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DESIGN AND FABRICATION OF A METAMATERIAL WAKEFIELD ACCELERATING STRUCTURE

D. C. Merenich[1], X. Lu[1,2], J. G. Power[2], D. S. Doran[2]
[1]Northern Illinois University, Dekalb, USA
[2]Argonne National Laboratory, Dekalb, USA

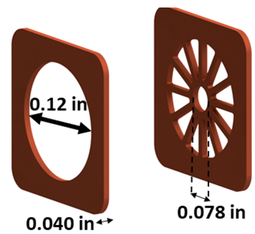
Abstract

Metamaterials (MTMs) are engineered materials that can show exotic electromagnetic properties such as simultaneously negative permittivity and permeability. MTMs are promising candidates for structure-based wakefield acceleration structures, which can mitigate the impact of radio frequency (RF) breakdown, thus achieving a high gradient. Previous experiments carried out at the Argonne Wakefield Accelerator (AWA) successfully demonstrated MTM structures as efficient power extraction and transfer structures (PETS) from a high-charge drive beam. Here we present the design, fabrication, and cold test of an X-band MTM accelerating structure for acceleration of the witness beam in the two-beam acceleration scheme. The MTM structure was simulated using the CST Studio Suite and optimized for high gradient when excited by a short RF pulse extracted from an X-band metallic PETS. Cold test of the fabricated structure shows good agreement with simulation results. Future work includes a beam test at AWA to study the short-pulse RF breakdown physics, as an important component towards a future compact linear collider based on two-beam acceleration.

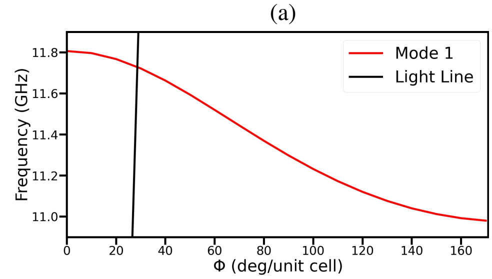
INTRODUCTION

Structure-based wakefield acceleration (SWFA) is an advanced accelerator concept, where a witness bunch is accelerated by the high-gradient wakefield excited by a drive bunch. One scheme of SWFA is the two-beam acceleration (TBA), where the power extracted from the drive bunch in a power extraction and transfer structure (PETS) is delivered to a separate accelerating structure to accelerate the witness bunch [1, 2]. SWFA shows promise to mitigate breakdown risks in RF accelerators. Empirical studies have found that the breakdown rate is proportional to $E_{\text{grad}}^{30} \times t_{\text{pulse}}^{5}$, where E_{grad} is the gradient, and t_{pulse} is the RF pulse length. This means that operating the structure at short pulse lengths can help lower the breakdown probability at a given gradient. SWFA with the pulse length on the order of a few nanoseconds requires advanced, specially design structures. Metamaterial (MTM) structures [3, 4] are found to be promising candidates for wakefield acceleration, in a series of previous experiments at the Argonne Wakefield Accelerator (AWA), where a peak power of 565 MW was extracted by a MTM PETS [5] from a high-charge beam.

MTM structures are periodic structures engineered to possess novel electromagnetic properties such as simultaneously negative permittivity and permeability in the so-called double-negative MTMs. MTMs of this type have negative group velocity and can overcome the limitation from the trade-off between the group velocity and the shunt impedance in conventional RF structures with positive group velocity. Therefore, MTMs can achieve higher gradients when used as wakefield structures.



(a)



(b)

Figure 1: (a) Unit cell of the MTM accelerating structure. (b) Dispersion curve for the fundamental TM_{01}-like mode of the optimized unit cell.

This paper outlines the design, fabrication, and and cold test of an MTM accelerating structure at 11.7 GHz for two-beam acceleration. A future high power test is planned at AWA, where short RF pulses with a peak power of 500 MW and a 3-nanosecond flattop will be extracted from an X-band metallic PETS [4] placed on the AWA 65 MeV drive beam and then fed into the MTM accelerating structure to generate a gradient of over 300 MV/m for RF breakdown studies.

DESIGN AND SIMULATIONS

Unit Cell Design

The MTM structure is designed as a periodic copper structure, with one period consisting of one wagon wheel plate and one spacer plate. The unit cell design is shown in Fig. 1a. The optimization of the structure is carried out using the CST Studio Suite. Figure 1b shows the dispersion curve of the fundamental TM_{01}-like mode, which has an interaction frequency with the 65 MeV electron beam at 11.7 GHz, aligned with the center frequency of the input RF pulse provided by the X-band metallic PETS.

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Table 1: Structure Parameters from Simulations

Frequency	11.70 GHz
Quality factor Q	2237
r/Q	21 kΩ/m
Group velocity v_g	-0.012c
Short-pulse gradient[1]	145 MV/m $\cdot\sqrt{P/(100\ \text{MW})}$

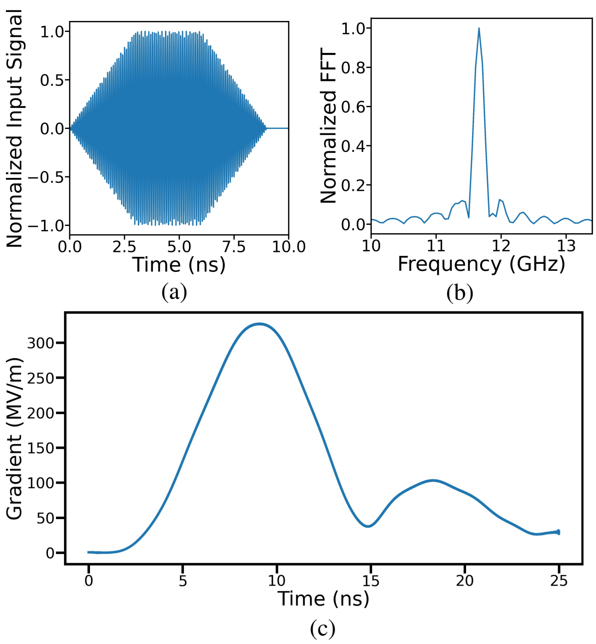

Figure 2: (a) Normalized input pulse (voltage signal) for the MTM structure, as extracted from the metallic PETS. (b) Normalized frequency spectrum of the input pulse. (c) Gradient from a probe at the center of the structure, when the peak power from the input pulse is 500 MW.

Table 1 displays a list of structure parameters from CST simulations. The gradient is calculated for a short input pulse, as shown in Fig. 2. In the optimization of the short-pulse gradient, there is a natural trade-off in the choice of the group velocity: a short filling time is desired for short RF pulses, which calls for a high group velocity; however, a high gradient cannot be achieved if the group velocity is too high.

Full Structure Design

The full MTM accelerating structure consisting of 6 MTM unit cells and a pair of couplers is shown in Fig. 3a (vacuum in blue). The signal transmission between the two waveguide ports, the S_{21} parameter, is shown in Fig. 3b.

In the planned AWA experiment, the structure will be excited by the extracted RF pulse from the metallic PETS [5]. The PETS could provide up to 500 MW of peak power, when excited by a train of eight electron bunches with a total charge of about 500 nC at the 65 MeV AWA beamline.

[1] Scaled for input RF pulses with a 3-nanosecond flattop and a peak power of P, as shown in Fig. 2.

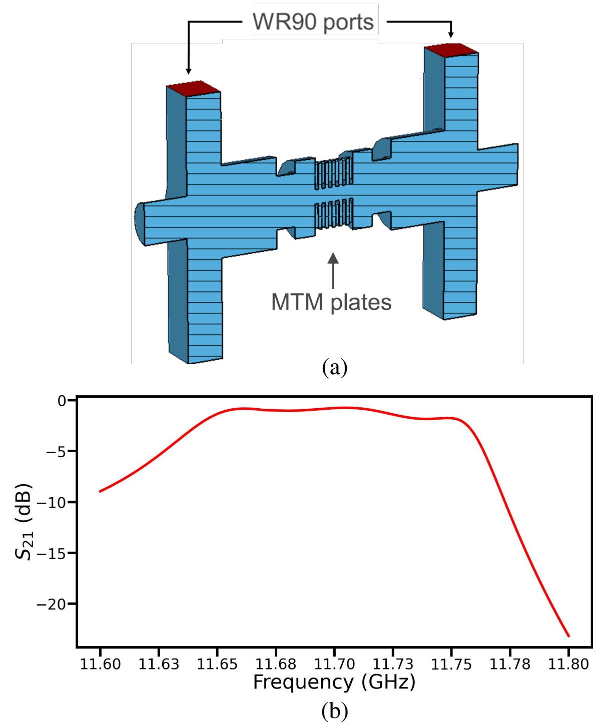

Figure 3: (a) Vacuum model of the 6-cell periodic MTM accelerating structure with couplers. (b) Simulated S_{21} parameter from CST frequency domain simulations.

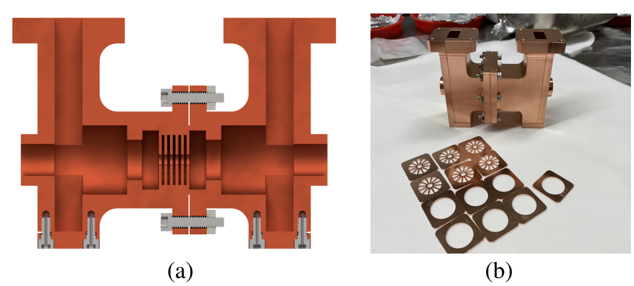

Figure 4: (a) Mechanical drawing of the MTM structure. (b) Fully-assembled structure (and spare plates for display).

Figure 2a shows the normalized, 3-nanosecond flattop input voltage signal for the MTM structure. The pulse shape is from coherent addition of the wakefield pulses from multiple bunches in the train. The frequency spectrum of this pulse is shown in Fig. 2b, with a center frequency of 11.7 GHz. The peak power used in the CST time domain simulation is 500 MW, and the resulting gradient in the center of the MTM structure with time is shown in Fig. 2c.The gradient reaches over 300 MV/m.

FABRICATION AND COLD TEST

Figure 4a shows the model drawings of the MTM accelerating structure, which has a brazeless design. Figure 4b displays the fabricated, fully assembled structure. Electropolishing was performed for good surface finishing and removal of sharp corners.

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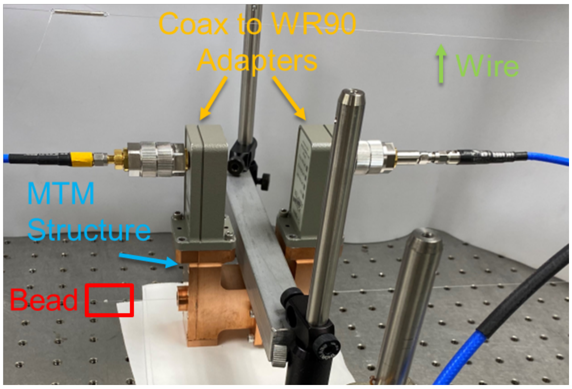
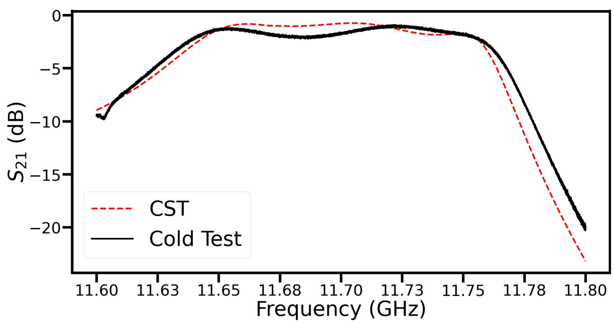


Figure 5: Experimental setup for cold test.



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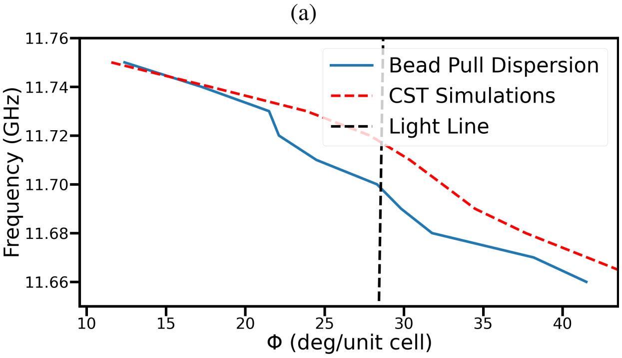

(b)

Figure 6: (a) Comparison of the S_{21} parameter from the cold test and from simulations. (b) Comparison of the dispersion curve from the bead pull test and from simulation. The dotted black line represents the dispersion curve for light (relativist electron beam).

A low-power microwave measurement (cold test) was performed using a vector network analyzer (VNA). The experimental setup is shown in Fig. 5, and the S_{21} parameter from the cold test is displayed in Fig. 6a, demonstrating good passing of a band of frequencies around 11.7 GHz, in good agreement with simulations. The phase variation of the electric field, $\Delta\Phi$, and thus the wave number, $k = \Delta\Phi/\Delta z$, are calculated at different frequencies. The resulting dispersion relation is shown in Fig. 6b, in good agreement with the design.

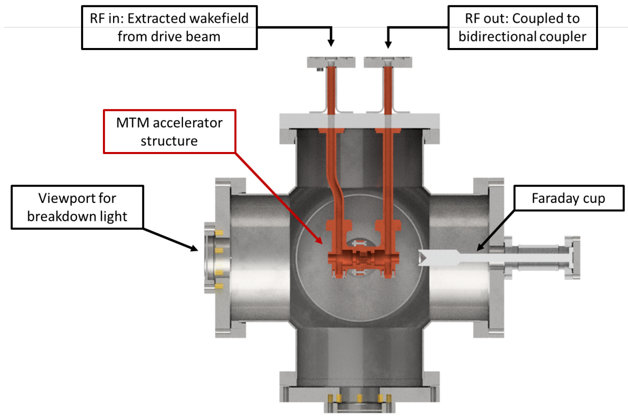

Figure 7: Schematic for a future high power test at AWA on the MTM accelerating structure.

FUTURE PLANS

Figure 7 shows a schematic for future experiments on the MTM accelerating structure at AWA. The structure will be placed in a vacuum chamber, with one RF coupler connected to the AWA X-band metallic PETS, providing short pulses with a peak power of up to 500 MW. The other coupler will be connected to a bidirectional coupler for RF measurements. A Faraday cup and a photo-diode will be used to measure dark currents and light, respectively, emitted in breakdown events.

CONCLUSION

SWFA operating with short pulses needs advanced wakefield structures due to its special RF requirements. A 11.7 GHz wagon wheel MTM structure is designed as an accelerating structure to be used for SWFA in the TBA scheme. The MTM structure is optimized to achieve a gradient of over 300 MV/m, when excited by 500 MW, 3-nanosecond flattop RF pulses from the X-band metallic PETS at AWA. The MTM structure has been fabricated and assembled, and cold test results show good agreement with simulations. A high-power test with breakdown diagnostics is currently being prepared at AWA.

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