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PRELIMINARY STUDY ON THz-TBA BASED X-RAY SOURCE

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Abstract

Two-beam acceleration (TBA) in Terahertz (THz) regime is the natural extension of Gigahertz TBA pursued in Structure Wakefield Acceleration Community. Recently proposed CSR-free shaping technique using deflecting cavities showed the feasibility of generating a high-charge (~1 nC per bunch) bunch train compatible with THz frequency. Wakefield from THz structure with such a high-charge bunch train has the potential to reach a few GV/m accelerating gradients or a few GW THz power levels. We present a concept of a compact accelerator using THz-TBA for generating coherent X-ray.

THZ-TBA BASED FEL

Short-pulse two-beam acceleration (TBA) is an attractive approach to realizing TeV colliders or miniaturizing existing large-scale accelerator facilities [1–4]. While most researches focus on TBA at 10-30 GHz level [2, 5, 6], the obtainable gradient at this frequency range is somewhat limited. An easy way to improve the gradient is to increase the operating frequency from GHz to THz. It is expected to achieve a few GV/m gradients while keeping the strength of the short-pulse TBA scheme (e.g., separate control on drive and main beams, breakdown insensitive regime [7], etc.).

On the other hand, THz structures usually have a small inner diameter that ranges from hundreds of microns to a few mm. Also, increasing the longitudinal wakefield strength for the gradient means strengthening of the transverse wakefield triggering beam break-up (BBU) instability. Thus, it wouldn't be easy to apply this concept to high-energy accelerators like TeV colliders. TBA is also not an attractive option for a few MeV accelerators due to the necessity of a separate drive beamline. We believe that the THz-TBA concept is more appropriate for reducing the footprint of hundreds of MeV to a few GeV accelerators to a few-meter scale.

As a demonstration target, we propose an FEL based on THz-TBA. In this concept, a short conventional beamline generates a drive bunch (e.g., 10-20 nC) and accelerates its energy to a high-enough level to provide the designed acceleration to the main beam. We use a deflecting-cavity-based beam shaper [8] for converting the single drive bunch to a THz-compatible drive bunch train, which generates intense and coherent wakefields in power extraction tubes (PET). The main beam will be generated by a miniaturized gun operating in THz frequency, and it will be accelerated by following accelerating tubes powered by PETs. The described concept is displayed in Fig. 1.

Currently, we consider a hard X-ray case in Table 1 as the main goal. However, it wouldn't be straightforward to demonstrate hard X-ray generation in the first place due to various RF and beam dynamics challenges in the concept. Thus, EUV generation with relaxed requirements has been considered for the proof-of-principle experiment. Corresponding design parameters are given in the right column of Table 1.

Table 1: Preliminary FEL Design Parameters

	Hard X-ray (0.1 nm)	**EUV (13.5 nm)**
Undulator period	20 mm	10 mm
Undulator gap	5 mm	2 mm
Undulator K	1.15	0.67
Beam energy	6.6 GeV	0.34 GeV
Charge	10 pC	500 pC
$\varepsilon_{n,x}$	0.1 µm	0.7 µm
σ_x	2.8 µm	33 µm
σ_z	2.5 µm	18 µm
I_{peak}	1.2 kA	8.8 kA
Pierce ρ	1.4×10^{-3}	4.7×10^{-3}
Saturation length	14 m	2.1 m
Saturation power	11.7 GW	14 GW

PRELIMINARY POWER EXTRACTION TUBE AND ACCELERATOR DESIGN

The main goal of the preliminary structure design was to explore drive beam and beam shaper requirements. Thus, we chose a dielectric lined waveguide as the test structure due to its simplicity. The structure parameters were chosen to achieve GW-power from PET with reasonable drive bunch requirements and >340 MeV energy gain. Design parameters are summarized in Table 2. These parameters were calculated based on Ref. [5]. Note that increasing the energy gain by adjusting the length of the accelerating structure was not effective due to a high group velocity. Thus, we decided to use two PET-ACC pairs providing >170 MeV gain instead of a single pair.

DRIVE BUNCH TRAIN GENERATION

THz-compatible drive bunch train was generated by TDC-based shaping (TDC stands for transverse deflecting cavity) [8]. Although the charge required for each microbunch is low (0.6 nC, see Table 2), we need a total of 16 bunches, which means that the initial drive bunch must have 9.6 nC or higher. Such charge level introduces a strong space-charge or CSR effect during the shaping process [9–12] if the shaping is performed at a low-energy region or is done by dispersive beamlines. Currently, laser shaping [13–15] and TDC-shaping [8] are the only available CSR-free shaping methods. Because the laser shaping obtains significant quality degradation due to the space-charge effect near the cathode,

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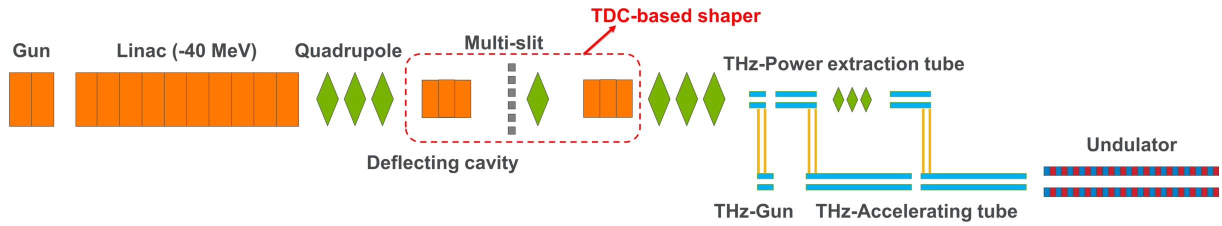

Figure 1: Schematic of beam splitting system. TDC stands for transverse deflecting cavity, TW stands for transverse wiggler, and PET stands for power extraction tube.

Table 2: Preliminary PET and ACC Design Parameters

	PET	ACC
ID	2 mm	0.9 mm
OD	2.07 mm	1.02 mm
R/Q	2.44 kΩ/m	35 kΩ/m
Q	3839	1378
f_{wake}	0.42 THz	0.42 THz
Number of drive bunch	16	
Charge per bunch	0.6 nC	
Microbunch bunch length	0.2 ps rms	
Structure length	10 cm	30 cm
Expected output power	1.7 GW	
Peak gradient		1.1 GeV/m
Expected energy gain		171 MeV
Expected avg. gradient		0.57 GeV/m

TDC-shaping would be the only method we can adopt for the high-charge THz-bunch-train.

During the particle tracking simulation, we adopted TDC-Q-TDC configuration, which is the simplest form [8]. Also, we assumed TDC strength (κ) of 4 m^{-1} and cavity-to-quad spacing of 1 m. The simulation results are displayed in Fig. 2. Note that we prepared the input particle distribution for the shaper using Argonne Wakefield Accelerator's drive beamline [16]. We used 4 accelerating columns to accelerate the beam to 40 MeV. The drive bunch charge was set to 35 nC at the beginning. Injector optimization provided normalized transverse emittance of 27 µm.

One of the major disadvantages of TDC-shaping is the mask. Masking beam for generating the bunch train introduces particle loss of 50% or more. Especially, the case we described in Table 2 required a significant loss of particles due to a large ratio of bunch spacing to micro-bunch length. Low transmission here means the increase of the initial drive bunch charge, and it results in the increase of the transverse emittance, which does not change during the shaping process. It eventually limits the beam transport through the PET. Thus, in this test case, we changed the strategy and increased the micro-bunch charge by sacrificing the longitudinal form factor. The originally designed slit's opening was increased so that we can achieve a higher charge per bunch but a longer bunch length. The shaped result is in panel (d) of Fig. 2. Here the average charge of micro-bunches is 0.86 nC (it is 0.95 nC if we exclude far left and right bunches), and the average micro-bunch length is 0.32 ps (corresponding form factor is 0.7).

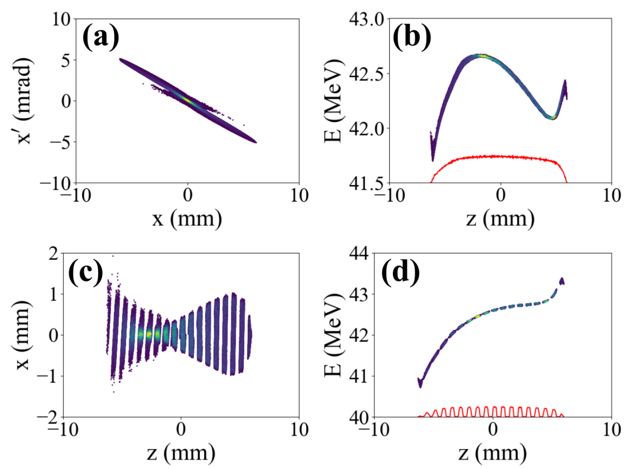

Figure 2: Particle tracking simulation results. (a) and (b) show beam's transverse and longitudinal phase spaces at the exit of linac. (c) and (d) is beam's z-x distribution and longitudinal phase space after a shaper.

BEAM TRANSPORT IN PET

While the beam transport up to the shaper was simulated using GPT [17], the beam transport in the PET has been tracked by a homemade Python script, which applies longitudinal and transverse kicks from wakefield to the beam at every small time step. As described earlier, we prepared two PETs to feed two accelerating structures. 100 µm horizontal offset was applied to the beam to confirm BBU. Note that we simply applied triplet focusing in front of each structure because BBU wouldn't be significant due to PET's short longitudinal length. The result is shown in Fig. 3.

The longitudinal wakefield showed expected energy losses. We expect 4.0 GW power from each PET according to the longitudinal wakefield and beam energy loss. This RF power corresponds to 215 MeV energy gain in each 30-cm long accelerating structure, which corresponds to 720 MeV/m gradient.

The beam was 100% transmitted through the first PET while 5% of particles were lost in the second PET. The particle loss in the second PET originated from the transverse

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wakefield that generated a large horizontal beam size (see panel a). It is worth to note that the structure was single-mode. The transverse and longitudinal wakefields have 180° phase offset. Thus, the transverse wakefield introduces a linear z-x correlation to each microbunch. This means that there is a chance of optical cancellation of the transverse wakefield's impact from the first and second PETs. Also, a significant reduction in micro-bunch length would weaken the transverse wakefield's impact.

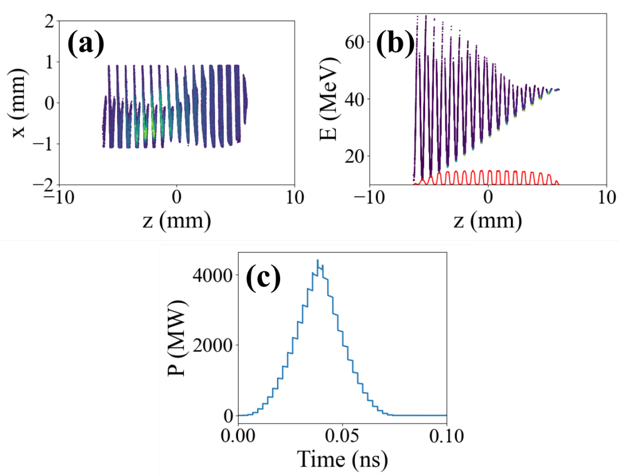

Figure 3: Particle tracking results after PETs. (a) and (b) show z-x distribution and longitudinal phase space after two PETs. (c) is expected RF pulse shape from the first PET.

NOTE ON THz-GUN

Operating two separate beamlines for drive and main beams is one of the biggest drawbacks of the TBA scheme. Thus, the proposed concept implemented a new type of gun powered by TBA for generating the main beam. We consider two options; a Trojan horse (TH) using structure wakefield (SWFA) [18] and a high-gradient metallic cathode gun [7]. Both options are high-gradient electron sources that can generate a low-charge beam having a low emittance and a short bunch length. Also, it is expected that the source works in breakdown insensitive regime [7] due to the input RF pulse's short duration.

OTHER REQUIRED R&D

The proposed concept includes several methods and equipment that have never been demonstrated experimentally while similar concepts or the same concept operating in different regimes were (partially) demonstrated. For example, TDC-shaping has never been experimentally demonstrated, and it must work with laser shaping to improve transmission. Power transfer of GW-level THz RF pulse has never been demonstrated. Simulation of gun and accelerator using extremely short RF pulse is currently unavailable. Major R&D challenges are listed below.

- High-transmission, high-precision drive beam shaper.
- Compact staging optics.
- Drive and main beam's BBU mitigation.
- Simulation tool for short-pulse TBA and THz-Gun.
- Design, fabrication, and test of THz-PET and THz-ACC.
- Design, fabrication, and test of GW-THz pulse transmission line.
- High-brightness, stable THz-Gun.

REFERENCES

[1] C.-J. Jing *et al.*, "Argonne Flexible Linear Collider," in *Proc. IPAC'13*, Shanghai, China, May 2013, pp. 1322–1324. https://jacow.org/IPAC2013/papers/TUPEA088.pdf

[2] C. Jing *et al.*, "Electron acceleration through two successive electron beam driven wakefield acceleration stages," *Nucl. Instrum. Methods Phys. Res., Sect. A*, vol. 898, pp. 72–76, 2018. doi:10.1016/j.nima.2018.05.007

[3] C. Jing *et al.*, *Continuous and coordinated efforts of structure wakefield acceleration (swfa) development for an energy frontier machine*, 2022. doi:https://doi.org/10.48550/arXiv.2203.08275

[4] C. Jing and G. Ha, "Roadmap for structure-based wakefield accelerator (SWFA) R&D and its challenges in beam dynamics," *J. Instrum.*, vol. 17, T05007, 2022. doi:10.1088/1748-0221/17/05/T05007

[5] J. Shao *et al.*, "Development and high-power testing of an *X*-band dielectric-loaded power extractor," *Phys. Rev. Accel. Beams*, vol. 23, p. 011 301, 2020. doi:10.1103/PhysRevAccelBeams.23.011301

[6] X. Lu *et al.*, "Generation of high-power, reversed-cherenkov wakefield radiation in a metamaterial structure," *Phys. Rev. Lett.*, vol. 122, p. 014 801, 2019. doi:10.1103/PhysRevLett.122.014801

[7] W. H. Tan *et al.*, "Demonstration of sub-GV/m accelerating field in a photoemission electron gun powered by nanosecond *X*-band radio-frequency pulses," *Phys. Rev. Accel. Beams*, vol. 25, p. 083 402, 2022. doi:10.1103/PhysRevAccelBeams.25.083402

[8] 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, 2020. doi:10.1103/PhysRevAccelBeams.23.072803

[9] F. Lemery *et al.*, "Drive beam sources and longitudinal shaping techniques for beam driven accelerators," *J. Instrum.*, vol. 17, P05036, 2022. doi:10.1088/1748-0221/17/05/P05036

[10] G. Ha, M. H. Cho, W. Gai, K.-J. Kim, W. Namkung, and J. G. Power, "Perturbation-minimized triangular bunch for high-transformer ratio using a double dogleg emittance exchange beam line," *Phys. Rev. Accel. Beams*, vol. 19, p. 121 301, 2016. doi:10.1103/PhysRevAccelBeams.19.121301

ISBN: 978-3-95450-231-8 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2023-TUPL057

[11] W. H. Tan, P. Piot, and A. Zholents, "Formation of temporally shaped electron bunches for beam-driven collinear wakefield accelerators," *Phys. Rev. Accel. Beams*, vol. 24, p. 051 303, 2021. doi:10.1103/PhysRevAccelBeams.24.051303

[12] G. Loisch *et al.*, "Observation of high transformer ratio plasma wakefield acceleration," *Phys. Rev. Lett.*, vol. 121, p. 064 801, 2018. doi:10.1103/PhysRevLett.121.064801

[13] T. Xu, M. E. Conde, G. Ha, P. Piot, and J. G. Power, "Ultrashort Laser Pulse Shaping and Characterization for Tailored Electron Bunch Generation," in *Proc. NAPAC'19*, Lansing, MI, USA, Sep. 2019, pp. 871–873. doi:10.18429/JACoW-NAPAC2019-WEPLO17

[14] T. Xu, C.-J. Jing, A. Kanareykin, P. Piot, and J. G. Power, "Spatio-Temporal Shaping of the Photocathode Laser Pulse for Low-Emittance Shaped Electron Bunches," in *Proc. IPAC'19*, Melbourne, Australia, May 2019, pp. 2163–2166. doi:10.18429/JACoW-IPAC2019-TUPTS104

[15] T. Xu, S. Carbajo, R. A. Lemons, and P. Piot, "Temporally-Shaped Ultraviolet Pulses for Tailored Bunch Generation at Argonne Wakefield Accelerator," in *Proc. NAPAC'22*, Albuquerque, NM, USA, 2022, pp. 222–225. doi:10.18429/JACoW-NAPAC2022-MOPA78

[16] M. E. Conde *et al.*, "Research Program and Recent Results at the Argonne Wakefield Accelerator Facility (AWA)," in *Proc. IPAC'17*, Copenhagen, Denmark, May 2017, pp. 2885–2887. doi:10.18429/JACoW-IPAC2017-WEPAB132

[17] *General particle tracer code*, http://www.pulsar.nl/gpt.

[18] G. Andonian *et al.*, "Dielectric Wakefield Acceleration with a Laser Injected Witness Beam," in *Proc. IPAC'21*, Campinas, Brazil, May 2021, pp. 481–484. doi:10.18429/JACoW-IPAC2021-MOPAB138