HIGH TRANSFORMER RATIOS IN COLLINEAR WAKEFIELD ACCELERATORS*

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Abstract

Based on our previous experiment that successfully demonstrated wakefield transformer ratio enhancement in a 13.625 GHz dielectric-loaded collinear wakefield accelerator using the ramped bunch train technique, we present here a redesigned experimental scheme for even higher enhancement of the efficiency of this accelerator. Design of a collinear wakefield device with a *transformer ratio R*>>2, is presented. Using a *ramped bunch train* (RBT) rather than a single drive bunch, the *enhanced transformer ratio* (ETR) technique is able to increase the transformer ratio R above the ordinary limit of 2. To match the wavelength of the fundamental mode of the wakefield with the bunch length (σ_z=2 mm) of the new Argonne Wakefield Accelerator (AWA) drive gun (where the experiment will be performed), a 26.625 GHz dielectric based accelerating structure is required. This transformer ratio enhancement technique based on our dielectric-loaded waveguide design will result in a compact, high efficiency accelerating structures for future wakefield accelerators.

INTRODUCTION

As one of the most promising techniques in the category of advanced accelerator concepts for high energy physics research applications, wakefield accelerators are being extensively investigated [1-2]. In a wakefield accelerator, the field generated by a leading high charge drive beam (either a single bunch or bunch train) is used to accelerate a trailing “witness” bunch which contains a small amount of charge. An important parameter that describes the performance of a wakefield accelerator is the transformer ratio *R* = (maximum energy gain behind the drive bunch) / (maximum energy loss inside the drive bunch). *R* characterizes the efficiency of the energy transfer from the drive bunch to the witness bunch and is less than 2 under very general conditions [3]. We present in this article a technique that uses Ramped Bunch Train (RBT) as a drive bunch to overcome this limit and obtain a much higher energy transfer efficiency.

The RBT method uses a bunch train with ramped (linearly increasing) net charge. The individual bunches in the train are symmetric (e.g. Gaussian) separated by an optimal distance, *d*. The net charge of each bunch and the intra-bunch spacing are adjusted to make all the drive bunches in the drive train experience the same maximum decelerating field, W^-, but the accelerating wakefield behind the bunch, W^+, is much larger, therefore the overall transformer ratio will increase as the number of drive bunches increases.

The RBT algorithm to achieve maximum transformer ratio enhancement has been fully discussed in [4], which emphasized that the two key parameters necessary to adjust in order to effect the transformer ratio enhancement in this technique are the optimized charge ratios and the spacing between bunches. For the case of a bunch train consisting of *N* drive bunches, the transformer ratio will be enhanced according to $R_n = R_{n-1} + (R_1-1)^{n-1} R_1$ (n = 2, ...N) if two critical conditions are satisfied: 1) the bunch intensity in the train follows a ramped charge relation $Q_n = (1+R_{n-1})Q_1$; 2) the separation between bunches is $d_n = (n + 1/2)\ \lambda_0$, $n = 1, 2...N-1$. The enhancement rate of the transformer ratio in a ramped bunch train mostly depends on the initial value, R_1, which is a function of σ/λ and has its maximum around σ/λ =1/4 [4]. Therefore, two paths are available to increase the wakefield transformer ratio, either adjustment of the bunch length of the drive bunches or by tuning the frequency of the accelerating structure to maintain σ/λ around ¼. Figure 1 shows the transformer ratio enhancement in a dielectric-loaded accelerating structure using the ramped bunch train technique. Our earlier structure to demonstrate *R* enhancement operated at 13.625 GHz because the Argonne Wakefield Accelerator (AWA) facility was using its classic drive gun, which could only provide electron bunches with bunch length close to 4.5 mm when the experiment was planned. Currently, the AWA beamline has been upgraded with a new photoinjector that can provide a shorter bunch length (σ_z=2 mm) for high gradient wakefield experiments. We performed a transformer ratio enhancement experiment using the 13.625 GHz structure at the current AWA facility [5]. We made the first ever observation of the enhancement of the wakefield transformer ratio during an experiment that had only two ramped drive bunches. The simulation of the transformer enhancement using the 13 GHz DLA structure is shown in Fig. 1(a), in which we can see that, for the shorter bunch length, there is no significant increase for the transformer ratio after the second drive bunch. Instead of requiring a longer bunch length, Figure 1(b) shows that a higher transformer ratio (>>2) can also be achieved if we raise the frequency of the accelerating structure. With the experience gained from the previous experiment and improved measurement capability, we plan to fabricate and experimentally test a 26.625 GHz dielectric based accelerating structure which, when excited by a bunch train consisting of 4 bunches with increasing charges, allows an enhancement of the transformer ratio by up to a factor of 3.5 (i.e. the transformer ratio is enhanced from

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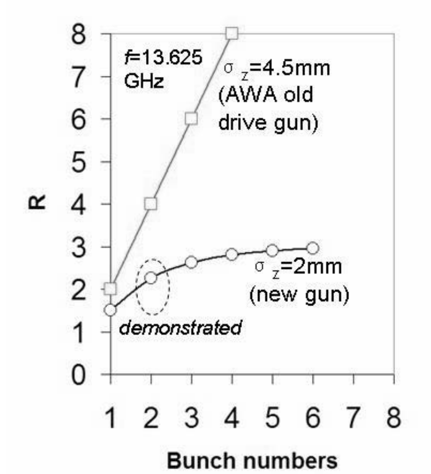
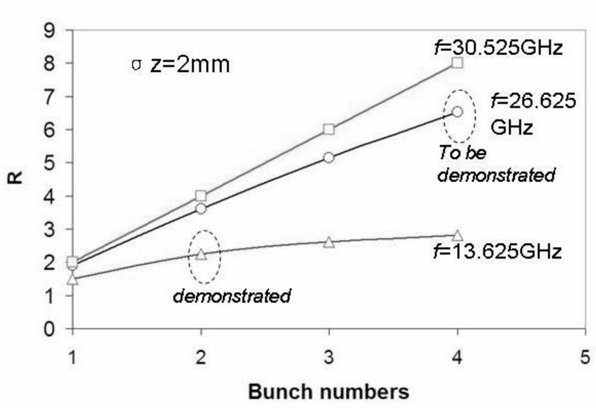
R_1=1.9 to R_4=6.7) compared to a single drive bunch collinear accelerating scheme.



(a)



(b)

Figure 1. Simulations of the transformer ratio *R* as a function of bunch length and number of RBT bunches. (a) The transformer ratio is enhanced in a 13.625 GHz dielectric-loaded accelerator with two different bunch lengths, one representative of the classic AWA drive gun, and the other of the replacement gun currently in use. (b) At the current AWA facility configuration (bunch length fixed), the transformer ratio is increased by choosing a structure operating at a different frequency. We propose here to use a 26.625 GHz structure to achieve a wakefield transformer ratio close to 6.7 after 4 ramped charge bunches.

26 GHZ DLA STRUCTURE

Parameters

A key issue for the success of the ETR demonstration is the dielectric loaded accelerating structure design and fabrication. The main parameters of the ceramic tube developed and tested in this project will be: 1) dielectric constant of 9.7; 2) inner radius of 3.5 mm and outer radius of 4.325 mm, which are designed to maintain a low field attenuation, a high R/Q, and a reasonable group velocity and size of the beam channel for the 26 GHz structure. Low group velocity is able to help maintain a longer drain time, which is defined as the time for the energy deposited by one bunch in the synchronous mode to travel out of the structure starting from the moment that the bunch has left the structure itself. At the AWA beamline, the bunch spacing is fixed to be 773 ps (one linac rf period), therefore, a few ns drain time is required for the wakefield interaction in a bunch train excitation.

Additional requirements for the dielectric loading are to maintain tight fabrication tolerances and uniformity to obtain a Transformer Ratio value in the range of 6.0 — 7.0 that is a target of the project. The material for the dielectric waveguide is to have extremely low dielectric loss tangent (~10^{-4} up to 30 GHz) and tolerate highly precise mechanical treatment (brazing and polishing). This material needs to provide a thermal expansion coefficient to match the thermal variation of the copper tube radius as well.

Table 1: Parameters of the 26 GHz DLA structure.

Geometric and accelerating parameters	**Value**
ID / OD of dielectric tube	7 mm /8.65 mm
Dielectric constant	9.7
Loss tangent	1×10^{-4}
Length of dielectric tubes	100×4 mm
Group velocity Vg	0.21c
Drain Time Td	5 ns
R/Q	9060(Ω/m)
Field ATTN	2.3 dB/m

Field Probe

Like the 13 GHz structure, we also plan to put a field probe (shown in Fig.2) to monitor the wakefield signals. With a 15 GHz oscilloscope, we can use a heterodyne circuit to obtain the down converted wakefield signal and restore it through software. We should point out that the RBT experiment is implemented with a traveling wave structure. But for simplicity of fabrication, instead of rf couplers, we put two short cutoff copper tubes at the both ends of the structure that are used to secure the dielectric tube and terminate the propagation of the wave. Due to proper placement of the field probe at 82 mm from the upstream end, the detected wakefield signal is still a traveling wave within the few ns measurement period.

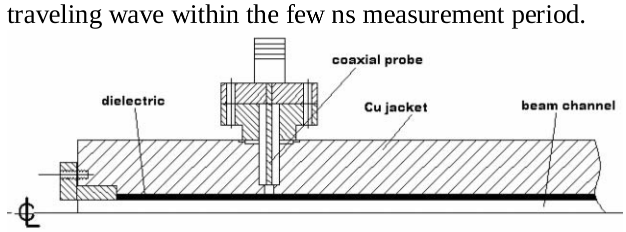


Figure 2. Part of the 26 GHz dielectric-loaded accelerating structure for the wakefield transformer ratio enhancement experiment.

BUNCH TRAIN GENERATION

In the previous experiment, the laser optics for bunch train generation was not able to measure the deceleration field inside the bunch using a witness bunch [5]. We measured the transformer ratio enhancement but the transformer ratio for each drive bunch was referred partially to the simulation. In the proposed experiment, we will use four drive bunches with ramped charge and one witness bunch to probe both the deceleration and acceleration peaks of the wakefield generated by each drive bunch. The laser optical configuration is shown in Figure 3. The laser pulses for drive bunches and witness bunch are separated by a polarizing beam splitter cube (in combination with a half wavelength plate), which can provide variable beam splitting ratio [6]. Three non-polarizing beam splitters (with properly designed splitting ratio) and accordingly reflective mirrors are used to form 4 ramped intensity drive pulses. The length of the witness bunch leg can be changed independently so that the generated witness bunch can probe either the decelerating or accelerating phase of the wakefield excited by each drive bunch.

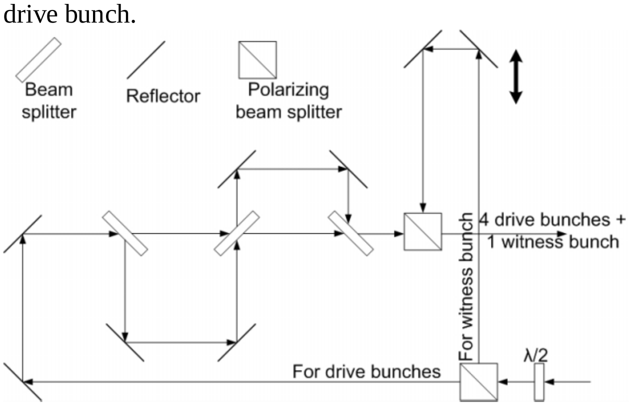


Figure 3. Laser configuration for the bunch train generation, consisting of 4 drive bunches and one witness bunch.

SUMMARY

We proposed a new experiment on wakefield transformer ratio enhancement using a ramped bunch train consisted of four drive bunches and a witness bunch. A 26 GHz DLA structure will be used at the AWA facility for this experiment. A transformer ratio of 6 is expected after 4 drive bunches.

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