Coherent High-Power RF Wakefield Generation by Electron Bunch Trains in a Metamaterial Structure

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We present an experimental study of coherent high-power wakefield generation in a metamaterial (MTM) structure at 11.7 GHz by 65 MeV electron bunch trains at the Argonne Wakefield Accelerator (AWA), following a previous experiment, the Stage-I experiment, at AWA. Both the Stage-II experiment, reported in this paper, and the Stage-I experiment were conducted using MTM structures, which are all-metal periodic structures with the period much smaller than the wavelength. Differences between the two experiments include: (1) Structure length (Stage-I 8 cm, Stage-II 20 cm); (2) Number of bunches used to excite the structure (Stage-I with 2 bunches, up to 85 nC of total charge; Stage-II with 8 bunches, up to 224 nC of total charge); (3) Highest peak power measured (Stage-I 80 MW in a 2 ns pulse, Stage-II 380 MW in a 10 ns pulse). The high-power radiofrequency (RF) pulses were generated by reversed Cherenkov radiation of the electron beam due to the negative group velocity in the MTM structures. Because the radiation is coherent, a train of bunches with a proper spacing can build up to achieve a high peak power. The observed output power levels are very promising for future applications in direct collinear wakefield acceleration or in transfer to a second accelerator for two beam acceleration.

Metamaterial (MTM) structures at microwave frequencies have been demonstrated as promising candidates in generating high-power electromagnetic microwaves[1–8]. We previously applied an MTM structure to an advanced accelerator concept, structure-based wakefield acceleration (SWFA), in an experiment carried out at the Argonne Wakefield Accelerator (AWA), referred to as the Stage-I experiment[1]. In this paper, we present the second experiment, the Stage-II experiment, with a modified MTM structure for higher peak power microwave generation.

An MTM structure, typically a periodic structure with a carefully tailored unit cell whose size is much smaller than the operating wavelength, can often be characterized as a continuous medium with an effective permittivity and an effective permeability. The group of MTM structures with the permittivity and the permeability simultaneously negative, i.e. double-negative MTMs, are of special interest in applications like perfect lenses, microwave cloaking and antenna designs[9,10]. When a double-negative MTM is excited by a moving charged particle beam, electromagnetic radiation happens in the form of reversed Cherenkov radiation, where the group velocity and the phase velocity of the microwave beam are in opposite directions[1,11–13]. This phenomenon is advantageous to the generation of intense microwave pulses as a result of an enhanced beam-wave interaction.

SWFA is a promising accelerator concept [14–20] for achieving higher microwave power and higher accelerating gradient compared to conventional radiofrequency (RF) linear accelerators. The operating gradient of RF accelerators powered by klystrons is often limited by the RF breakdown rate[20–23], which could be reduced by driving the accelerators with a shorter RF pulse[24]. In SWFA with short RF pulses of only a few nanoseconds long, common initiators of RF breakdown events, such as field emission or multipactor, do not have enough time to fully develop; as a result, RF breakdowns can be suppressed to increase the accelerating gradient.

In SWFA, a high charge drive beam travels through an RF structure in vacuum and excites a strong wakefield behind it. The generated wakefield could be applied towards a trailing witness beam in the same RF structure, as in the collinear acceleration scheme, or guided to another RF structure where a separate witness beam travels, as in the two-beam acceleration scheme. In both acceleration schemes, a power extractor with a high shunt impedance to generate high power RF pulses from a drive beam is needed. In the Stage-I experiment, we have demonstrated an MTM structure, the 'wagon wheel' structure, as a high power, metallic extractor for a practical wakefield acceleration system. The goal of the Stage-II experiment is to further improve the peak power and the gradient by adding more bunches to the train.

Both the Stage-I and Stage-II MTM structures have a similar 'wagon wheel' unit cell, while the Stage-II structure has more periods and a slightly different interaction frequency compared to the Stage-I structure. Figure 1 (a) shows the stacked periodic structure comprised of the 'wagon wheel' plates in stainless steel and the spacer plates in copper, with each plate 1 mm thick. The dimensions are shown in Fig. 1 (b). The length of one period (one 'wagon wheel' plate and one copper plate) $p = 2$ mm is much smaller than the wavelength, so the electron beam traveling through the structure does not see the individual plates, but rather a quasi-homogeneous medium. Stainless steel was used in the 'wagon wheel' plates for its good mechanical strength

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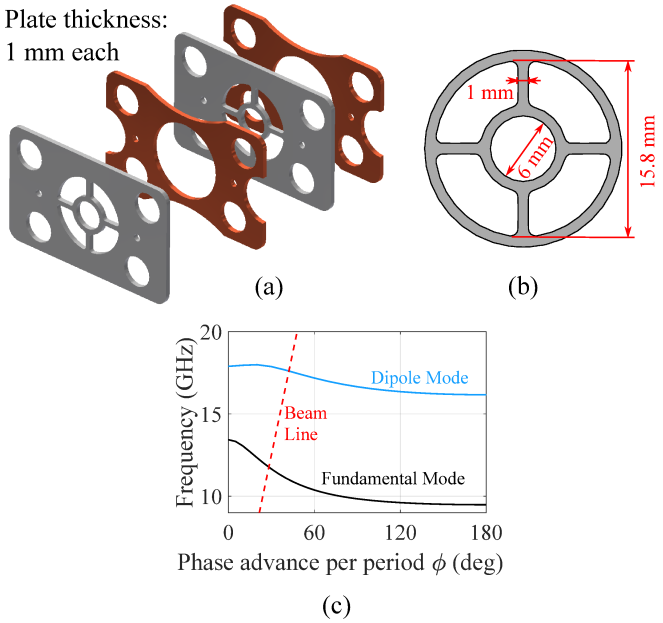

FIG. 1. Stage-II MTM structure design. (a) Periodic stacks of the 'wagon wheel' plates in stainless steel and the spacer plates in copper. (b) Wagon wheel design with dimensions. (c) Dispersion relation between the mode frequency $f = \omega/(2\pi)$ and the phase advance per period $\phi = k_z p$ for the fundamental mode (operating mode) and the dipole mode in the Stage-II structure. Here k_z is the longitudinal wave number, and p is the structure period. The relativistic beam line $\omega = k_z v_z \approx k_z c$ (where v_z is the longitudinal velocity of the 65 MeV electron beam traveling in the $+z$ direction) intersects the fundamental mode dispersion at 11.7 GHz and the dipole mode dispersion at 17.5 GHz.

to fabricate the small features, and copper was used in the spacer plates for the low transmission loss. Such a design creates a fundamental MTM mode whose dispersion diagram from CST[25] Microwave Studio (MWS) simulations is shown in Fig. 1 (b). The fundamental mode is a transverse magnetic (TM) mode[26], which provides a longitudinal electric field E_z (with the electron beam traveling in the $+z$ direction) to interact with the beam at 11.7 GHz. The group velocity $v_g \equiv \partial\omega/\partial k_z$ is $-0.154\ c$ at the design frequency, where ω is the mode angular frequency, k_z is the longitudinal wave number, and c is the speed of light. The negative group velocity is made possible by the 'wagon wheel' design, in which the below-cutoff beam pipe with an outer diameter of 15.8 mm provides a negative effective permeability, and the wheel spokes provide a negative effective permittivity. The 'wagon wheel' geometry is not the only MTM design with this feature; it is the result of optimization for a strong beam-wave interaction, which can be characterized by the quantity r/Q, where r is the shunt impedance per unit length of a structure, and Q is the quality factor[27]. The structure beam aperture was set to 6 mm as the result of a trade-off between a high r/Q value (small aperture preferred[19,28]) and a high charge transmission (large aperture preferred). The calculated r/Q value is 20.8 kΩ/m for the fundamental mode. The dipole mode at 17.5 GHz was also observed in the experiment, as will be discussed later in the paper.

Forty periods of the 'wagon wheel' unit cells formed the 8 cm long Stage-I structure, which was excited by both single bunches and 2-bunch trains with a repetition rate around 1.3 GHz. In the Stage-I experiment, a single 45 nC bunch with a Gaussian root-mean-square (rms) length of $\sigma_z = 1.1$ mm generated 25 MW of coherent radiation at 11.4 GHz in 2 ns pulses. A train of two bunches with 85 nC of total charge generated a peak RF power of 80 MW from coherent addition, and this corresponds to a decelerating gradient of 50 MV/m on the second bunch in the train.

The Stage-II structure has 100 periods with a total length of 20 cm and it was excited with a train of up to eight bunches. A longer structure is needed to increase the peak power level because for the coherent wakefield pulses from multiple bunches to overlap with each other, the RF pulse length from a single bunch t_p needs to be longer than the multi-bunch train duration[29]. In a structure with a length L and a group velocity v_g ($v_g < 0$), t_p is determined by

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

For the 8 cm long Stage-I structure, $t_p = 2$ ns is only long enough for a train of three bunches to add coherently on top of each other, and this means that the extracted RF pulse would saturate in its power level with three bunches. To achieve a higher peak RF power from a train of eight bunches, the longer Stage-II structure was designed and built.

Both experiments were performed at the AWA facility, which is capable of generating a train of intense and short relativistic electron bunches in the 65 MeV drive beam line. The AWA beam line is advantageous for demonstrating high power wakefield extraction as the drive beam is short while carrying a high charge. The bunch rms length σ_z is much shorter than the X-band wavelength, so the Gaussian form factor Φ is very close to 1, as $\Phi = \exp[-(k_z\sigma_z)^2/2] = 0.96$; this indicates that short bunches are helpful for generating high-power beam-driven wakefield radiation in RF structures.

The experimental layout of the AWA beam line with the Stage-II structure installed is shown in Fig. 2. Laser pulse trains are generated by beam splitters and delay stages, and the delay stages can be tuned to achieve a phase accuracy of within 1 degree in the L-band[19]. The electron bunch trains are then emitted from a photocathode electron gun and accelerated to 65 MeV in the L-band linacs. The Stage-II structure was designed at the frequency of the 9$^{\text{th}}$ harmonic of the nominal bunch repetition rate of 1.3 GHz. Various beam optical components including quadrupoles were commissioned for a good beam transport to the vacuum chamber which held the MTM structure. The MTM structure was suspended by two X-band waveguides which directed the generated RF pulses to the RF probes for power measurement and finally into the RF loads. The two RF probes measured the backward-going power and the forward-going power, for a direct verification of the reversed Cherenkov radiation. The backward port was expected to receive much higher power compared to the forward port in the MTM experiments. The port signals were measured by a fast oscilloscope with a bandwidth of 23 GHz. There were also beam diagnostics both

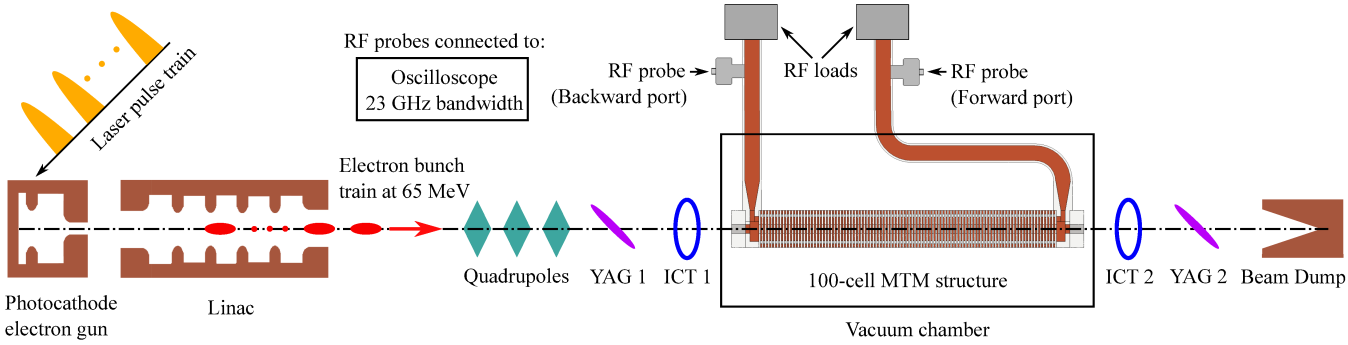

FIG. 2. Schematic diagram of the experimental facilities for the 100-cell MTM structure driven by electron bunch trains at AWA.

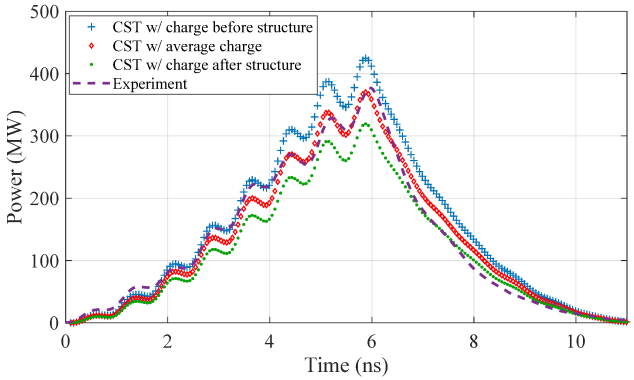

FIG. 3. Measured and simulated microwave power from 8 bunches with a total charge of 224 nC before the structure and 194 nC after the structure (beam transmission 86.5%). The experimental measurement is in black, and the three other curves are from CST Particle Studio simulations in which the 'effective charge' contributing to the extracted wakefield is the charge before the structure, the charge after the structure and the average of the two, respectively. CST simulations assumed equal charge in all the bunches, while in experiment, the missing charge happened mostly in later bunches; this caused the small discrepancy in the extracted power between experiment and simulations for the first few bunches.

before and after the structure including yttrium aluminum garnet (YAG) screens to measure the transverse beam profiles and integrating current transformers (ICTs) to measure the total charge before the structure and the transmitted charge after the structure.

The highest charge in a train of eight bunches that was sent through the 6 mm beam aperture was 224 nC in total before the structure and 194 nC in total after the structure. The beam transmission was thus 86.5% for the 8-bunch train; however, when we sent only a single bunch with 224 nC$/8 =$ 28 nC to the structure the beam transmission was almost 100%. In the 8-bunch train, the charge was almost equal in individual bunches at the electron gun, while the missing charge after the structure happened mostly in later bunches of the train because they experienced a stronger wakefield from the previous bunches passing through the structure.

The extracted RF pulse in the backward port measured in the experiment is shown as the black curve in Fig. 3. The peak power in the backward port reached about 380 MW after the 8$^{\text{th}}$ bunch entered the structure, while the forward port received a much lower power of less than 10 MW, consistent with the reversed Cherenkov radiation going to the backward port in the MTM structure. In the shown pulse, the peak decelerating electric field reached 110 MV/m on the last bunch. The short pulse length of 10 ns is favorable to suppress RF breakdowns.

Beam simulations were performed in the CST Particle Studio using the particle-in-cell (PIC) solver. Since beam loss happened between the entrance and the exit of the structure, the part of the beam which failed to pass through the complete structure still radiated into the wakefield. Therefore, the 'effective charge' which contributed to the radiated wakefield is bounded between the total charge of 224 nC and the transmitted charge of 194 nC. In the simulations, we examined three different cases in which the 'effective charge' is the total charge before the structure (224 nC), the total charge after the structure (194 nC), and the average of the two (209 nC), respectively, as shown in Fig 3. A set of CST simulations where small beam misalignments are introduced predicts that the charge depletion happens in the later bunches of the train near the exiting end of the structure. Another possible uncertainty comes from the RF transmission loss. The transmission loss from one output port to the other through the 100-cell MTM structure was measured 2 dB lower in a separate low-power test in air compared to CST MWS simulations. This would lead to a 2 dB uncertainty in the estimated power if the generated power always propagated the full length of the structure. However, the wakefield generated by the traveling beam radiates backwards and passes through a varying number of cells from 1 cell to the full 100 cells. Including this variation in loss with path length results in an uncertainty of about 1 dB in the estimated peak power from a train of eight bunches.

The peak power is expected to scale with the total charge q as q^2 (when the beam transmission is 100%), and the scaling law has been verified experimentally, as presented in Fig. 4, in good agreement with the theoretical prediction. The larger variation of the peak power at high charge values is due to the

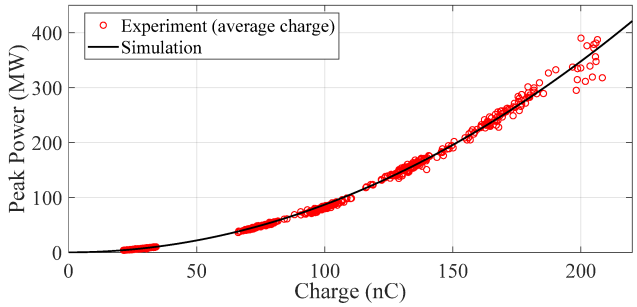

FIG. 4. Scaling of the extracted peak rf power in the backward port from 8-bunch trains in the Stage-II structure with the average of the charge before and after the structure (the 'effective charge'). The beam transmission is above 85% for all the presented experimental data.

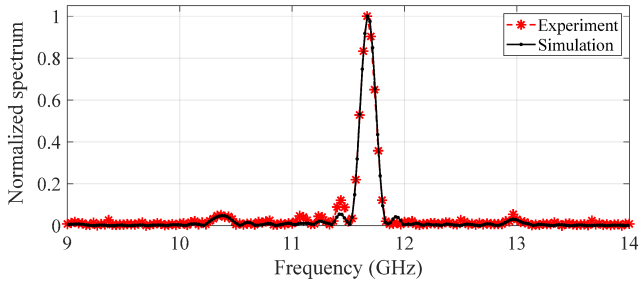

FIG. 5. Frequency spectrum of the Stage-II structure driven by a train of 8 bunches. The interaction frequency with the drive beam is 11.7 GHz, while there are two tiny peaks at 10.4 GHz and 13.0 GHz corresponding to the RF frequency minus or plus the 1.3 GHz bunch repetition rate.

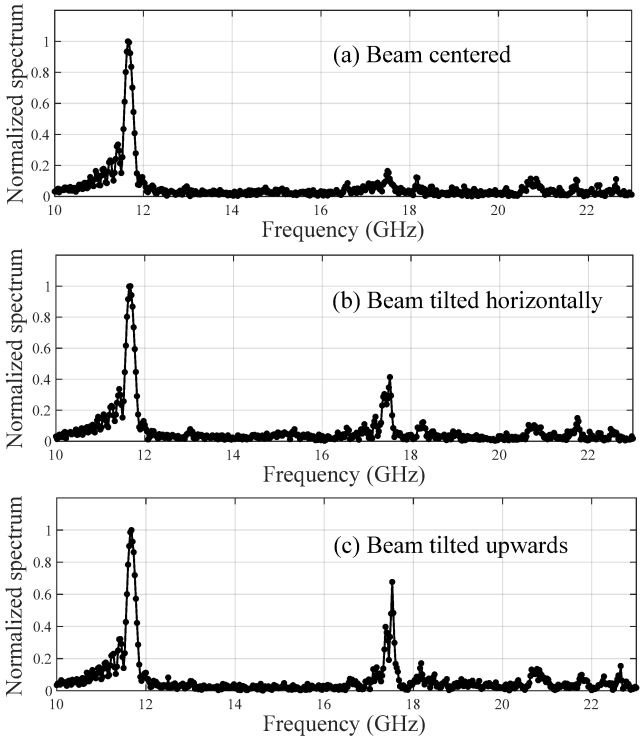

FIG. 6. Frequency spectra with the dipole mode observed at 17.5 GHz at the backward port when the Stage-II structure was excited by single bunches centered or tilted. The beam was (a) centered on axis with 100% charge transmission, (b) tilted horizontally with 80% charge transmission, (c) tilted upwards with 78% charge transmission.

fact that the beam transmission has a large variation for such high values of the charge.

Figure 5 shows the normalized frequency spectrum of the RF pulse measured by the fast oscilloscope at the backward port when the Stage-II structure was excited by an 8-bunch train. The spectrum showing a coherent radiation signal which peaks at 11.7 GHz agrees well with the CST PIC simulation results. The two small bumps in the spectrum around 10.3 GHz and 13.0 GHz are present in both the experiment and the simulation due to the modulation of the 11.7 GHz signal and the 1.3 GHz repetition rate of the electron bunches.

With the 23 GHz bandwidth oscilloscope, we were able to detect the dipole mode, which can interact with an off-axis beam at 17.5 GHz. Note that the X-band waveguide (WR90) is only single-moded below 13.1 GHz, which is the cutoff frequency of the second lowest mode in the waveguide; as a result, the RF probes could not be accurately calibrated to measure the absolute power level above 13.1 GHz. In the experiment, we observed the dipole mode by comparing its relative amplitude with the beam entering the structure at different angles. Figure 6 shows the frequency spectra measured at the backward port when a single bunch was manipulated by trim magnets to be centered on-axis, tilted horizontally and tilted upwards, respectively. The asymmetry between the horizontal and vertical tilting stems from the vertical power coupling waveguide system. As a result, the dipole mode was stronger when the beam was tilted upwards than horizontally with similar tilting angles (indicated by similar beam transmission rates). Dipole modes can potentially lead to unwanted beam break-up instabilities in structure-based acceleration[30,31]. Future work is planned to suppress the dipole mode by modifications to the design of the structure and the couplers. The large parameter space in MTM structure designs provides flexibility for addressing the dipole modes.

The 'wagon wheel' structure when excited by a train of electron bunches has been demonstrated as a promising power extractor. The current design with the bunch-train operation is more favorable to the two-beam acceleration scheme. When the 'wagon wheel' structure is applied to the collinear acceleration regime, the transformer ratio and the acceleration efficiency of a witness bunch could be improved by the ramped bunch train technique[32,33], the detuned cavity design[34], or by shaping a single-bunch drive beam[18].

To conclude, the Stage-II 'wagon wheel' MTM structure with 100 periods has been tested at the 65 MeV AWA drive beam line. Intense coherent wakefield radiation at 11.7 GHz was generated by the mechanism of reversed Cherenkov

radiation, which was directly verified in the experiment. The 20 cm long Stage-II structure was excited by 8-bunch trains with a total charge of up to 224 nC before the structure and 194 nC after the structure. The highest peak power in 10 ns long pulses reached 380 MW, corresponding to a peak decelerating electric field of 110 MV/m on the 8th bunch. This is by far the highest RF power that MTM structures have generated. The approach of using metamaterial structures to generate high power wakefield RF radiation demonstrated at AWA can be adapted to other beam-driven facilities with different beam parameters. For example, the 'wagon wheel' structure can be scaled to higher frequencies for a higher energy drive beam to further enhance beam-wave interaction.

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Data Availability

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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