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Generation of High-Power, Reversed-Cherenkov Wakefield Radiation in a Metamaterial Structure

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We present the first demonstration of high-power, reversed-Cherenkov wakefield radiation by electron bunches passing through a metamaterial structure. The structure supports a fundamental transverse magnetic mode with a negative group velocity leading to reversed-Cherenkov radiation, which was clearly verified in the experiments. Single 45 nC electron bunches of 65 MeV traversing the structure generated up to 25 MW in 2 ns pulses at 11.4 GHz, in excellent agreement with theory. Two bunches of 85 nC with appropriate temporal spacing generated up to 80 MW by coherent wakefield superposition, the highest rf power that metamaterial structures ever experienced without damage. These results demonstrate the unique features of metamaterial structures that are very attractive for future high-gradient wakefield accelerators, including two-beam and collinear accelerators. Advantages include the high shunt impedance for high-power generation and high-gradient acceleration, the simple and rugged structure, and a large parameter space for optimization.

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Novel accelerator concepts have been proposed and demonstrated in recent years with the goal of identifying attractive designs for future TeV colliders at the high-energy physics frontier [1,2]. Among these novel concepts, wakefield acceleration is a very promising approach for achieving high accelerating gradient up to the GeV/m level [3–16]. Different wakefield drivers, including laser pulses [3–5], electron beams [6–14], positron beams [15], and proton beams [16] have been studied. Among these studies, structure-based wakefield acceleration shows great promise, either in dielectric structures [4–10] or metallic structures [11–13]. Based on these findings, particle colliders up to the tens of TeV level [17–21] and advanced light sources [22,23] have been proposed.

We report results on a unique approach to high-gradient wakefield acceleration, using a metallic metamaterial (MTM) structure. In beam-driven, structure-based wakefield acceleration, a high-charge drive beam travels through a structure in vacuum and transfers its energy as a wakefield into a high-power radiofrequency (rf) pulse. The extracted rf pulse can be used to accelerate a low-charge witness bunch, either in the same structure (collinear wakefield acceleration regime), or in a different structure (two-beam acceleration regime) [1,2]. Compared to rf linear accelerators [24–26], structure-based wakefield acceleration can have a much shorter rf pulse length to achieve a high accelerating gradient. The reason is that one limiting factor in raising the gradient is the phenomenon of rf breakdown, and the breakdown rate goes down with a shorter rf pulse length [27].

A MTM structure has numerous potential advantages for particle-beam driven, wakefield acceleration. First, the MTM structure is inherently a subwavelength interaction space so that the shunt impedance is increased and the generated fields are highly concentrated at the witness bunch [28]. Second, the metallic MTM structure is simple and rugged. Third, the MTM structure with a large parameter space presents a new direction of engineered structures, opening the path to more precise control of the electromagnetic properties. The accelerating performance of an MTM structure can be optimized in various ways such as increasing the group velocity to shorten the pulse length for reduction of rf breakdowns, increasing the shunt impedance to improve the energy efficiency, and suppressing the harmful higher order modes. As a first step to demonstrate the potential of MTM structures for wakefield acceleration, we report here the first results on high-power microwave wakefield generation by a drive bunch in a simple, rugged metamaterial structure, with 80 MW of peak power achieved at 11.4 GHz from a pair of drive bunches.

Metamaterials are subwavelength periodic structures with novel electromagnetic characteristics [29,32]. MTMs can

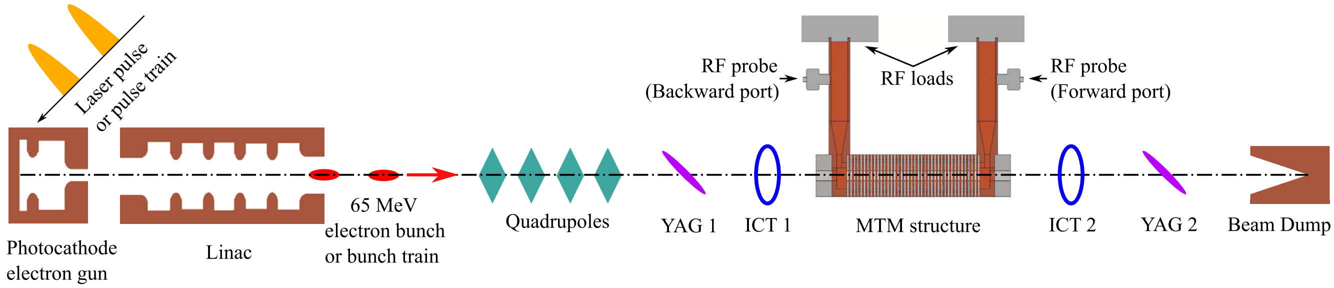

FIG. 1. Schematic diagram of the experimental setup.

have a negative group velocity and emit reversed-Cherenkov radiation [32–39]. Unlike ordinary 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 reversed-Cherenkov radiation is also called backward Cherenkov radiation. The MTM structure was built at MIT and tested at the Argonne Wakefield Accelerator (AWA) Facility [40]. Figure 1 shows the experimental setup with the AWA beam line and the MTM structure inside a vacuum chamber (hidden in Fig. 1). The electron bunch was generated from a laser photocathode gun and accelerated in an L band (1.3 GHz) linac to 65 MeV. With precise spatial beam control from a set of quadrupoles, electron bunches of up to 45 nC per bunch were sent through the 6 mm diameter beam hole of the MTM structure with almost 100% transmission, which was measured by the integrating current transformers (ICTs) before and after the MTM structure. The single drive bunches used in the experiment were 65 MeV and up to 45 nC with an estimated bunch length of $\sigma_z = 1.2$ mm in a Gaussian distribution [11,41]. Electron bunch trains were generated by sending a laser pulse train onto the photocathode with a bunch spacing tuned to the 1.3 GHz linac frequency. The output power generated by the bunches in the structure was measured with calibrated rf probes on the two output ports, namely, the backward port close to the beam entrance and the forward port close to the beam exit. In this setup, the reversed-Cherenkov radiation phenomenon can be directly verified by comparing the power in the two ports. The backward port is expected to get most of the power from the reversed-Cherenkov radiation.

The MTM structure is an 8-cm long structure of stainless steel plates with a “wagon wheel” design alternating with copper spacer plates, as shown in Fig. 2. The structure is clamped with 40 periods with a period length $p = 2$ mm, much shorter than the wavelength at 11.4 GHz of 26 mm. The fundamental mode in the structure is a transverse magnetic (TM) mode with a negative group velocity $v_g = -0.158\ c$, whose dispersion is shown in Fig. 3. The TM mode dispersion curve intersects the 65 MeV beam line at 11.42 GHz. This frequency is below the cutoff frequency (14.2 GHz) for the TM_{01} mode of an empty circular waveguide with the same outer diameter of 16 mm. The below-cutoff operation results in a negative permeability [42]. The wagon wheel design provides a negative permittivity for frequencies near 11.4 GHz, allowing a propagating wave with a negative refractive index with both the permeability and the permittivity negative. The double-negative feature is characteristic of MTMs, and the details are explained in Supplemental Material [28]. The dispersion with the negative group velocity has been verified in experiment by a bead pull test, shown as the cold test in Fig. 3.

The wakefield radiation excited in the MTM structure by an electron beam is plotted in Fig. 4. In a two-beam accelerator, this radiation would be extracted at the backward port to power a witness bunch in an adjacent accelerator beam line. In a collinear wakefield accelerator, the high-gradient accelerating field available to a witness bunch trailing the drive bunch can be seen in Fig. 4 as the blue region of the electric field. A trailing witness bunch would be positioned in the blue region to be accelerated at a high gradient. Though the group velocity of the mode is in the backward direction, the phase velocity matches the velocity of the relativistic beam.

The rf pulse length t_p of the wakefield propagating in the backward direction is

$$t_p = L/|v_g| + L/c = 2\ \text{ns}. \tag{1}$$

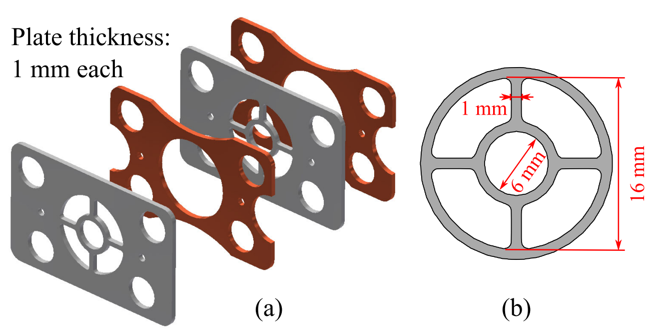

FIG. 2. MTM structure design. (a) Alternating wagon wheel plates and spacer plates. Forty plates of each type are clamped together to form an 8 cm long structure. (b) Wagon wheel plate geometry.

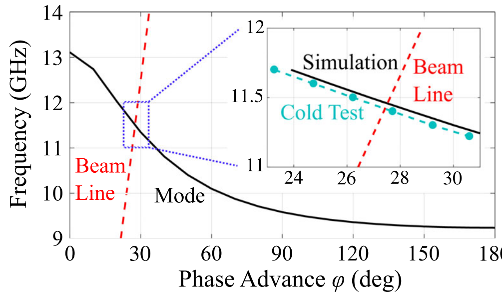

FIG. 3. Dispersion curve of the fundamental transverse magnetic mode intersecting with the beam line $\omega = k_z v_z$ at 11.42 GHz, where k_z is the longitudinal wave number, and v_z is the beam longitudinal velocity. The horizontal axis represents the phase advance per period as $\phi = k_z p$, where $p = 2$ mm is the period. A bead pull measurement was done around the design frequency, as shown in the blow-up figure along with the simulation result.

When a single electron bunch with a charge of q travels through the structure, the output power P can be calculated analytically as [24]

$$P = q^2 k_L |v_g| \left(\frac{1}{1 - v_g/c}\right)^2 \Phi^2, \tag{2}$$

where $k_L = (\omega/4)(r/Q)$ is the loss factor, $\Phi = \exp[-(k_z\sigma_z)^2/2] = 0.96$ is the form factor, which is high due to the short bunch length, the shunt impedance per unit length over the quality factor is $r/Q = 21\ \mathrm{k\Omega/m}$ for our structure, and the group velocity v_g can be obtained from the wave dispersion (Fig. 3). Our value of r/Q is higher compared to some other structures with a forward traveling wave at about the same frequency [11,12], while maintaining a high group velocity, showing another advantage of the subwavelength design. A detailed comparison is presented in Supplemental Material [28].

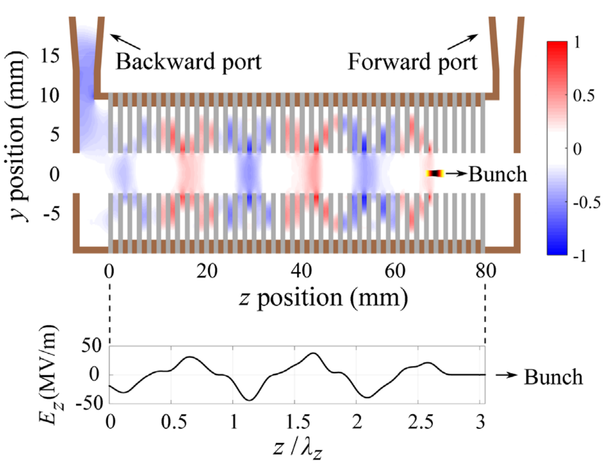

FIG. 4. Plot of the longitudinal electric field E_z. The two-dimensional field plot on the top shows the normalized E_z field on the middle plane in the linear scale. The MTM structure is represented in grey. The one-dimensional plot on the bottom shows the E_z field on the beam axis for a single 45 nC bunch. The distance is normalized to the longitudinal wavelength λ_z. In both figures, the electron bunch travels to the right. The peak accelerating field available to a trailing bunch (in the blue region) is 43 MV/m.

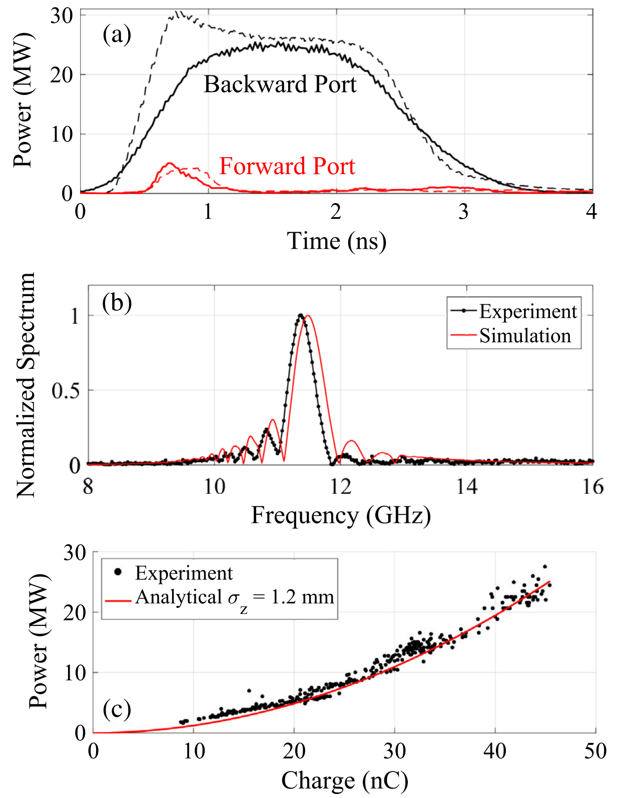

FIG. 5. High-power microwave extraction from a single bunch. (a) Output microwave power in the two ports from a single 45 nC bunch. Solid lines: experiment, dashed lines: CST simulations. (b) Frequency spectrum. (c) Comparison of experiment and analytical theory of the extracted microwave power as a function of the transmitted charge.

The measured output power from the two output ports in the beam test is presented in Fig. 5(a). 25 MW of power was generated by the 45 nC bunch, in good agreement with the CST particle-in-cell (PIC) simulation and the analytical calculation in Eq. (2). Between the two output ports, the backward port has much higher power than the forward port, indicating that the radiated microwaves indeed travel in the backward direction. Therefore, this experiment provides a clear proof of the reversed-Cherenkov radiation generation in an MTM structure with a negative group velocity. Figure 5(b) shows good agreement between the measured frequency spectrum and the PIC simulation, with a central frequency of 11.4 GHz and a bandwidth $\mathrm{BW} = 1/t_p = 0.5$ GHz.

A scaling study of the extracted microwave power with the charge q was carried out and is shown in

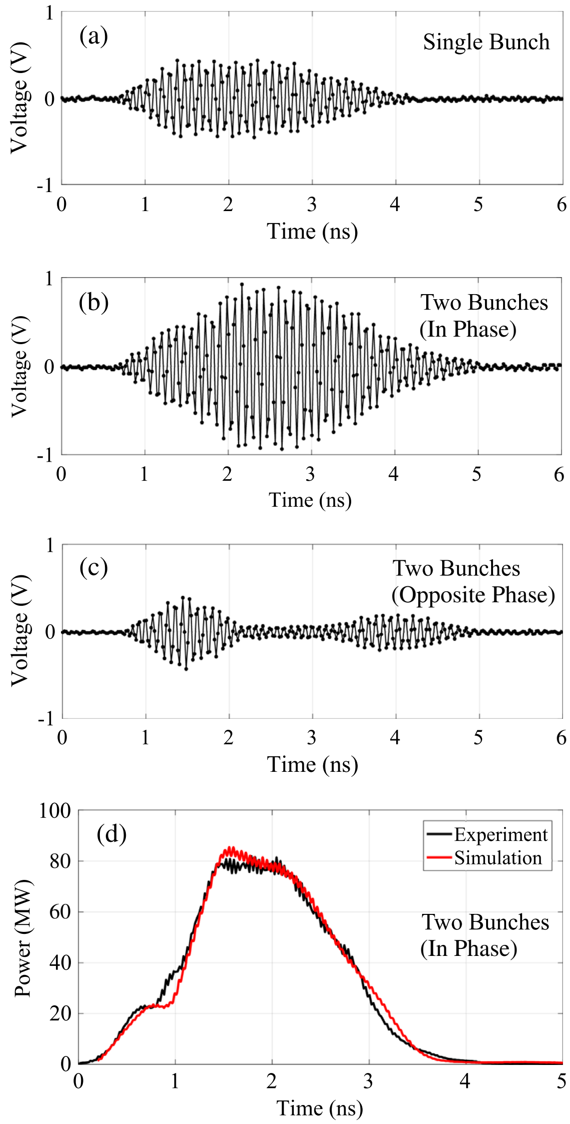

FIG. 6. Experimental measurements of backward power with two bunches. Voltage signal from (a) a single bunch, (b) two bunches with 0 deg phase difference, (c) two bunches with 180 deg phase difference. (d) Highest rf power from two bunches in phase with a total charge of 85 nC in perfect agreement with the CST PIC simulation.

Fig. 5(c). The good agreement with the analytical theory indicates that the structure operation is very reliable, without evidence of the beam breakup instability [43].

The laser photocathode can generate two or more bunches separated at the 1.3 GHz frequency with laser splitters that provide precise control of the spacing between bunches. The wakefield radiation from these bunches can add or cancel, depending on the exact spacing of the bunches. Figure 6 compares the results of a single bunch with a train of two bunches. Figures 6(a)–6(c) present the output voltage signal from a single bunch, two bunches with the same phase, and two bunches with the opposite phase, respectively. The highest power achieved in the experiment was from two bunches radiating in phase with a total charge of 85 nC. The peak power reached 80 MW, with the waveform shown in Fig. 6(d). In the present experiment, this power was extracted and it thus represents the power that would be available in a two-beam accelerator configuration. Alternatively, if this power were applied to a trailing witness bunch in a collinear wakefield accelerator, it would provide an accelerating gradient of 75 MV/m. The peak surface electric field was estimated as 130 MV/m from CST simulations. No breakdown or multipactor events were observed in the experiment, possibly due to the pulse length of 2 ns. A visual inspection and a cold test of the structure after completion of the high-power tests showed no evidence of damage.

In conclusion, the experimental results of the X-band wagon wheel MTM structure are presented in this paper. The experiment provides direct evidence of the reversed-Cherenkov radiation from a short and relativistic electron bunch in a MTM structure. We have also demonstrated that the MTM structure is a promising power extractor design for wakefield acceleration with good reliability and simple fabrication. From a single bunch with a charge of 45 nC and a length of $\sigma_z = 1.2$ mm, 25 MW of microwave power at 11.4 GHz has been extracted with a pulse length of 2 ns. 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 a peak power of 80 MW. The available gradient for a witness bunch was 75 MV/m. Our calculations indicate that a longer version of the structure with $L =$ 22 cm saturating on a train of eight bunches would generate up to 1.2 GW of power with a pulse length of 11 ns. The available gradient for a witness bunch would be about 300 MV/m, making a strong candidate for structure-based wakefield acceleration. Such a future experiment would be possible at the AWA.

One advantage is that the MTM structure allows great flexibility. If the structure is to be applied for two-beam acceleration as the accelerator structure, the beam aperture can be smaller to raise the shunt impedance for higher accelerating gradient. At the same time, dispersion engineering in the huge parameter space of the unit cell geometry makes the MTM structure easily scalable with frequency. These features are also advantageous for collinear wakefield acceleration. If the MTM structure were scaled to a much higher frequency and excited with a GeV electron beam, which can be focused to a much smaller transverse size, the output power defined in Eq. (2) would scale with the frequency f as f^2, and the gradient as f, leading to a much higher extracted wakefield power and a much higher gradient for a witness bunch, comparable or greater than the results from some existing THz wakefield experiments.

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