

A W-BAND CORRUGATED WAVEGUIDE FOR HIGH-EFFICIENCY HIGH-GRADIENT WAKEFIELD ACCELERATION

B. Leung¹, A. Ody², C. Phillips¹, C. Whiteford², D. Mihalcea¹, E. Wisniewski², G. Chen², G. Ha¹, O. Ramachandran¹, J. Power², P. Piot², S. Doran², W. Liu², X. Lu^{1,2}

¹Department of Physics, Northern Illinois University, DeKalb, IL, USA

²Argonne National Laboratory, Lemont, IL, USA

Abstract

Radiofrequency (RF) structures in the sub-terahertz regime are promising for structure wakefield acceleration due to their ability in achieving high gradients in a reduced footprint. We report on the design, fabrication, and testing of a metallic corrugated waveguide operating at 110 GHz, tailored to the 45 MeV electron beam parameters at the Argonne Wakefield Accelerator (AWA). The experiment utilized the emittance exchange (EEX) beamline at AWA for longitudinal bunch shaping in two configurations: (1) a single short drive bunch to demonstrate high decelerating gradients, and (2) a two-bunch scheme featuring a triangularly shaped drive bunch followed by a long witness bunch to probe the wakefield and achieve a high transformer ratio. We present the experimental design and results, which show good agreement with simulation predictions.

INTRODUCTION

Collinear wakefield acceleration (CWA) is one of the two schemes in structure wakefield acceleration (SWFA). In this approach, a high-charge drive bunch and a trailing, lower-charge witness bunch are sent through the same structure. The wakefield generated by the drive bunch is used to accelerate the witness bunch. The transformer ratio (TR)—defined as the accelerating gradient experienced by the witness bunch divided by the decelerating gradient experienced by the drive bunch—quantifies how efficiently energy is transferred from the drive to the witness. Longitudinally symmetric bunches (e.g., Gaussian) have a theoretical upper limit of 2 for the TR. This limitation can be exceeded using longitudinal bunch shaping techniques [1–3].

Various longitudinal distributions, such as the triangular and doorstep profiles, have been shown to yield TRs greater than 2 [4]. Sending such shaped drive bunches through dielectric structures has demonstrated high-gradient, high-efficiency acceleration [5], and the feasibility of achieving similar performance in metallic structures has also been demonstrated [6].

CWA is particularly attractive in the sub-terahertz (THz) regime due to the high shunt impedance resulting from frequency scaling, which enables high gradients at lower drive bunch charges, especially with shaped bunches. Moreover, RF pulses in this regime are confined to short durations, allowing efficient acceleration. The combination of short pulse length and high frequency can also reduce the RF breakdown probability of the structure [7, 8].

Our objective in this work was to design, fabricate, and test a metallic W-band corrugated waveguide operating at 110 GHz at the Argonne Wakefield Accelerator (AWA), using the 45 MeV electron beam under various bunch shaping configurations. The electron beam is generated by an L-band photocathode RF gun and accelerated in a linac. It then passes through an optional transverse mask before entering the emittance exchange (EEX) beamline for bunch shaping [9]. The EEX beamline consists of two dipole magnet pairs sandwiching a transverse deflecting cavity, enabling exchange between the beam's horizontal and longitudinal phase spaces.

We utilized the EEX for two primary purposes: (1) to generate short drive bunches for demonstrating high-gradient wakefield excitation, and (2) to generate two-bunch trains—comprising a longitudinally shaped drive bunch and a delayed witness bunch—to demonstrate wakefield acceleration with a high transformer ratio (TR). In the single-bunch case, the EEX was used without a mask to produce a high-charge, short electron bunch with a high peak current. In the two-bunch case, a triangular-shaped mask was inserted to produce a longitudinally triangular drive bunch followed by a long witness bunch, allowing the demonstration of a high TR.

In both configurations, the beam was sent through the W-band corrugated structure. Wakefield measurements were performed using a single-shot longitudinal phase space (LPS) diagnostic system at the end of the beamline, comprising a transverse deflecting cavity and a spectrometer. A schematic layout of the EEX beamline at AWA is shown in Fig. 1.

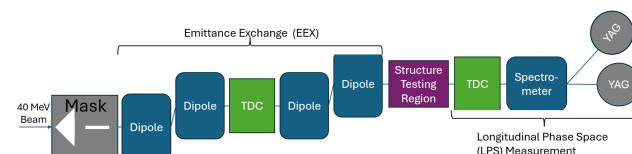


Figure 1: The beamline layout of the emittance exchange (EEX) beamline at the AWA facility. When a transverse mask is placed in the beam path, the EEX beamline can be utilized to create a longitudinally shaped drive bunch. A longitudinal phase space (LPS) measurement system, which includes a transverse deflecting cavity and a dipole magnet, is at the end of the beamline.

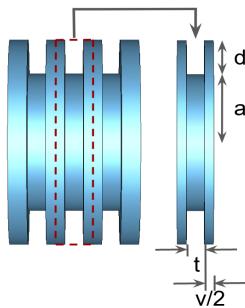


Figure 2: The position of a unit cell (right) in a set of cells outlined (left).

Table 1: Design Parameters of the Unit Cell

Aperture radius (a)	1.016 mm
Corrugation depth (d)	0.5 mm
Plate thickness 1 (t)	0.254 mm
Plate thickness 2 (v)	0.254 mm
Frequency (f)	110.2 GHz
r/Q	36.5 kΩ/m
Group Velocity (v_g)	0.261 c

STRUCTURE AND BEAMLINE SIMULATIONS

A copper corrugated waveguide was designed to operate at 110 GHz, providing high gradient, low RF loss, and sufficient aperture for transmitting a nominal 10 nC, 45 MeV electron bunch at AWA. Particle-in-cell (PIC) simulations were performed to study the wakefield driven by a shaped bunch and compare it to a Gaussian bunch. Beamline simulations were then used to identify suitable parameters for demonstrating high gradients in the single-bunch case and a high transformer ratio in the two-bunch case.

The unit cell design of the sub-THz structure and its final parameters are shown in Fig. 2 and Table 1, respectively. The full structure consists of 80 unit cells, along with two matching cells and beam pipes at both ends. CST Microwave Studio simulations confirmed a passband centered around the operating frequency of 110 GHz.

Next, we simulated the structure using the PIC solver in CST. A 45 MeV triangular bunch with a charge of 2.1 nC and a Gaussian bunch of equal charge and energy were also compared in simulations. Figure 3 shows the resulting field profiles for both the symmetric and asymmetric bunch profiles. The triangular bunch achieved a TR of 6.6, demonstrating significantly higher efficiency for wakefield acceleration than the Gaussian case.

To generate the desired beam profiles, we then performed beam dynamics simulations using IMPACT-T [10]. We optimized the beamline for the two cases to maximize the achievable decelerating gradient in the single-bunch case and maximize the TR in the two-bunch case [11].

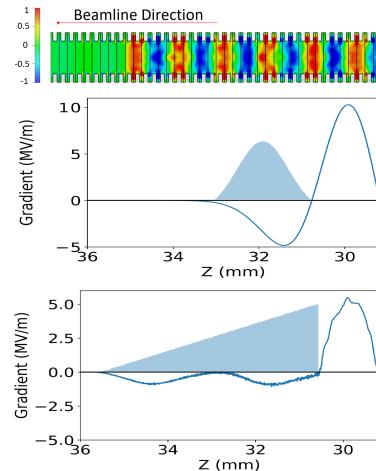


Figure 3: Simulations comparing a triangular distribution with a Gaussian bunch of the same charge and energy. The E_z field plot for the triangular distribution (top) is shown, along with plots of the accelerating gradient on axis for the Gaussian bunch (middle) and the triangular distribution (bottom). Here Z indicates the distance into the structure, not counting the beam pipe.

EXPERIMENTAL SETUP AND RESULTS

Structure Fabrication and Installation

The copper plates forming the corrugated waveguide were initially manufactured via laser cutting, with two small holes machined for alignment rods to ensure minimal offset between plates. The plates were then stacked to form the full 80-cell structure. The fully assembled and clamped structure, secured in its mount, is shown in Fig. 4.



Figure 4: The fully assembled 80-cell clamped structure.

Single-Bunch Case

In the single-bunch case, short electron bunches with a charge of approximately 10 nC achieved over 50% transmission through the sub-THz structure. An average maximum energy loss of about 2.2 MeV was observed in the drive bunch, attributed to the excited wakefield. Figure 5 shows example energy spectra with the structure inserted and removed from the beam path, illustrating the effect of the decelerating wakefield.

The experimental decelerating gradient was obtained and compared with CST simulation results and analytical calculations, which involved convolving the measured drive bunch

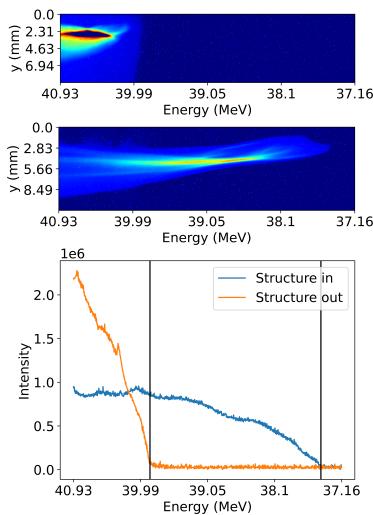


Figure 5: Beam images from the energy measurement of a single electron bunch with the structure removed (top) and inserted (middle) into the beam path. The corresponding energy spectra (bottom) reveal the energy loss due to the wakefield.

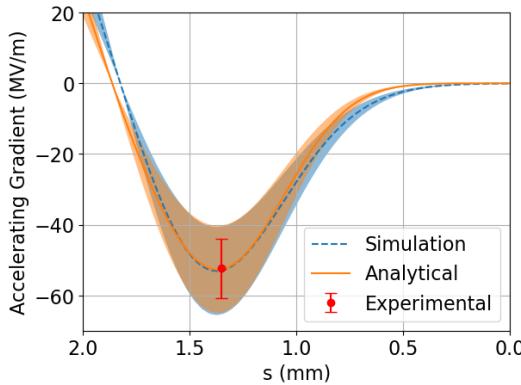


Figure 6: The measured decelerating gradient of (52.3 ± 8.4) MV/m is compared with simulation and analytical predictions based on a 270 μ m (rms) Gaussian bunch and the average experimental charge. Shaded bands represent $\pm 1\sigma$ variations in bunch charge measured during the experiment.

profile with the structure's Green's function. Both simulation and analytical models assumed a 270 μ m (rms) Gaussian bunch, matching the experimentally measured mean bunch length. Figure 6 shows the simulated and analytical wakefields along the bunch axis, along with the measured peak decelerating gradient. The experimental value of (52.3 ± 8.4) MV/m is in good agreement with both simulation and theory. Uncertainty bands for the simulation and analytical results reflect the statistical spread of the measured bunch charge.

Two-Bunch Case

In the two-bunch case, 5 nC electron bunches were produced at the photocathode, with the charge reduced to ap-

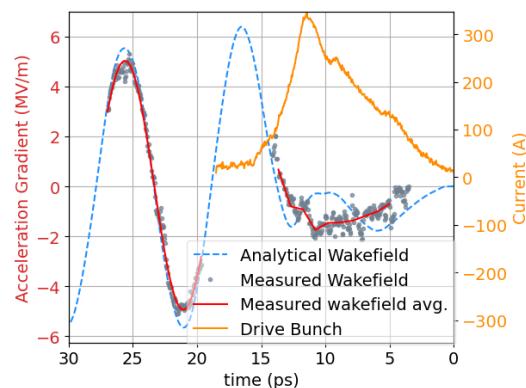


Figure 7: Measured wakefield (gray dots) and its average (red) from the two-bunch experiment, plotted alongside the experimental drive bunch current profile (orange) and the corresponding analytical wakefield (blue dashed). Strong agreement is observed between the experiment and theory.

proximately 2.9 nC after passing through the transverse mask. After the EEX beamline, a two-bunch train was generated, consisting of a triangular-shaped drive bunch followed by a long, low-charge witness bunch. This train was sent through the beamline with the structure alternately inserted and removed. The measured wakefield is shown in Fig. 7, along with an analytical calculation based on the measured drive bunch profile (also shown). The results again show excellent agreement with theory. The transformer ratios from multiple shots yield a value of 3.08 ± 0.75 , demonstrating enhanced acceleration efficiency.

CONCLUSION

This work demonstrates the potential of sub-THz CWA as a path toward compact, efficient, high-gradient accelerators. A W-band (110 GHz) corrugated waveguide structure was designed, fabricated, and experimentally tested at AWA using shaped electron bunches produced via emittance exchange. Simulations guided the structure design and beam parameters, predicting both high gradient and high transformer ratio performance. Experiments confirmed these predictions, achieving an average decelerating gradient of 52.3 MV/m with a short, high-charge bunch, and a transformer ratio of 3.08 with a shaped two-bunch configuration. These results validate the feasibility of efficient wakefield acceleration in the sub-THz regime using metallic structures.

ACKNOWLEDGMENTS

This research was supported by the U.S. Department of Energy, Office of Science, Office of High Energy Physics under Award DE-SC0022010 and DE-SC0021928. The work at the AWA was funded through the U.S. Department of Energy, Office of Science under Contract No. DE-AC02-06CH11357.

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