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STATUS OF THE EXPERIMENTAL DEMONSTRATION OF GW POWER GENERATION FROM THz-TBA

G. Ha*, Northern Illinois University, DeKalb, IL, USA
S. H. Park, K. Kim, J. Ko, B. Oh, M. Seo, Korea University, Sejong, Korea
H.-S. Kong, J. H. Kim, J. Kim, H. J. Kwak, S.-H. Kim
Pohang Accelerator Laboratory, Pohang, Korea
G. Chen, S. Doran, W. Liu, J. Power, B. Popovic, E. Wisniewski
Argonne National Laboratory, Lemont, IL, USA
C. Jing, Euclid Techlabs, Bolingbrook, IL, USA

Abstract

We present the current status of preparation for the experimental demonstration of GW power generation from THz-TBA. This paper covers the status of structure fabrication, RF power extraction and absolute power measurement plan, and THz drive beam preparation. Currently, 0.4 THz structures are being fabricated using two improved methods over previous fabrication techniques. RF power extraction will be achieved using an on-axis horn antenna and off-axis parabolic mirrors. The RF power will be detected with a bolometer and calibrated based on the total beam energy loss measured by a spectrometer. In recent machine studies, we successfully generated a high-charge bunch train (1 nC/bunch) compatible with 0.4 THz structure.

INTRODUCTION

A multi-institutional collaboration is underway to develop the physics and technology for terahertz two-beam acceleration (THz-TBA). This collaboration has developed a fabrication method for corrugated wakefield structures in the sub-THz regime [1]. The fabrication quality of the structure was confirmed at Argonne Wakefield Accelerator facility by benchmarking simulated wakefields against measured wakefields using a 40-MeV electron beam [1, 2].

Following this initial successful demonstration, efforts have been made to pursue the next major milestone of the collaboration: generating >1 GW of power from a corrugated structure. In preparation for a subsequent high-gradient demonstration, we selected 0.4 THz as the structure's fundamental frequency. While retaining the disk-stacking method and high-temperature, high-pressure bonding, the disks forming the corrugation were produced using the LIGA process at Pohang Accelerator Laboratory storage ring [3]; see Fig. 1. This structure was fabricated in the summer of 2024.

After the structure fabrication, two major challenges have been explored over the past year including machine study. An experiment to demonstrate high-power generation is now planned for early 2026. This paper mainly discusses the two aforementioned challenges: (i) drive bunch train generation, and (ii) power extraction and its measurement.

* gha@niu.edu

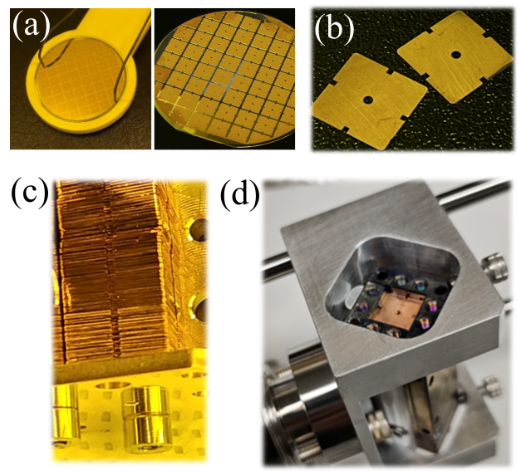

Figure 1: Corrugated structure fabrication. (a) Fabrication of plates with a hole. (b) Fabricated plates with different inner hole diameters. The design specifications are: (1) a hole diameter of 1.00 mm with a plate thickness of 40 µm, and (2) a hole diameter of 1.08 mm with a thickness of 230 µm. (c) Stacked plates prior to bonding. (d) Fabricated structure mounted on a motorized actuator.

DRIVE BUNCH TRAIN GENERATION

Laser Pulse Train

We considered two different methods for generating sub-THz compatible bunch trains [4, 5]. While the deflecting cavity-based method can produce high-quality bunch trains, it requires significant space and multiple cavities. In contrast, the laser-based method showed surprisingly reasonable quality with a much simpler setup compared to the cavity-based approach. The laser-based method was implemented, and a laser splitter system was constructed as shown in Fig. 2 (a).

During the initial experimental verification, we encountered an intensity unbalance issue. Each beam splitter divides the laser pulse into two. However, the intensity ratio can easily deviate from the ideal 50:50, typically ranging from 45:55 to 50:50. The intensities of the first four laser pulses can be easily balanced using attenuators or even irises, thanks to the MLA [6]. However, the next splitter stages uses both the transmitted and reflected pulses from the previous stage. As a result, any imbalance introduced at this

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stage cannot be compensated. Similarly, subsequent splitters introduce the same issue. This imbalance resulted in more than an order of magnitude difference in intensity between the first and third groups of four laser pulses.

To address this, we devised a simple, highly tunable—though lossy—solution, as Fig. 2 (b). In this configuration, the intensity of each path can be independently controlled. Once the first four laser pulses are perfectly balanced, the remaining pulses can be balanced by adjusting the attenuation in the four branches of the second stage.

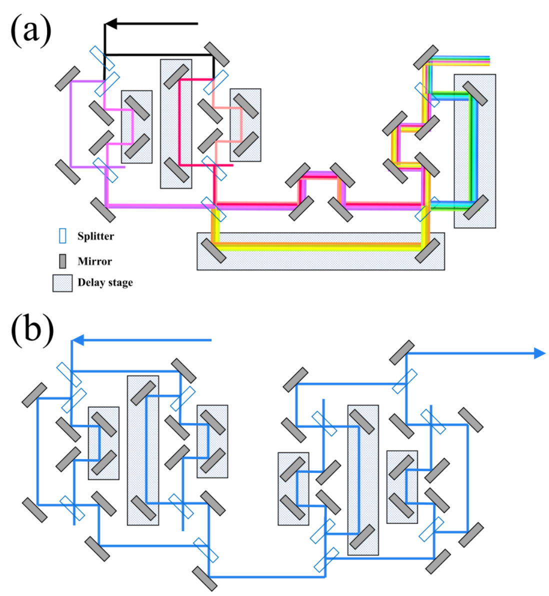

Figure 2: Laser splitting system for generating 16 pulses. (a) Layout of the initial setup for machine studies. (b) Layout of the setup for the high-power demonstration planned in 2026.

THz Compatible Bunch Train

We conducted two machine study runs to confirm the generation of THz-compatible bunch trains. During the first run, it was confirmed that the bunch spacing could not be reduced below 3–4 ps; see Fig. 3 (a). When the spacing became shorter than this threshold, the bunches merged and behaved as a single bunch; see Fig. 3 (b). It turned out that the issue arose from insufficient initial acceleration caused by low RF power fed into the first two accelerating columns. While the final beam energy didn't deviate significantly (only 1-2 MeV out of 44 MeV), the reduced acceleration significantly increased the microbunch length, which led to the observed merging behavior. Simulations accounting for the low input power showed that the rms bunch length at the end of the beamline was 0.28 mm, which is in good agreement with the measured bunch value.

In the second machine study, the drive bunch train generation was revisited with increased klystron power to mitigate the bunch lengthening issue. The results are shown in Fig. 3 (c-d). The longitudinal phase space clearly exhibited smaller spacing between bunches. The Fourier transform of the current profile in the panel (d) shows a pronounced spectral peak in the 0.4–0.5 THz range. It should be noted that the bunch spacing was not yet optimized in this run; thus, the spectral peak is expected to become stronger and narrower with proper optimization. Another important observation is that the FWHM bunch lengths of the microbunches were approximately 2.0, 2.0, 1.6, and 3.1 ps FWHM, which is still longer than simulated value of ~1 ps FWHM. Further investigations will be required to understand and address this discrepancy.

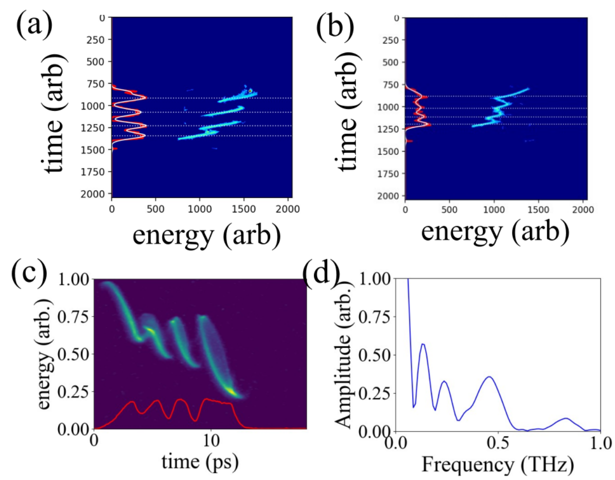

Figure 3: Longitudinal bunch train. (a-b) show longitudinal phase space measured during the first machine study. The bunch spacing in (a) is approximately 5 ps while the spacing in (b) is shorter than 5 ps. (c) is a longitudinal phase space measured during the second machine study. (d) is corresponding frequency spectrum of the beam.

An additional noteworthy result from the first machine study relates to the measured acceleration gradient. Although proper bunch spacing was not achieved, the beam was transported through the structure, and the energy gain and loss were measured. Raw longitudinal phase space images are shown in Fig. 4. Based on the energy gain observed in the tail of the last bunch, the estimated wakefield gradient was approximately 28 MV/m. This result was obtained using only four bunches with large macro bunch lengths, doubled bunch-to-bunch spacing, and 50% transmission through structure. Therefore, transporting a properly configured 16-bunch train is expected to yield a gradient of 200-300 MV/m gradient, which corresponds to GW-level power.

POWER EXTRACTION AND MEASUREMENT

Extracting the generated GW-level radiation and accurately measuring its absolute power presents another major challenge due to the scale involved. We have considered several methods to extract the radiation with minimal losses (see Fig. 5). The key design goal is to minimize power loss (i.e., maximize capture efficiency) while separating the radiation from the electron beam so that the beam can continue to propagate to the next power extraction stage.

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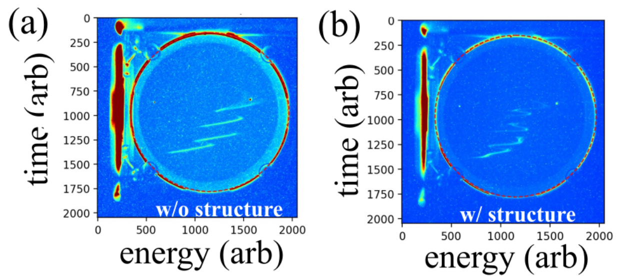

Figure 4: Comparison with and without structure. (a) shows longitudinal phase space measured without the structure inserted in the beam path. (b) shows a longitudinal phase space of the beam after passing through the structure.

A coupler with waveguides (see panel b) is always an option. However, it poses challenges such as coupler fabrication and mode conversion to minimize RF losses. Although this method has the significant advantage of enabling efficient power transfer to accelerating structures in the future, these technical difficulties are unlikely to be resolved in the near term. Therefore, for the high-power demonstration, we focus on optics-based approaches.

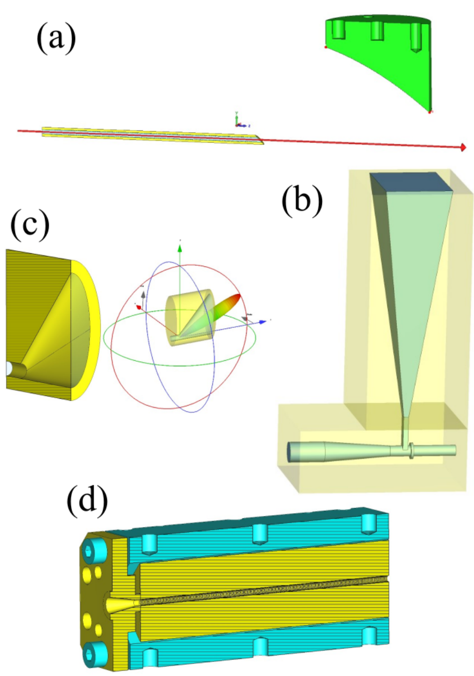

Figure 5: Power extraction approaches. (a-d) corresponds to the following power extraction methods, respectively: (a) a Vlasov antenna with OAPs, (b) a coupler with waveguides, (c) an asymmetric horn antenna with OAPs, and (d) an on-axis, symmetric horn antenna with OAPs.

The first approach considered was a Vlasov antenna (see panel a) [7]. A 45-degree cut at the end of the structure emits radiation at an angle to the axis. While the method naturally separates the radiation from the beam, the emitted radiation has a large divergence and must be collected using an off-axis parabolic mirror (OAP). This introduces challenges in both capture and beam-radiation separation. A large OAP is required to capture the radiation effectively, but it may interfere with the beam path. Although a custom-designed OAP could potentially solve this, no commercially available form factor was suitable. The best capture efficiency achieved with this method was below 50%.

Based on insights gained from this approach, we designed an asymmetric elliptical horn antenna as shown in Fig. 5 (c). Previous studies showed that the cut angle can influence the angular radiation distribution, and similarly, modifying the horn geometry can help control both the emission angle and the angular spread. This approach significantly improved the capture efficiency (>80%) and avoided beam-path interference from the OAP. However, fabricating such a structure at millimeter and sub-millimeter scales remains challenging.

The third and ultimately chosen approach employs an on-axis horn antenna. Simulations showed that the emission from the structure has a conical distribution with minimal intensity along the beam-axis. Therefore, if sufficient separation is maintained between the structure and the OAP, an OAP with a hole can be used to extract radiation while allowing the beam to pass through. This approach simplifies the optical geometry and avoids beam obstruction. The antenna will be mounted directly at the exit of the structure as illustrated in Fig. 5 (d). The OAP with a hole will be placed within the same vacuum chamber

Absolute power measurement will be performed using a bolometer. A key challenge in this measurement is the lack of accurate calibration sources at the relevant frequencies. To address this, we plan to send single bunches with varying charge levels through the structure and correlate the resulting beam energy loss with the bolometer signal. With the aid of simulation tools, this will allow us to estimate the total radiated power.

CONCLUSION

The collaboration between Korea university, Pohang Accelerator Laboratory, Argonne National Laboratory, and Northern Illinois university is advancing toward the demonstration of GW-level power generation in sub-THz regime. A 0.4 THz structure has been successfully fabricated, and a drive bunch train compatible with 0.4–0.5 THz range has been experimentally produced. In addition, design studies for power extraction and detection have been conducted. A previously measured gradient of 28 MV/m, along with relevant beam parameters, indicates promising potential once all components are properly prepared and optimized. The demonstration is currently planned for early 2026.

ACKNOWLEDGEMENTS

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