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SHORT PULSE HIGH POWER RF GENERATION WITH AN X-BAND DIELECTRIC POWER EXTRACTOR

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Abstract

Short pulse high power rf generation is one of the key technologies for the Argonne Flexible Linear Collider (AFLC), a proposed 3 TeV electron-positron linear collider based on two-beam acceleration (TBA) scheme. Compared with metallic power extractors, dielectric structures have the potential to achieve lower fabrication cost and to withstand higher gradient. Recently, an X-band dielectric power extractor (a.k.a, DPETS) has been developed at the Argonne Wakefield Accelerator (AWA) facility and achieved 105 MW output power when driven by a high charge 8-bunch train separated by 770 ps. The design, the cold test measurement, the preliminary high power test results, and the structure inspection 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 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 beam lines, which has been devoting much effort to the short pulse dielectric TBA research [2, 5, 6]. Demonstrating short pulse high power rf generation with DPETS is one of the key technologies of AFLC and one main mission of AWA. In a proof-of-principle dielectric TBA experiment, 55 MW rf power has been obtained by a K-band 26 GHz DPETS, the prototype of AFLC [6]. The power extractor, however, was damaged during the experiment. Although the mechanism is still under investigation, beam irradiation might be ascribed because the transmission of the high charge drive beam through the structure was less than 70% and more than 50 nC beam were lost within the structure. The low transmission was a result of the high aspect ratio of the structure (30 cm long with 7 mm inner diameter) and the relatively low energy of the drive beam (~70 MeV), which could be well-solved in AFLC with GeV drive beam. In order to achieve higher rf power by improving the transmission with the current AWA configuration, an X-band 11.7 GHz DPETS with a larger inner diameter has been developed recently.

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STRUCTURE DESIGN

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. 1(a). Its parameters are listed in Table. 1. 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. 1(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. 1(c).

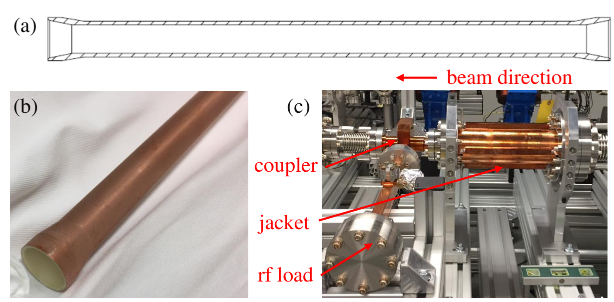

Figure 1: The X-band DPETS. (a) Section view of the dielectric tube; (b) The tube after copper coating; (c) The setup of the DPETS.

The synchronizing frequency with the ~70 MeV beam is designed to be 11.7 GHz, the ninth harmonic of the 1.3 GHz drive beam, for wakefield superposition with the bunch train operation [5]. The bunch train from a Cs_2Te cathode is obtained by splitting the 248 nm UV laser with delay lines and launched in every rf cycle with a separation of ~770 ps [7]. The number of bunches can be a power of 2 (up to 32) and the maximum charge of the bunch train is ~600 nC. Based on wakefield theory, the pulse shape and generated power with the X-band DPETS when driven by different bunch train configurations are illustrated in Fig. 2. Saturation of rf power can be obtained after the fifth bunch.

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Table 1: Parameters of the X-band Dielectric Tube

Parameter	**value**
Inner diameter	14.99 mm
Outer diameter	18.79 mm
Total length	30 cm
Uniform section length	26 cm
Dielectric constant	9.8 (Alumina)
Dielectric loss tangent	1×10^{-4}
Group velocity β_g	0.1959 c
Quality factor	3392
r/Q	4.32 kΩ/m

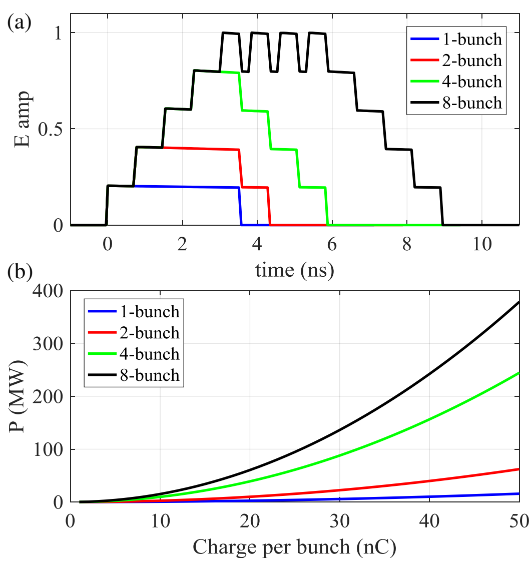

Figure 2: Phase shape (a) and generated power (b) as a function of the bunch number. Only the uniform section is considered in the calculation.

COLD TEST

In order to conduct the bead-pull test to measure the on-axis electric field distribution of the dielectric tube, a mode launcher has been designed to be inserted into the uniform section, as illustrated in Fig. 3. A small copper cylinder has been soldered onto the inner conductor of an rf cable which is supported in the dielectric tube by a large holder. The mode launcher converts the TEM mode in the rf cable to the TM_{01} mode in the tube. ϕ0.5 mm holes have been drilled on the small cylinder and the holder to guide the wire during the bead-pull test.

The bead pull results show nice agreement with the CST simulation, as illustrated in Fig. 4. The phase velocity of the TM_{01} mode can be derived from the slope of the phase distribution in Fig. 4(b). By changing the driven frequency in the bead-pull measurement, the synchronizing frequency with the relativistic beam has been calculated to be 11.675 GHz, as illustrated in Fig. 5. The detuning from 11.7 GHz has been compensated in the bunch train operation by launching the bunches at slightly different phases.

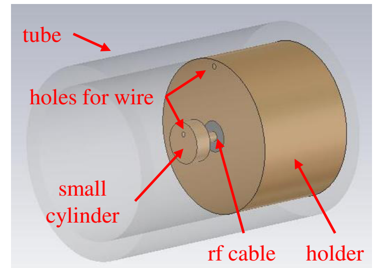

Figure 3: 3D model of the mode launch in CST simulation.

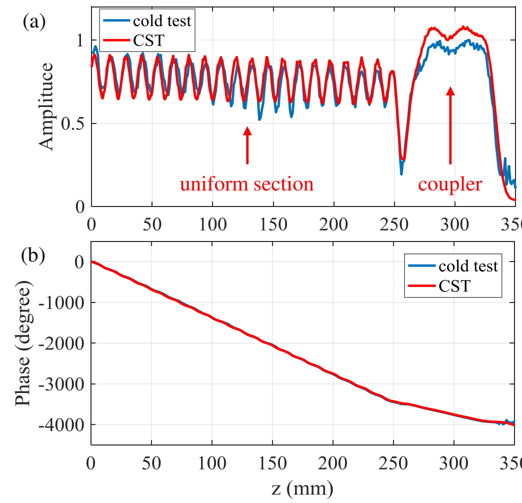

Figure 4: Comparison of the on-axis electric field distribution between the cold test and the CST simulation. The field of the beam input end could not be measured due to the insertion of the mode launcher. (a) Amplitude; (b) Phase.

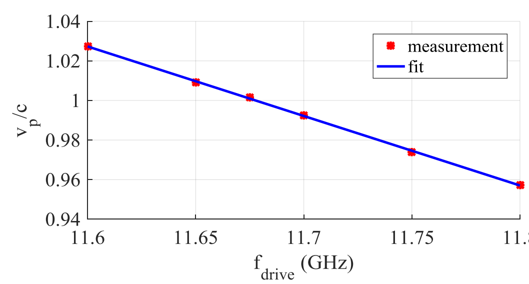

Figure 5: The ratio of the phase velocity to the speed of light as a function of the driven frequency.

HIGH POWER TEST

The diagnostics involved in the high power test include two integrating current transformers (ICT) before and after the structure to measure the current and an rf pickup to measure the output rf power. All signals were recorded by a fast oscilloscope with a 50 GS/s sampling rate and a 16 GHz bandwidth.

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

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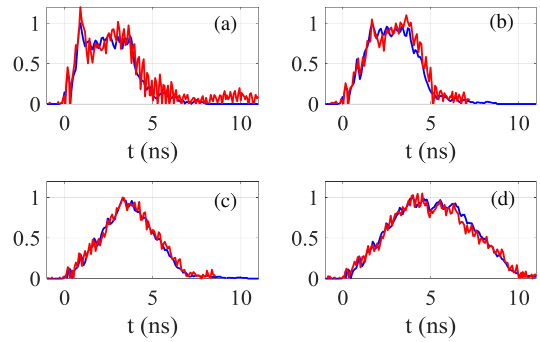

Figure 6: Comparison of the rf pulse shape between the high power test results (red) and the CST simulation (blue). (a) Single bunch; (b) 2-bunch train; (c) 4-bunch train; (d) 8-bunch train.

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 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

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

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. 7(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. 7(b).

STRUCTURE INSPECTION

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. 8. This discovery is consistent with the experiment observation of the gradual degrading of the structure's r/Q, which suggests that a thick coating of hundreds of μm is necessary for dielectric structures [4].

CONCLUSION

An X-band 11.7 GHz dielectric power extractor has been developed at AWA for short pulse high power rf generation. Good agreement of the rf pulse shape and the generated power has been observed among the theoretical prediction, the CST simulation, and the high power test with low charge drive beam. A new record of generated power with DPETS, 105 MW, has been obtained with 8-bunch train. The dielectric shows nice resistance to short pulse high power, but severe damage has been found on the thin copper coating. The dielectric tube will be re-coated with thicker layer and re-tested soon.

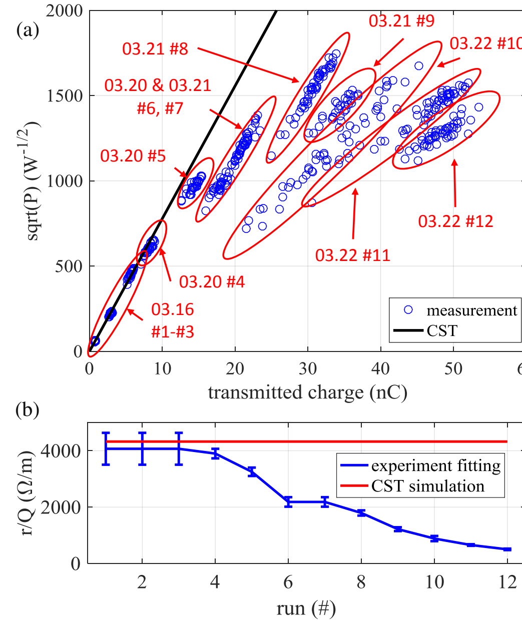

Figure 7: The high power test history with single bunch. (a) $\sqrt{P}$ as a function of Q_b; (b) The evolution of r/Q.

Figure 8: The X-band DPETS after the high power test.

ACKNOWLEDGMENT

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