# Short-pulse wakefield structure R&D for high gradient and high efficiency acceleration in future large-scale machines

Jiahang Shao,[i] John Power,[i] Chunguang Jing,[i,ii] Gwanghui Ha,[i] Philippe Piot,[i,iii] Alexander Zholents,[i] Xueying Lu,[i,iii] Richard J Temkin,[iv] Julian F Picard,[iv] Vasili M. Tsakanov,[v] Chuanxiang Tang,[vi] Yingchao Du,[vi] Jiaru Shi,[vi] Emilio A Nanni,[vii] Brendan O'Shea,[vii] Yuri Saveliev,[viii] Thomas Pacey,[viii] James Rosenzweig,[ix] Gerard Andonian,[ix] Evgenya I. Simakov,[x] Francois Lemery,[xi]

**Abstract:** Structure Wakefield Acceleration (SWFA) is one of the three Advanced Accelerator Concepts (AAC) recommended by the HEPAP Accelerator research and development (R&D) Subpanel to pursue the goal of reducing the construction and operation costs of future colliders. Acceleration at high gradient and high efficiency is critical to cost reduction in SWFA, and it heavily relies on the wakefield structure. In the baseline design of the conceptual 3 TeV Argonne Flexible Linear Collider (AFLC), dielectric-loaded structures are powered by 20 ns short pulses with targets of ~300 MV/m gradient and ~27% rf-to-beam efficiency [1]. Since the last Snowmass and P5 report, progress on accelerating structure R&D has shown promising paths toward and beyond these targets, making SWFA a very attractive option for TeV-scale machines and compact acceleration in general. In Snowmass 2021, we propose to strengthen short-pulse wakefield structure R&D to facilitate milestones and deliveries.

**Introduction**: The AAC field conducts long-term research aimed at a future large-scale collider that will operate at substantially higher energy and lower cost than is possible with current accelerator technology [2]. In SWFA, a high-charge drive beam traveling through a structure excites wakefields, which are then used to accelerate a low-charge main beam, in either the same structure (collinear wakefield acceleration, CWA) or a parallel structure (two-beam acceleration, TBA). Based on extensive research in the high-gradient community, short radiofrequency (rf) pulses are expected to decrease the rf breakdown rate and increase the operating accelerating gradient [3]. Therefore, 20 ns rf pulses, more than an order of magnitude shorter than those typically used in pulsed machines, are proposed for the TBA-based AFLC so as to achieve an ~300 MV/m gradient [4]. Gradient and efficiency considerations in the short pulse approach lead to unique requirements of the wakefield structure, namely high shunt impedance, high group velocity, and low structure losses. Several candidate structures are under development and their preliminary tests show promising results. Meanwhile, fundamental research is ongoing to understand the physics of gradient limitations. Taking the opportunity of Snowmass 2021, we summarize the current status and future directions of wakefield structure R&D as follows. In order to realize a practical short-pulse structure, deeper and further explorations are needed.

**Advanced wakefield structures:** The high group velocity requirement results in low shunt impedance in the current metallic disk-loaded structures. Therefore, advanced structures with simultaneous high group velocity, high shunt impedance, and low loss is a core of the short-pulse SWFA research. The low-cost dielectric-loaded accelerator (DLA) is currently the most developed advanced structure, having demonstrated 200 MW generated power and GV/m sustainable gradient [5]. However, its relatively low shunt impedance and high loss limits the further improvement of rf-to-beam efficiency. Recently, two other candidates with the potential to overcome these disadvantages have begun development: a dielectric disk-loaded accelerator (DDA) using low-loss dielectric disks between cylindrical cells [6], and an all-metal metamaterial structure (MTM) with sub-wavelength features [7]. If successful, these structures could improve the rf-to-beam efficiency by 50% and therefore reduce the site power and operation costs. Future work in the advanced wakefield structures includes: (1) push the power and gradient achieved in DLA, DDA, and MTM in high power beam test; (2) use the ultralow-loss dielectric developed in Japan [8] to reduce the rf loss in DLA and DDA; (3) improve the fabrication technique to obtain higher reliability and to reduce the cost; (4) study and demonstrate higher-order mode damping methods to mitigate long-range transverse wakefield; (5) build fully functional prototypes for AFLC; and (6) explore other novel structures that could meet the requirements in short-pulse TBA.

**High-frequency wakefield structures:** Recently, interest in high-frequency structures has increased. It is well known that such structures have the advantage of strong beam-structure interaction (high gradient) and small transverse size, which could potentially reduce the construction cost of future colliders. However, most wakefield structures proposed for TeV-scale colliders operate in the microwave range with maximum frequency lower than 30 GHz. This limit is due to conventional fabrication technologies. Recent advances in fabrication, such as additive manufacturing [9], two-half assembly without brazing [10], and precise etching control of dielectric, have made it possible to consider wakefield structures with frequency in the mm-wave and THz regime. Researchers have tested 400 GHz DLAs, and ~300 MV/m acceleration gradient was observed [11]. There are also 200 GHz metallic corrugated waveguide structures under development for a CWA-based multi-beamline XFEL [9]. A theoretical calculation of 1.4-THz structures shows that a GV/m gradient could be achieved when driven by THz bunch trains [12]. Future directions of high-frequency wakefield structures include: (1) fabricate matched power extractor (decelerator) and accelerator to demonstrate the TBA concept; (2) study advanced approach to improve the power coupling between decelerator and accelerator; (3) develop collider concept based on high-frequency short-pulse TBA; and (4) study short-range and long-range BBU control.

**Fundamental gradient limitations:** The accelerating gradient in SWFA will be eventually limited by fundamental physics, such as rf breakdown, multipacting, and beam loading from field emission. These issues are common for the high-gradient community and extensive research has been conducted to solve the issues or improve the understanding of them, such as cryogenic operation [13], curved surface to reduce internal multipacting current [14], and multipacting suppression by external magnetic field [15]. However, most of the research focuses on long-pulse operation (>100 ns) and the information on short-pulse operation (~20 ns) is based on theoretical assumptions. There is an urgent need to experimentally investigate the structure limitation in short-pulse regime with direct high-power tests. Future work to understand the fundamental gradient limitations includes: (1) study the gradient scaling law in a short-pulse regime; (2) build and demonstrate high-gradient structures taking full advantage of recent discoveries of the limiting factors; and (3) continue fundamental research to understand the complicated physics behind the limiting factors and propose reliable methods to overcome them.

## Author Affiliations:

[i] Argonne National Laboratory, Lemont, IL.
[ii] Euclid Techlabs LLC, Bolingbrook, IL
[iii] Northern Illinois University, Dekalb, IL.
[iv] Massachusetts Institute of Technology, Cambridge, MA
[v] CANDLE SRI, Yerevan, Armenia
[vi] Tsinghua University, Beijing, China
[vii] SLAC National Accelerator Laboratory, Menlo Park, CA
[viii] Cockcroft Institute, Sci-Tech Daresbury, Warrington, U.K.
[ix] University of California, Los Angeles, CA
[x] Los Alamos National Laboratory, Los Alamos, NM
[xi] Deutsches Elektronen-Synchrotron DESY, Hamburg, Germany

## References:

[1] Available at: https://www.anl.gov/awa

[2] L.K. Len, in *Report of the DOE Advanced Accelerator Concepts Research Roadmap Workshop*, Gaithersburg, United States (DOE, Gaithersburg, MD, 2016).

[3] A. Grudiev et al., "New local field quantity describing the high gradient limit of accelerating structures," *Phys. Rev. Accel. Beams* 12, 102001 (2009).

[4] W. Gai et al., "Short-pulse dielectric two-beam acceleration," *J. Plasma Phys*. 78, 339 (2012).

[5] J. Shao et al., "Development and high-power testing of an X-band dielectric-loaded power extractor," *Phys. Rev. Accel. Beams* 23, 011301 (2020).

[6] J. Shao et al., in *Proceedings of the 9th International Particle Accelerator Conference*, Vancouver, BC, Canada, pp. 1539–1541 (2018).

[7] X. Lu et al., "Generation of High-Power, Reversed-Cherenkov Wakefield Radiation in a Metamaterial Structure," *Phys. Rev. Lett*. 122, 014801 (2019).

[8] D. Satoh et al., "Dielectric assist accelerating structure," *Phys. Rev. Accel. Beams* 19, 011302 (2016).

[9] A. Zholents et al., in *Proceedings of the 9th International Particle Accelerator Conference*, Vancouver, BC, Canada, pp. 1266–1268 (2018).

[10] D. Wang et al., "Interaction of an Ultrarelativistic Electron Bunch Train with a W-Band Accelerating Structure: High Power and High Gradient," *Phys. Rev. Lett*. 116, 054801 (2016).

[11] B. O'Shea et al., "Observation of acceleration and deceleration in gigaelectron-volt-per-metre gradient dielectric wakefield accelerators," *Nat. Commun*. 7, 12763 (2016).

[12] G. Ha et al., "Coherent synchrotron radiation free longitudinal bunch shaping using transverse deflecting cavities," *Phys. Rev. Accel. Beams* 23, 072803 (2020).

[13] A.D. Cahill et al., "High gradient experiments with X-band cryogenic copper accelerating cavities," *Phys. Rev. Accel. Beams* 21, 102002 (2018).

[14] H. Xu et al., "Measurement of internal dark current in a 17 GHz accelerator structure with an elliptical sidewall," *Phys. Rev. Accel. Beams* 23, 031003 (2020).

[15] C. Jing et al., “Complete multipactor suppression in an X-band dielectric-loaded accelerating structure,” *Appl. Phys. Lett*. 108, 193501 (2016).