ISBN: 978-3-95450-247-9 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2024-MOPR24

PROGRESS ON HIGH-POWER GENERATION USING SUB-THz CORRUGATED WAVEGUIDE

G. Ha*, Northern Illinois University, DeKalb, IL, USA
S.-H Shin, J. Ko, M. K. Seo, Korea University, Korea
H.-S Kong, S.-H Kim, J. H. Kim, J. Kim, H. J. Kwak, Pohang Accelerator Laboratory, Korea
G. Chen, E. Wisniewski, W. Liu, J. Power, Argonne National Laboratory, Lemont, IL, USA

Abstract

Previously we had developed a new method to fabricate corrugated waveguides (CW) operating in sub-THz frequency regime. As the next step, collaborative effort is underway to demonstrate GW-level high-power sub-THz pulse generation using a CW. We plan to fabricate a CW operating at around 400 GHz. This waveguide will be driven by a bunch train including 16 bunches with nanocoulomb-level charges per bunch. We present an overview of project's current status.

INTRODUCTION

A collaboration is currently underway to develop methods and technologies for two-beam acceleration in the Terahertz regime, so-called THz-TBA [1]. The collaboration aims to explore new opportunities for TBA in sub-and THz regimes, with the goal of achieving O(1) GW peak power from the power extractor (PET) and approximately 1 GV/m gradient from the accelerating structure (ACC). The ultimate goal is to develop a demonstrator, which will provide an integrated demonstration of developed methods and technologies. The demonstrator will target the generation of EUV or Soft X-ray within a 10-15 m facility footprint [1]. This paper describes the plan and provides a summary of ongoing activities.

R&D PLAN

The final objective, the demonstrator, will be pursued in a stepped approach. Four major milestones are listed below, and each phase of the project will include several new developments.

High-power Demonstration

- Demonstrating GW-level peak power generation using a single PET
- Comparison of different structures and development of a new structure
- Generation of nC-level bunch train compatible with sub- and THz frequencies

High-gradient Demonstration

- Demonstrating GV/m-level accelerating gradient using a single PET and ACC pair
- R&D for power extraction/injection and power transfer from PET to ACC
- R&D for energy gain and efficiency improvement

High-gradient Staging Demonstration

- Demonstrating staging with GV/m-level accelerating gradient using two PET and ACC pairs
- Mitigation of beam break-up in the drive beam
- Development of compact staging optics

EUV/X-ray Generation

- Generation of EUV/X-ray from a ~400 MeV THz-TBA accelerator
- R&D for THz-TBA powered electron gun

We have previously developed a fabrication method for sub-THz corrugated waveguides and characterized their performance using beam-based measurements [2]. There have been several improvements in the fabrication process (e.g., lithography-based plate production and enhancement in the stacking procedure) [3, 4]. Currently, fabrication of a 424 GHz structure is underway using the improved process. This structure will serve as the PET for high-power generation. The first experiment is planned for August at the Argonne Wakefield Accelerator facility. The goal of the experiment is generating over 1 GW peak power.

STRUCTURE DESIGN

Table 1: Corrugated waveguide dimensions and RF characteristics

Parameter	Value
a	1 mm
d	0.08 mm
w	0.04 mm
g	0.23 mm
Frequency	424 GHz
Group velocity	0.62c

We plan to continue using a corrugated structure for the experiment because it provides more tuning knobs than a dielectric-lined waveguide. The new structure was designed to operate at a higher frequency (424 GHz) than the previously tested structure (~200 GHz). While we maintain the same approach to fabricating the tiny corrugations, there have been several improvements. More details for structure design can be found from Ref. [3] and [4].

* gha@niu.edu

ISBN: 978-3-95450-247-9 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2024-MOPR24

The structure design to achieve >1 GW is complete. Table 1 summarizes the structure dimensions and relevant RF characteristics. Figure 1 shows CST simulated RF pulse from the structure and its frequency spectrum. This simulation assumes 16 bunches separated by one RF period. Here, the charge per microbunch is assumed to be 1 nC, and the microbunch length is 0.1 mm.

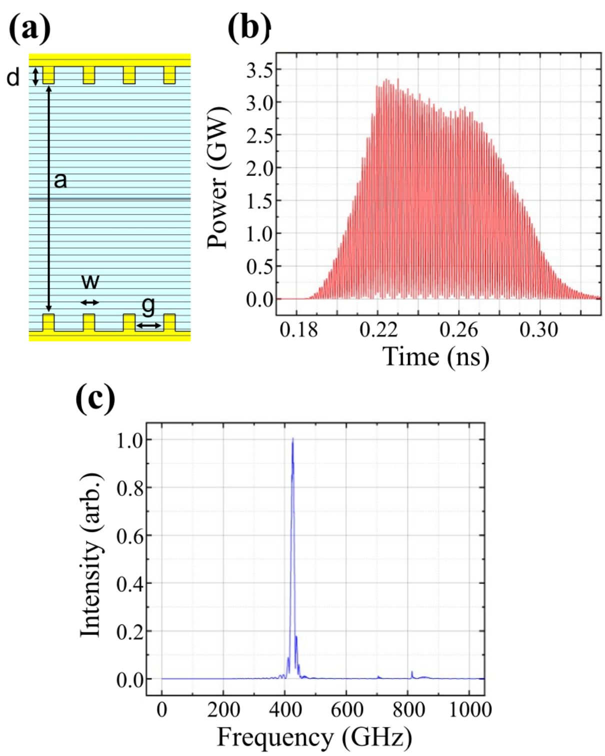

Figure 1: Schematic of corrugated structure and RF simulation results.

DRIVE BEAM GENERATION

Among the many existing methods to generate sub-THz bunch trains [5], we have explored two methods. As mentioned in the previous section, the planned experiment requires a drive bunch train with 16 microbunches and a charge of 1 nC or higher per microbunch.

The first method we explored was deflecting cavity-based shaping [6]. Unlike other shaping methods [5], this method does not use a dipole magnet. Thus, it avoids any degradation in beam quality or shaping quality from CSR, which could significantly increase the emittance and wash out density modulation due to the high-frequency and high-charge nature of the bunch train. As shown in Fig. 2, this method provides high-precision shaping. Additionally, the method does not introduce any extra increase in the energy spread because it projects the beam onto the transverse plane and cuts the beam. Thus, each microbunch has an extremely small energy spread. While the figure we provided here exhibits large and nonlinear macro chirp, this can be adjusted using linac phase. Note that nonlinearity correction is not straightforward but is not necessary.

While this method has several attractive points, it also presents challenges. The method requires at least two transverse deflecting cavities (TDC) and corresponding power sources. Also, significant space between TDCs is needed to achieve good shaping resolution. Additionally, there is significant charge loss. In our simulation, the beam had to start with 35 nC due to 44% transmission through the mask. While increasing the opening of the multi-slit could improve transmission, it also increases the microbunch's bunch length, which results in a reduction of expected output power due to the reduced form factor. This trade-off is a significant limitation of the method. Although compressing microbunches is possible, it would require a dispersive compressor, which negates the advantage of using TDC-based shaping. Moreover, complex control over each microbunch would be necessary to control the compression and quality.

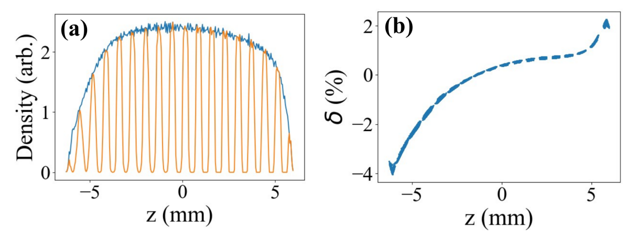

Figure 2: Drive bunch train from TDC-based shaping.

Due to the limitations of the TDC-based shaping, we have also explored an alternative method employing a laser pulse train to generate a bunch train from the gun. This method has been previously used in the structure test experiment [2]. While there are various methods to generate a laser pulse train, we adopted the configuration shown in Fig. 3 due to its flexibility in tuning both the spacing and intensity of each microbunch.

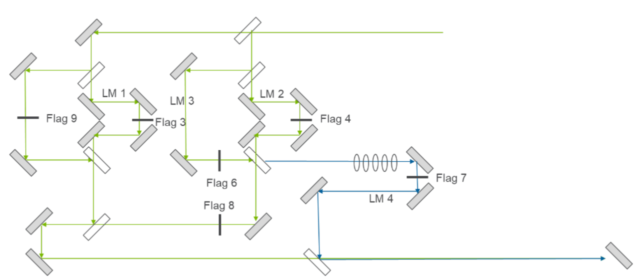

Figure 3: Example optics layout for 4-pulse laser train generation.

Despite concerns about the space-charge effect, the simulation demonstrated the successful extraction of a bunch train from the gun. Additionally, we managed to maintain a consistent central energy for each microbunch; see Fig. 4. This method proves to be significantly more cost-effective and space-efficient compared to the TDC-shaping option. However, we should note that its shaping quality is not as

ISBN: 978-3-95450-247-9 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2024-MOPR24

high as that achieved with TDC-shaping. The strong space-charge effect increased the emittance. The total charge of 19.2 nC had a transverse emittance that is only 2/3 of the one from the TDC-shaping case. Also, the space-charge effect inevitably results in a low form factor, and each microbunch has a substantial energy spread (O(1)%).

While the laser shaping approach has several disadvantages, we have opted to utilize it for the experiment due to its cost-effectiveness, space-efficiency, and ease of implementation. Simulations were conducted to test if the shaping quality is sufficient to generate the targeted RF power. It is expected to generate the RF pulse similar to panel (b) in Fig. 1.

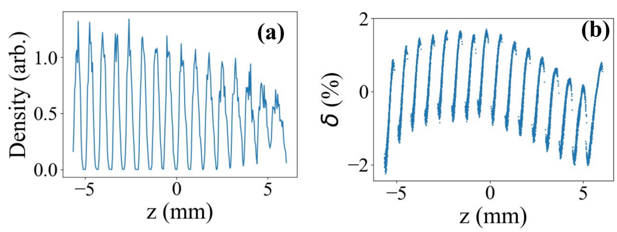

Figure 4: Drive bunch train from laser shaping.

RF MEASUREMENT

One concern for the upcoming experiment is the accurate measurement of high-power RF. The operating frequency is slightly high for conventional RF diagnostics but may be somewhat low for optical methods. Additionally, the short pulse duration (O(100) ps) and high-power (O(1) GW) nature of the RF signal could be another obstacle for conventional measurement techniques.

In addition to challenges with detection, power extraction is another concern. We are considering both fully optical and RF-optics combined options; see Fig. 5.

Placing an off-axis parabolic mirror (OAP) on the beam axis is a common approach for measuring radiation characteristics. However, this method has a significant limitation in terms of charge or RF power losses. Given the staging requirements, it is necessary to deliver the beam without losses, and RF losses are also not allowed for high-gradient acceleration. Unfortunately, using an OAP with a hole introduces RF losses while using an OAP without a hole results in a beam losses.

Another option is to place an OAP away from the beam axis. This approach involves radiating the RF pulse at an angle. By cutting the structure end at an angle, it becomes possible to radiate the RF at an angle [7]. CST simulations have shown that a 45° cut, as depicted in Fig. 6, results in RF radiating at a 30° from the axis. This configuration in Fig. 6 could be an attractive option for avoiding both RF and beam losses.

We are also exploring the option of combining a coupler with optics. In this setup, a coupler will be attached to the exit of the structure to extract the power while the beam continues in a straight path. The RF pulse will then be radiated via an antenna and delivered to the detector using optics. One major concern with this approach is the Ohmic loss in the coupler and subsequent short waveguide and antenna. Studies on this option have recently been initiated, and initial simulations have shown the possibility of achieving a transmission of 80-90%.

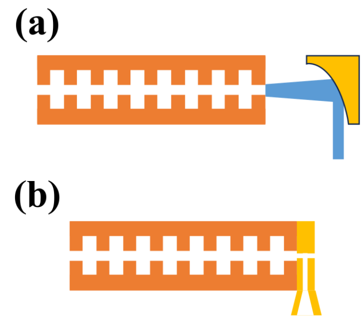

Figure 5: Schematics illustrating extraction approaches.

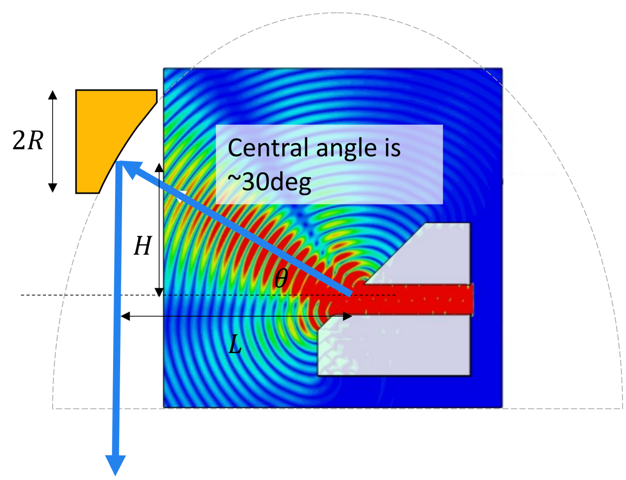

Figure 6: Off-axis OAP configuration with simulated RF radiation at an angle.

SUMMARY

We have outlined the overall R&D plan for the THz-TBA collaboration along with its current status. Our objective is to construct a demonstrator capable of generating EUV or soft X-ray within a 10-15 m facility footprint. This goal will be achieved through a stepped approach. The first step involves demonstrating the generation of O(1) GW peak power. The design of the structure has been finalized, and the fabrication is currently underway. Two methods for generating drive bunch train have been explored. The laser shaping was selected for the upcoming demonstration. Our primary concern at present is the extraction and detection of the generated RF pulse. We are currently evaluating several options for this purpose. The first experiment is planned for August at the Argonne Wakefield Accelerator facility.

ISBN: 978-3-95450-247-9 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2024-MOPR24

REFERENCES

[1] G. Ha, "Preliminary study on THz-TBA based X-ray source," in *Proc. IPAC'23*, Venice, Italy, 2023, pp. 1885–1888. doi:10.18429/JACoW-IPAC2023-TUPL057

[2] H. Kong *et al.*, "Fabrication of THz corrugated wakefield structure and its high power test [doi: 10.1038/s41598-023-29997-9]," *Sci. Rep.*, vol. 13, no. 1, p. 3207, 2023. doi:10.1038/s41598-023-29997-9

[3] S. Shin, J. Ko, J. H. Kim, and G. Ha, "Fabrication of THz corrugated structure using X-ray based lithography," presented at IPAC'24, Nashville, TN, USA, May 2024, paper MOPR12, this conference.

[4] H. Kong *et al.*, "Fabrication study of corrugated structure for sub-THz by stacking disks," presented at IPAC'24, Nashville, TN, USA, May 2024, paper MOPR28, this conference.

[5] G. Ha, K.-J. Kim, J. G. Power, Y. Sun, and P. Piot, "Bunch shaping in electron linear accelerators," *Rev. Mod. Phys.*, vol. 94, p. 025 006, 2 2022. doi:10.1103/RevModPhys.94.025006

[6] G. Ha, J. G. Power, J. Shao, M. Conde, and C. Jing, "Coherent synchrotron radiation free longitudinal bunch shaping using transverse deflecting cavities," *Phys. Rev. Accel. Beams*, vol. 23, p. 072 803, 7 2020. doi:10.1103/PhysRevAccelBeams.23.072803

[7] S. Antipov *et al.*, "Efficient extraction of high power THz radiation generated by an ultra-relativistic electron beam in a dielectric loaded waveguide," *Applied Physics Letters*, vol. 109, no. 14, p. 142 901, 2016. doi:10.1063/1.4963762