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DESIGN OF A DIELECTRIC-LOADED ACCELERATOR FOR SHORT PULSE HIGH GRADIENT RESEARCH

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Abstract

The short-pulse two-beam acceleration approach is a promising candidate to meet the cost and luminosity requirements for future linear colliders. Dielectric-loaded structure has been intensely investigated for this approach because of its low fabrication cost, low RF loss, and potential to withstand GV/m gradient. An X-band 11.7 GHz dielectric-loaded accelerator (DLA) has been designed for high power test with short RF pulses (~3 ns) generated from a power extractor driven by high charge bunches at Argonne Wakefield Accelerator (AWA) facility. The gradient is expected to be over 100 MV/m with the maximum input power of 400 MW.

INTRODUCTION

Structure wakefield acceleration (SWFA) is one of the Advanced Accelerator Concepts aiming to significantly reduce the cost of future TeV-scale linear colliders [1]. In this scheme, high charge drive bunches traveling through a structure exist wakefields which are used to accelerate the low charge main beam in either the same structure (collinear wakefield acceleration, a.k.a. CWA) or a parallel structure (two-beam acceleration, a.k.a. TBA). Based on current understanding, the TBA approach is favored over CWA due to the less challenging beam transportation as well as the flexibility of independent accelerating/decelerating structures optimization [1].

RF breakdown is a potential limitation to reach high accelerating gradient in the SWFA scheme. To improve the gradient, the short pulse (~20 ns) TBA method has been proposed [2] based on the experimental observation of the exponential dependence of RF breakdown rate on pulse length [3]. Various advanced structures with high group velocity and relatively high shunt impedance are under study to efficiently accelerate the main beam with such short RF pulses [4–6]. The dielectric-loaded accelerator, in which the electromagnetic wave is slowed by a uniform dielectric layer, is attractive due to its low fabrication cost, low RF loss, and the potential to withstand high gradient [1]. Although various key technologies of DLA have been successfully tested, its high gradient performance in the short-pulse TBA approach is yet to be demonstrated.

In this study, an X-band 11.7 GHz traveling-wave DLA structure has been designed to be tested with power extractors capable to generate over 100 MW RF pulses at AWA [1, 7, 8]. In our recent study of a tunable metallic power extractor, ~3 ns ~400 MW rf pulses are expected when driven by 8-bunch high charge drive trains [8]. The corresponding accelerating gradient will be over 100 MV/m in the DLA structure. The design, the fabrication, and the experimental plan will be introduced in this manuscript.

STRUCTURE DESIGN

The high gradient structure consists of a uniform section and two tapered sections at both ends to match the impedance between the uniform section and the dual-feed rf couplers, as illustrated in Fig. 1.

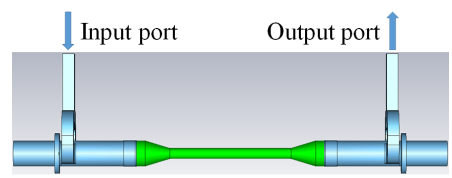

Figure 1: The layout of the X-band DLA structure (green) together with rf couplers (blue).

The uniform section has been optimized so as to achieve over 100 MV/m accelerating gradient with 400 MW input power. The detailed parameters of the DLA structure are listed in Table 1.

Table 1: Parameters of the Uniform Section

Parameters	Unit	Value
Dielectric material		MCT-16
Dielectric constant		16
Dielectric loss tangent		1×10^{-4}
Dielectric inner diameter	mm	6
Dielectric outer diameter	mm	9.448
Outside metallic material		copper
Metallic conductivity	S/m	5.8×10^{7}
Length	mm	100
Group velocity v_g	c	0.068
Quality factor Q		2468
Shunt impedance r	MΩ/m	23.3

The tapered section has been optimized to obtain a wide coupling bandwidth. The optimized structure has been simulated with the frequency domain solve in CST Microwave

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Studio. Its on-axis field distribution and S-parameters are illustrated in Fig. 2 and Fig. 3, respectively. The S_{11}<-10 dB coupling bandwidth is above 175 MHz.

The length of the entire dielectric structure is 165 mm. The length of the full structure including two rf couplers is 382 mm.

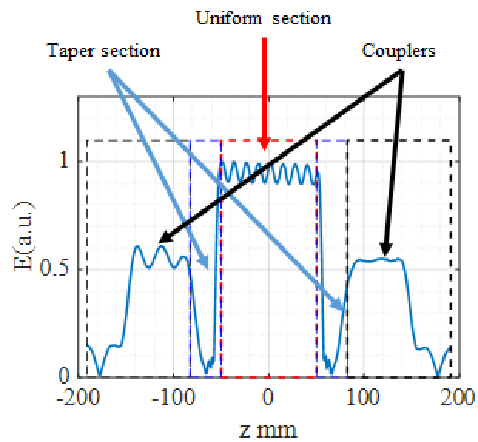

Figure 2: The amplitude distribution of the on-axis longitudinal electric field. The small modulation of the uniform section field is caused by the imperfect matching (small reflection) of the matching section and the output coupler.

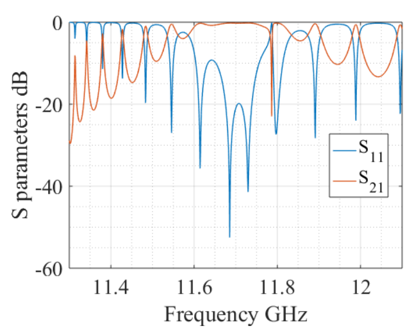

Figure 3: S-parameters of the DLA structure with rf couplers.

SHORT PULSE SIMULATION

In the previous section, the simulation is conducted at the steady state. When driven by short RF pulses, however, the build-up field could be lower if the structure is not completed filled or resulted from other factors. In this section, transit time domain simulation is applied to study the structure response in order to determine the gradient. The input RF pulse shape from the power extractors at AWA is simplified as a trapezoid with 3 ns rising time, 3 ns flat-top duration, and 3 ns falling time, as illustrated in Fig. 4(b). Long RF pulses with 100 ns flat-top and the same rising/falling time as the short ones are also used for comparison, as illustrated in Fig. 4(a). In this section, the input power at the flat-top is fixed at 400 MW.

For dielectric-loaded traveling-wave structures, the field is built up from the input end to the output end at the group velocity when driven by external RF pulses. The uniform longitudinal boundary condition between vacuum and dielectric in the uniform section leads to the excitation of only the π mode and the uniform on-axis field distribution. When ignoring the structure attenuation, the steady state accelerating gradient when driven by long pulses could be calculated as

$$E = \sqrt{\frac{P_{in}\omega}{v_g}\frac{r}{Q}} \qquad (1)$$

where P_{in} denotes the input power and ω denotes the frequency.

When driven by short RF pulses, however, the gradient could deviate from that in Eqn. 1 due to several reasons: 1) the pulse length is shorter than the filling time; 2) the pulse shape is distorted after the rf coupler due to its limited bandwidth; 3) the structure dispersion. When considering a realistic DLA with tapered sections, the gradient could also be affected by the modes excitation with the tapered vacuum/air boundary condition. In our study, the average gradient G_{ave} of the uniform section is defined by the energy gain of a ultrarelativistic beam over the uniform section length L as

$$G_{ave} = \int_0^L E(z,t)dz/L = \int_0^L E(z,z/c)dz/L \qquad (2)$$

where E(z,t) is the transit on-axis field.

In CST Microwave Studio, time domain simulation with a series of probes along the axis has been conducted to obtain $E(z,t)$ so as to calculate the accelerating gradient. From the long pulse cases as illustrated in Fig. 4(c) and (e), the steady state could be reached after ~30 ns. Small amplitude variation along the axis could be observed due to the imperfect matching between the uniform section and the output coupler, as illustrated in Fig. 4(c). The averaged value of the field amplitude in steady state is ~114 MV/m, in good agreement with the theoretical value of ~117 MV/m calculated from Eqn. 2. For the short pulse case, the maximum transit electric field near the center of the uniform section could reach the steady state gradient, as illustrated in Fig. 4(d). However, the maximum average gradient is slightly lower (105 MV/m) than the steady state gradient, as illustrated in Fig. 4(f). A main reason is the filling time is longer than the flat-top duration.

FABRICATION

The X-band DLA structure, including the uniform section and the tapered sections, has been fabricated as a single piece to avoid multipacting in the otherwise existing longitudinal gaps, as illustrated in Fig. 5. The outer wall of the dielectric tube has been metalized with a 100 μm thick copper layer to prevent charging. The dielectric structure will be placed inside a copper jacket for the high power test.

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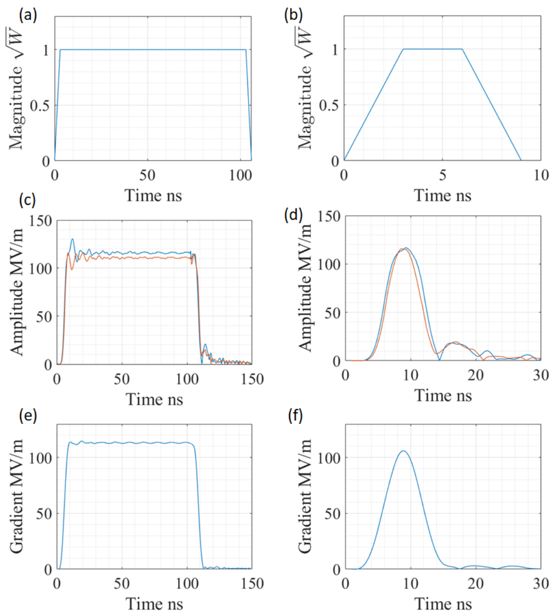

Figure 4: Comparison of the structure response between short RF pulse (right) and long RF pulse (left). (a-b) Normalized input pulse shape. (c-d) Transit on-axis electric field. The blue and the red lines in (c) represent the field at the peak and the valley near the structure center. The lines in (d) represent the fields at the location as (c). (e-f) The average gradient.

Figure 5: The fabricated dielectric structure with copper coating (right) and the copper jacket (left). High power RF flanges will be brazed onto the jacket. The opening at the jacket center is designed for pumping.

TEST PLAN

Currently, the X-band DLA structure is under assembly and the experiment will be conducted next year. The high power test layout will be similar to that with a single-cell metallic disk-loaded structure [9], as illustrated in Fig. 6. The diagnostics will include directional couplers to measure forward, reflected, and transmitted RF power; upstream and downstream Faraday cups to measure the dark current; and a photo-multiplier tube with a fluorescent screen to detect X-ray accompanying RF breakdown.

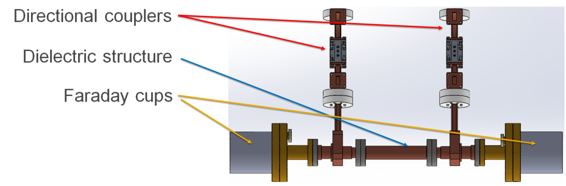

Figure 6: The high power test layout (the pumping port of the copper jacket is not shown).

CONCLUSION

An X-band dielectric-loaded accelerator has been designed for high power test with ~3 ns short RF pulses generated from power extractors. Transit time domain analysis and simulation have been conducted to determine the gradient under such short RF pulses. With 400 MW input power, the maximum transit field and the maximum average gradient of the uniform section are expected to reach 114 MV/m and 105 MV/m, respectively. The structure is currently under assembly and the experiment will be conducted next year.

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