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USER RESEARCH AT BNL'S ACCELERATOR TEST FACILITY*

I. Pogorelsky[1,†], M. Babzien[1], M. Polyanskiy[1], D. Choge[1], M. Fedurin[1], W. Li[1], Y. Sakai[1], N. Vafaei-Najafabadi[1,2], S. Biedron[3,4], M. A. Palmer[1]
[1]Brookhaven National Laboratory, Upton, USA
[2]Stony Brook University, Stony Brook, USA
[3]Element Aero, Chicago, USA
[4]Center for Bright Beams, Ithaca, USA

Abstract

The Accelerator Test Facility (ATF) at Brookhaven National Laboratory (BNL) is a U.S. Department of Energy (DOE) Office of Science user facility, equipped with a high-brightness RF electron LINAC, a femtosecond Ti:sapphire laser, and a multi-terawatt long-wave infrared (LWIR) laser. This unique suite of tools, capable of both synchronized and independent operation, enables transformative research across a wide range of disciplines. This paper outlines the advanced capabilities available at ATF and highlights present and emerging opportunities for user collaboration.

INTRODUCTION

The ATF [1] has supported user experiments for over 30 years and has been formally recognized as one of the DOE Office of Science's proposal-driven, peer-reviewed user facilities since 2015 [2]. It serves as a flagship facility under the Accelerator Stewardship program and, as of 2024, is also a member of the BeamNetUS network [3].

ATF delivers 20–75 MeV electron beams from a linear accelerator (LINAC) initiated by a high-brightness RF photocathode gun. Typical beam parameters include a normalized emittance of 1 µm, energy spread of 0.1%, charge around 1 nC, and bunch durations ranging from 200 fs to 10 ps, including multi-bunch operation.

The ATF's 5-TW, 9.2-µm LWIR laser is a one-of-a-kind system that has pioneered several technological breakthroughs, such as the first use of chirped-pulse amplification in a gas laser, multi-isotope CO_2 laser amplification, and a solid-state laser front end. Together with the co-located electron LINAC and lower-power NIR lasers, these resources provide a powerful platform for frontier research in laser-plasma acceleration, high-brightness X-ray sources via inverse Compton scattering (ICS), and other advanced studies. Some of these opportunities are illustrated in this paper.

LWIR LASER DEVELOPMENT

LWIR radiation is advantageous for both fundamental and applied science due to its strong ponderomotive interaction with electrons, low critical plasma density, and other favourable wavelength-dependent scaling laws. ATF is extending current laser capabilities from a 5 TW, 2 ps toward the multi-terawatt, sub-picosecond regime. By 2028, the goal is to achieve 15 TW in 500 fs using a 10 mJ OPCPA seed; by 2029, the facility aims for 25 TW in 100 fs using a post-compression stage [4]. These upgrade steps are illustrated by Fig. 1.

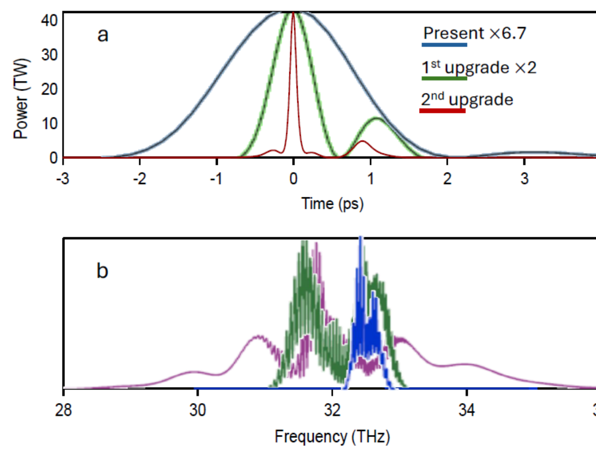

Figure 1: (a) Simulated laser output pulse profiles normalized to the 2nd upgrade's peak power; (b) corresponding normalized output pulse spectra.

USER RESEARCH PROGRAM

A broad range of user experiments are conducted using ATF's laser and electron beams, supported by additional diagnostic and computational tools as detailed on the ATF website [1]. These activities are also summarized in the annual ATF user meetings [5], with the latest held April 29–May 1, 2025 [6].

Combined Laser and Electron Beam Studies

LWIR lasers are particularly suited to particle acceleration due to favourable scaling of electron quiver energy ($\sim\lambda^2$) and critical plasma density ($\sim 1/\lambda^2$) with laser wavelength. In laser wakefield acceleration (LWFA) at low plasma densities ($n_e \approx 10^{16}$ cm $^{-3}$), the increased trapping volume ($\sim n_e^{-3/2}$) facilitates LWFA regimes where beam qualities approach conventional RF accelerators [7, 8].

Precise *collinear* injection of relativistic electron bunches into plasma wakes is critical: spatial tolerances are on the order of tens of microns. Simulations in Fig. 2 [9] illustrate how misalignment affects energy spread. With co-located LWIR laser and high-brightness electron LINAC, the ATF is uniquely positioned for this kind of

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† igor@bnl.gov

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studies, especially after the planned femtosecond upgrade discussed in the previous section.

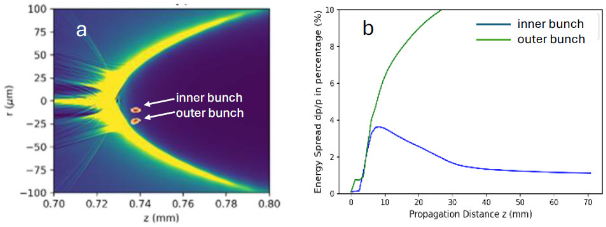

Figure 2: Simulated energy spread for electron bunches injected off-axis by 10 µm and 23 µm into wakes driven in $n_e \approx 10^{16}$ cm $^{-3}$ plasma by a 10-µm, 500-fs laser pulse [9].

ATF experiments have provided new insights into the characteristics of laser-generated plasma wake fields by utilizing electron bunches from the ATF's linac, directed *perpendicular* to the laser beam. These bunches create radiographic images of plasma fields on a luminescent screen positioned at a variable distance from the wake. This technique offers a rare opportunity to visualize wake fields, which are otherwise understood primarily through simulations.

Figure 3 illustrates this approach by comparing experimental and simulated electron beam (e-beam) patterns produced by a collimated e-beam traversing a plasma wake generated by a CO_2 laser [10].

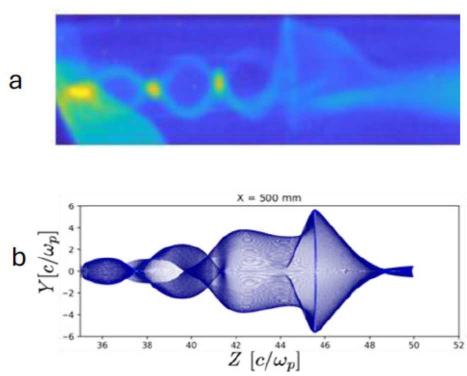

Figure 3: Experimentally observed (a) and simulated (b) radiographic patterns produced upon the e-beam passage across a plasma wake generated in $n_e = 10^{15}$ cm^{-3} plasma by a 2 TW, 2 ps CO_2 laser pulse [10].

Studies of plasma instabilities lead to better understanding of astrophysical phenomena as well as fast ignition in inertial confinement fusion. Again, the LWIR laser driver is ideal for these studies because it strongly affects plasma temperature, and has a low critical plasma density, allowing optical diagnostic of the plasma with NIR lasers. This was capitalized in the ATF experiment that probed B-fields generated by Weibel plasma instability (see Fig. 4) [11].

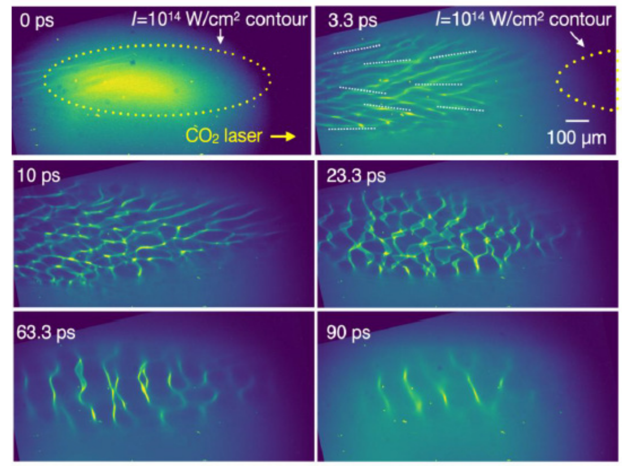

Figure 4: Electron radiography of Weibel instability [11].

Direct interaction between laser and e-beam in vacuum is another active area of the ATF user research. LWIR lasers offer an order-of-magnitude higher number of photons per joule of energy than NIR systems. This advantage supports the expectation of high quantum yields of X-rays produced via ICS.

The ATF's LWIR laser focused to $w_0 \approx 20$ µm provides ~2×10^{25} laser photons per cm^3. For 1 nC picosecond electron bunches supplied by the ATF linac and focused to a size compatible with the laser focus the ICS X-ray yield reaches 2×10^9 photons per shot [12]. This allows for single-shot imaging of X-ray fluxes using microchannel plates, facilitating a broad range of applied ICS studies.

One such application is a single-shot phase-contrast tomography, which also benefits from the spatial coherence of the ICS X-rays radiated by an electron beam of a several micron cross-sections. The ability to retrieve phase information from single-shot images of material and biological test objects using ICS sources was first demonstrated in ATF experiments [13, 14].

Additionally, the scaling of the electron's ponderomotive energy with λ^2 facilitates access to the nonlinear ICS regime. This regime was rarely explored experimentally before ATF experiments, which successfully achieved single-shot visualization of the characteristic intensity distribution of second and third ICS harmonics, along with a redshift consistent with theoretical predictions [15, 16].

Laser-Only Research

The same favourable wavelength scaling of physical phenomena relevant to LWFA benefits other applications such as quasi-monoenergetic MeV-class proton beam generation using supersonic gas jets as laser targets [17, 18]. Here, the ATF experiment generated proton beam from an initially gaseous hydrogen target via the radiation pressure driven shock. Such proton and ion sources will find applications in cancer treatments [19] as well as in the generation of beams for radiation testing, including microelectronics.

Another example of laser-only experiments at the ATF illustrated by Fig.5 is remote detection of radioactive materials. A short-pulse LWIR laser generates a strong light

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filament in air over an extended distance to produce localized optical avalanche breakdown in the vicinity of a radioactive source. The location of the breakdown can be visually detected, and the distance to the radioactive source accurately measured by the return laser signal [20].

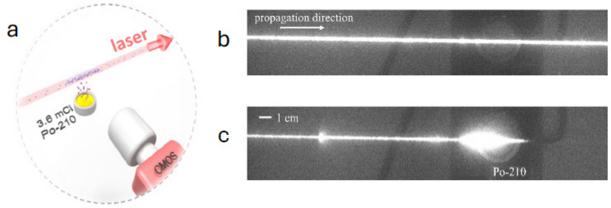

Figure 5: Remote detection setup (a); filament propagation with blocked (b) and open (c) Po-210 alpha source [20].

CONCLUSION

Over its operational history, ATF has supported more than 130 user teams. This paper highlights several recent experiments, while a full overview of capabilities and results is available online. ATF welcomes new proposals and user input to help shape future upgrades and research directions.

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