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RECENT PROGRESS OF SHORT PULSE DIELECTRIC TWO-BEAM ACCELERATION

J. Shao[1,*], C. Jing[1,2], E. Wisniewski[1], J. Power[1], M. Conde[1], W. Liu[1], L. Zheng[1,3], N. Neveu[1,4], D. Doran[1], C. Whiteford[1], and W. Gai[1,3]
[1]Argonne National Laboratory, Lemont, IL 60439, USA
[2]Euclid Techlabs LLC, Bolingbrook, IL 60440, USA
[3]Tsinghua University, Beijing 100084, China
[4]Illinois Institute of Technology, Chicago 60616, IL, USA

Abstract

Two-Beam Acceleration (TBA) is a structure-based wakefield acceleration method with the potential to meet the luminosity and cost requirements of a TeV class linear collider. The Argonne Wakefield Accelerator (AWA) facility is developing a dielectric-based short pulse TBA scheme with the potential to withstand high acceleration gradients and to achieve low fabrication cost. Recently, the dielectric short pulse TBA technology was successfully demonstrated using K-band 26 GHz structures, achieving 55 MW output power from the power extractor and 28 MeV/m gradient in the accelerator. To improve the generated rf power, an X-band 11.7 GHz power extractor has been developed, which obtained 105 MW in the high power test. In addition, a novel dielectric disk accelerator (DDA) is currently under investigation to significantly increase the efficiency of linear colliders based on short pulse TBA. Details of these research will be presented in this paper.

INTRODUCTION

TBA is an approach to the structure-based wakefield acceleration which may meet the luminosity, efficiency, and cost requirements of future linear colliders and has been selected as the baseline design of CLIC [1] and the Argonne Flexible Linear Collider (AFLC) [2]. Due to the strong dependence of rf breakdown rate on pulse length [3], AFLC applies a much shorter rf pulse (~20 ns) than CLIC (~240 ns) to obtain a higher loaded accelerating gradient (267 MV/m vs. 100 MV/m). Rather than metallic power extractors and accelerators, AFLC adopts dielectric structures which may potentially reduce the fabrication cost with their simple geometries and withstand high gradient as there is no surface electric field enhancement [2, 4].

The AWA facility is a flexible, state-of-art linear collider testbed with two parallel L-band beam lines. The 70 MeV drive beam line applies Cs_2Te cathode and can deliver high charge (up to 100 nC for single bunch and 600 nC for bunch train) for rf generation in power extractors. The 15 MeV main beam line generates low charge beam to witness the acceleration. A unique double emittance exchange beam line is under construction at the end of the drive beam line, which is capable for bunch shaping [5]. Besides, AWA also has two separated test-stands for the fundamental rf breakdown study [6, 7]. With the beam lines, AWA has been devoting much effort to the short pulse dielectric TBA research.

TWO-BEAM ACCELERATION WITH K-BAND DIELECTRIC STRUCTURES

To demonstrate the short pulse dielectric TBA technology, a pair of K-band 26 GHz power extractor and accelerator has been developed at AWA, as illustrated in Fig. 1. The dielectric tube used in the power extractor consists of three pieces and has been inserted into a copper jacket without any coating. The tube in the accelerator is a single piece with thick copper coating of 100 µm applied onto the outer surface. Detailed parameters of the structures can be found in Ref. [8].

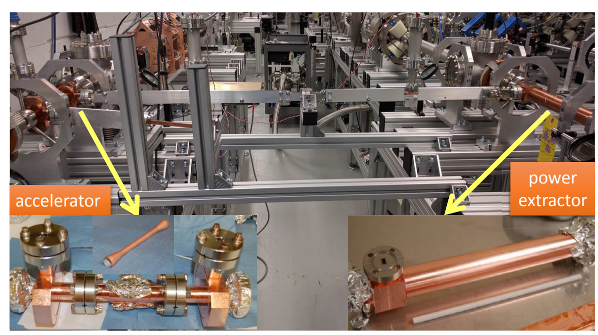

Figure 1: Configuration of the short pulse dielectric TBA experiment with the K-band structures.

With a 4-bunch train (~20 nC/bunch), up to 55 MW output power was measured, as illustrated in Fig. 2. The power was lower than prediction by wakefield theory [9] and CST simulation. In addition, damage spots on the dielectric tube were observed after the high power test, which might result from improper handling or beam irradiation. The mechanism is still under investigation.

With the 55 MW power transferred to the dielectric accelerator, short pulse dielectric TBA has been successfully demonstrated with the maximum energy gain and accelerating gradient measured to be 1.8 MeV and 28 MeV/m respectively, as illustrated in Fig. 3. No damage was found on the coated structure after the test.

* jshao@anl.gov

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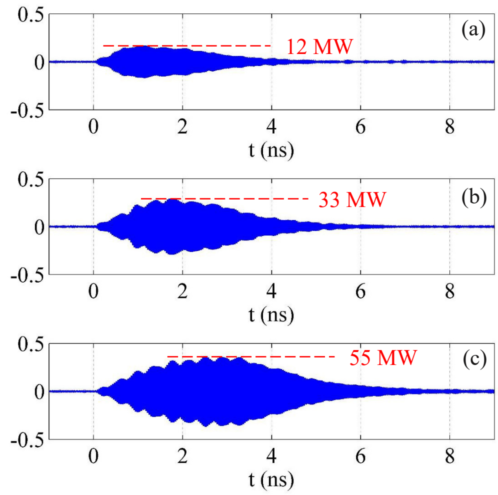

Figure 2: Measured rf signal from the power extractor. (a) Single bunch; (b) 2-bunch train; (c) 4-bunch train.

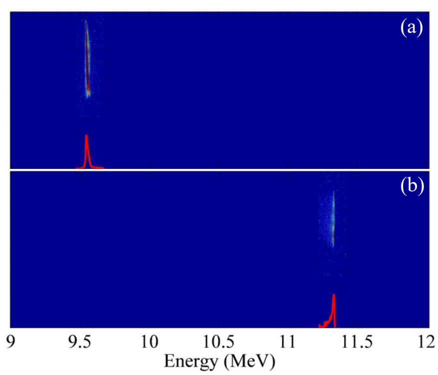

Figure 3: The image of the main beam in the spectrometer screen. The horizontal projection of the profile is plotted below each image (red). (a) Drive beam off, ~0.7 nC; (b) Drive beam on, ~0.2 nC.

HIGH POWER GENERATION WITH X-BAND DIELECTRIC STRUCTURE

To address the possible beam irradiation issue in the K-band structure, an X-band power extractor with a larger opening has been developed. The dielectric tube consists of a uniform section for power extraction and two tapered sections at the ends for impedance matching, as illustrated in Fig. 4(a). Its detailed parameters can be found in Ref. [10]. The whole dielectric tube is made as a single piece and coated with 1 μm-thick copper at the outer wall to mitigate the charging effect, as illustrated in Fig. 4(b). The structure is placed in a copper jacket where a SLAC-type duel-port coupler is attached to couple the generated rf power to a load, as illustrated in Fig. 4(c).

With low charge drive bunch-train (<6 nC/bunch), the measured rf phase shapes show prefect agreement with the CST simulation, as illustrated in Fig. 5.

The maximum charge transmitted through the structure was ~300 nC and the transmission remained to be ~100%. The maximum generated power obtained with 4-bunch train

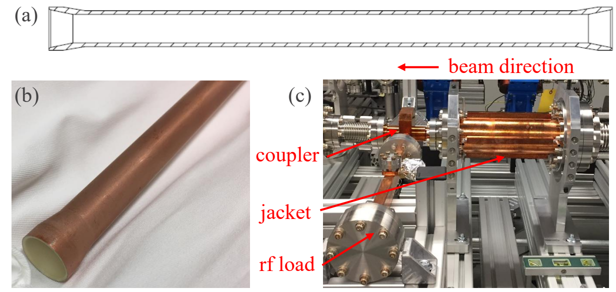

Figure 4: The X-band power extractor. (a) Section view of the dielectric tube; (b) The tube after copper coating; (c) The experimental setup.

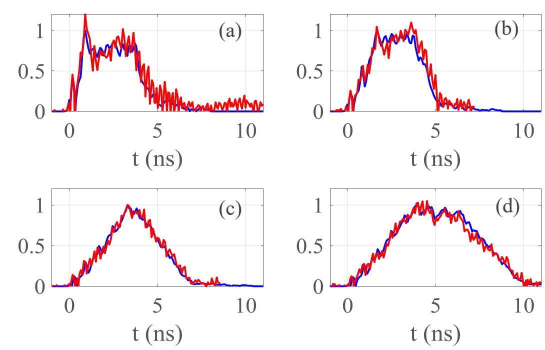

Figure 5: Comparison of the rf pulse shape between the high power test results (red) and the CST simulation (blue). (a) Single bunch; (b) 2-bunch train; (c) 4-bunch train; (d) 8-bunch train.

and 8-bunch train was 90 MW and 105 MW, respectively. These power levels are the highest ones achieved so far with dielectric power extractors.

Based on wakefield theory, the square of the generated power $\sqrt{P}$ is proportional to the charge Q_b as

$$\sqrt{P} = \sqrt{\frac{\omega}{4}\frac{r}{Q}c\beta_g}\frac{F}{1-\beta_g}Q_b \tag{1}$$

where F is the form factor. In each running during the high power test, the linearity predicted by Eqn.1 could be observed, as illustrated in Fig. 6(a). With the charge raised, however, the slope of the linearity decreased and was not repeatable with lower charge. The r/Q of the dielectric structure can be fitted from the experiment data according to Eqn.1, assuming fixed group velocity, frequency, and form factor. Its evolution during the high power test suggests continuous structure damage, as illustrated in Fig. 6(b).

In the cold test afterwards, the S21 of the structure dropped from -2.5 dB to -32.5 dB, which could account for the lower than predicted generated power during later runnings in the experiment. No damage has been observed on the dielectric surface, which demonstrates its good resistance to short pulse high power. On the other hand, the thin copper coating has been severely damaged with small pieces peeled off, as illustrated in Fig. 7. This discovery is consistent with the experiment observation of the grad-

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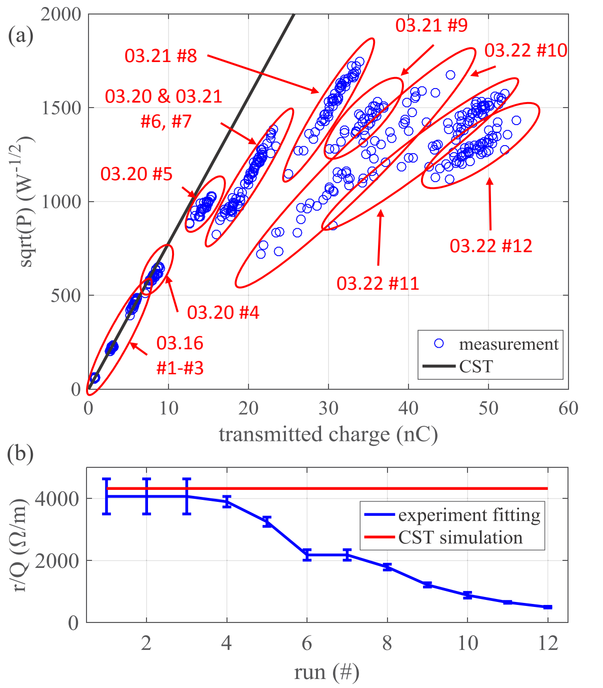

Figure 6: The high power test history with single bunch. (a) $\sqrt{P}$ as a function of Q_b; (b) The evolution of r/Q.

ual degrading of the structure's r/Q, which suggests that a thick coating of hundreds of μm is necessary for dielectric structures [4].

Figure 7: The X-band DPETS after the high power test.

DIELECTRIC DISK ACCELERATOR

In order to reduce the operation cost by increasing the rf to main beam efficiency $\eta_{rf-beam}$, several alternative types of the main accelerator for AFLC have been studied at AWA. With the dielectric disk accelerator (illustrated in Fig. 8(b)), simulation results show that $\eta_{rf-beam}$ can be significantly increased by ~45% after optimizing the disk thickness t and the dielectric constant ϵ_r, as illustrated in Fig. 8(c). Together with the main beam shaping technology [5] and high efficiency klystrons [11], the AC power of AFLC using DDA (only consider the rf part without magnets, detectors, targets, etc.) can be reduced from 297 MW to 84 MW and the AC to main beam efficiency can be improved from 9.4% to 33.0%.

In addition to its higher efficiency, DDA is also easier for machining and tuning compared with DLA, especially for high frequency and constant gradient structures. An X-band prototype has been designed to test the key technologies of DDA, including the brazing between copper and dielectric, the tuning method, the multipacting and charging effect, and the resistance to high surface electric field. The prototype

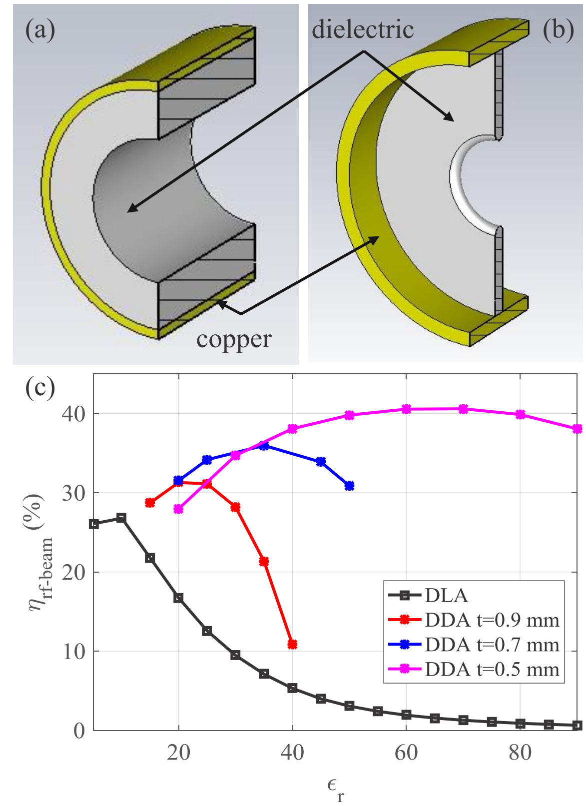

Figure 8: Comparison between DLA and DDA. (a) DLA; (b) A single cell of DDA; (c)$\eta_{rf-beam}$ as a function of the dielectric constant.

will be driven by an X-band metallic power extractor at AWA with a maximum power of 300 MW and a pulse length of ~10 ns. More details of the DDA study can be found in Ref. [12].

CONCLUSION

AWA is continuously working on the R&D of short pulse dielectric two-beam acceleration. The recent progress includes the dielectric short pulse TBA demonstration with K-band structures (55 MW output power and 28 MeV/m gradient), the high power generation with an X-band power extractor (105 MW output power), and the simulation of a dielectric disk accelerator (~45% improvement in efficiency). More study, such as the high power test of the X-band structure with thick coating, the full optimization of DDA, and the demonstration of full staging, is currently ongoing.

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