Transformer Ratio Enhancement for Structure-Based Wakefield Acceleration

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Abstract. A limiting factor in the efficiency of wakefield accelerators is the fact that the transformer ratio R, the parameter that characterizes the energy transfer efficiency from the accelerating structure to the accelerated electron beam, is less than 2 for most technologically realizable beam-structure configurations. We are planning an experiment to study transformer ratio enhancement in a 13.625 GHz dielectric wakefield structure driven by a ramped bunch train [1]. In this paper we present an experimental program for the demonstration of this Enhanced Transformer Ratio Dielectric Wakefield Accelerator (ETR-DWA).

INTRODUCTION

This paper outlines the design, development and demonstration of an Enhanced Transformer Ratio Dielectric Wakefield Accelerator (ETR-DWA) [1]. The principal goal of this project is to increase the *transformer ratio* R, the parameter that characterizes the energy transfer efficiency from the accelerating structure to the accelerated electron beam. For collinear wakefield devices (those in which the high current drive beam and the accelerated "witness" beam are transported along the same path through a structure that serves as the means to transfer energy from the drive to the witness beam) R is less than 2 under very general assumptions [2].

Considerable effort has been directed at the development of high transformer ratio schemes and their experimental demonstration. The increased efficiency will result in dramatic reduction in the size (and presumably cost) of future high energy accelerators that has provided much of the stimulus for research in this area. There have been a number of attempts to design acceleration schemes with enhanced R through the use of asymmetric drive beam axial distribution [3, 4], noncollinear drive beam/witness beam geometry [5], nonlinear beam dynamics [6] and nonlinear plasma dynamics [7].

More recently interest in R enhancement has arisen in the context of the Stimulated Dielectric Accelerator [8] and with the subsequent discussions [9] and experimental efforts [10]. At the same time, no experimental results for Transformer Ratio Enhancement in collinear devices have been reported due to the experimental difficulties inherent in the accelerating schemes and methods discussed above.

One attractive method of obtaining $R > 2$ is to use a drive beam with an asymmetric longitudinal charge distribution. The difficulty in this method is in generating very high-current electron bunches of short duration with a controlled longitudinal profile. The new AWA photoinjector [11] will generate 40−60 nC electron bunches 0.1 cm rms in length. Longitudinal shaping of a beam with these parameters represents a challenge. We consider here an approach to bunch shaping that builds upon well founded techniques for multibunch beam generation and manipulation in photoinjector based linacs. We refer to this approach as the <u>Ramped Bunch Train</u> (RBT) method.

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The Enhanced Transformer Ratio technique/experiment is based upon the idea of substituting asymmetric shaping of a single high charge drive bunch with a train of symmetric drive bunches with linearly increasing intensity [12]. This technology is to be experimentally studied at the Argonne Wakefield Accelerator (AWA) facility where the short pulse high charge beam technology and experience in generation of bunch trains can be exploited.

Critical technologies relevant to the demonstration of the RBT/ETR have been demonstrated recently

- accelerating structure fabrication with extremely high dielectric constant homogeneity;
- laser beam splitting to produce a pulse train with the ramped intensity;
- numerical simulations of high charge bunch train dynamics.

The ceramics to be used in the accelerating structure have been manufactured and the required mechanical tolerances of (3−10) μm and uniformity of dielectric properties in the range of 0.35% have been achieved. We fabricated and tested a 13.625 GHz accelerating structure (dielectric permittivity of 16 and loss-factor in the range (1−1.2) x 10^{-4}) which, when excited by a bunch train, will allow an enhancement of the transformer ratio by up to a factor of 4 compared to the conventional collinear accelerating scheme. (Choice of the structure frequency is dictated by the requirement that the bunch spacing be an odd number of structure wavelength and an integral number of linac rf wavelengths. The bunch separation here corresponds to 10.5 wavelengths.)

We installed and tested a prototype laser beam splitter to produce a ramped bunch train of 4 bunches, predicted to achieve a transformer ratio of 7.6 in the 13.625 GHz structure. The multisplitter as currently implemented produces a pulse train of fixed bunch spacing, spot size and intensity ratio. Special efforts have been directed towards refinement of the laser multisplitter to provide independent control of the intensities of the individual bunches in the train, beam transverse size and interbunch distances.

Ramped bunch train parameters have been simulated and optimized for the 13.625 GHz accelerating structure. Numerical simulations of the beam dynamics of the electron bunches in the accelerating structure have been completed and the FODO lattice parameters have been calculated. A final bench test validation of the 13.625 GHz ceramic waveguide electrical properties has been done. The transformer ratio enhancement experiment at the AWA (ramped beam generation and wakefield measurements using a witness beam) is being assembled.

ENHANCED TRANSFORMER RATIO EXPERIMENT

We plan to experimentally demonstrate the ETR-DWA in 2004 - 2005. Our initial proof of principle demonstration will use an RBT of 4×15 MeV bunches, with charge ratio of 2:6:10:14 nC and bunch length of $\sigma_z = 0.4$ cm. These parameters are predicted to yield R = 7.8. A somewhat more challenging experiment to demonstrate a high accelerating gradient and enhanced R simultaneously is also planned. This will use an RBT of ~10:30:50:70 nC to achieve R = 7.6 and E = 104 MV/m. (The parameters for this experiment are given in Table 2 and the wakefield for this case (computed using the rigid bunch approximation) are shown in Figure 2.)

The design of these experiments includes a laser multisplitter to produce a ramped train of laser pulses from the AWA photoinjector, and a 13.625 GHz dielectric loaded accelerating structure supplied with an external focusing FODO lattice to minimize BBU effects in the RBT. The accelerating structure will be installed into the AWA beamline. This transformer ratio enhancement technique based on ceramic waveguide design will result in a highly efficient accelerating structure for future generation wakefield accelerators.

EXPERIMENTAL DESIGN

Accelerating Structure Fabrication

The dielectric for the 13.625 GHz structure is a ceramic composition based on $MgTiO_3$-Mg_2TiO_4 systems that have been sintered using the solid-phase synthesis method [13]. This material is characterized by a unique homogeneous fine-grained structure and minimum porosity, with a dielectric constant of 16 (Fig. 1). The dielectric loss factor has been measured with the dielectric loaded resonator method. Measurement of test samples at 9 GHz showed the following results: $Q \times f = (6.0 - 7.7)\times10^4$, loss factor of $(1.12 - 1.17)\times10^{-4}$.

a b

Figure 1. 13.626 GHz ETR-DWA ceramic (a) and vacuum chamber (b).

A set of 5 waveguide sections tuned for 13.625 GHz TM_{01} mode has been designed and fabricated of the ceramic discussed above using a special press-form. The dielectric tubes were formed with a specially developed two-stage technology involving hydraulic and isostatic pressing. The accelerating structure bench test parameters are presented in Table 1.

Mechanical tolerances and dielectric constant heterogeneity along the accelerating structure have been studied intensively due to the critical impact of structure imperfections on the Transformer Ratio to be measured. The mechanical tolerances obtained by this manufacturing process did not exceed 10 μm. The maximum deviation of the dielectric constant measured in the bench from the mean value for the structure was less than 0.055. The dielectric constant deviations were within 0.2% of the average and 0.35% of the maximum deviation. As discussed in the next section, a transformer ratio in the range of 7.5 – 7.8 can be obtained under these mechanical and electrical tolerances. The effect of these tolerances is to shift the frequency of a segment of the structure by ±20 MHz.

Transformer Ratio Dependence on Beam and Structure Parameters

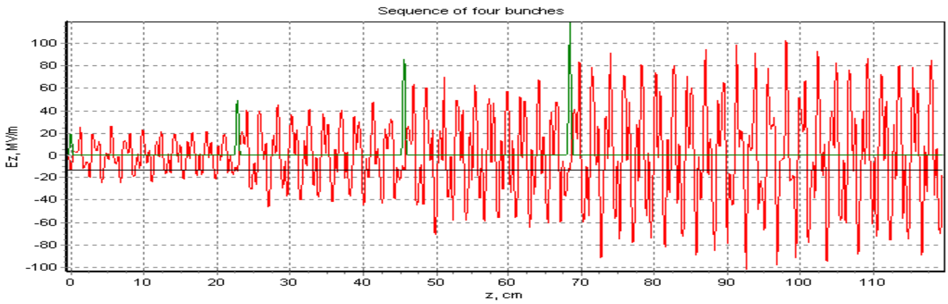


Figure 2. 13.625 GHz structure longitudinal wakefield produced by 4 bunch high current RBT (green), $\sigma_z = 0.1$ cm. Structure parameters are presented in Table 2. The maximum accelerating gradient is ~100 MV/m.

An Enhanced Transformer Ratio can be demonstrated if an RBT is generated with the required charge distribution and interbunch distances. The condition for R to be maximized corresponds to the requirement that all bunches in the RBT lose energy at the same rate. This will occur for a train of intensities increasing linearly in odd integer multiples of the leading bunch intensity (2:6:10:14 nC for the proof of principle experiment) for a bunch spacing $d = (n + 1/2)\lambda_{wakefield}$. The rf frequency of the AWA linac (1.3 GHz) corresponds to bunch spacing $d = (10 + 1/2)\lambda_{wakefield} = \lambda_{rf} = 23$ cm,

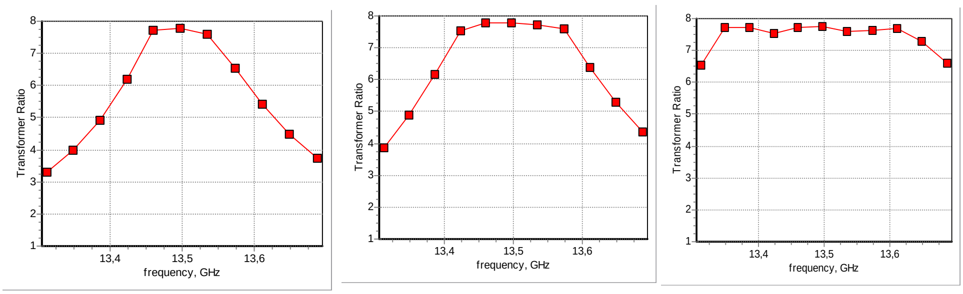


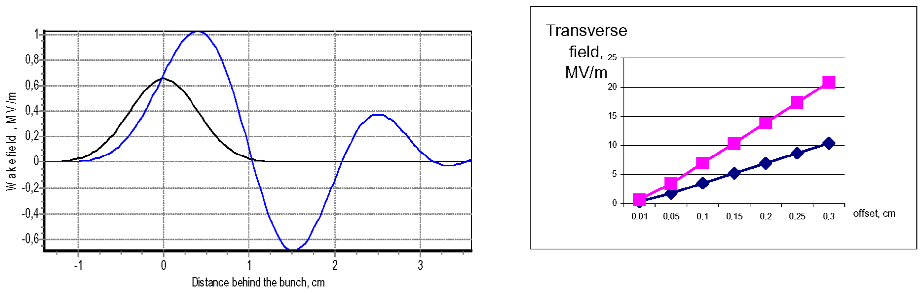
Figure 3. Plots showing the maximum transformer ratio R that can be obtained for TM_{01} mode frequency shifts caused by dielectric constant heterogeneity and mechanical tolerances in the dielectric wakefield structure assuming maximum interbunch distance adjustments of 0.1cm, 0.3 cm and 0.7 cm.

since the entire drive train has to be accelerated on successive maximum of a single linac rf pulse. We have analyzed the effects of dielectric heterogeneity and machining errors on the transformer ratio that can be obtained in this experiment, and to the extent these errors can be compensated by adjusting the bunch spacing with respect to the nominal using the laser pulse splitter.

The average Transformer Ratio of 7.45 and maximum of 7.8 can be demonstrated with mechanical tolerances of 10 μm and dielectric constant deviation of 0.35% if the interbunch distances are adjustable within 7 mm. We studied both multimode and single mode cases and verified numerically this method of transformer ratio optimization for the multimode structure parameters. The effect of imperfections at the level obtained for the structure as manufactured can easily be compensated by intensity and interbunch distance adjustments of the RBT using the laser multisplitter system.

RBT BEAM DYNAMICS SIMULATIONS

The use of a Ramped Bunch Train of 4 electrons bunches for the ETR experimental demonstration implies that the effects of transverse wakefields must be considered. Strong deflecting transverse fields will affect not only the bunch itself that exited the structure but all the trailing bunches will experience both the self-defocusing field and the transverse wake of the previously passing bunches of the train.



a b

Figure 4 (a) Transverse deflecting force inside of a 100 nC bunch with σ_z of 4 mm passing through the 13.625 GHz structure with an initial offset of 0.03 cm. A peak deflecting field of 1.0 MV/m is present in the bunch tail. (b) Peak deflecting field as a function of transverse beam offset for a single 100 nC bunch (Blue: 4 mm rms bunch length, Magenta: 1 mm).

We have studied beam breakup (BBU) related effects for both the drive beam train and accelerating beam passing through the 13.625 GHz accelerating structure. The intrabunch head-tail instability caused by the misalignment of the RBT can be controlled by using BNS damping [14], with the additional complication that the focusing channel has to control the drive bunch train of different charges passing through the same accelerating structure.

A particle dynamics code (DWA-BD-02 2D) has been developed to simulate particle motion in wakefield structures for a single electron beam and a bunch train as well. The basic concepts of the simulation have been used before in the single beam BBU analysis for the Step-Up transformer design [14]. The program simulates 2D-dynamics of an electron bunch in a dielectric-filled cylindrical waveguide. The model we use represents an electron bunch by a limited number of test particles, treated as point-like and characterized by their position, momentum and charge.

The field in the waveguide is represented by eigenfunction expansion method. The code does not self-consistently compute the wakefields; instead, analytic expressions for the longitudinal and transverse mode fields are used to compute the wakefields at each time step using the macroparticle currents as sources.

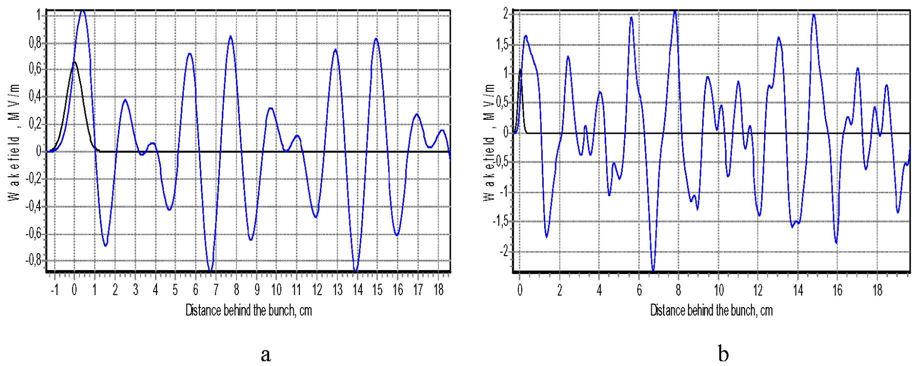


Figure 5. Transverse deflecting field behind a 100 nC bunch, long (a) and short (b) bunch cases.

In this section we present results for a ceramic dielectric structure with the parameters shown in Table 1. Single bunch results are obtained assuming 100 nC total charge. Two ramped drive bunch trains are considered, a low charge case corresponding to the beam parameters shown in Table 1 and a high charge with a (10:30:50:70) nC intensity distribution. Two bunch lengths are considered, a long case with rms length $\sigma_z =$ 0.4 cm, and a short with $\sigma_z = 0.1$ cm. The rms beam radius is $\sigma_r = 0.05$ cm and the initial radial offset for all our simulations is 0.03 cm. Longitudinal and radial beam distributions are assumed Gaussian. Fig. 4 shows the amplitudes of the transverse wakefields generated for the long and short 100 nC bunches.

Fig. 5 shows the transverse force behind a 100 nC bunch over an expanded distance roughly equal to the interbunch separation. The additional transverse field magnitude from the head bunches of the train will be 0.8 MV/m (8 kV/m/nC) for the long bunch case and 20 kV/m/nC for the short bunch. (These transverse field magnitudes are calculated at a radius equal to the 0.03 cm nominal offset of the driver.)

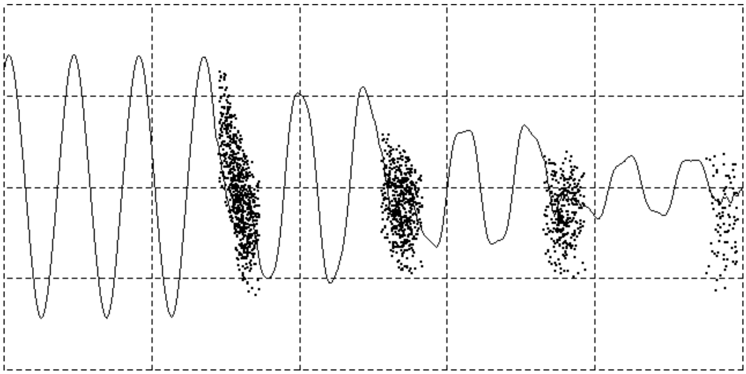


Figure 6. The Ramped Bunch Train (r-z plot of particle positions) and longitudinal wakefield at t = 2 ns, z = 60 cm for the ETR experimental demonstration at the Argonne Wakefield Accelerator. Bunch charge ratio is (2:6:10:14) nC. (Particle dynamics calculation performed with DWA-BS-02.)

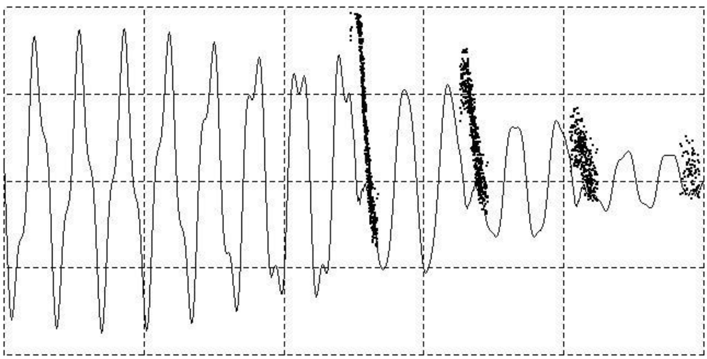


Figure 7. High current experiment simulation. t = 900 ps. 22% of the particles in the 4^{th} bunch have been lost. The wakefield shows significant frequency components beyond the fundamental due to the beam shape deformations that have occurred.

The bunch center will be deflected significantly soon after the bunch enters the structure and the offset can increase up to 0.3-0.4 cm after the bunch propagates for some distance. In this case the transverse field magnitude will increase dramatically and becomes comparable with the accelerating field gradient. For the long bunch the maximum deflecting peak can exceed 10 MV/m, at the same time the short bunch will be deflected by an 18 MV/m field at 0.25 cm offset, half of the waveguide radius.

We have studied extensively the dynamics of the low charge beam that we plan to use in the ETR proof-of–principle experiment. Our simulation showed that one can control the bunch train in a 52-60 cm structure without any FODO lattice present. No significant particle loss is incurred, and the average transformer ratio still exceeds 7.0. At the same time, we studied the propagation in the structure with a FODO lattice applied as well; the "optimal" beam traversed 90 cm without particle losses. Fig. 6 shows the RBT after 60 cm distance traversed through the structure. No particle loss has occurred and the beam is still well controlled. (Note that in this plot and in Fig. 7 the bunch separation is 2 ½ $\lambda_{wakefield}$ to reduce computation time. Use of the smaller separation in the calculation does not significantly affect the results [15].)

The high charge case is more problematic. Simulations without the FODO lattice present demonstrate significant disruption of the final drive bunch by 0.9 ns (Fig. 7). The application of a FODO lattice along the structure will improve this although extensive studies remain to be done. It is important to point out that the fields involved are large enough (~10 MV/m) so even with a relatively short structure and no external focusing the experiment can be performed to study the high charge configuration.

SUMMARY

The proposed Enhanced Transformer Ratio experiment is based upon the Ramped Bunch Train (RBT) technique. The 13.625 GHz accelerating structure has been manufactured and the uniformity of dielectric properties is in the range of 0.35%. We have installed and tested a prototype laser beam splitter to produce a ramped bunch train of 4 bunches, predicted to achieve a transformer ratio of R=7.8. RBT parameters have been simulated and optimized. Numerical simulations of the beam dynamics of the RBT have been presented and the appropriate FODO lattice parameters have been calculated.

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Proof of Principle	
TM_{01} frequency	13497.6 MHz
Inner radius	0.4999 cm
Outer radius	0.6345 cm
Dielectric constant	16.038
RBT Intensities	2:6:10:14 nC
RMS Bunch Length	4 mm
Transformer Ratio	7.8

Table 1. Parameters for the proof of principle experiment.

High Gradient	
TM_{01} frequency	13631.5 MHz
Inner radius	0.1 cm
Outer radius	0.268 cm
Dielectric constant	16.038
RBT Intensities	15:39:67:93 nC
RMS Bunch Length	1.5 mm
Transformer Ratio	7.2
Accelerating Gradient	104.3 MV/m

Table 2 Parameters for the high gradient experiment.

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