TRANSFORMER RATIO ENHANCEMENT EXPERIMENT

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Abstract

Recently, a multibunch scheme for efficient acceleration based on dielectric wakefield accelerator technology was outlined in [1]. In this paper we present an experimental program for the design, development and demonstration of an Enhanced Transformer Ratio Dielectric Wakefield Accelerator (ETR-DWA). The principal goal is to increase the transformer ratio R, the parameter that characterizes the energy transfer efficiency from the accelerating structure to the accelerated electron beam. We present here an experimental design of a 13.625 GHz dielectric loaded accelerating structure, a laser multisplitter producing a ramped bunch train, and simulations of the bunch train parameters required. Experimental results of the accelerating structure bench testing and ramped pulsed train generation with the laser multisplitter are shown as well. Using beam dynamic simulations, we also obtain the focusing FODO lattice parameters.

INTRODUCTION

There has been tremendous progress in ceramic structure-based acceleration schemes in the past few years. One of the most critical issues for dielectric wakefield acceleration is the improvement of the transformer ratio R, commonly defined as R = (Maximum energy gain behind the bunch) / (Maximum energy loss inside the bunch). It is crucial that methods be found to increase *R* in order to fully realize this technique as a practical option for high energy accelerators. According to the *wakefield theorem* [2] the accelerated beam cannot gain more than twice the energy of the drive beam, or in other words, *R* is less than 2 for collinear acceleration. Several schemes have been proposed to obtain $R > 2$ in collinear wakefield accelerators, but no experimental results have been obtained due to the inherent difficulties of these experiments. One proposed scheme operates with the driver beam having an *asymmetric* axial current distribution [2]. Using a similar idea, another scheme tailors the profile of a train of individually symmetric drive bunches [3] into a triangular ramp to produce $R > 2$. In this paper we consider the latter, here termed the *ramped bunch train* (RBT) method of transformer ratio enhancement. Experimental implementation of the proposed method [1] allows an enhancement of the transformer ratio by up to a factor of 4 compared to a conventional collinear accelerating scheme. The Enhanced Transformer Ratio (ETR) Experiment is under commissioning at Argonne National Laboratory's Argonne Wakefield Accelerator (AWA) facility, in cooperation with Euclid Concepts LLC.

ENHANCED TRANSFORMER RATIO EXPERIMENT

We plan to experimentally demonstrate ETR-DWA in 2003 - 2004. Our initial proof of principle demonstration will use a ramped bunch train (RBT) of 4 bunches, with charge ratio of 2-6-10-14 nC and bunch length of $\omega_z = 0.4$ cm we predict an R pf 7.8. Simulations also show that both high gradient and high R can be obtained by using an RBT parameters of 10-30-50-70 nC to achieve R = 7.6 and E = 104 MV/m. Experimental design includes a laser multisplitter, producing a ramped train of laser pulses for the AWA photoinjector, and a 13.625 GHZ dielectric loaded accelerating structure supplied with a focusing FODO lattice to minimize BBU effects for RBT. The accelerating structure is to be installed into the AWA beamline [4]. 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

A ceramic composition based on $MgTiO_3$-Mg_2TiO_4 systems have been sintered using the solid-phase synthesis method [5]. This material is characterized by a unique homogeneous fine-grained structure and minimum porosity, with a dielectric constant of 16. The dielectric loss factor has been measured with the dielectric loaded resonator method. Measurement of the witness samples at 9 GHz frequency showed the following results: $Q \times f = (6.0 \div 7.7)\times 10^4$, loss factor of $(1.12 \div 1.17)\times 10^{-4}$.

Table 1. Bench measurements of the dielectric loaded accelerating structure.

#	Structure parameters	Bench test
1.	TM_{01} frequency	13497.6 MHz
2.	Inner radius	0.4999 cm
3.	Outer radius	0.6345 cm
4.	Dielectric constant	16.038

The set of 5 waveguide sections tuned for 13.625 GHz TM_{01} mode have been designed and fabricated of the ceramics composition discussed above. The dielectric tubes were formed with a specially developed two-stage technology: hydraulic and isostatic pressing. The special press-form for the 13.625 GHz ceramic waveguide fabrication has been designed and produced. 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. We found the maximum deviation of the dielectric constant was within 0.055.

It was shown that the mechanical tolerances did not exceed 3 ÷ 10 σm and the dielectric constant deviation measured at the bench test appeared within 0.2% of the average and 0.35% of the maximum deviation. It should be noticed that one can obtain the maximum transformer ration in the range of 7.5 ÷ 7.8, Fig. 2.

Ramped Bunch Train Generation.

An Enhanced Transformer Ratio can be demonstrated if a RBT is generated with the required charge distribution and interbunch distances. Maximal R is achieved by requiring that all bunches lose energy at the same rate. Our simulations show that this happens when the bunch train has a charge ratio of (2-6-10-14) nC.

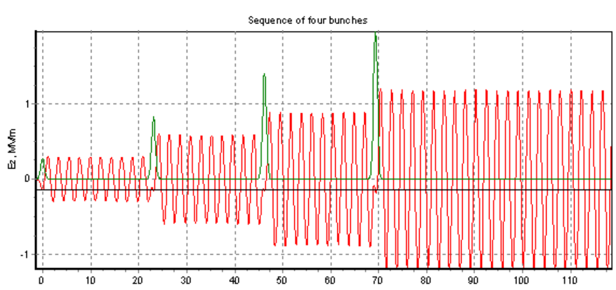

Figure 1. Single mode 13.625 GHz structure, 4 bunch (2-6-10-14) nC Ramped Bunch Train ω_z = 0.4 cm, Structure parameters are presented in Table 1**.**

We studied the interbunch distance adjustment for the transformer ratio enhancement as well. The repetition frequency of the AWA corresponds to the interbunch distance variation in the range of 22 ÷ 23 cm that in turn relates to d = (10 + 1/2)ς. The optimal RBT parameters for the proof-of principal experiment are (2-6-10-14) nC. Wakefields and charge distribution for this case are presented in Fig. 1, while the accelerating structure parameters are presented in Table 1. We have studied the impact of tolerances and dielectric heterogeneity on the R value to be measured in the experiment. It was shown that the imperfection factors effect discussed above can be compensated with the laser multisplitter system by intensity and interbunch distance adjustments.

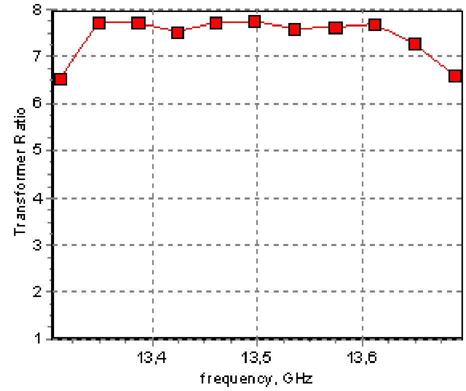

Figure 2. Transformer Ratio R vs. the TM_{01} mode frequency shift caused by the dielectric constant heterogeneity and mechanical tolerances. Interbunch distances adjustments are within 0.7 cm.

The average Transformer Ratio of 7.45 and maximum of 7.8 can be demonstrated with mechanical tolerances of 10σm and dielectric constant deviation of 0.35% if the interbunch distances adjusted within 0.7 cm, Fig. 2. We studied the multimode and single mode cases and demonstrated the method of transformer ratio optimization for the multimode structure parameters.

It was shown that one can perform high gradient acceleration with the wakefield gradient exceeding 100 MV/m and at the same time to provide an enhanced transformer ratio up to 7.27 with the following parameters of the drive bunch and the structure (the "target" case): inner radius of a = 0.1 cm, outer radius of b = 0.268 cm, dielectric constant of κ = 16, bunch length of ω_z = 0.15 cm charge distribution of 15, 39, 67 and 93 nC, Transformer Ratio **R = 7.27,** accelerating gradient of **E = 104.3 MV/m.**

Laser Multisplitter Design and Testing

The laser beamsplitting system is a critical issue for the success of the project. To generate the electron bunch-train, a laser pulse train is injected into the AWA drive photoinjector. This laser train is made by optically splitting a single laser pulse into four separate pulses with a combination of mirrors and beam splitters [6]. We have modified the original multisplitter at the AWA to create a Ramped Pulse Train required for the RBT generation. We installed and tested this beam splitting system at the AWA facility. The 4 output laser pulses have been generated and measured with an energy meter and streak camera. We measured the energy ratio of the pulse train, and have made a detailed study of each individual mirror. Based upon measured reflection coefficients, the energy ratios matched the expected ones for the 2nd, 3d and 4th bunches. We investigated the origin of the 1st bunch energy deviation and found out that the mirrors did not match the vendor's specification. Since then we have corrected this problem and are confident that we can make the required Ramped Laser Pulse train.

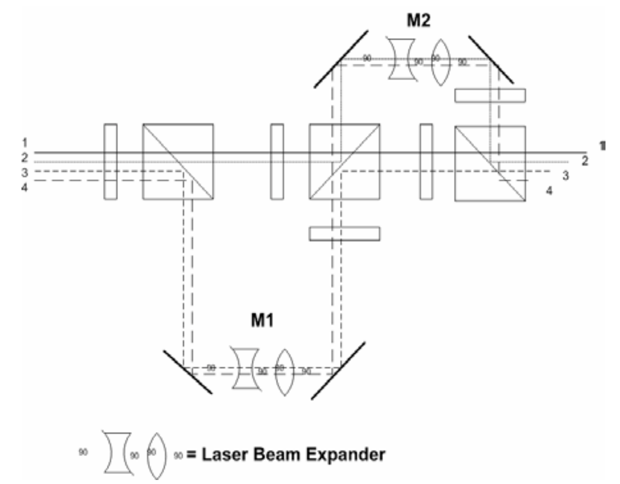

Figure 3. Adjustable and Variable Pulse Radius laser multisplitter design.

The measured laser pulse length was 8 ps and the interbunch spacing was 780 ps, just as anticipated.

We have recently redesigned the multisplitter so that one can adjust the pulse intensities as well as interbunch distances. Fig. 3 presents an Adjustable Laser Multisplitter design that is able to vary the laser pulse intensity and therefore to compensate for mechanical tolerances and other imperfections in the value of transmission and reflection coefficients. The adjustable multisplitter uses a half-wave retardation plate and a polarizing cube beamsplitter to continuously vary the pulse intensities.

The RBT introduces different space charge defocusing for the differing bunch intensities. We accommodate this by including a Variable Beam Radius option for the Laser Beamsplitter [6]. In order to generate different laser pulses with variable radius one can use a beam expanding telescope in the 2 legs of magnification M1 and M2 (Fig. 3) and clipping iris after the multisplitter. Thus we can determine the bunch train radii required for a periodic FODO channel. In general, we have designed the optical multisplitter system and performed preliminary tests on the laser beam splitting required for the Ramped Bunch Train generation.

RBT Transportation Beam Dynamic Simulations

We have studied BBU related effects for the beam train and accelerating beam both passing through the 13.625 GHz accelerated structure. The head-tail instability caused by the misalignment of the RBT can be controlled by using BNS damping [7], with the additional complication that the focusing channel has to control the drive bunch train of different charges passing through the same accelerating structure.

We have studied the beam dynamics of the most interesting and optimal beam that we plan to use in the ETR proof-of–principle experiment; a charge distribution of (2-6-10-14) nC. Our simulation showed that one can control the “optimal” bunch train in the structure up to 52÷60 cm without any FODO lattice, with no significant particle loss, and that the average transformer ratio still exceeded 7.0. At the same time, we studied the propagation in the structure with the FODO lattice applied as well; the “optimal” beam traversed 90 cm, Fig. 4 shows this RBT at 60 cm distance passed, no particle loss, beam is under control.

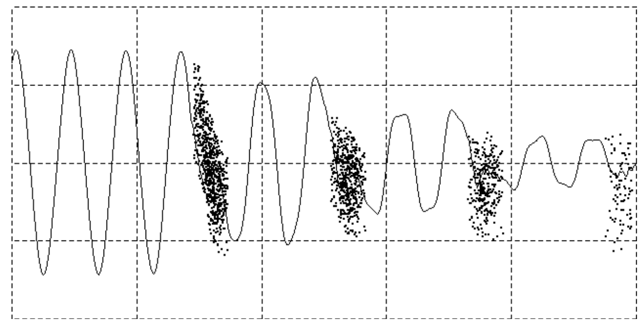

Figure 4. Beam dynamics simulations of the optimal (2-6-10-14) nC RBT, FODO focusing applied, 60 cm passed.

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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REFERENCES

[1] J.G. Power, W. Gai, A. Kanareykin, X. Sun. PAC 2001 Proceedings, pp. 114-116, 2002.

[2] P.B. Wilson, SLAC Report No296, p.273, 1983, K.L. Bane, P. Chen, P.B. Wilson, IEEE Trans. Nucl. Scien, 32, 3524, 1985.

[3] P. Schutt, T. Weiland, V.M. Tsakanov, Nor Amberb Conf. Proc., Armenia, 7(15) pp.12-17, 1989.

[4] www.hep.anl.gov/pmalhotr/AWA/docs/2p041.pdf

[5] E. Nenasheva et al. The 9th Int. Conference “Physics of Dielectrics”, St.Petersburg, Russia, 2000, p.142.

[6] http://www.hep.anl.gov/pmalhotr/AWA/pubs.htm WF-198, WF-213, WF-215.

[7] W. Gai, A.D. Kanareykin, A.L. Kustov, J. Simpson, Phys. Rev. E, v. 55, N 3, pp. 3481-3488, 1997.