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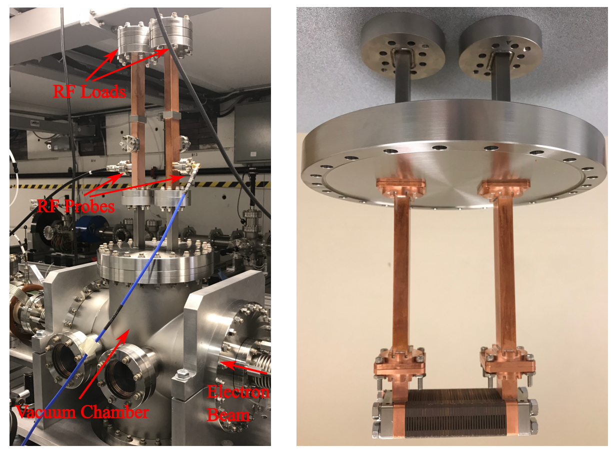
A METAMATERIAL WAGON WHEEL STRUCTURE FOR WAKEFIELD ACCELERATION BY REVERSED CHERENKOV RADIATION

X. Lu*, M. A. Shapiro, I. Mastovsky, R. J. Temkin
Massachusetts Institute of Technology, Cambridge, MA 02139, USA
M. Conde, J. G. Power, J. Shao, E. E. Wisniewski, C. Jing[1]
Argonne National Laboratory, Lemont, IL 60459
[1]also at Euclid Techlabs LLC, Solon, Ohio 44139, USA

Abstract

We present the design and experimental operation on an X-band metamaterial (MTM) 'wagon wheel' structure for wakefield acceleration. The structure was designed and fabricated at MIT, and tested at the Argonne Wakefield Accelerator (AWA) laboratory at Argonne National Lab. The MTM 'wagon wheel' structure is an all-metal periodic structure at 11.4 GHz. The fundamental TM mode has a negative group velocity, so when an electron beam travels through, energy is extracted from the beam by reversed Cherenkov radiation, which was verified in the experiment. Single bunches up to 45 nC were sent through the structure with a beam aperture of 6 mm and generated microwave power up to 25 MW in a 2-ns pulse, in agreement with both the analytical wakefield theory and the numerical CST simulations. Two bunches with a total charge of 85 nC generated 80 MW of microwave power. The structure is scalable to a power extractor of over 1 GW by increasing the structure length from 8 cm to 22 cm.



(a) (b)

Figure 1: Photos of the experiment. (a) Vacuum chamber holding the test structure on the AWA beamline. (b) Suspended MTM structure with the two output ports.

INTRODUCTION

Structure based wakefield acceleration operating at a short microwave pulse length is promising for achieving high accelerating gradient [1–3]. In radiofrequency (RF) accelerators, one limiting factor in raising the gradient is RF breakdown. The breakdown rate (BDR) increases with the accelerating gradient E_a and the RF pulse length t_p as BDR $\propto E_a^{30} \cdot t_p^5$ [4]. So at a certain BDR, the achievable gradient E_a scales as $t_p^{-1/6}$. As a result, operating at short pulses of a few nanoseconds can help push up the accelerating gradient.

Metamaterials (MTMs) refer to a category of periodic structures with novel electromagnetic characteristics, such as negative refractive index. An MTM structure often has a period much smaller than the microwave wavelength, so it can be seen as an artificial medium with the effective ϵ and μ determined by the unit cell design. Some all-metal MTM designs for wakefield acceleration are discussed in Refs. [5, 6]. The advantages of metallic MTMs include great flexibility in the choice of frequency, possibilities to optimize in the huge parameter space of the unit cell design, and resistance to beam damage by the all-metal structure.

MTMs with a negative group velocity are of great interest for novel phenomena like negative refraction. When such MTMs interact with a relativistic beam, reversed Cherenkov radiation (RCR) is generated [6, 7]. Unlike Cherenkov radiation in normal materials where the radiated waves travel forward with respect to the beam, in MTMs with a negative group velocity, the radiated waves travel backward, so the RCR is also called the backward Cherenkov radiation.

The motivation of the 'wagon wheel' MTM structure experiment includes verification of the RCR, and extraction of high power microwaves for two-beam acceleration applications. In this paper, we will present the first successful high power microwave extraction experiment from short and intense electron bunches based on a MTM structure.

EXPERIMENTAL FACILITIES

The MTM structure built by MIT has been tested at the Argonne Wakefield Accelerator (AWA) Facility [1]. Figure 1 (a) shows the vacuum chamber holding the test structure on the AWA 65 MeV beam line. Figure 1 (b) shows the suspended structure with the two X-band waveguides. A 65 MeV bunch travels through the structure, and the generated output power is measured from the two output ports. Power is designed to be extracted from the backward port close to the beam entrance. The other forward port close to the beam exit is set up for comparison to verify the RCR. The output RF signal is measured by an oscilloscope with a bandwidth of 16 GHz and a sampling rate of 50 GS/s.

* xylu@mit.edu

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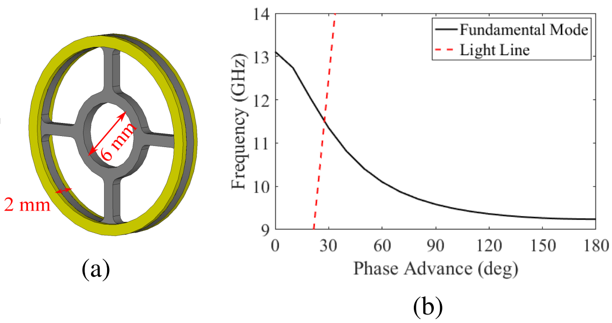

Figure 2: MTM unit cell design. (a) Unit cell geometry. Beam aperture is 6 mm. (b) Dispersion curve of the fundamental mode.

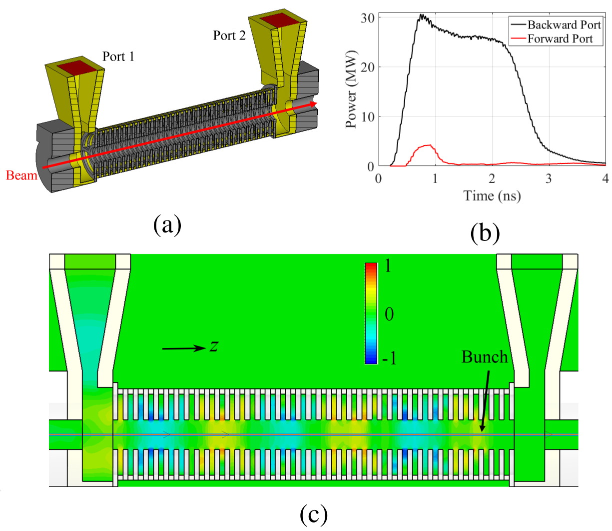

Figure 3: CST simulations. (a) Model of the 40-cell structure. (b) Output power from the two ports in CST Wakefield Solver. (c) Plot of longitudinal electric field in linear scale on the middle plane.

THEORY AND SIMULATIONS

The MTM wagon wheel structure is a periodic structure with the unit cell shown in Fig. 2 (a). The beam aperture is 6 mm, and the structure length L is 8 cm, with 40 unit cells, each 2 mm long. This design has a TM fundamental mode with a negative group velocity $v_g = -0.1583c$, whose dispersion is shown in Fig. 2 (b). The mode interacts with the 65 MeV beam at 11.42 GHz. The RF pulse length $t_p = L/|v_g| + L/c = 2$ ns, and the output power P from an electron bunch with a charge $q = 45$ nC and a longitudinal (z direction) Gaussian distribution of $\sigma_z = 1.5$ mm is given by

$$P = q^2 k_L |v_g| \left(\frac{1}{1 - v_g/c}\right)^2 \Phi^2 = 25 \text{ MW}. \qquad (1)$$

where $k_L = (\omega/4) \cdot (r/Q)$ is the loss factor, r/Q= 21 kΩ/m, and $\Phi = \exp[-(k_z\sigma_z)^2/2]$ is the form factor.

Microwave and wakefield simulations were performed with the CST codes. The CST Particle Studio simulation model is shown in Fig. 3 (a). The beam travels through the beam hole, and the output power is recorded at the two output ports. The power traces are shown in Fig. 3 (b). The simulation result in Fig. 3 (b) agrees with the analytical beam loading theory of Eq. (1). In the two output ports, the backward port (Port 1 in Fig. 3 (a)) has much higher power than the forward port, indicating that the radiated microwaves travel in the backward direction as a result of the RCR. Figure 3 (c) is a longitudinal electric field E_z plot on the middle plane. The beam travels in the $+z$ direction, and leaves the RCR pattern after it. The field structure has a similar bouncing feature as that in a dielectric tube, so the MTM structure is acting as an artificial dielectric tube with all parts made of metal.

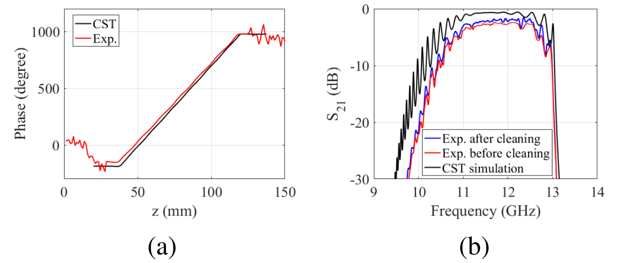

Figure 4: Cold test results of the 40-cell structure in comparison with CST simulations. (a) Phase of the electric field on axis with axial position at 11.4 GHz. (b) Transmission S_{21}.

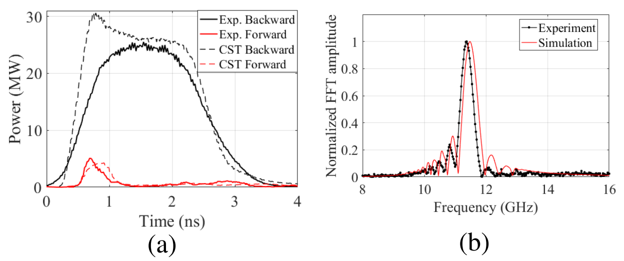

Figure 5: High power test results with a single 45 nC bunch. (a) Output microwave power in the two ports. (b) Frequency spectrum measured and simulated.

EXPERIMENTAL RESULTS

Cold Test

Cold test were performed, and measurement of the electric field phase and transmission (S_{21}) are shown in Fig. 4 (a) and Fig. 4 (b), respectively. The measured phase advance at 11.4 GHz measured agrees very well with the design, so the interaction frequency of the traveling wave with the beam agrees well with the design frequency.

Single Bunch Experiment

Single bunches up to 45 nC were sent through the structure. 25 MW of microwave power was measured mainly in the backward port at 11.4 GHz. Figure 5 shows the power traces in the two output ports, and the frequency spectrum. With the 2 ns pulse length, the bandwidth is $1/t_p = 0.5$ GHz.

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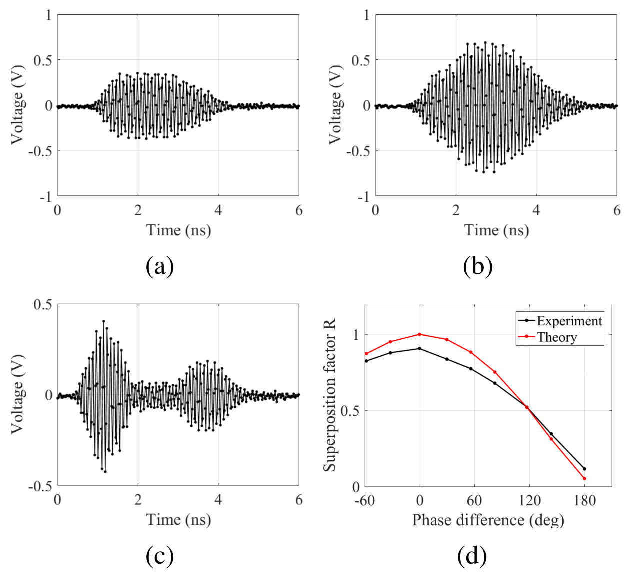

Figure 6: Results from two 4 nC bunches. Voltage signal from (a) a single bunch, (b) two bunches with 0 deg phase difference, (c) two bunches with 180 deg phase difference. (d) Variation of superposition factor R with phase difference.

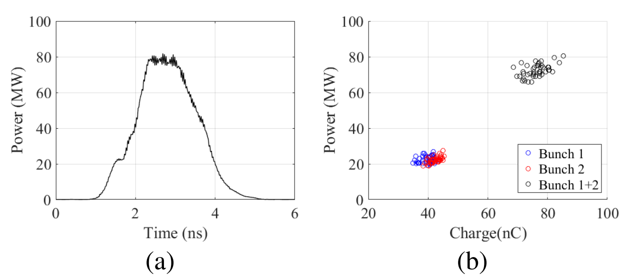

Figure 7: Highest power shot from two bunches with a total charge of 85 nC. (a) Output power in the backward port. (b) Power over charge plot for Bunch 1, Bunch 2, and two bunches together at the same phase.

The experimental power level and the frequency agree very well with the analytical theory and the CST simulations. The backward port has much higher power than the forward port, and this verifies the coherent RCR generation in a MTM structure with a negative group velocity.

Two-Bunch Experiment

From the coherent RCR, the RF signals from two bunches generated by the 1.3 GHz photoinjector can be added up. The voltage from a train of two bunches is $V_t(t) = V_1 \sin(\omega t) + V_2 \sin(\omega t + \xi)$, where ω is the angular frequency of the coherent radiation, V_1, V_2 are the voltage amplitudes from Bunch 1 and Bunch 2 separately, and ξ is the phase difference between the two bunches. We define a superposition factor R as $R = (2V_t/q_t)/(V_1/q_1 + V_2/q_2)$, where q_t is the total charge in the two bunches. When the two bunches have equal charge $q_1 = q_2$, R varies from 0 to 1.

Figure 6 shows the result of a train of two 4 nC bunches. Figure 6 (a), (b) and (c) present the output voltage signal from a single bunch, two bunches with the same phase, and two bunches with the opposite phase, respectively. Figure 6 (d) shows the variation of the defined superposition factor R with the phase difference between the two bunches, where the experiment agrees very well with theory.

The highest power achieved was from two bunches with a total charge of 85 nC, as shown in Fig. 7. The peak power reached 80 MW, and this corresponds to a decelerating gradient of 50 MV/m. The peak surface electric field was estimated as 125 MV/m from CST simulations. No signs of breakdown or damage to the structure have been observed.

CONCLUSIONS

The X-band 'wagon wheel' MTM structure has been tested at the AWA facility. From a single bunch with a charge of 45 nC and a length of $\sigma_z = 1.5$ mm, 25 MW of microwave power at 11.4 GHz has been extracted with a pulse length of 2 ns. The backward port receives much higher power than the forward port, and this proves the RCR in the MTM structure. The experimental results agree very well with the analytical calculation and CST simulations. The highest power from two bunches with a total charge of 85 nC reached 80 MW, and the gradient was 50 MV/m.

A longer version of the structure with $L = 22$ cm saturating on a train of 8 bunches is expected to generate up to 1.2 GW of power with a pulse length of 11 ns, making a strong candidate for structure-based wakefield acceleration.

ACKNOWLEGEMENT

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