FULFILLING THE MISSION OF BROOKHAVEN ATF AS DOE'S FLAGSHIP USER FACILITY IN ACCELERATOR STEWARDSHIP*

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Abstract

The Accelerator Test Facility (ATF) at Brookhaven National Laboratory has served as a user facility for accelerator science for over a quarter of a century. In bringing advanced accelerator-science and technology to individual users, small groups of researchers, and large collaborations, the ATF offers a unique combination of a high-brightness 80-MeV electron beam synchronized to a Terawatt-class picosecond CO_2 laser. The ATF is now the flagship user facility of the Accelerator Stewardship program of the DOE OHEP. In this role, it will also provide opportunities for small businesses to develop accelerator-based products, running the full gamut from the laboratory to the applications. At this juncture, the ATF has embarked upon a transformational upgrade of its capabilities designed to meet ever-growing demands of the user community. We describe our plan for greatly expanding the ATF's floor space along with critical enhancement of our laser and electron accelerator capabilities to enable forefront research for advanced acceleration techniques and radiation sources. We will discuss emerging opportunities for scientific breakthroughs in several areas of R&D enabled by the ATF upgrade.

INTRODUCTION

25 years ago, a newly created Brookhaven Accelerator Test Facility (ATF), sponsored by the U.S. Department of Energy (DOE) Office of High-Energy Physics (OHEP), pioneered the concept of a proposal-driven user facility for advanced accelerator research using lasers and electron beams. Since then, the ATF has become an internationally recognized destination for researchers who benefit from free access to unique scientific capabilities not otherwise affordable to individual institutions and businesses.

We explore several examples that demonstrate the tremendous productivity of collaborative user research utilizing the ATF's unique accelerator capabilities and professional staff. Researchers from academia, industry and national laboratories have successfully investigated a wide range of topics at the ATF: from free electron lasers (FEL) to their opposites – inverse FEL accelerators; from x-ray Compton scattering by colliding laser- and electron-beams to THz radiation generated by beams interacting with tiny radiation structures; from testing radiation damage to electronics for space missions to the study of wakefields in plasmas and dielectric capillaries; and finally the investigation of novel methods of accelerating electrons and ions without using RF cavities.

The ATF, which was designated a DOE Office of Science National User Facility in 2015, serves as the flagship research facility for the Accelerator Stewardship Program. ATF continues to broaden its user community by reaching out to federal agencies, universities, and industrial users. It serves as a community catalyst and incubator for new creative ideas.

Building on the success of the ATF user research program, DOE has begun investment in the upgrade of both the electron beam and laser capabilities of the facility. We describe how the ATF-II upgrade will transform the facility's science reach and productivity by offering new opportunities for innovative research in strong-field physics and advanced accelerator design with a range of parameters not previously accessible. By enabling first-of-kind technical demonstrations and workforce training, ATF-II will fulfil a broad Accelerator Stewardship mission and will support a wide variety of user needs.

ACCELERATOR STEWARDSHIP: FROM CONCEPT TO IMPLEMENTATION

Much of the U.S. effort in accelerator science and engineering takes place in the Department of Energy's National Laboratories. However, researchers from universities and small businesses play a vital role in advancing the field. An important question is how can these diverse groups afford to undertake state-of-the-art experimental research to explore bold new ideas, test new techniques, and prove theoretical models? The answer is clear: It lies in the ready availability of modern user facilities. Indeed, user facilities are the mainstay of many sciences, and, by hosting a free service for users, they deter waste and duplication of effort. They are invaluable in that they enable investigators with a small research budget to carry out their experimental work using high-performance accelerators and lasers, supported by experts dedicated to this task. To understand how the Accelerator Stewardship Program developed into a strategic direction for accelerator science and technology (AST), we must go back in the history of accelerator R&D, starting from the 1980 recommendations of the M. Tigner Panel on the Long Range Accelerator R&D at OHEP. The members of this panel were largely responsible for establishing the proposal-based program that has supported long-range accelerator R&D over the past few decades. The ATF was established in mid-1980s as a part of this program.

The "accelerator stewardship" concept emerged in 1994 recommendations of the J. Marx Panel. Established

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by DOE's Office of Energy Research (OER) as a High Energy Physics Advisory Panel (HEPAP), this panel was tasked with undertaking a broad assessment of the status and promise of the field of accelerator physics and technology with respect to five OER programs, which included High Energy Physics, Nuclear Physics, and Basic Energy Science. A notable excerpt from the panel's report states: "This subpanel believes that the DOE and its predecessor agencies—primarily through their long-standing and sustained investments in accelerator science and technology development—have de facto held a national trust for the stewardship of accelerator science and accelerator-based technology development."

In 2006, the Federal advisory board, HEPAP, established a subpanel on Accelerator R&D, also chaired by J. Marx [1]. This subpanel offered several concrete recommendations on the stewardship role of the OHEP for long- and mid-term accelerator R&D as well as the need for providing opportunities for workforce training at the experimental accelerator science facilities of the National Laboratories. They also examined the need for the stewardship role to be maintained, enhanced, and properly funded permanently.

Further strides towards broadening of the OHEP-support accelerator R&D were made at the 2009 symposium "Accelerators for America's Future" [2]. The symposium was extremely successful in showing the importance of accelerators for our nation and in making the case for Federal support. Consequently, in 2011 the US Senate issued a report that directed the DOE "…to submit a 10-year strategic plan for accelerator-technology research and development to advance accelerator applications in energy and the environment, medicine, industry, national security, and discovery science." [3]

After the Accelerators for America's Future symposium, a series of workshops and panels offered guidance to the OHEP on how best to fulfill this mission. A clear statement of the program goals reads as follows [4]: *The mission of the DOE Long-Term Accelerator R&D Stewardship Program is to:*

- *Support fundamental accelerator science and technology R&D, and*
- *Disseminate accelerator knowledge and training.*

This mission is implemented through:

- *Facilitating access to national laboratory accelerator facilities and infrastructure† for industrial and U.S. government agency users and developers of accelerators and related technology,*
- *Developing innovative solutions to critical problems, to the benefit of both the broader user communities and the DOE discovery science community,*
- *Serving as a catalyst to broaden and strengthen the community that relies on accelerators and accelerator technology.*

In FY 2014 DOE Funding Bill, the US Senate wrote the following: "Within the funds for High Energy Physics, the Committee also recommends $20,000,000 for Accelerator Stewardship. The Committee recognizes the critical role accelerator technology can play in addressing many of the economic and societal issues confronting the country. The Committee supports the Office of Science's efforts to make unique test facilities available to U.S. industry to accelerate applications of accelerator technology…"

Based on this guidance, targeted programs in accelerator science were established by the OHEP in 2014 [5]. These included:

- A Funding Opportunity Announcement (FOA) in Accelerator Stewardship;
- The Accelerator Stewardship Test Facility Pilot Program wherein the ATF is recognized as a flagship user-facility;
- Accelerator Stewardship Program funding to support ATF operations and the ATF-II upgrade.

ATF'S ROLE IN THE ACCELERATOR STEWARDSHIP PROGRAM

The elements of the above implementation underscore the importance of dedicated user facilities in fulfilling that mission as well as the unique role of the ATF. Historically, the ATF [6] has served a stewardship function for the accelerator physics community, long before a formal concept for accelerator stewardship was formulated. The ATF presently operates as a DOE Office of Science National User Facility, funded through the U.S. DOE OHEP Accelerator Stewardship Program. It provides a platform for proposal-driven and peer-reviewed research that offers qualified researchers free access to high quality laser and electron beams. In particular, the facility offers a multi-terawatt, picosecond, carbon-dioxide, infrared laser system that is synchronized to high-brightness electron bunches from a state-of-the-art 80-MeV linear accelerator. This unique combination of capabilities allows users to explore the long-wavelength scaling of strong-field electromagnetic processes and provides an unsurpassed opportunity to users to explore a new parameter space of potential importance to future accelerator capabilities.

As a DOE National User Facility, the ATF accepts proposals from across the scientific community including universities, laboratories, and industry, regardless of the source of funding or the intended application of the accelerator-science being pursued. Access to the facility is free for qualified users and approved proprietary research can be conducted on a cost-recovery basis. The opportunities provided by the ATF have been widely recognized by the research community and, over more than two decades of operation, the facility has been utilized by hundreds of users. These users have carried out ground-breaking experimental research in the physics of accelerator beams, particle sources, and beam instrumentation. They have also explored novel acceleration techniques and radiation sources. All this work has been carried out with the close, dedicated, and expert support of the ATF staff.

The broad range of research opportunities afforded by the ATF is illustrated by the following examples taken from its more than two decades of operation.

Research carried out at the ATF was critical to the advent of x-ray Free Electron Laser (FEL) facilities. This work encompasses the first demonstrations of very high-brightness electron beams generated from a photocathode radiofrequency (RF) gun [7], self-amplified spontaneous emission in the visible wavelengths [8], and the first seeded FEL high-gain harmonic generation [9]. These ATF developments laid the foundation for the Linac Coherent Light Source (LCLS) and other leading worldwide FEL projects.

A range of demonstrations were made possible by the availability of the unique CO_2 laser system at the ATF. The first-ever demonstration of multi-stage laser acceleration was carried out at the ATF [10] using the Inverse Free Electron Laser (IFEL) process. This demonstration, a novelty at the time, validated the ability to produce beams with narrow energy spread. Secondly, Compton scattering by colliding infrared photons with an electron beam resulted in strong bursts of x-rays [11], thus supporting ultra-fast, high-contrast tomography. Thirdly, a focused laser beam interacting with a supersonic hydrogen-gas jet has been shown to produce monoenergetic MeV-scale proton beams [12], thus enabling an ongoing research effort towards the medical application of such beams.

Exploration of plasma wakefields driven by an electron beam was another notable part of the ATFs' research program during the last decade. The introduction of a capillary discharge as a plasma source embedded in the electron beamline [13] enabled experimental measurements of the phase relationship between the longitudinal- and the transverse-components of the wake fields acting on a drive electron-bunch [14]. Proposals for a series of plasma-based studies quickly followed that entailed comprehensive studies of a wide spectrum of the electron bunch's modulation effects, i.e., longitudinal, transverse, and in electron momentum. These studies provided the first experimental demonstrations of the high-gradient, controlled acceleration of a short electron bunch trailing the driver electron-bunch [15], electron beam filamentation [16], seeding of the self-modulation instability [17], and the demonstration of the resonance multi-bunch plasma wakefield acceleration (PWFA) along with a masking technique to generate a train of sub-picosecond electron bunches with well-controlled spacing [18].

Recent examples of user experiments based on combining CO_2 laser capabilities with an electron beam include: the demonstration of 50 MeV energy-gain and 100 MeV/m acceleration gradient realized in the IFEL RUBICON experiment [19], which represent record numbers for electron acceleration in vacuum; and the observation of the mass-shift effect and up to the 3rd harmonic component in the spectrum observed in the Inverse Compton Scattering (ICS) process [20].

A core element of the Accelerator Stewardship mission is the training of the next generation of accelerator scientists. This has always been a focus of the ATF research program with 39 PhD theses having been successfully defended based on graduate research conducted at the facility. The ATF contribution to accelerator physics education has recently been further enhanced with a hands-on graduate training course for students in the Center for Accelerator Science and Education (CASE) Program at the State University of New York - Stony Brook campus.

The above history of cutting edge research, development of techniques and technology leading to new accelerator capabilities, and strong support for accelerator physics education established the ATF's stewardship role. Thus it was a natural choice for the lead facility in OHEP's Accelerator Stewardship Program.

THE ATF-II UPGRADE AND ITS POTENTIAL FOR DISCOVERY SCIENCE

Given the established role played by the ATF in cutting edge accelerator research, the DOE has initiated funding of a plan to significantly expand the capabilities and science reach of the ATF. The ATF-II Upgrade will improve the facility's infrastructure, expand its electron accelerator research capabilities, and enable a transformational increase in the available peak power from its CO_2 laser. These upgrades will allow the ATF user community to continue to conduct experiments at the forefront of advanced accelerator research and radiation-source development for years to come. The expanded science reach of the ATF-II will support the most innovative ideas in these fields and stimulate the emergence of new ones.

In order to provide added flexibility for the facility, the ATF-II plan aims to move the facility to a new location on the Brookhaven site. The new location in Building 912 will provide more than 3 times the floor space of the present facility. This additional space will enable deployment of multiple, individually isolated experimental halls, which will greatly improve our ability to support multiple experimental groups simultaneously and is expected to lead to a substantial increase in user throughput. It also provides ample room for future updates to the facility.

One of the first benefits to be realized from the relocation of the facility has been the ability to add new electron beam research capabilities to the ATF portfolio. The first operational element of the new ATF-II is an Ultrafast Electron Diffraction facility [21], which will explore the uses and further develop the capabilities of this class of device.

More broadly, the relocation of the facility will allow us to improve the ATF electron beam's quality, stability, and energy through installing a new electron gun and a UV photocathode laser system, adding linac sections and higher power klystrons, and providing space for a bunch compressor capable of providing bunch lengths measured in femtoseconds. The upgrade will provide a set of state-of-the-art beam lines that have laser-tracker alignment and excellent thermal stability.

A central element of the ATF-II plan is an expansion of the CO_2 laser system, which will provide the foundation to achieve ultra-fast (sub-picosecond) and ultra-high power (100 TW class) IR laser performance. Attaining these operating levels will provide ATF-II users with unique opportunities to explore wavelength scaling of strong-field physics phenomena up to the laser-strength parameter $a_o = eE/m\omega c = 10$ at a laser wavelength of λ = 10 µm, where E is the laser's electric field, e and m are the electron charge and mass, respectively, c is the speed of light, and $\omega = 2\pi c/\lambda$ is the laser's frequency. This regime represents nearly a hundred-fold increase in peak power over the present ATF laser system. In order to achieve these parameters, the upgraded ATF-II facility will be designed to enable advances in four key areas: a solid-state, femtosecond, optical parametric amplifier (OPA) front end [22]; a chirped pulse amplification (CPA) system [23]; the use of multiple CO_2 isotopes [24] in the expanded chain of laser amplifiers; and nonlinear pulse-compression down to three cycles [25].

It is worth discussing, for a moment, the scientific reach that will be enabled by a λ = 10 µm laser system operating in the 100 TW regime. We note that the ponderomotive potential of electrons produced at the laser interaction point with a gas medium scales as $\Phi = I/4\omega^2$. Thus a 1 µm laser will require an intensity that is one hundred times higher than that required for a 10 µm laser. This wavelength scaling has been previously demonstrated by comparing the intensity required to produce the same ion acceleration, via the Target Normal Sheath Acceleration (TNSA) mechanism, with a 10 µm CO_2 laser system (10^{16} W/cm^2) and a 1 µm solid state laser system (10^{18} W/cm^2) [26].

In addition to the effect of the ponderomotive potential, we must also consider the number of electrons and ions that effectively interact with the field of the laser as a function of its wavelength. When working at the diffraction limit of the laser beam, the yield of hot electrons will be determined by the surface area of the laser spot. Thus the integral yield of hot electrons from a laser-induced plasma is expected to be one hundred times smaller for a 1 µm laser system in comparison to one with a 10 µm wavelength. These types of considerations drive interest in two current research thrusts which we describe below.

The first is Laser Shock Wave Acceleration (LSWA) of protons, which has been previously demonstrated with the CO_2 lasers [12, 27]. This method of producing and accelerating protons holds the promise of providing proton beams that are suitable for medical treatments. A key feature of this methodology is the ability to produce nearly mono-energetic ion beams. The near linear scaling of the ion energy with laser intensity allows us to project that 170-MeV low-energy spread proton beams can be obtained with a CO_2 laser intensity of ~10^{18} W/cm^2, which is achievable at 100 TW peak power. More detailed simulation studies support this projection [28].

Our second thrust is associated with the potential of longer wavelength lasers for developing a path to very high energy collider capabilities using Laser Wakefield Acceleration (LWFA) techniques. Near-infrared (λ=0.8-1 μm) solid-state lasers, offering Petawatt peak power and femtosecond pulses, have been shown to be capable of driving a plasma wake that can accelerate electrons with up to 100GV/m longitudinal fields [29]. We note that longer laser wavelengths have the potential of inducing stronger ponderomotive excursions of plasma electrons, thus achieving bigger blowout structures, or plasma "bubbles". This opens the possibility for increasing both the size and charge of the electron bunches being accelerated. By creating a bubble with a thousand-fold greater volume than presently achievable with solid state lasers, a CO_2 laser system operating at λ = 10 µm would significantly reduce the problem of space charge and simplify electron injection into the acceleration stages envisioned for prospective compact plasma-based, TeV-class electron-positron and gamma colliders [30-32]. These features, in combination with a femtosecond-class electron injector as envisioned for ATF-II, demonstrate the potential of the LWFA research that could be carried out in the upgraded facility. These experiments would provide an important complementary research path to that being pursued at world-wide PW laser facilities based on solid state laser technologies.

The above examples represent just two of many cutting edge research thrusts that can be supported with the ATF-II. User access to these novel research capabilities will be greatly enhanced by the increase in floor space available to the facility where we intend to provide at least one experimental hall dedicated to research on e-beam/laser interactions and another dedicated to "laser only" experiments (such as ion-acceleration from gas jets and foils, strong-field experiments, and novel radiation sources). The new layout of the ATF-II will provide ample space for future evolution the novel CO_2 laser system, along with significantly increased control room and research support space.

CONCLUSION

The ATF user program, spanning more than two decades, has provided a rich legacy of research for discovery science and accelerator applications. The ATF user community represents a broad range of researchers from universities, national research centers, and small businesses who are engaged in accelerator science and technology development important to a multitude of stakeholders. Having been designated a U.S. DOE Office of Science National User Facility under the Accelerator Stewardship Program, the ATF will continue to be able to provide unique research capabilities at no cost to the international community. It will also be able to support proprietary industrial users on a cost recovery basis.

The ATF-II upgrade aims to significantly enhance our capabilities to support transformational accelerator science and technology developments, which are a key element of the Accelerator Stewardship mission. This upgrade will pave the way for a range of scientific initiatives – from ion acceleration, which is relevant for future radiotherapy methodologies, to the creation of ultra-bright sources of monochromatic X-rays through inverse Compton scattering, which may serve as university-scale compact light sources or for mobile interrogation of nuclear materials [33]; from novel opportunities for investigating laser wakefield acceleration of electrons, which may lead to a new generation of colliders on the energy frontier, to new strong-field applications of high-power, short pulse laser systems. Perhaps the most important initiatives will be those that have not yet been foreseen.

The ATF welcomes proposals from researchers both in the United States and the international accelerator community for work that is synergistic with the Accelerator Stewardship mission supported by the DOE Office of Science. We look forward to continuing to provide world-class accelerator research capabilities for many years to come.

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