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DEVELOPMENT OF A PAIR OF 182 GHz TWO-HALF POWER EXTRACTOR AND ACCELERATOR FOR SHORT PULSE RF BREAKDOWN STUDY*

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Abstract

High-frequency structures are favorable in structure wakefield acceleration for their strong beam-structure interaction. Recent progress of advanced fabrication technologies, such as high-precision two-half milling and additive machining, has enabled experimental research of mm-wave/THz structures. In this work, we have designed a pair of 182 GHz two-half copper power extractor and accelerator for short pulse RF breakdown study. When driven by a 182 GHz 4-bunch train with 4 nC total charge and 0.3 mm rms bunch length, the power extractor will generate 0.4 ns ~8 MW RF pulses and the corresponding gradient in the single-cell accelerator will reach ~460 MV/m. RF and mechanical design of the proof-of-concept structures will be reported in this manuscript.

INTRODUCTION

Accelerators capable to reach a few hundreds of MV/m to GV/m acceleration gradient are attractive for future large-scale colliders, X-ray free electron lasers, and compact applications. Recently, several groups have reported progress of high gradient mm-wave/THz acceleration study with ns-scale short pulses. Various drive sources have been used in these studies, such as wakefield from drive beam in the same structure [1]; and external power from optical rectification [2, 3], gyrotron with fast switch [4–6], and coherent transition radiation [7]. In this work, we propose to generate RF power from a beam-driven power extractor for mm-wave/THz high gradient study. The experimental setup will be a two-beam acceleration configuration, which has the advantages of relaxed beam lattice design and high acceleration efficiency [8].

The structure design is based on realistic drive beam parameters at the Argonne Wakefield Accelerator facility (AWA) [9]. The drive beam will be 182 GHz 4-bunch train with 4 nC total charge that generated by laser splitters. The power extractor has been optimized to obtain high power, low transverse field, wide bandwidth, and full drive beam transmission. The output power is expected to be ~8 MW with 0.4 ns flat-top. Preliminary design of the single-cell accelerator shows the acceleration gradient will reach ~460 MV/m with such short pulse.

This work is enabled by the latest development of high-precision two-half milling [4,10,11]. A short power extractor test structure has been built to demonstrate the fabrication/assembly feasibility.

POWER EXTRACTOR RF DESIGN

The power extractor layout is illustrated in Fig. 1. The design procedure starts with the normal cell that determines the generated power level and duration. The optimized design consists of 84 normal cells with 0.9 mm minimal beam aperture to ensure 100% drive beam transmission (assuming 30 µm normalized emittance for the drive bunch train in the worst case). A choke cell at the structure end is designed to mitigate RF leakage. Single output port is used to reduce fabrication complexity and a shorten waveguide is placed opposite to the output waveguide to minimize transverse field. In addition, a matching cell is used to match the impedance between normal cells and the output waveguide. It should be noted that the choke cell, the shorten waveguide, and the matching cell need to be optimize together to obtain small RF leakage, low transverse field (Fig. 2), and wide bandwidth (Fig. 3), simultaneously. After full structure optimization, the power extractor is capable to generate 8.1 MW (averaged over the 0.4 ns flat-top) 182 GHz pulses.

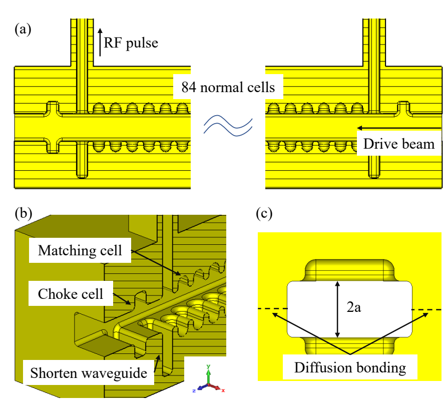

Figure 1: (a) Layout of the 182 GHz power extractor. (b) Zoom-in view of the structure end. (c) Cross-section of the normal cell.

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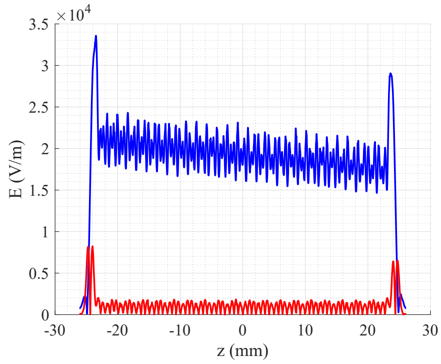

Figure 2: On-axis distribution of the longitudinal (blue) and the vertical (red) electric field. The horizontal one is zero due to the structure symmetry.

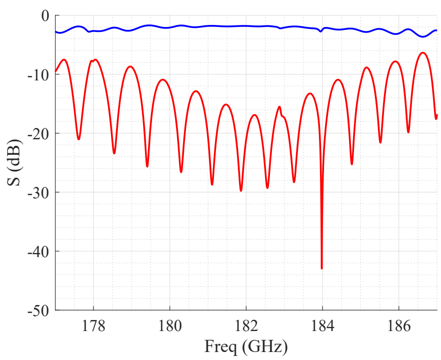

Figure 3: S21 (blue) and S11 (red) of the power extractor.

The simulated result by CST wakefield solver is in good agreement with the theoretical calculation based on RF properties of the normal cell, as illustrated in Fig. 4.

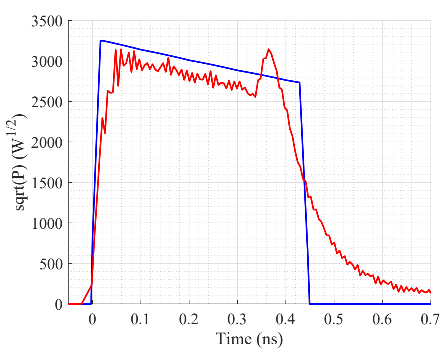

Figure 4: Comparison of the output waveguide signal with 4-bunch driven beam between theoretical prediction (blue, considering normal cell only) and CST wakefield simulation (red, considering full structure).

ACCELERATOR RF DESIGN

A 182 GHz two-half traveling-wave accelerator consisting of a normal cell and two matching cells has been designed to pair with the power extractor, as illustrated in Fig. 5. The witness beam is expected to have low charge and low emittance. Therefore, the beam aperture is designed to have cut-off frequency above 182 GHz and no choke cell is required. The RF power from the power extractor will be transferred to the

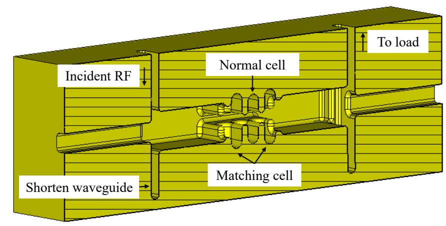

Figure 5: Cross-section of the single-cell accelerator.

To determine the acceleration gradient with short RF pulse, we first simulate the impulse response of probes along the normal cell axis by CST and convolute it with the input pulse shape to obtain the time domain response of the probes. Then, we calculate the energy gain of an ultra-relativistic beam moving along the axis based on the probe field and define the gradient as the energy gain over the normal cell length. Figure 6 presents the transient gradient when the accelerator is driven by short pulse from the power extractor and long pulse with the same power level. The maximum gradient in the short pulse case is ~460 MV/m although the structure doesn't reach steady status.

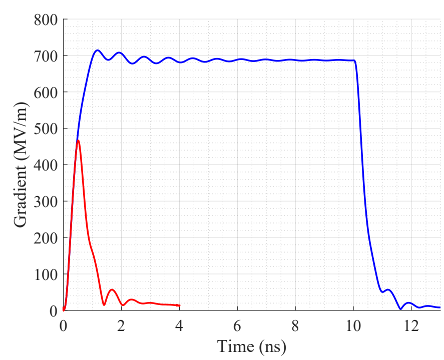

Figure 6: The transient gradient of the normal cell as a function of witness beam injection time under long (blue) and short (red) drive pulse. In both cases, the flat-top power level of input pulse is fixed at 8 MW.

The key geometry parameters and RF properties of the power extractor and the accelerator are summarized in Table 1.

STRUCTURE MECHANICAL DESIGN

The engineering design starts with a tolerance study on one of the most critical point of the split structure – misalignment of the two halves. In preliminary CST simulation, it has been found that the vertical displacement of the two halves should be kept within ±5 µm. This range will ensure maximum power degradation of less than 10% and minor frequency shift. The tolerance on horizontal displacement is more relaxed – ±20 µm, and finally the angular

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Table 1: Parameters of the 182 GHz Two-H
The RF Properties Are for the Normal Cells

Parameter	Power extractor
Minimal aperture 2a	9 mm
Structure length	52.2 mm
Phase advance	$2\pi/3$
Shunt impedance	60.7 kΩ/m
Quality factor	1837
Group velocity	26.8%c

misalignment tolerance is reasonably tight – ~ ±25 µm depending on the alignment featu

Considering the difficulty of fabricating/b flanges, the entire power extractor/acceleratoı be placed in a large vacuum chamber. Figure 7 presents the mechanical design of the power extractor (the accelerator's design will be similar). The main device will effectively be constructed in two halves and the WR5 transition parts will be micro-wire EDMed. The structure will be lightly diffusion bonded at the surfaces adjacent to the primary gap. This will ensure that the as-machined dimensions are closely matched without the uncertainty of clamping or utilizing braze alloy. In addition, the concept of elastic averaging will be applied for the alignment mechanism. Rather than just the minimum 2 solid pins, 12 compliant spring pins are spread along the structure so the random hole machining positional errors and hole/pin diameter fabrication errors are averaged out without over-constraining the system.

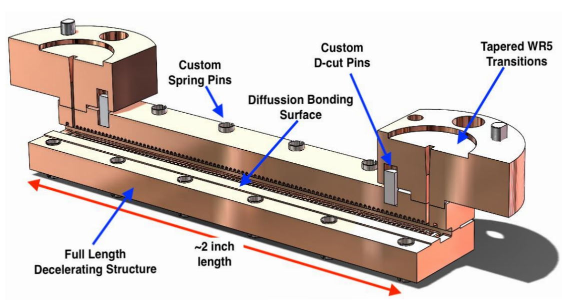

Figure 7: Cross-section of the full power extractor shown with WR5 transitions.

TEST STRUCTURE FABRICATION

A test structure nearly identical to the power extractor except with reduced number of normal cells has been built to study the fabrication/assembly feasibility, as illustrated in Fig. 8.

The halves were inspected through an optical CMM system with 0.25 µm resolution and the targeted tolerances are largely met with some room for future improvement through process development and handling clarification with the vendor. Surface finishes are measured to be better than 5 µ-inch Ra before etching.

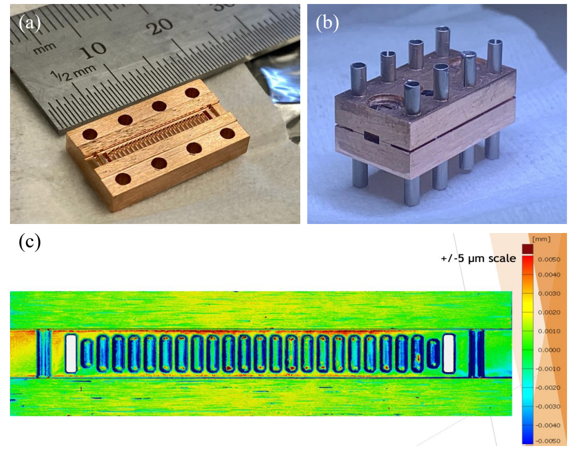

Figure 8: (a) Lower half of the test structure with scale. (b) Fully assembled test structure. (c) Top down contour map of the fabricated structure demonstrating generally excellent compliance to tolerancing requirements.

CONCLUSION

A pair of 182 GHz two-half copper power extractor and accelerator for short pulse RF breakdown study has been designed in this study. Based on the realistic drive beam available at AWA, the power extractor is capable to generate 0.4 ns ~8 MW RF pulses and the corresponding gradient in the single-cell accelerator will reach ~460 MV/m. Fabrication and characterization of a short test structure validates the machining/assembly feasibility. We plan to complete accessory components design (waveguide, RF load, directional coupler, etc.) and conduct the full assembly high-power test in the next phase of the project.

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