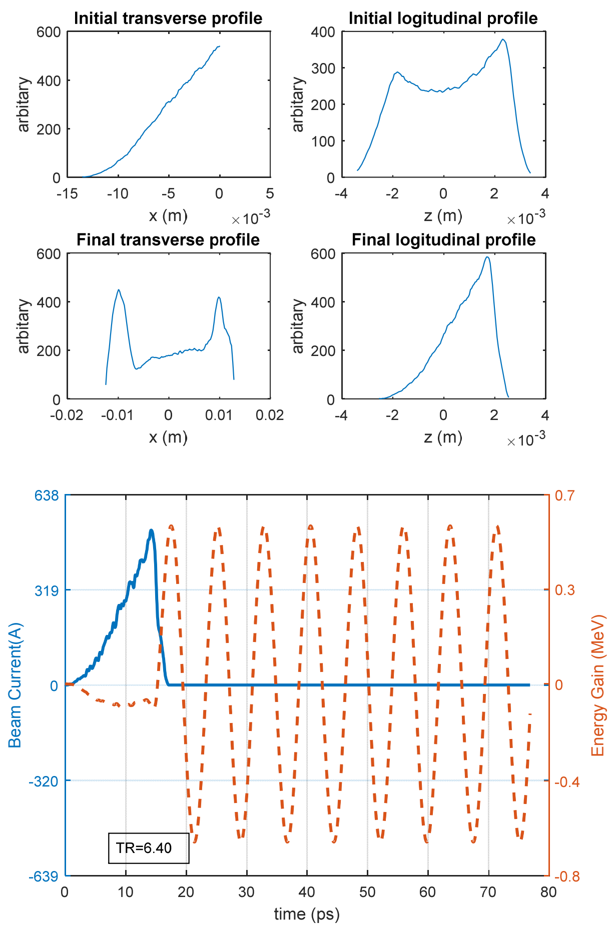

Figure 6: (a) The transverse and longitudinal profile right after the mask and them at the end of EEX. (b) The current profile of the drive bunch after EEX and its wakefield.

The full simulation has been done using General Particle Tracer, the space charge and coherent synchrotron radiation (CSR) effect are taken into consideration. The beam transverse and longitudinal profile before and after EEX have been shown in Fig 6(a). As mentioned in the previous section, the ideal TR for this quadratic head triangle is 9.4. The TR decreases to 6.4 in the simulation due to the CSR effect in the second dogleg. Still some method such as slope control should be applied to suppress this effect. Fig 6(b) shows that the decelerating field inside the drive bunch has a similar uniformity as predicted, and the maximum energy gain is 0.64 MeV which should be measurable.

ACKNOWLEDGMENT

This work is supported by the National Natural Science Foundation of China (NSFC) No. 11375098.

CONCLUSION

We have designed and optimized an experiment to enhance the transformer ratio based on emittance exchange beamline. The preliminary simulation results show that this experiment setup can increase the TR as high as 6.4. The fabrication and installation of all the parts is expected to be finished by the end of this month. Then we will conduct this experiment aiming to obtain a highest transformer ratio up to now.

REFERENCES

[1] Bane, K. L. F., Pisin Chen, and P. B. Wilson. "ON COLLINEAR W. 4KE FIELD ACCELERATION.", 1985.

[2] Jing, C., *et al.,* "Increasing the transformer ratio at the Argonne wakefield accelerator." *Physical Review Special Topics-Accelerators and Beams,* 14.2, 2011,: 021302.

[3] Sergey Antipov, *et al.,* "Transformer ratio enhancement with triangle beam.", AAC 2016.

[4] Cornacchia, M., and P. Emma. "Transverse to longitudinal emittance exchange." *Physical Review Special Topics-Accelerators and Beams* 5.8, 2002, 084001.

[5] Jiang, B., *et al.,* "Formation of a novel shaped bunch to enhance transformer ratio in collinear wakefield accelerators." *Physical Review Special Topics-Accelerators and Beams* 15.1 (2012): 011301.

[6] Piot, Ph, et al. "Generation of relativistic electron bunches with arbitrary current distribution via transverse-to-longitudinal phase space exchange." Physical Review Special Topics-Accelerators and Beams 14.2 (2011): 022801.

[7] Lemery, Francois *et al.,* "Tailored electron bunches with smooth current profiles for enhanced transformer ratios in beam-driven

ISBN 978-3-95450-180-9

acceleration." *Physical Review Special Topics-Accelerators and Beams,* 18.8, 2015, p. 081301.

[8] Ha, Gwanghui *et al.*, "Initial EEX-based bunch shaping experimental results at the Argonne Wakefield Accelerator Facility, in *Proc. 2015.*