PLANNED ENHANCED WAKEFIELD TRANSFORMER RATIO EXPERIMENT AT ARGONNE WAKEFIELD ACCELERATOR

A. Kanareykin, Euclid Techlabs LLC, Solon, OH 44139, USA
W. Gai, C. Jing, R. Konecny, J. G. Power. ANL, Argonne, IL, 60439, USA
P. Avrakhov, PTC of Lebedev Physical Institute, Protvino, Moscow region, 141284, Russia

Abstract

In this paper, we present a preliminary experimental study of a wakefield accelerating scheme that uses an electron pulse train to produce wakefields that increases the transformer ratio greater than 2 by appropriate bunch spacing and current ramp. A dielectric structure was designed and fabricated to operate at 13.625 GHz with dielectric constant of 16. The structure will be excited by two beams with the first and second beam charge ratio of 1:3 for the initial experiment. The expected transformer ratio is 3 and the setup can be easily extended to the case of 4 pulses which develops a transformer ratio of more than 7. Dielectric structure cold test results show that the tube is within the specifications. A set of laser splitters was also tested to produce ramped bunch train of 2 pulses. Overall design of the experiment and initial results will be presented.

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 [1].

Considerable effort has been directed at the development of high transformer ratio schemes and their experimental demonstration through the use of asymmetric drive beam axial distributions [2], noncollinear drive beam/witness beam geometry, Stimulated Dielectric Accelerator, nonlinear beam dynamics and nonlinear plasma dynamics [3,4].

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 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 Ramped Bunch Train (RBT) method.

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 [1, 5]. This technology will be experimentally studied at the Argonne Wakefield Accelerator (AWA) facility where the short pulse high charge beam technology and experience in the generation of bunch trains can be exploited [1, 3, 4].

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; and numerical simulations of high charge bunch train dynamics [3, 4].

ENHANCED TRANSFORMER RATIO EXPERIMENT

We plan to experimentally demonstrate ETR-DWA in 2005. Our initial proof of principle demonstration will use a ramped bunch train (RBT) of 2 bunches, with charge ratio of 10-30 nC, and bunch length σ_z = 0.4 cm followed by a 10-30-50-70 nC ramped bunch train experiment. We predict a transformer ratio, R of around 3.0 for the 2-bunch experiment and 7.4-7.8 for the 4-bunch measurements. Simulations also show that both high gradient and high R can be obtained by using 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 installed in the test section of the AWA beamline. The transformer ratio enhancement technique based on ceramic waveguides will result in highly efficient accelerating structures for future wakefield accelerators.

A set of 4 ceramic waveguide sections tuned for the 13.625 GHz TM_{01} mode has been designed and fabricated using an especially designed press-form. The dielectric tubes were formed with a two-stage technology involving hydraulic and isostatic pressing. The ceramic composition based on $MgTiO_3$-Mg_2TiO_4 systems has been produced by sintering. This material is characterized by a unique homogeneous fine-grained structure and minimal porosity, with a dielectric constant of 16. The dielectric loss factor has been measured using the dielectric loaded

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resonator method. Measurement of the witness samples at 9 GHz yielded a dielectric constant of 16.038, loss factor of 10^{-4} at 10 GHz, and TM_{01} mode frequency of 13497.6 MHz. The inner (outer) radius of the structure is 0.5 (0.6345) cm. Beam charge intensities for the initial experiment are 10 and 30 nC, 2 mm RMS bunch length. The expected transformer ratio is in the 3.0-3.5 range.

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 [4].

Accelerating Structure Bench Testing

The total length of the fabricated ETR-DWA structure is about 45 cm long and consists of four segments of ceramic tube loaded into a conducting sleeve. We tested the structure using the microwave lab at the ANL/AWA where a set of RF bench measurement and vacuum conditioning equipment is available. We evaluated the performance of the dielectric-loaded accelerating structures after completion of the machining and assembly process. The first bench measurement of the 13.625 GHz structure was been done using the HP-8510C vector network analyzer. Fig. 1 shows the 13.625 GHz DLA structure under the test at the ANL/AWA RF testing facility. The transmission and reflection performance of the structure is characterized using two properly optimized RF couplers (Figure 2) which provide a good impedance match between the coaxial cable and dielectric-loaded waveguide.

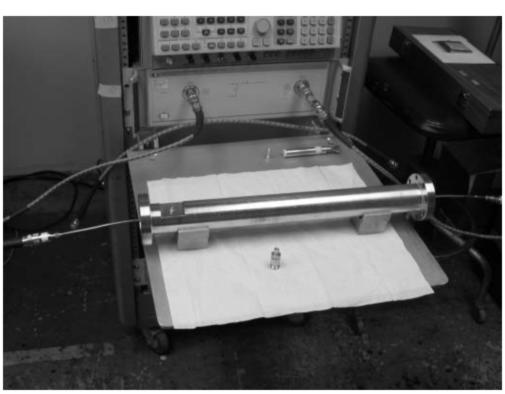

Figure 1. Bench test of the 13.625 GHz dielectric based accelerating structure at Argonne Wakefield Accelerator, Argonne National Laboratory.

The transmission measurement shows that the structure has 9 dB RF power attenuation at the operating frequency while the refection is -6dB. RF simulation shows the reason that the transmission coefficient is far below the theoretical prediction (-3dB) is partly caused by air gaps between the ceramic tube segments and the copper jacket.

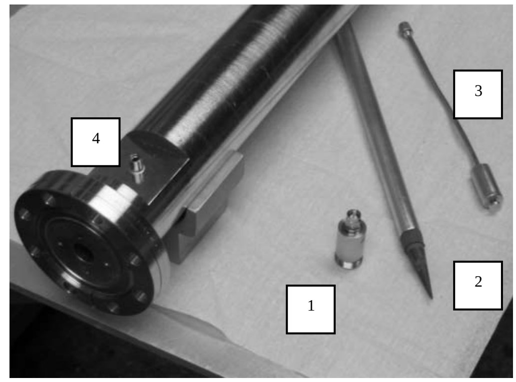

Figure 2. 13.625 GHz DLA structure for the ETR experiment with a probe for wakefield measurements (1); RF power absorber (2) and coupler (3) for bench testing; current probe feedthrough from the DLA structure (4).

Probe Antenna Wakefield Measurements

In the ETR-DWA experiment, we acquire the generated wakefield signal by coupling the generated RF out of the structure [6]. The basic steps of this technique can be summarized as: 1) detect the wakefield signal by a electric dipole antenna (probe shown in Fig. 2) located on the sidewall of the tube; 2) down-convert the high frequency wakefield signal (~13.625 GHz) to a lower frequency (~5GHz) through a heterodyne RF circuit; 3) digitize and observe the down-converted signal in a 6 GHz fast real time scope; 4) reconstruct the 13.625 GHz wakefield signal by data processing performed by a MATLAB® routine. Note that the duration of the wakefield signal of the structure is in the ns range and the down-converted rf pulse still contains the full wakefield information.

We should point out that the wakefield signal obtained by this technique is from the radial component of the electric field because the longitudinal wakefield signal W_z diminishes near the sidewall of the copper tube. However, we can obtain the longitudinal wakefield by mode matching in the frequency domain. Comparing the spectrum of the measured wakefield signal to the theoretical calculation, we can identify the modes (different propagation constants) of the generated wakefield, and transform the E_r to the E_z by solving Maxwell's equations. The summation of E_z obtained in this manner provide a full presentation of the longitudinal wakefield.

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.

The wakefields generated by a single 50 nC bunch passing through the 13.625 GHz structure are presented in Fig. 3. (MAFIA simulations). The 4 ceramic waveguide segments will be filled by the wakefields within 0.9 ns.

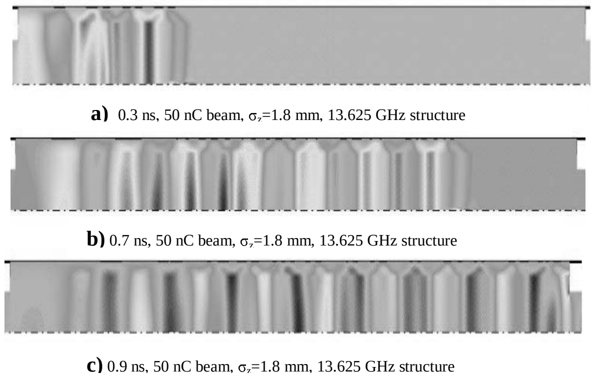

Figure 3. Single beam wakefields snapshots in the 13.625 GHz DLA structure. The beam charge is 50 nC, and bunch length is 1.8 mm. Snapshots at a) - 0.3 nsec, b) - 0.7 nsec and c)-0.9 ns.

We studied the interbunch distance adjustment for transformer ratio enhancement previously [4, 5]. The rf frequency (1.3 GHz) of the AWA linac corresponds to the interbunch distance variation in the range of 22 - 23 cm that corresponds to $d = (10 + 1/2)\lambda$ of the 13.625 GHz dielectric structure.

Recently wakefield excitation with the newly commissioned AWA gun has been demonstrated (Fig. 4) [6]. The wakefield was recorded with the rf pick-up probe presented in Fig. 2. This experimental beam train test demonstrated that a beam train can be generated with the beam positions required for the maximum transformer ratio to be obtained.

We have studied the impact of tolerances and dielectric heterogeneity on the R value to be measured in the experiment [4]. It was shown that the effects of imperfections discussed above can be compensated using intensity and interbunch distance adjustments in the laser multisplitter system.

It was shown that one can perform high gradient acceleration with the wakefield gradient exceeding **E=104.4 MV/m** and at the same time to provide an enhanced transformer ratio **R= 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 $\varepsilon = 16$, bunch length of $\sigma_z = 0.15$ cm and charge distribution of 15-39-67-93 nC [4].

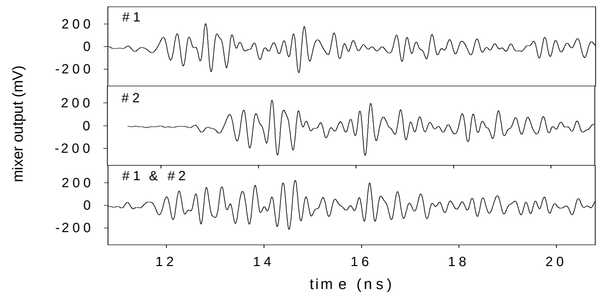

Figure 4. Experimental results using the new AWA gun and linac to excite a wakefield using a two bunch train. Each bunch has an intensity of 15 nC. #1 is the wakefields of beam 1 alone, #2 of the beam 2 alone, #3 wakefields of the two bunches simultaneously.

SUMMARY

The proposed Enhanced Transformer Ratio experiment is based on the Ramped Bunch Train (RBT) technique to produce a longitudinally asymmetric charge distribution. The 13.625 GHz dielectric accelerating structure has been manufactured and bench tested. Wakefield excitation by a train of the 2 equal charge beams has been demonstrated with the SHV rf pick-up probe.

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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] A. Kanareykin et al. Proceedings PAC 2003, Portland USA, pp.1894-1896, 2003.
[4] A. Kanareykin, W. Gai, J.G.Power and P.Schoessow. AIP Conference Proceedings, v.737, New York, p.272-280, 2004
[5] P. Schutt, T. Weiland, V.M. Tsakanov, Nor Amberb Conf. Proc., Armenia, 7(15) pp.12-17, 1989.
[6] W.Gai, private communication.

0-7803-8859-3/05/$20.00