

MODERNIZING THE AWA FACILITY: ENHANCED BEAM QUALITY AND CAPABILITIES FOR HIGH-GRADIENT RF AND BEAM PHYSICS RESEARCH *

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Abstract

The Argonne Wakefield Accelerator (AWA) is a 1300 MHz, 65 MeV normal-conducting photoinjector LINAC supporting a broad research program in high-gradient RF acceleration, beam physics, and AI/ML-based accelerator operations. The facility produces electron bunches spanning 1 pC to 100 nC, including high-charge (~100 nC, ~25 kA), high-brightness (~hundreds nm emittance), and arbitrarily shaped formats, and delivers beam to 5 device-under-test zones along two primary experimental beamlines.

Over the past decade the AWA has undergone extensive modernization, including replacement of the drive gun with an RF-symmetrized photoinjector; upgrade of the drive laser from a 248 nm excimer to a 262 nm Ti:sapphire system; transition to a distributed EPICS-based control system; and deployment of a digital LLRF system developed by the LBNL BACI group. Recent experiments have demonstrated accelerating gradients >300 MV/m in X-band structures, peak cathode fields >400 MV/m, and beam-driven RF power generation >565 MW.

Near-term plans include RF-symmetrized linac cavity replacements and an asymmetric EEX beamline upgrade. A proposed AWA-II upgrade would double the beam energy to ~130 MeV, further expanding the facility’s reach for high-gradient RF and beam physics research.

INTRODUCTION

Accelerator test facilities play a critical role in the development of new technologies for future use at major accelerator user facilities. The Argonne Wakefield Accelerator (AWA) facility at Argonne National Laboratory supports a cost-effective accelerator research program spanning high-gradient normal-conducting RF acceleration [1,2], novel electron source development, advanced beam physics and diagnostics, and AI/ML-based accelerator operations.

In recent years, the AWA facility has undergone substantial modernization aimed at improving beam quality, operational reliability, diagnostics capability, and support for AI/ML-based accelerator operation. Major upgrades include deployment of an EPICS control system [3], an RF-symmetrized photocathode gun, digital low-

level RF (LLRF) [4], and upgrades to the photocathode drive laser system.

The modernization program also supports the growing role of the AWA as an AI-ready testbed for developing and validating new AI/ML techniques towards autonomous accelerator operations: fast tuning, drift stabilization, virtual diagnostics, and performance optimization [5,6].

This paper summarizes the present status of the AWA facility, recent modernization efforts, current experimental capabilities, and future development directions.

FACILITY OVERVIEW

The AWA facility (Fig. 1) is centered around a normal-conducting, 1300 MHz, 65 MeV photoinjector LINAC. The RF gun uses a Cs₂Te photocathode and can produce electron bunches with charges spanning from 1 pC to 100 nC in a single electron bunch and trains of 2–16 bunches with total charge exceeding 500 nC. The facility supports a variety of beam formats including high-charge, high-current beams (~100nC, ~25kAmps) or high-brightness beams (~hundreds nm) or shaped bunches (e.g. flatbeams and/or ramped bunches).

The flexible experimental area includes two primary experimental beamlines: the straightahead beamline and the emittance-exchange (EEX) beamline. Distributed along these beamlines are five experimental device-under-test (DUT) zones supporting high-charge beam physics, high-gradient RF acceleration, 6D phase-space manipulation, coherent synchrotron radiation (CSR) [7], coherent radiation generation, THz-driven acceleration, and advanced longitudinal beam diagnostics. The straightahead beamline primarily feeds Zones 3a, 3b, and 5, while the EEX beamline delivers beam to Zone 4. Zone 2 supports beam preparation and shaping prior to injection into downstream beamlines.

The AWA includes extensive diagnostics and infrastructure. Longitudinal phase-space diagnostics are provided by transverse deflecting cavities located at the end of each beamline, while transverse phase-space diagnostics and YAG:Ce screens are distributed throughout the DUT zones. Additional diagnostics include a 12 GHz oscilloscope for RF measurements. Facility infrastructure includes an EPICS-based control system, five high-power RF systems, and two synchronized laser systems: Ti:Sa-based 262 nm photocathode laser system [8] and a low-power commercial erbium-doped fiber 1550 nm laser system [9] used for laser-electron beam diagnostics.

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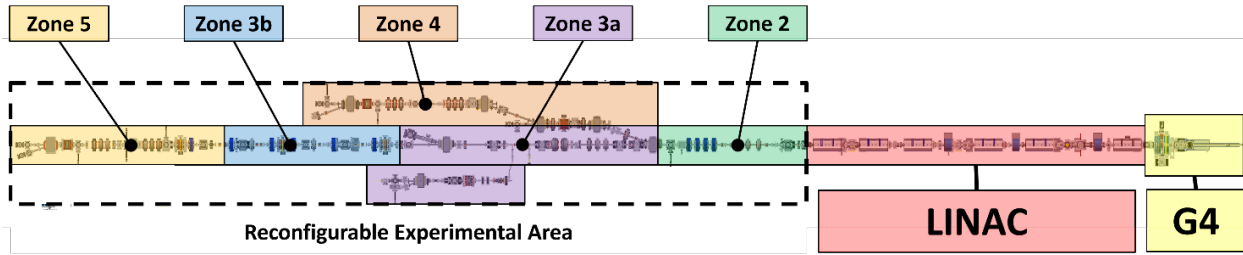


Figure 1: Layout of the Argonne Wakefield Accelerator (AWA) facility showing the 65 MeV photoinjector LINAC and the reconfigurable experimental area with multiple device-under-test (DUT) zones.

The combination of reconfigurable beamlines and semi-specialized experimental zones enables the AWA to support multiple classes of accelerator experiments, including high-gradient RF research, advanced beam manipulation studies, coherent radiation generation, and accelerator technology R&D within a single facility environment

MODERNIZING THE AWA

Over the past decade, the AWA has undergone extensive modernization of its core subsystems to improve beam quality and RF stability (Fig. 2). To improve beam quality, a new RF-symmetrized photoinjector (Fig. 1, G4) replaced the previous drive gun. In addition, the first two linac RF cavities (Fig. 1 LINAC) are planned to be replaced with RF-symmetrized structures next year. To improve RF phase and amplitude stability, the two legacy klystrons were replaced with modern Canon RF stations, and the old National Instruments LLRF system was replaced with a digital system developed by the LBNL BACI group.

The control system was upgraded from a centralized Windows-based architecture to a distributed EPICS-based system running on Linux with embedded controllers. This new control system enables scalable operation,

improved maintainability, and integration with modern data acquisition frameworks.

The photocathode laser was upgraded from a 248 nm excimer-based system to an all-Ti:Sa system. Light from a Coherent Vitara-T oscillator is amplified using Ti:Sapphire regenerative and multipass amplifier stages driven by Spectra Physics Ascend and Powerlite DLS laser systems. The pulse is compressed to 300 fs and frequency tripled to 262 nm. A pulse-train generator (“multisplitter”) produces up to 8 pulses separated by 769 ps [8]. The laser pulse is subsequently stretched to 6 ps using a series of α -BBO crystals and shaped into a smooth flat-top transverse profile using a microlens-array homogenizer system [10], before delivery to a Cs2Te photocathode. These upgrades improve operational stability, maintainability, and laser pulse shaping capabilities for advanced beam generation.

Together, these modernization efforts support the growing role of the AWA as an AI-ready, risk-tolerant testbed for developing and validating new AI/ML techniques prior to deployment at user facilities. Current activities include autonomous accelerator operations encompassing fast tuning, drift stabilization, diagnostics, and performance optimization [5,6]. Future plans include the deployment of AI-agentic platforms such as Osprey [11], in collaboration with APS and the MOAT community [12].

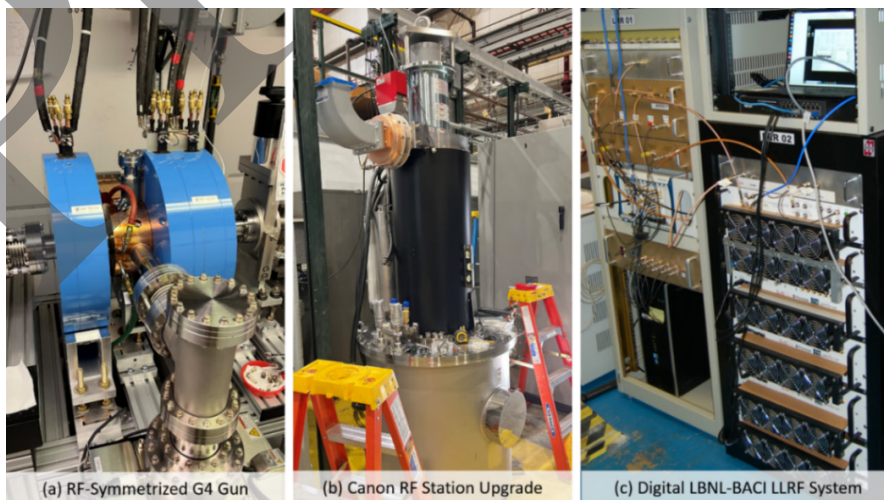


Figure 2: Examples of major AWA modernization upgrades including the RF-symmetrized G4 photoinjector gun, upgraded Canon RF station hardware, and the digital LBNL-BACI LLRF system.

EXPERIMENTAL PROGRAM

The AWA experimental program includes both in-house research and externally led collaborative experiments spanning high-gradient RF acceleration, beam physics, accelerator diagnostics, and advanced accelerator concepts. External collaborators can engage directly with AWA researchers to develop and execute experimental proposals utilizing the facility's flexible beam and diagnostics capabilities.

AWA also participates in the BeamNetUS network [13], which supports external users and researchers seeking access to advanced accelerator test facilities. In addition to supporting collaborative research, the facility plays an important role in workforce development by training graduate students and early-career researchers in accelerator science and technology.

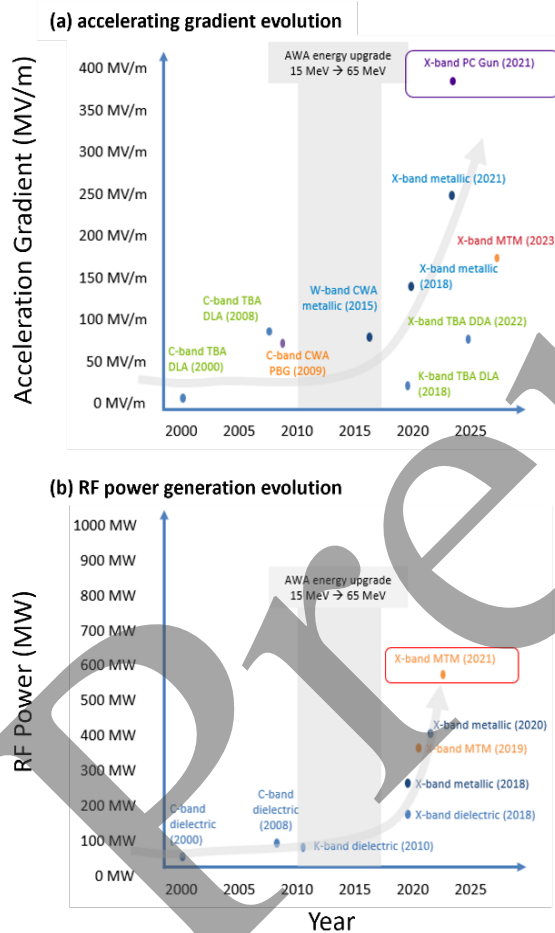


Figure 3: Evolution of short-pulse RF performance at the AWA (a) demonstrated accelerating gradients and (b) beam-driven RF power generation. Recent experiments have demonstrated accelerating gradients exceeding ~ 300 MV/m in accelerating structures, peak fields exceeding ~ 400 MV/m in RF photoinjectors, and beam-driven RF power generation exceeding ~ 565 MW.

RECENT RESULTS

Recent experiments at the AWA have demonstrated significant progress in short-pulse high-gradient RF acceleration and beam-driven RF power generation. Figure 3 summarizes the evolution of demonstrated accelerating gradients and RF power generation at the AWA over the past two decades, highlighting the impact of the facility energy upgrade from 15 MeV to 65 MeV and continued development of advanced RF structures.

In accelerating structures, experiments have demonstrated accelerating gradients exceeding ~ 300 MV/m corresponding to surface electric fields approaching ~ 500 MV/m [14]. In RF photoinjector operation, peak accelerating fields exceeding ~ 400 MV/m corresponding to surface fields approaching ~ 600 MV/m have been achieved [15].

The AWA has also demonstrated beam-driven RF power generation exceeding ~ 565 MW in short-pulse X-band structures [16]. These results establish the AWA as a leading facility for experimental studies of high-gradient normal-conducting RF acceleration and high-power beam-driven RF generation.

FUTURE DIRECTIONS

Near-term operation will focus on continued commissioning of beam quality and phase-space control. Near-term planned upgrades include replacement of the first two linac RF cavities with RF-symmetrized structures and upgrades to the EEX beamline to an asymmetric configuration to suppress CSR and improve phase-space manipulation.

A proposed AWA-II upgrade [17] would increase the beam energy from approximately 65 MeV to 130 MeV, expanding the accessible parameter space for beam-driven acceleration and high-gradient RF studies.

In parallel, ongoing efforts are focused on the development of AI/ML-based accelerator control techniques for beam tuning, diagnostics, and optimization. These efforts build upon the facility's modern EPICS and digital LLRF infrastructure with the goal of improving reproducibility, stability, and autonomous operation.

CONCLUSION

The AWA has undergone significant modernization, resulting in improved beam quality, stability, reproducibility, and operational flexibility. The facility provides unique capabilities for high-charge beam physics, high-gradient RF research, and advanced accelerator diagnostics within a flexible and collaborative experimental environment. Recent upgrades position the AWA as a platform for advanced data-driven accelerator operation, including the development and validation of AI/ML-based accelerator techniques. Planned subsystem upgrades and the proposed AWA-II energy upgrade will further expand the facility's performance and relevance for future accelerator science and technology R&D.

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