High-Gradient Accelerators at THz Frequencies

Emilio A. Nanni,† Valery Dolgashev and Sami G. Tantawi
SLAC National Accelerator Laboratory, Menlo Park, CA

Richard J. Temkin
Massachusetts Institute of Technology, Cambridge, MA

Bruno Spataro
INFN-LNF, Frascati, Rome, Italy

Franco di Paolo
University of Rome Tor Vergata, Rome Italy

Matthew Franzi
Air Force Research Laboratory, Albuquerque, NM

† nanni@slac.stanford.edu

Introduction

The development of advanced accelerator concepts is recognized as a fundamental requirement for future exploration of the Energy Frontier with e^+e^- colliders in the multi-TeV range. The cost and size of a multi-TeV collider based on available technology is prohibitive to its construction, and no accelerator technology has established itself as the fully vetted option in this range. A successful accelerator technology for future colliders must be low cost, achieve high accelerating gradients, accelerate beams efficiently and provide high-luminosity beams for experiments. The 2015 HEPAP Accelerator Research and Development Subpanel report identifies the "…greatest challenges to the design of a high-energy e^+e^- collider based on RF acceleration are high accelerating gradient and low power consumption", with a recommendation that research efforts focus on "…high-efficiency power sources and high-gradient normal conducting RF structures."

One potential approach to achieving GeV/m accelerating gradients with efficient structures is to operate in the THz gap which sits nearly two orders of magnitude above where accelerating structures typically operate. The THz frequency regime (~0.1-1 THz) holds great promise for an advanced accelerator technology that can excel in all of the key metrics for future colliders. Most critically, THz frequencies provide a pathway to achieving higher gradients with pulse lengths that are greatly reduced and lead to a major improvement in the gradient that can be achieved with a very low breakdown rate. The mm-size dimensions of the structure produce more efficient RF cavities, and the increased frequency results in significantly shorter fill times, thus the energy needed to power the accelerator decreases dramatically, enabling higher repetition rates. Efficient cavities allow for operation at high gradient with exceptionally high rf-beam efficiency in contrast with most advanced concepts. Increased accelerating gradients allow for higher charge densities and improve electron beam quality. Additionally, the THz frequency range is a unique area of source development where either conventional electron beam-driven RF sources or optically-driven sources may be used. The high frequency allows the THz pulses from these sources to be transported, switched and compressed with overmoded and quasi-optical systems opening up new possibilities for power distribution. Through the combination of these traits we see the potential for THz accelerators to efficiently power high-luminosity experiments.

Progress in THz Accelerator Technology

High-gradient THz accelerators also hold the promise of having an immediate broad impact with many potential applications of relevance to biologists, chemists and physicists investigating ultrafast science and to physicians developing new tools for medical therapy. This broad appeal has allowed this technology to progress rapidly by leveraging additional resources to further expedite the development and investigation of high-power, high-repetition-rate THz sources and high-gradient accelerators.

Over the last five years advances in THz technology have demonstrated accelerating structures operating with high gradients,[1,2] linear acceleration[3,4,5] and staging;[6] developed and deployed beam diagnostics;[7,8] demonstrated beam manipulation;[9,10] produced initial prototypes[11] and designs of bright electron sources;[12,13] extended the reach of high power vacuum electron devices;[14,15,16] demonstrated high power transport and pulse shaping;[17,18] and made significant progress with laser source conversion efficiency, energy and spectral purity.[19,20]

While the potential for THz accelerators has been made clear with rapid progress and its adoption as a diagnostic tool on beamlines, our understanding of the physics and limitations of high-gradient structures in this frequency range remains limited. In order to explore the potential for this technology, R&D is being pursued in the physics of breakdown in the THz frequency regime and electrodynamic optimization of accelerating structures to limit breakdown; new methods for the fabrication of THz accelerating structures; developing high-power RF sources which operate efficiently and are tailored to the inherent nanosecond timescales of THz accelerator operation; and the generation of high-charge, high-brightness beams.

Outlook

Now that THz accelerator technology has entered the prototyping phase, understanding the potential impact of this technology for High Energy Physics applications should be explored in detail. This includes its potential for utilization as a high brightness source, beamline diagnostics, beam manipulation and high gradient acceleration. This must include detailed modeling of wakefields and beam dynamics in these structures to find the optimal mode of operation. Exploring this new technology will also inform related work in rf accelerators and the advanced acceleration communities (in particular related work in structure wakefield acceleration). We must also explore the THz source technologies that can power these structures (including high frequency klystrons, vacuum electron devices, frequency multipliers and laser-based sources) and power distribution technology (switches, waveguides, couplers and converters) to realize the full potential of this paradigm shifting technology.

References

[1] Dal Forno, Massimo, et al. *PRAB* 21.9 (2018): 091301

[2] Othman, Mohamed AK, et al. "Experimental demonstration of externally driven millimeter-wave particle accelerator structure." *Applied Physics Letters* 117.7 (2020): 073502.

[3] Nanni, Emilio A., et al. "Terahertz-driven linear electron acceleration." *Nature communications* 6.1 (2015): 1-8.

[4] Zhang, Dongfang, et al. "Segmented terahertz electron accelerator and manipulator (STEAM)." *Nature photonics* 12.6 (2018): 336-342.

[5] Hibberd, Morgan T., et al. "Acceleration of relativistic beams using laser-generated terahertz pulses." *arXiv preprint arXiv:1908.04055* (2019).

[6] Xu, Hanxun, et al. "Cascaded high-gradient terahertz-driven acceleration of relativistic electron beams." *arXiv preprint arXiv:2005.11714* (2020).

[7] Zhao, Lingrong, et al. "Terahertz oscilloscope for recording time information of ultrashort electron beams." *Physical review letters* 122.14 (2019): 144801.

[8] Li, R. K., et al. "Terahertz-based subfemtosecond metrology of relativistic electron beams." *Physical Review Accelerators and Beams* 22.1 (2019): 012803.

[9] Snively, E. C., et al. "Femtosecond Compression Dynamics and Timing Jitter Suppression in a THz-driven Electron Bunch Compressor." *Physical Review Letters* 124.5 (2020): 054801.

[10] Zhao, Lingrong, et al. "Femtosecond Relativistic Electron Beam with Reduced Timing Jitter from THz Driven Beam Compression." *Physical Review Letters* 124.5 (2020): 054802.

[11] Huang, W. Ronny, et al. "Terahertz-driven, all-optical electron gun." *Optica* 3.11 (2016): 1209-1212.

[12] Fallahi, Arya, et al. "Short electron bunch generation using single-cycle ultrafast electron guns." *Physical Review Accelerators and Beams* 19.8 (2016): 081302.

[13] Lewis, S. M., A. A. Haase, D. Kim, E. A. Nanni, M. A. K. Othman, E. I. Simakov, and A. V. Sy. *Design of a High Gradient THz-Driven Electron Gun*. No. SAPAF04. SLAC National Accelerator Lab., Menlo Park, CA (United States), 2019.

[14] Toufexis, Filippos, et al. "Experimental demonstration of a 5th harmonic mm-wave frequency multiplying vacuum tube." *Applied Physics Letters* 110.26 (2017): 263507.

[15] Nanni, Emilio A., et al. "Photonic-band-gap gyrotron amplifier with picosecond pulses." *Applied Physics Letters* 111.23 (2017): 233504.

[16] Soane, Alexander V., et al. "Operation of a 140-GHz gyro-amplifier using a dielectric-loaded, severless confocal waveguide." *IEEE Transactions on Plasma Science* 45.10 (2017): 2835-2840.

[17] Picard, Julian F., et al. "Laser-driven semiconductor switch for generating nanosecond pulses from a megawatt gyrotron." *Applied Physics Letters* 114.16 (2019): 164102.

[18] Kutsaev, S. V., et al. "Nanosecond rf-power switch for gyrotron-driven millimeter-wave accelerators." *Physical Review Applied* 11.3 (2019): 034052.

[19] Jolly, Spencer W., et al. "Spectral phase control of interfering chirped pulses for high-energy narrowband terahertz generation." *Nature communications* 10.1 (2019): 1-8.

[20] Moriguchi, Y., et al. *Applied Physics Letters* 113.12 (2018): 121103.