A 7.8GHz Power Extractor Using a Circular Dielectric Loaded Waveguide

***F. Gao*[1, 2], *M. E. Conde*[1], *W. Gai*[1], *C. Jing*[3], *R. Konecny*[1], *W. Liu*[1], *J.G. Power*[1], *T. Wong*[2], *Z. Yusof*[1]**

[1]Argonne National Laboratory, Argonne, IL 60439, U.S.A. gaofeng@iit.edu

[2] Illinois Institute of Technology, Chicago, IL 60616, U.S.A.

[3] Euclid TechLabs, LLC, Solon, Ohio, U.S.A.

Abstract

We report on the design and beam tests of a 7.8GHz power extractor recently conducted at the Argonne Wakefield Accelerator (AWA) facility. Wakefields are excited when an electron beam travels through a dielectric loaded waveguide, and the generated RF power is subsequently extracted with a properly designed RF coupler. The experiment shows that 30MW of output power is excited by a 66nC single electron bunch. Field superposition is also clearly demonstrated with a train of 4 electron bunches. Tests results are in good agreement with predictions.

1. Introduction

The use of dielectric loaded structures is one of the few new techniques for radio frequency (RF) particle acceleration [1, 2, 3]. Unlike conventional cavity-based metallic structures, a dielectric loaded waveguide uses dielectric tubes/slabs to slow down the phase velocity of RF waves for on-crest particle acceleration. As shown in Figure 1(a), a circular dielectric loaded waveguide consists of a metallic sleeve (usually a copper sleeve), a dielectric tube with outer radius b and inner radius a, and a vacuum channel (the region $r < a$) for the beam to pass. Since this simple structure is uniform in the longitudinal direction, it can be easily made even when high precision is needed at high frequencies. Also, a simple scheme makes it easy to damp undesired deflection modes in this structure [4].

Based on the circular dielectric loaded waveguide, a two beam acceleration (TBA) scheme has been experimentally demonstrated [5]. The TBA scheme consists of two stages: a first stage which generates RF energy from a driving beam (a particle bunch or a bunch train) passing in a decelerating structure, and then the RF energy is transferred through an RF output coupler to a second stage to accelerate another beam. Therefore, the first stage acts as a high power RF source, and it is commonly known as a power extractor. Figure 1(b) shows a power extractor using a circular dielectric loaded waveguide as the deceleration section, where an RF output coupler is placed at the downstream end to extract the RF power. This power extractor has interesting properties: the frequency of the output RF wave can be easily changed by choosing different dielectric constants, inner and outer radii for the dielectric tube; the output power can be easily adjusted by changing the charge of the driving beam; and the output RF pulse length can be adjusted by the number of bunches in a train.

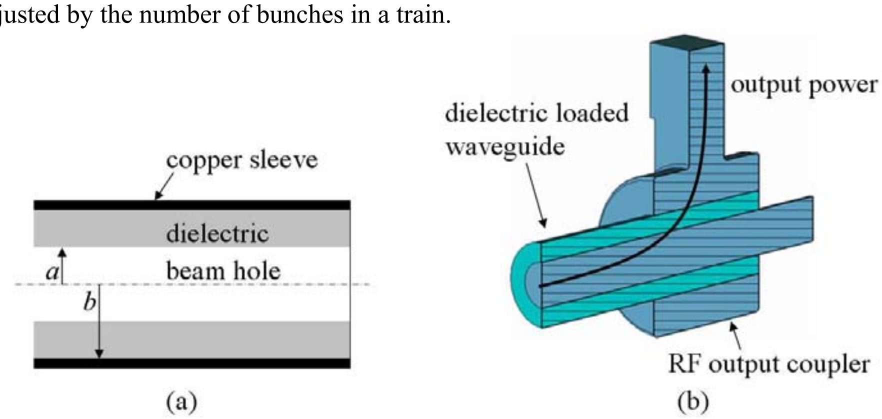

Figure 1. (a) A circular dielectric loaded waveguide; (b) a power extractor using (a) as the deceleration section.

Specifically for the power extractor, a proof-of-principle experiment was performed using a 21 GHz dielectric tube at the CLIC Test Facility [6]. In order to reach higher power for the TBA scheme, one has to increase the beam current and also improve the transfer efficiency and compactness of the RF output coupler. In this paper, we report on initial tests of a 7.8GHz dielectric loaded power extractor with both single bunch and bunch train excitation. The planned future AWA operating beam parameters (50nC per bunch, 64 bunches) make this device potentially capable of generating 280MW of power. With such a high power level, it can be used as a general RF source to do high power/gradient tests on accelerating structures.

2. Deceleration Tube and RF Output Coupler Design

There are mainly two goals in the power extractor design: first the deceleration tube needs to be optimized for maximum power generation, second the RF output coupler needs to be optimized for maximum power extraction.

The current design uses the TM_{01} mode for beam deceleration, and the dielectric tube parameters are listed in Table 1. The dielectric material is Corderite with a relative permittivity 4.6, provided by Trans-Tech. In the calculation, the inner radius of the tube is set according to the typical transverse size of the driving beam. By changing the outer radius, the tube is carefully adjusted so that the phase velocity of the TM_{01} mode is equal to *c*, the speed of an ultrarelativistic particle (i.e. the speed of light in free space), at 7.8GHz, the 6th harmonic of the AWA linac frequency 1.3GHz. The length is chosen to be long enough for effective interaction, also not too long to allow most particles to pass through. With the current AWA Gaussian bunch length 2mm, CST Mafia T2 simulation shows that with a 100nC single driving bunch, the induced gradient will be 18MV/m, corresponding to 79MW of power generated. If a bunch train with a bunch frequency 1.3GHz and 50nC charge per bunch is used as the driving beam, the excited gradient will be 34.5MV/m, corresponding to 280MW of power generated. In the bunch train excitation, at least four bunches are needed for the gradient and power to reach the above values.

Table 1. Deceleration Tube Parameters

f	7.8GHz	frequency		ε_r	4.6	relative permittivity
a	6.02mm	inner radius		v_g	0.23c	group velocity
b	11.17mm	Outer radius		Q	2745	quality factor
L	266mm	tube length		r/Q	6.09KΩ/m	r over Q

The RF output coupler is designed with CST Microwave Studio to extract the generated power to a standard WR112 rectangular waveguide. The geometry of the coupler is the same as that has been shown in Figure 1(b). In the design, a circular cavity and a stepped rectangular waveguide are added to the downstream end of the dielectric loaded tube for impedance matching with the WR112 waveguide. The beam hole at the downstream end is cutoff for the 7.8GHz TM_{01} mode. Figure 2 shows a good agreement between simulated and measured S-parameters of the coupler. Specifically at 7.8GHz, the insertion loss is -0.41dB, which means the power coupling efficiency is 91%.

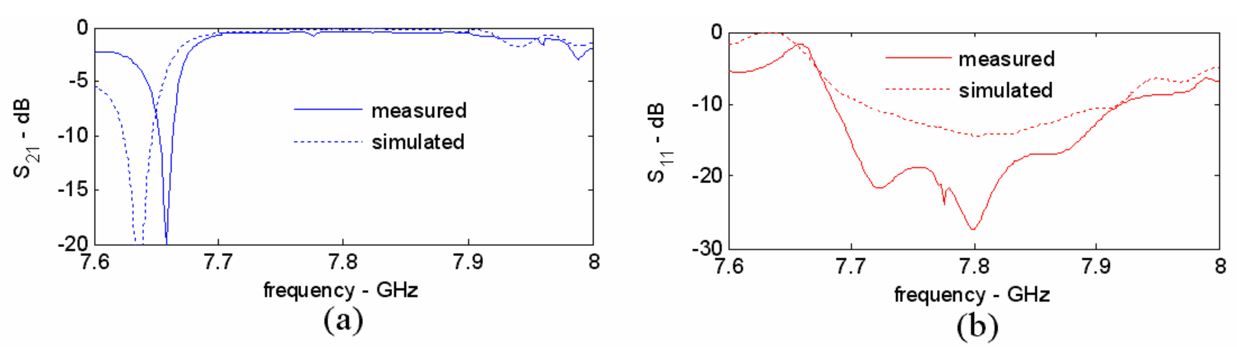

Figure 2. Simulated and measured S-parameters of the RF output coupler: (a) insertion loss S_{21}; (b) reflection S_{11}.

3. Beam Measurement

The AWA beamline is dedicated to fundamental research on dielectric loaded acceleration techniques. This beamline is able to deliver up to 160nC charge in a single Gaussian bunch out of the gun, with an rms bunch length

2mm and energy 8MeV, which is later on accelerated to 14MeV by a linac section. Figure 3 shows the experimental setup for the power extraction tests. When a drive beam travels through the deceleration section, the generated RF power is coupled into the rectangular waveguide. A bidirectional coupler is used to couple weak signals to a Tektronix 15GHz digital real time oscilloscope, where the data is recorded. After the bidirectional coupler, the output waveguide is terminated with a shorted waveguide which can provide a time delay of 14ns for signal identification, since a load for such a high power level (~100MW) is not commercially available at 7.8GHz. At the downstream end of the power extractor, an integrating current transformer (ICT) is used to monitor the charge passing the structure. The vacuum inside the power extractor reached 7×10^{-9}Torr after ten days of pumping.

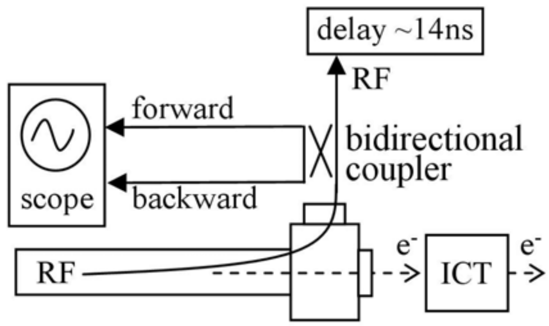

Figure 3. Experimental setup for the beam test.

In the single bunch experiment, to maximize charge passing the power extractor, the beam is carefully steered with dipole magnets, and focused/unfocused with quadruple magnets. Furthermore, the charge is also varied by changing the intensity of the laser beam on the cathode, to find out power generated with different drive charge. The measured voltage signal is shown in Figure 4(a), and its spectrum is shown in Figure 4(b), where it can be seen the frequency is right at 7.8GHz. After correction on the attenuation, the generated power by the power extractor is experimentally obtained for different charge. Figure 5 shows both the simulated and measured values, where a good agreement is found. The maximum power generated is 30MW, where charge passing the power extractor is 66nC, which is 40% of what is delivered from the gun. The power extractor is planed to be moved to an optimal position in the beamline for future experiments, where higher charge is expected to pass the structure for higher power generated.

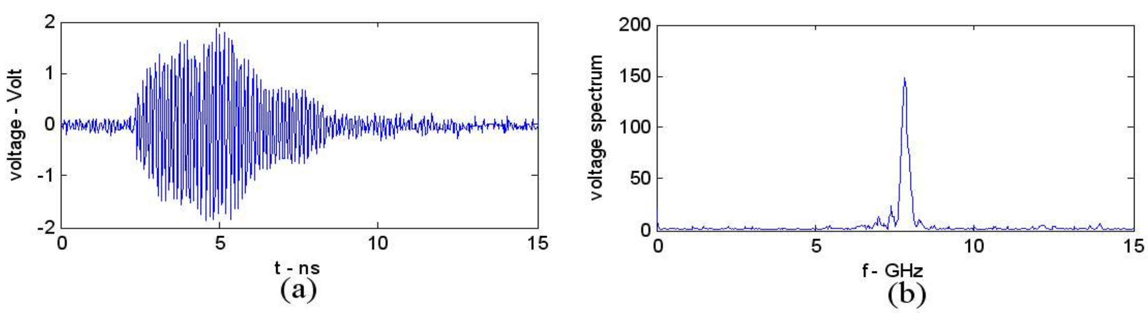

Figure 4. Detected signal excited by a single 66nC electron bunch: (a) voltage; (b) spectrum of (a).

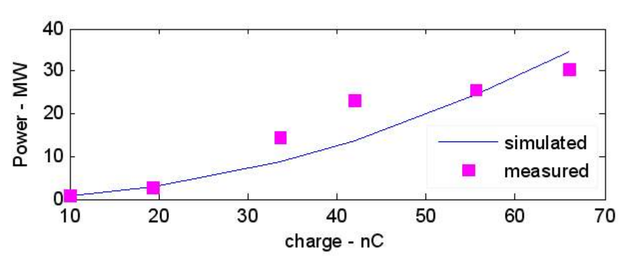

Figure 5. Simulated and measured power excited by bunches with different charge.

In the bunch train experiment, we use a laser splitting set to generate a train consisting of four equal electron bunches. To obtain in-phase superposition, the bunch spacing is set to 769ps, corresponding to a bunch frequency of

1.3GHz, the same as the AWA linac frequency. Figure 6(a)-(c) clearly shows that the RF pulse length is getting longer when more bunches are added in phase. Figure 6(d) shows the spectrum of the signal in Figure 6(c), where is can be seen the frequency is also at 7.8GHz. A 16-bunch experiment is being planned at the AWA facility to increase the pulse length to ~10ns.

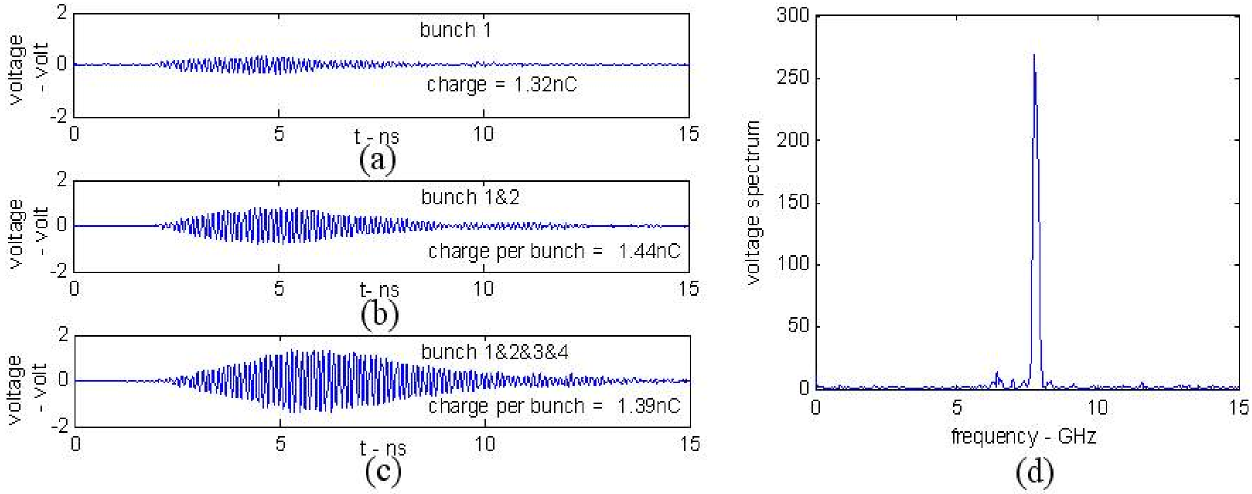

Figure 6. Measured voltage signals in the bunch train experiment excited by different bunch combinations: (a) by a single bunch; (b) by the first two bunches; (c) by all four consecutive bunches; (d) spectrum of (c).

4. Summary

The 7.8GHz power extractor experiment demonstrated high power generation and extraction with a circular dielectric loaded waveguide. As a high power RF source in beam acceleration, this type of power extractors is promising due to its simplicity in design, low cost to fabricate, and ease to use. In the future, we plan to move the power extractor further away from the gun for optimal location to improve charge transmission. Furthermore, a 16-bunch experiment is being planned at the AWA facility to increase the pulse length to ~10ns.

5. Acknowledgement

This work is supported by the US Department of Energy under contract No. DE-AC02-06CH11357.

6. References

1. G. Flesher and G. Cohn, “Dielectric Loading for Waveguide Linear Accelerators”, AIEE Transactions, 70(1951), 887-893.

2. J. Fang, et al, “An Experimental Test of the Theory of the Stimulated Dielectric Wakefield Accelerator”, Proc. of 1999 Particle Accelerator Conference, New York, 3627-3630.

3. P. Zou, et al, “Construction and Testing of an 11.4GHz Dielectric Structure Based Traveling Wave Accelerator”, Rev. of Sci. Instru. 71(2000), 2301-2304.

4. E. Chjonacki, et al, “Measurement of deflection-mode damping in an accelerating structure”, J. Appl. Phys. 69(1991), 6257-6260.

5. W. Gai, M. Conde et al, “Experimental Demonstration of Two Beam Acceleration Using Dielectric Step-up Transformer”, Proc. of 2001 Particle Accelerator Conference, Chicago, 1880-1882.

6. D. Newsham, et al, “Construction and Testing of a 21 GHz Ceramic Based Power Extractor”, Proc. of 2003 Particle Accelerator Conference, Portland, 1156-1158.