

DESIGN OF A SHORT-PULSE SEPTUM POWER SPLITTER FOR DISTRIBUTED X-BAND HIGH-GRADIENT ACCELERATION

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Abstract

Using short radiofrequency (RF) pulses is a promising method for increasing achievable accelerating gradients while significantly suppressing RF breakdown probability. However, short-pulse operation requires a structure with a commensurately low filling time to ensure efficient gradient buildup. To achieve this, we utilize a distributed power coupling scheme that delivers RF power to each cavity simultaneously through a waveguide array. This parallel feeding mechanism drastically reduces the filling time of the entire accelerating structure compared to traditional series-fed designs. Furthermore, this topology allows for greater flexibility in cavity optimization and yields higher shunt impedance. This work presents the design and simulation of a novel septum power splitter specifically engineered to drive an accelerating structure in this short-pulse regime. The splitter is integrated with a four-cell prototype, enabling each cavity to be powered individually and concurrently. The system is designed for short X-band RF pulses with peak powers up to 400 MW at 11.7 GHz. The four-cell structure is over-coupled and maintains a 120° phase advance between adjacent cells. CST simulation results confirm the performance of this design in achieving high accelerating gradients. Finally, we outline the experimental plan for the prototype demonstration at the Argonne Wakefield Accelerator.

INTRODUCTION

Achieving high accelerating gradients is crucial for a wide range of accelerator applications to reduce the overall size and cost. As the attainable gradient is limited by radiofrequency (RF) breakdown [1], short RF pulses have emerged as an effective method for achieving higher gradients. Empirical scaling laws [2] describe the relationship between pulse length and attainable gradient at a constant breakdown rate, suggesting that gradients well beyond conventional limits may be achieved using nanosecond-scale pulses. This regime provides a viable path toward the next generation of ultra-compact accelerator applications.

Accelerating structures driven by short RF pulses require short structure filling times. It is challenging to achieve both a short filling time and a high accelerating gradient in conventional accelerators, as sequential RF power transfer between cells inherently leads to a trade-off between these two requirements. In contrast, distributed power coupling [3, 4] enables efficient RF power delivery to each accelerating cavity driven by short RF pulses, thereby reducing the structure

filling time. This approach also provides greater flexibility in the cavity geometry optimization, which can lead to improved shunt impedance [5, 6].

Motivated by the demands of short-pulse operation and distributed power coupling schemes, we previously introduced, fabricated, and low-power tested an X-band parallel waveguide power splitter at 11.7 GHz [7]. Power coupling among the four output waveguides is achieved by three triangular septa with optimized dimensions, each placed between two adjacent waveguides. This previously reported splitter [7] equally divides the incident RF power into four output ports with a 90° phase advance between adjacent ports. The low-power measurement results showed good agreement with simulations.

In this work, following the successful validation of the 90° waveguide splitter design, we present a reconfigured septum-based RF power splitter integrated with a four-cell accelerating structure, designed to provide a 120° phase advance between adjacent cavities for short-pulse acceleration. In this architecture, the RF power is delivered simultaneously to each cavity through the waveguide array. To accommodate short-pulse operation, the standing-wave accelerating structure is designed in an over-coupled regime to reduce the filling time and ensure efficient RF power coupling at 11.7 GHz. Simulation results demonstrate that the proposed architecture achieves a high shunt impedance and a high accelerating gradient in the X-band under short-pulse operation. The complete structure, comprising the RF power splitter integrated with the four-cell accelerating structure, is currently under fabrication, and high-power tests are planned at the Argonne Wakefield Accelerator (AWA).

WAVEGUIDE ARRAY POWER SPLITTER

We previously designed a prototype of a 1-to-4 power splitter based on a waveguide array for short-pulse operation at X-band [7]. Specially designed septums on the

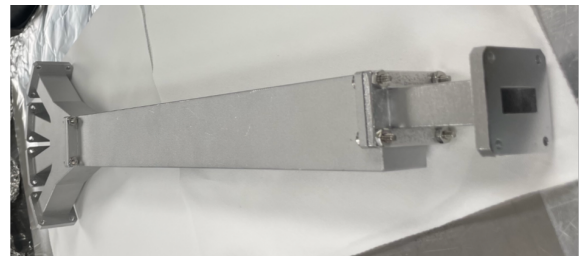


Figure 1: 3D-printed waveguide array prototype used for low-power measurements.

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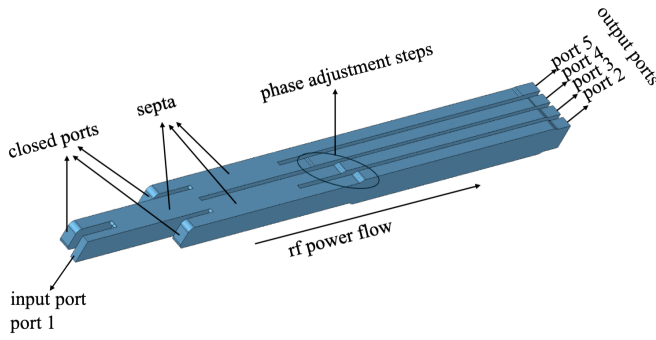


Figure 2: Vacuum representation of the 1-to-4 power splitter optimized for 120° phase advance between adjacent output ports and equal power distribution. Port 1 is the input port, and Ports 2-5 are the output ports.

shared waveguide walls are used to divide the RF power from a single source to four waveguide outputs with controlled phase advances and magnitudes. Phase and power distribution at the output ports can be adjusted by tuning the dimensions of the septa and waveguides. Figure 1 shows the 3D-printed prototype employed in the low-power microwave measurements. Both CST simulation results and cold test measurements demonstrate that the prototype successfully performs power splitting in the short-pulse regime with the desired phase difference between the output ports.

In this work, we connect the output waveguides of the above waveguide power splitter to individual accelerating cavities to drive them simultaneously and independently for short-pulse acceleration at 11.7 GHz. Following the validation of the previously designed 90° phase advance prototype [7], shown in Fig. 1, the concept is extended by modifying the septum-based RF power splitter to achieve a 120° phase advance between adjacent output ports while maintaining equal power distribution. Figure 2 shows the vacuum representation of the 1-to-4 power splitter optimized for short-pulse operation at 11.7 GHz in X-band while Fig. 3 represents frequency domain responses of the splitter. As seen in Fig. 3, the S-parameter magnitudes converge at 11.7 GHz to approximately -6 dB, confirming equal power distribution across the output ports while the 120° phase advance is achieved. The design is compatible with the current Power Extraction and Transfer Structure (PETS) at AWA, which delivers short RF pulses at 11.7 GHz [8, 9].

ACCELERATING CAVITY DESIGN DRIVEN BY THE WAVEGUIDE ARRAY

We design the accelerating structure to integrate it with the reconfigured RF power splitter. Since the power splitter features four output waveguide ports, the accelerating structure is designed as a four-cell configuration. We first designed the single cavity in the CST Microwave Studio, as illustrated in Fig. 4 (a). The coupler is designed to operate in the over-coupled regime to reduce the filling time and to achieve a high transient gradient. There is a 120°

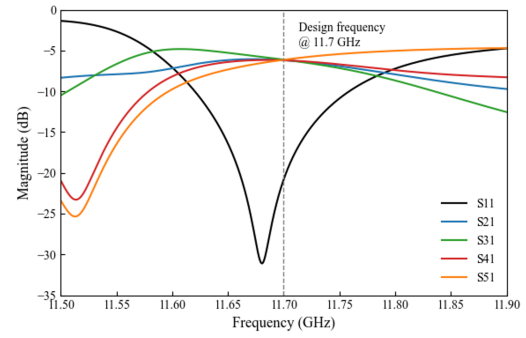


Figure 3: Simulated S-parameters of the power splitter shown in Fig. 2

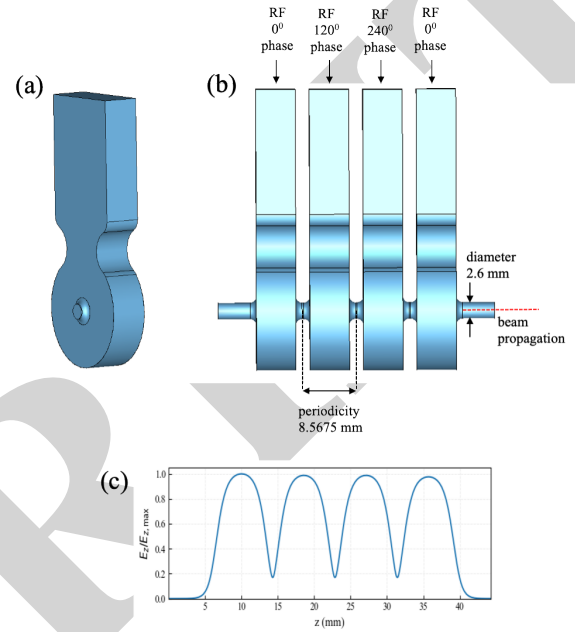


Figure 4: (a) Vacuum model of the single cell with a coupling waveguide. The four-cell accelerating structure is then designed based on this unit cell. (b) Vacuum representation of the four-cell accelerating structure. (c) Normalized electric field E_z on the axis.

phase advance per cell for relativistic particles to match the waveguide array power splitter design. The beam aperture is designed to limit cell-to-cell coupling [3].

Table 1 summarizes the design parameters of the single-cell structure with the coupler. Here P_{peak} is the peak input power of the short RF pulse available at AWA [9], with a 3 ns rise, 3 ns flatter and a 3 ns fall. Figure 4 (b) shows the vacuum model of the four-cell accelerating structure, while Fig. 4 (c) illustrates the normalized electric field on-axis along the structure with four identical cavities. Figure 5 shows that the reflection coefficients (S_{11} , S_{22} , S_{33} , S_{44}) of the four-cell structure overlap, confirming that the cavities are effectively isolated with negligible cell-to-cell coupling.

Figure 6 shows the integrated assembly of the waveguide array power splitter and the accelerating cavities. Particle-in-

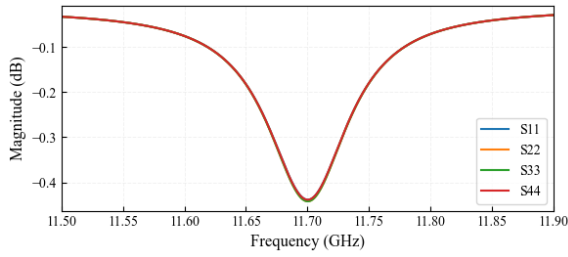


Figure 5: Simulated reflection coefficients (S_{11} , S_{22} , S_{33} , S_{44}) (overlapping) of the four-cell accelerating structure excited by their corresponding waveguide ports as shown in Fig. 4 (b).

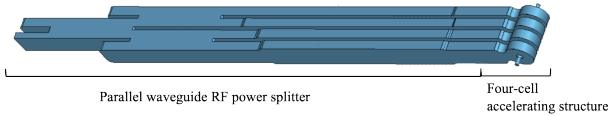


Figure 6: Vacuum model of the integrated waveguide array power splitter and accelerating cavities.

cell (PIC) simulations were performed in CST under short-pulse, high-peak-power excitation, using 9 ns RF pulses available at the AWA facility [9]. The integrated structure is excited through the input port (Port 1, as shown in Fig. 2), while an electron bunch with an initial energy of 10 MeV is injected through the beam hole. Such electron bunches can be generated by the X-band photocathode gun [10] at AWA. The particle energy is recorded and presented as a function of its longitudinal position in Fig. 7. The accelerating gradient is calculated as 168 MV/m at 400 MW.

HIGH-POWER TEST DESIGN AT AWA

We have completed the mechanical design of the integrated assembly for a high-power test at AWA. Figure 8 (a) shows the exploded view of the clamped copper structure built as individual plates, and Fig. 8 (b) shows the assembled structure mounted inside the vacuum chamber in preparation for high-power testing.

Table 1: Design parameters of the single-cell cavity

Parameter	Value
Frequency	11.7 GHz
Beam aperture (diameter) $2a$	2.6 mm
Period	8.5675 mm
Phase advance per cell	120°
Quality factor (unloaded) Q_0	6016
Loaded Q_L	141.6
Coupling coefficient (β)	41.5
R_s/Q	18.6 k Ω /m
Average gradient E_a	$28\sqrt{P_{\text{peak}} \text{ (MW)}}$ MV/m
E_{peak}/E_a	1.70
$H_{\text{peak}}Z_0/E_a$	1.39

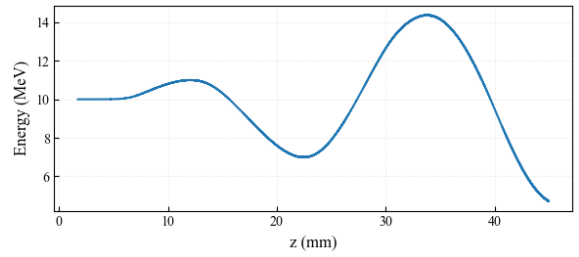


Figure 7: Particle energy as a function of position along the accelerating structure obtained from CST PIC simulations.

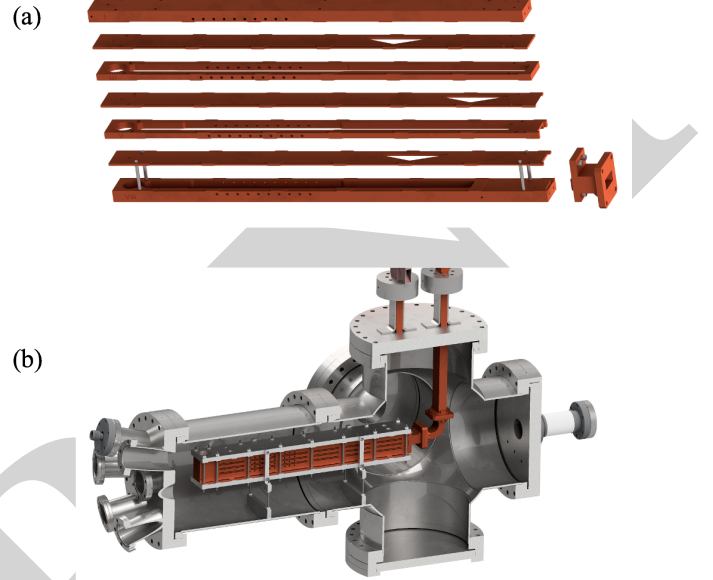


Figure 8: (a) Exploded view of the clamped copper structure, revealing the individual slotted plates and the input coupler piece. (b) Cross-sectional view of the vacuum chamber with the assembled structure mounted inside, prepared for high-power testing.

CONCLUSION AND FUTURE WORK

In this study, the power splitter and the four-cell accelerating structure are sequentially designed and integrated into a unified assembly, achieving a 120° phase advance per cavity. The integrated structure demonstrates promising performance in simulation results for high-gradient short-pulse acceleration. The structure is currently being fabricated, and high-power testing is scheduled at the AWA facility.

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