Brookhaven National Laboratory October 1-2, 2015

ATF Newsletter

Special Issue:
18th ATF Users' Meeting

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BROOKHAVEN NATIONAL LABORATORY | Accelerator Test Facility

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1. Introduction

The Brookhaven Accelerator Test Facility (ATF) is the first and by far oldest user facility dedicated to advanced accelerator science and technology. Sponsored by the U.S. Department of Energy's (DOE's) Office of High-Energy Physics (HEP), the ATF has provided a broad category of qualified researchers with free access to its laser- and electron-beams for over 25 years. As a proposal-driven user facility, the ATF welcomes proposals that are synergistic with the missions of the DOE's Office of Science with specific focus on high-energy physics and accelerator stewardship activities. The ATF Program Advisory Committee (APAC) is in place to aid the Scientific Program Director (Ilan Ben-Zvi) in selecting qualified proposals for building up a comprehensive scientific program for the ATF.

The ATF's 18th Users' Meeting served multiple purposes; it was a forum for collaboration, a platform for users to report their work to APAC and the research community, an arena for assessing new experimental proposals and an opportunity to get an overview of ATF's performance and achievements. Presentation slides from the meeting are available at http://go.usa.gov/3SzRV

Based on the APAC's recommendations in relation to continuation of current experiments and approval of new experiments, the ATF's user program has been updated as is discussed in Section 4 of this Report.

2. The status of the ATF

In April 2015 the DOE announced that the ATF had been awarded the status of Office of Science user facility. Brookhaven National Laboratory recognizes the value of such a designation, as noted by the Lab Director, Doon Gibbs, in his lab-wide message:

"Our Accelerator Test Facility (ATF) just began an exciting new chapter that promises to reach new heights of accelerator research and development. The ATF was named a DOE Office of Science User Facility in recognition of its past innovations and ongoing value to the global network of scientists who use accelerators to explore the foundations of matter or develop new medical therapy techniques. Congratulations to the entire ATF team on this honor! The ATF is also undergoing a series of major upgrades, which will accommodate more users and offer more versatile and powerful electron and laser beams. The next few years at ATF will be especially exciting for Brookhaven Lab and the larger accelerator physics community."

The Director's message was reinforced by the DOE's Accelerator Stewardship Program Director, Eric Colby, in his talk at this User Meeting titled "The Accelerator Stewardship Program and the Role of the BNL-ATF as an Office of Science National User Facility":

"*As the flagship facility of the DOE's Accelerator Stewardship Program and an Office of Science user facility (http://science.energy.gov/hep/research/accelerator-rd-stewardship/), the ATF is available to a wide range of accelerator users providing support for accelerator science, first-of-kind technical demonstrations, and workforce training.*

ATF will continue to diversify into its broadened mission

- *Broadening its user community by reaching out to federal agencies, universities, and industrial users*
- *Developing new support models for a wider range of users' needs*
- *Serving not only as a facility, but as a community catalyst & incubator."*

In FY2015 the ATF made 1556 hours of user time available for use of the electron accelerator and 1033 hours for the CO_2 laser. This time was dedicated to 13 of the ATF's active user experiments, with 33 users in attendance at BNL.

Alongside our usual operations, the ATF is dedicated to design and implementation of the upgrade to ATF-II, with the CO_2 laser upgrade to 100 TW already begun at the present ATF. Next year we might expect some reduction in available experiment time to accommodate the ATF upgrade. This, together with users' advance beam time requests, means that the ATF is over subscribed for accelerator time in FY2016 but can meet the user demands in CO_2 laser run time. Beam time allocation will be coordinated with user groups to ensure that critical programmatic goals are met.

This year has seen a notable procedural change in the implementation of a new proposal submission system, which was used for the first time in preparation for this meeting. This new, on-line system helps with satisfying new reporting requirements arising from our Office of Science user facility status and has, so far, proved to be an efficient way for users to submit new proposals. It also facilitates the change in the proposal review process that now sees the APAC give PI's an overall proposal rating as well as a recommendation for or against approval. A second on-line system has also been developed for end-of-run reports; this is being rolled out during the first quarter of FY2016.

More details about the ATF and how to become a user can be found on our website at http://www.bnl.gov/atf.

3. Reports from active and completed experiments

Each research group presents a status report to the APAC committee at the Users' Meeting. This year, we heard reports from 22 experiments:

AE37 – An X-band, traveling wave, deflection mode cavity. Radiabeam
AE39 – DWA –high-gradient dielectric wakefield acceleration experiment. UCLA
AE41 – RUBICON - helical IFEL experiment at BNL. UCLA
AE43 – PWFA Holography. Univ of Texas at Austin
AE45 – Advanced imaging and ultra-fast material probing with inverse Compton scattering. INFN
AE48 – Experimental study of electron-beam microbunching dynamics. UCLA, Tel-Aviv Univ.
AE50 – Plasma Wakefields in the Quasi-Nonlinear Regime. UCLA
AE52 – Beam Manipulation by Self-Wakefield at the ATF. Euclid Technilabs
AF58 – ERL BPM Test. BNL (C-AD)
AE59 – Recirculated Inverse Compton Source. Radiabeam
AE60 – Ultrafast High-Brightness Electron Source. Advanced Energy Systems
AE62 – Sub-femtosecond beam line diagnostics. UCLA
AE63 – Stony Brook Accelerator Laboratory Course, CASE@ATF. Stony Brook University
AE64 – Surface Wave Accelerator and Radiation Source Based on Silicon Carbide. Univ of Texas at Austin
AE65 – NOCIBUR; an inverse free electron laser decelerator experiment. UCLA
AE66 – Ion Acceleration. NRL, Imperial College
AE67 – Space radiation. NASA
AE68 – Ramped beam generation using dielectric wakefield structures. RadiaBeam
AF69 – Key physics study of laser plasma interactions with near-critical density plasma using laser machined plasma. Tsinghua Univ.
AE70 – Nonlinear inverse Compton scattering. UCLA

AE71 – CO_2 laser driven GeV wakefield accelerators with external injection. SUNY SB
AE72 – Material interaction physics. NRL

Five experiments from this list, viz., AE37, AE41, AE45, AF50 and AE59, were reported as complete, adding to the legacy of total 56 user experiments and feasibility studies completed through the ATF's history. The remainder continues as active experiments.

Presented users' reports convincingly demonstrate that the experimental program at ATF continues to excel. We give here highlights from the ATF's landmark experiments in FY2015:

AE65 – NOCIBUR; an inverse free electron laser decelerator experiment, UCLA

It is always exciting to watch how productive new ideas evolve on the scale of a few months in experimental demonstration of new effects. NOCIBUR is one such example of a quick path from a proposal, presented at the 17th ATF Users' Meeting a year ago, to its first practical implementation. Figure 1 illustrates the underlying principle of energy exchange in the reversed IFEL where light is amplified while electrons are decelerated in a wiggler. A clear, strong and reproducible effect of electron deceleration is readily observed. A team of UCLA students led by Prof. Pietro Musumeci continues the experiment towards demonstrating a cleaner deceleration and measurable surplus to the laser power due to energy exchange from electrons.

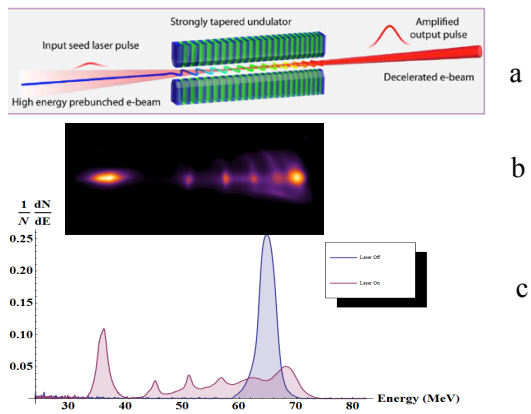


Figure 1. NOCIBUR experiment; a) concept; b) e-beam spectrum after interaction; c) plot of the above spectrum (pink) against the initial spectrum (blue)

AE68 – Ramped beam generation using dielectric wake field structures, RadiaBeam

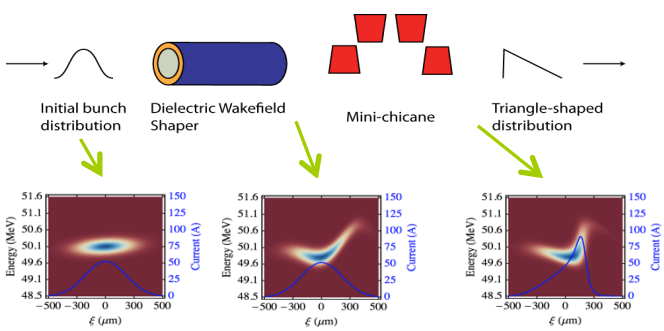


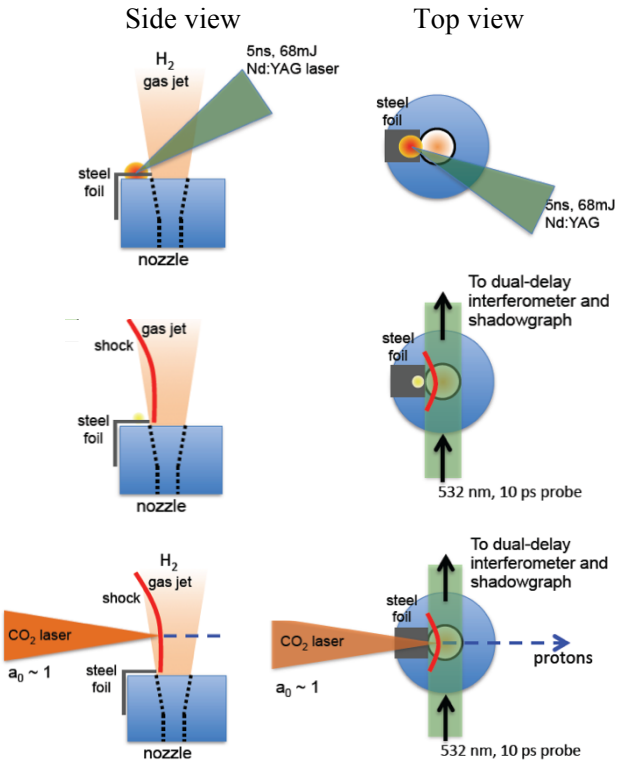
Figure 2. Principle diagram and experimental e-beam spectra at different stages of the pulse shaping process

Another quick implementation of a new proposal has been accomplished by RadiaBeam (Gerard Andonian) where the predicted bunch ramping by a dielectric wake field has been demonstrated (see Fig. 2). Such ramping might improve the transform ratio in wake field acceleration experiments. The experiment continues towards achieving an improved DWFA action for the case of an outgoing electron bunch being sent into another dielectric structure.

AE66 – Ion Acceleration, NRL and Imperial College

New modification of this experiment, performed now by a collaboration of NRL and Imperial College, explores the shock-wave acceleration of ions in a gas-jet which has been hydro-dynamically shaped using

an external solid-state (Nd:YAG) laser . This shaping resulted in better control over proton- and helium-beams generated from the CO_2 laser focused onto a blast wave, originated from the Nd:YAG focused on a metal foil placed at the edge of a gas jet. The experiment achieved an energy spread of 10%, a spectral brightness up to 10^9 proton/MeV/str, and proton energy up to 3.2 MeV.



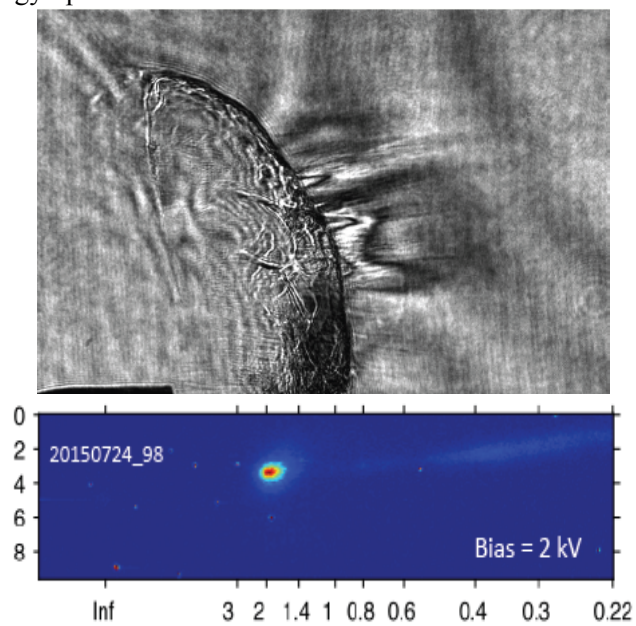


Figure 3. Ion acceleration experiment; (to the left) a sequence of diagrams illustrating progression of processes leading to the production of controllable ion beams; (top-right) a shadowgram of blast wave immediately after CO_2 pulse deposition; (bottom-right) the proton beam energy spectrum obtained with a Thomson parabola

AE59 – Recirculated inverse Compton scattering source, RadiaBeam

RadiaBeam successfully completed their phase II SBIR project with the first demonstration of a train of Compton x-rays from a recirculating laser cavity imbedded into the electron beamline. The increase in the cumulative x-ray signal is proportional to the number of synchronized laser- and electron-pulses. Its high stability and reproducibility hold a promise for this technique to become a backbone for variety of applications ranging from EUV lithography to polarized positron sources for linear colliders.

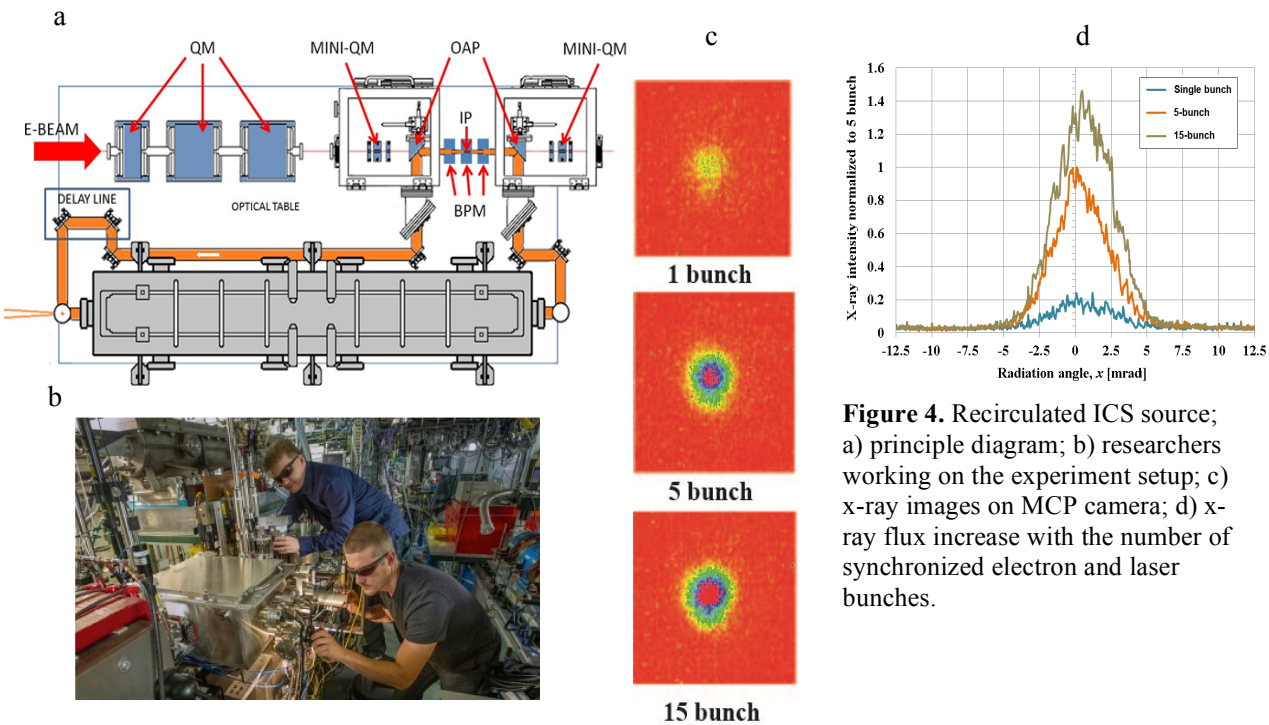


Figure 4. Recirculated ICS source; a) principle diagram; b) researchers working on the experiment setup; c) x-ray images on MCP camera; d) x-ray flux increase with the number of synchronized electron and laser bunches.

AE63 – Stony Brook Accelerator Laboratory Course, CASE@ATF

Figure 5. The first Accelerator laboratory class pictured with their BNL instructor, Dr. M. Fedurin, in the ATF's control room.

The first semester of a practical Accelerator Physics Laboratory course for SUNY SB graduate students was a success. This new initiative will increase the ATF impact on education of a new breed of accelerator scientists. This course provides the opportunity for students to receive first-hand experience in accelerator operation.

Here we wrap up a showcase of last year's user experiments with a mosaic of images, further illustrating a wide variety of projects supported by the ATF as is pertinent to the Accelerator Stewardship mission:

- Achievement of a transverse electron beam size of 5 μm RMS , by remotely adjustable mini-quads, designed for the Quasi-Nonlinear Plasma Wakefield Acceleration experiment (AE50) (Fig.6a) has become an important asset for many other experiments, such as AE39 that explores photonic structure for ultra-compact dielectric wakefield accelerator program GALAXIE (Fig. 6b-c).
- A sub-millimeter TEM01-like laser focus, achieved with the Terawatt CO_2 laser, inside an undulator (Fig. 6d), combined with an X-band deflection cavity, will create a snake-like streak (Fig. 6e) to enable energy-correlated sub-femtosecond e-bunch time resolution in AE62.
- Figure 6f illustrates THz radiation from a wedged dielectric structure that allows separation of Cherenkov radiation from transition radiation to produce cleaner signals for experiment AE52.
- The mass-shift effect in the inverse Compton scattering spectrum has been directly observed for the first time using a Bragg curved crystal spectrometer in AE70 (Fig.6g).
- The ATF continues to serve as a testbed for investigating the survival of on-board electronics in preparation for NASA's Europa Clipper mission. The motivation and setup for this experiment, AF57, are illustrated by Fig. 6h-i.

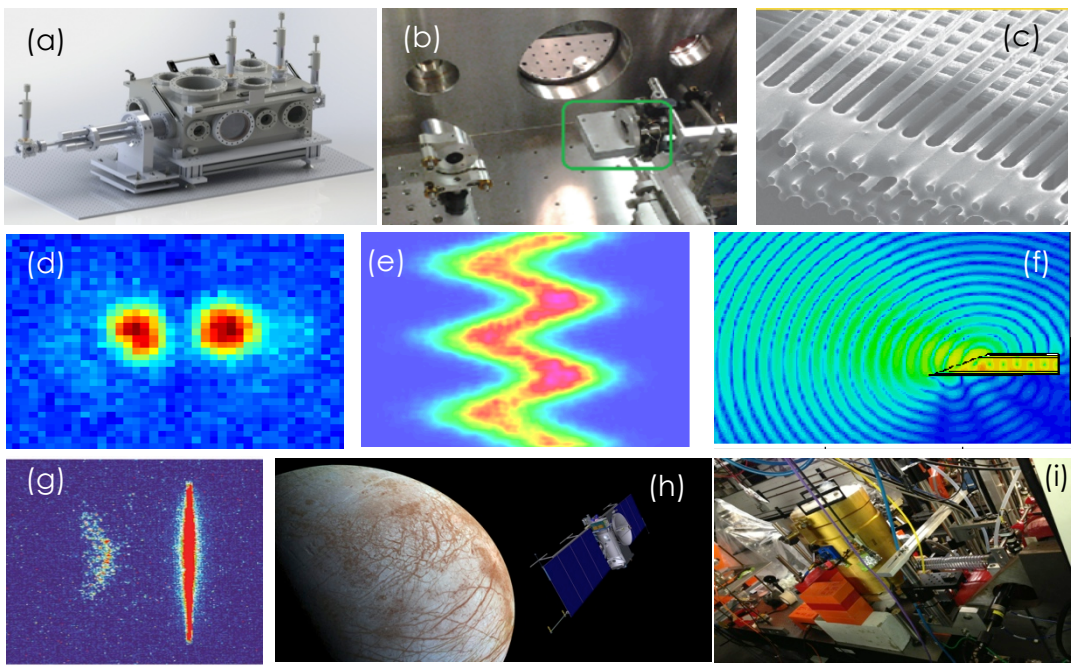


Figure 6. Mosaic of images from a variety of recent user experiments: (a) an interaction chamber extended with focusing mini-quads for AE50; (b) the same interaction chamber serves as a testbed in AE39 for GALAXIE photonic structures placed in a holder outlined with a green rectangle; (c) an example of the GALAXIE photonic structure for AE39; (d) sub-millimeter TEM01 CO_2 beam for AE62; (e) simulated trace on e-beam spectrometer that will allow sub-fs time resolution; (f) simulated THz Cherenkov radiation monitored in AE52; (g) sample image from x-ray spectrometer in AE70; (h) cartoon of Europa NASA mission to be launched in 2022; (i) NASA's "space radiation" experiment AF57 set in the ATF's electron beam line.

4. New experiments

Several proposals for new experiments, presented to the APAC at the 18th ATF Users' Meeting, were recommended for receiving beam time:

AE73 – Energy chirp compensation in plasma, DESY

Off-crest acceleration in a wakefield normally results in energy-chirped bunches exiting the plasma wakefield accelerator. This project addresses the need for beam de-chirping to mitigate their emittance degradation during transport. The idea is to utilize self-generated wakefields in plasma for the chirp compensation. During the experiment, researchers will generate and characterize linearly chirped beams. They will generate e-beams to drive wakes in plasma, vary charge and plasma density, and measure the beam energy spectrum after the beam has exited the plasma. The experiment will benefit from the X-band deflector that is soon to be installed at the ATF. Proof-of-principle validation of the chirp compensation by the method illustrated in Fig.7 will provide the foundation for designing and integrating de-chirper sections into pilot plasma-wakefield accelerator experiments at FACET II, FLASHForward and future ATF II.

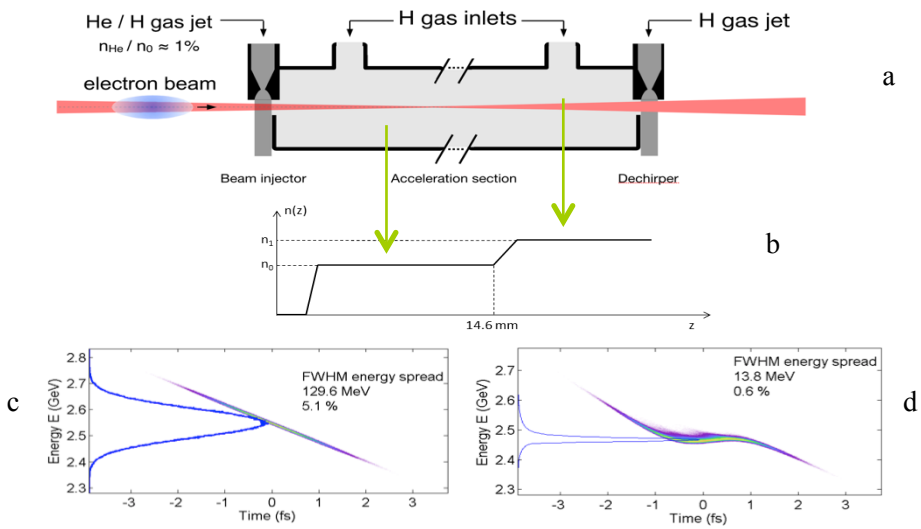


Figure 7. PWA de-chirper; (a) plasma source; (b) plasma density ramping in the plasma cell; (c) chirped bunch spectrum after accelerating section; (d) compressed spectrum after the de-chirper section.

AE74 – Self-channeling of CO_2 laser in air, UCLA

The main goal of this proposal is to explore, through experiment and simulations, the basic physics of propagation of a picosecond 10-μm pulse in air under the condition where the laser power exceeds the critical power for self-focusing.

According to preliminary modeling, an intense CO_2 laser beam will be guided in a macroscopic single filament of ≤1 cm diameter over many Rayleigh lengths. Such many meters long, large-diameter filament will contain 10-20 J of laser energy and provide an opportunity to study fundamentals of plasma physics and nonlinear mid-IR atmospheric optics in an unexplored long wavelength part of the spectrum.

By using a combination of time resolved interferometry and fluorescence measurements, researchers plan to investigate ionization mechanisms and plasma dynamics of partially ionized air waveguides. They will also theoretically model the atmospheric propagation of high-peak power pulses and compare the simulation results with experiments.

Very-long-range guiding and distant projection of high-energy laser pulses are of interest for LIDAR-based multicomponent pollution monitoring, lightning protection and defense related applications. Low-loss propagation of radiation in air over long distances is naturally limited to few transparency windows in the mid-IR range of the spectrum, from 3-14 μm.

AE75 - MEMS undulator for EUV lasers, UCLA

The concept of a MEMS micro-undulator was recently introduced by the UCLA collaboration to push the frontier of short-wavelength free-electron laser (FEL) performance. MEMS techniques permit very short period (100's of micron) electromagnetic undulators, with up to 1 T peak field, to be fabricated for the first time.

MEMS techniques can also be utilized to provide extremely strong micro-quadrupoles, with gradients of the order of a few kT/m. They can serve to produce the dense beams required for micro-undulators.

The first test of a soft X-ray Raman FEL micro-undulator and micro-quad system is naturally placed at the ATF, which also has a convenient beam energy permitting operation in the EUV, at wavelengths of interest to lithography applications. These tests are necessary to establish the physics performance of the first generation micro-undulator systems, with goals including: measurement of the spectral output of the devices in the presence of bremsstrahlung backgrounds; exploration of the effects of collimation on beam preparation; examination of potentially deleterious wakefield effects; investigation of radiation-induced performance changes in magnet performance.

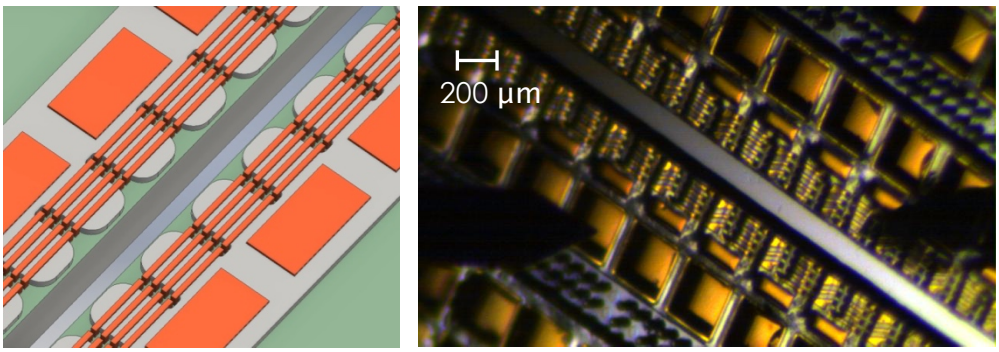


Figure 8. Micro-undulator with 200 μm gap for testing at ATF

AE76 - High duty cycle inverse FEL, Radiabeam

The Inverse Free Electron Laser (IFEL) enables strong energy exchange between electron and laser beams over extended lengths (~ 1 m) making the IFEL an attractive technology for compact GeV-class electron beam sources. Such accelerators can drive compact soft X-ray free electron lasers, and gamma-ray Compton sources. However, the IFEL repetition rate is limited by a maximum attainable repetition rate of the state-of-the-art TW lasers, generally not sufficient for most practical applications. In response to this problem, it is proposed herein to develop and demonstrate, for the first time, IFEL operation in a pulse train recirculated mode, whereby the entire IFEL system is placed within an active CO_2 laser cavity, operating at 40 MHz pulse train mode. Such intracavity IFEL can become a viable technological advance, comparable in cost and characteristics to conventional linear accelerators, but much more compact and versatile. A principle diagram of the proposed experiment is shown in Fig.9. It will use the same laser amplifier as depicted in Fig.4.

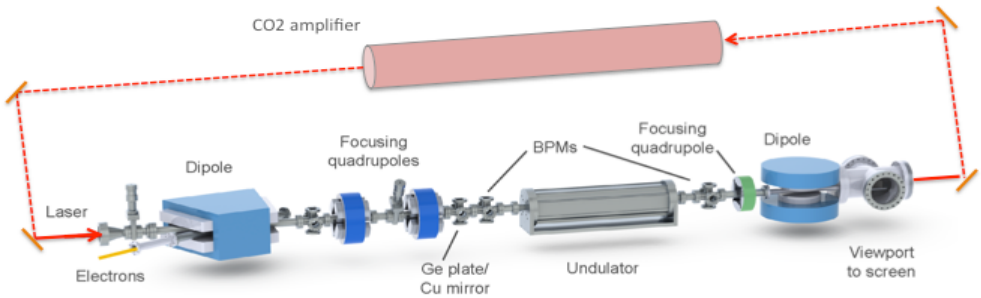


Figure 9. Principle diagram of recirculating FEL experiment

5. Near-term facility upgrades

Maintaining a dynamic user program with a strong forward momentum requires ATF vigilance in continuing upgrades of the facility's technical capabilities. This approach is rooted deep into the ATF's history and continues now with unprecedented intensity. Work is in progress in installing a new important capability in e-beam manipulation and diagnostic long awaited by our users. This is an X-band RF deflector to allow sub-femtosecond diagnostic of electron bunches and temporal evolution of the e-beam energy. Figure 10 serves to illustrate the extent of this project that involves installation of an X-band RF power supply (klystron with modulator), waveguide to the deflection cavity, and users' experiments, such as the AES X-band ultra-fast electron gun. This new capability should become available to users within the next few months.

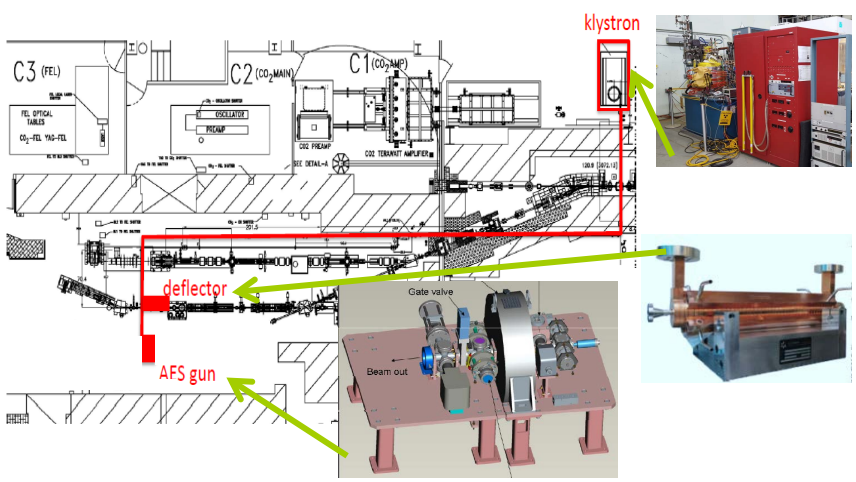


Figure 10. X-band RF system, waveguides to the deflection cavity, and user's experiments, such as AES electron gun (AE60).

Another traditionally strong area of ATF technical advancement, its picosecond CO_2 laser system, is marked this year with a milestone achievement of demonstrating chirped pulse amplification (CPA). This method of is an integral part of present-day ultra-intense laser systems, which normally employ near-infrared (~1 μm) solid state lasers. We anticipate that implementing the CPA technique will allow a new breakthrough towards multi-terawatt, ultra-fast mid-IR lasers as well. The use of the CPA scheme is essential for removing the limitation on the pulse intensity due to non-linear interaction with optical elements, and the atmosphere, and increasing the optical damage threshold of these elements.

In their first proof-of-principle experiments completed and published this year, ATF researchers demonstrated stretching of a 1 ps, 9 μm pulse to 80 ps, improved energy extraction from a regenerative CO_2 laser amplifier by one order of magnitude. We explain this accomplishment by the reduction in nonlinear absorption and refraction on the amplifier's optical elements. We consider these findings as being a pivotal step toward establishing next-generation ultra-intense CO_2 CPA laser systems for strong-field mid-IR research and its applications.

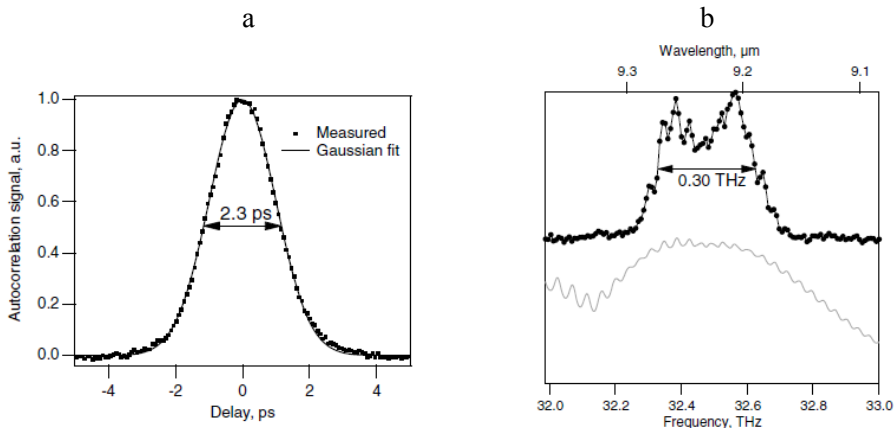


Figure 11. Experimental demonstration of bandwidth-limited recompression of 80-ps chirped laser pulses amplified by 4 orders of magnitude in the CO_2 regenerative amplifier; a) autocorrelation curve of the recompressed pulse; b) spectrum of the amplified pulse (black) against the amplifier's gain curve (gray).

Work on the CO_2 laser upgrade continues at the ATF towards demonstrating CPA through the final amplifier, improving the beam quality, generating controllable double pulses for certain user's needs, and testing a new method of femtosecond nonlinear compression of CO_2 pulses. The last approach is illustrated in Fig.12. All of these developments contribute to building the next generation 100-TW ultra-fast CO_2 laser system, BESTIA, at ATF-II, which is our long-term upgrade project addressed in Section 6.

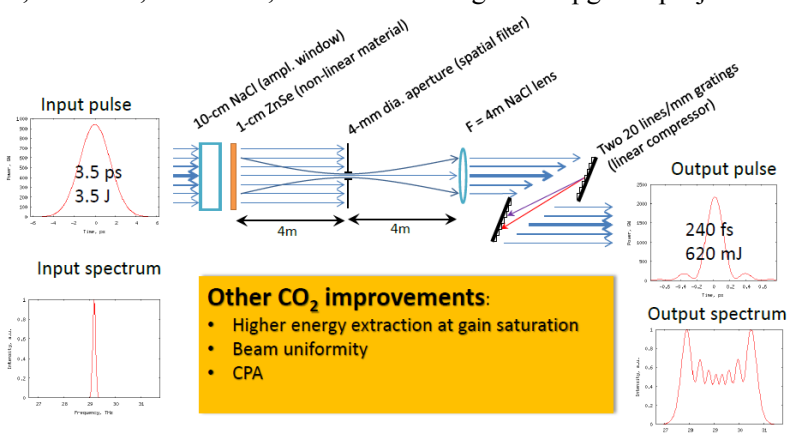


Figure 12. Principle diagram of the nonlinear femtosecond compression method to be tested at ATF; output pulse and spectrum to the right are simulated for the input delivered by the presently operational CO_2 laser system. Yellow insert lists other laser improvements being implemented.

6. Long-term facility upgrades and thinking forward

Within the three-year time frame, the ATF II upgrade will transform the facility by increasing its science reach and productivity. Following the resounding successes of the ATF both as a user facility and in its research programs, BNL is planning a considerable expansion of the ATF's capabilities, its science reach and its value via simultaneously upgrading the parameters of the e-beam and laser. The status of this project was outlined in several talks on the second day of the meeting.

The first stage of the ATF-II upgrade covers construction of two experimental halls with 100 MeV electron beamlines and multiple locations for experimental stations concurrent with installing a new CO_2 laser system BESTIA (Fig.13). The ATF relocation will allow an ample space for the expanding the laser system, along with a bigger control room, and the enlargement of other technical areas. At least one experimental hall will be assigned to research using e-beam/laser interactions, with another one dedicated to "laser only" experiments (such as ion acceleration from gas jets and foils).

a b

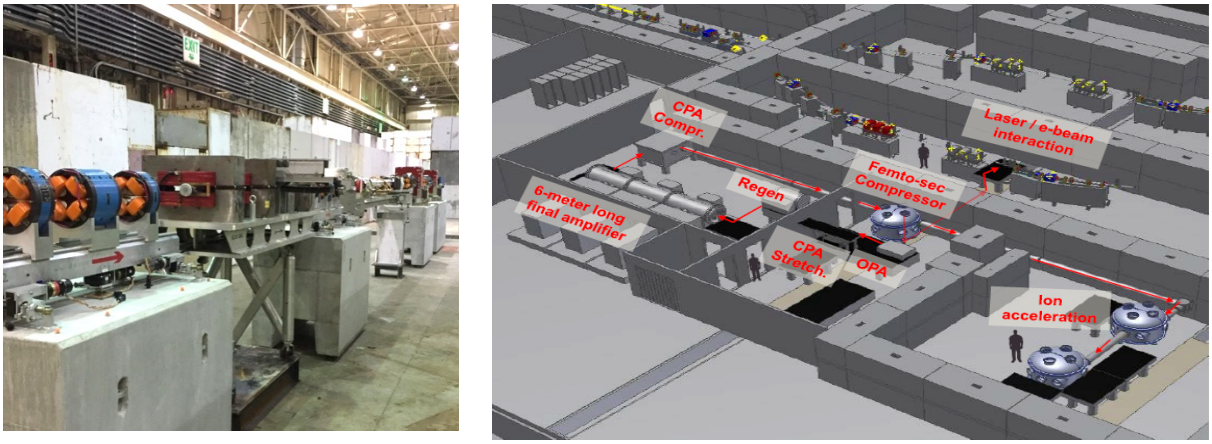


Figure 13. Planning and progress in the ATF-II upgrade; a) the first e-beam line in construction; b) layout of the CO_2 laser BESTIA and locations for user experiments

Our current plan is to complete the 25-TW 2-ps CO_2 laser in 2017. The first step in this upgrade, a solid-state OPA front end, has been commissioned already.

A series of high-pressure discharge-pumped amplifiers with isotopic carbon dioxide will boost the energy of the pulse to tens of joules while only minimally distorting its temporal structure. This advantage has been demonstrated already at ATF at a smaller scale with the first operational isotopic regenerative CO_2 laser amplifier. The CPA technique will be implemented for the first time in a CO_2 laser in order to eliminate effects of Kerr-lensing and self-phase modulation in the active medium and optical components. The first seminal demonstration of CPA in molecular gas lasers has been reported recently from ATF (see Section 5).

Finally, we plan to further increase pulse peak-power to ~100TW (10J in 100fs) via nonlinear pulse compression; this is arguably the most innovative part of the upgrade plan that requires considerable research and development. We anticipate that this upgrade will be complete in 2018.

The availability of a 100-terawatt-class 10-micron laser will open up invaluable opportunities for innovative research in strong-field physics and advanced accelerator design within a range of parameters not accessible previously with mid-IR lasers. For these studies, the ATF-II will provide its users with two radiation shielded experiment areas for strong-field physics research (see Fig.13b). In one experiment hall, the BESTIA laser beam will be brought to interaction with femtosecond, multi-MeV electron bunches in vacuum or plasma enabling advanced studies in laser wakefields, inverse Compton scattering, inverse FEL acceleration, etc. The second experiment hall will be dedicated to laser interaction with gas- and material- targets for Ion Acceleration, THz radiation and other user-inspired experiments.

Many ionization based injection methods for generating high quality electron beams in laser wakefield plasma accelerators (LWFA) can be tested at the ATF. This particular class of experiments, that benefits from uniquely available at ATF-II combination of mid-IR (CO_2) and near-IR (Ti:Sapphire) lasers, was the subject of two presentations by Carl Schroeder (LBNL) and Wei Lu (Tsinghua Univ.). Presenting a variety of technical scenarios for implementing two-color ionization-injection LWFA, both researchers converged on the same conclusion that both proposals, illustrated by Fig.14, should allow obtaining electron beams with unprecedented low emittance.

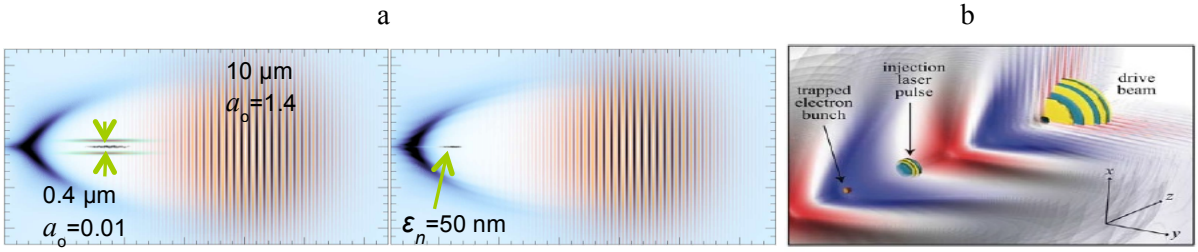


Figure 14. Simulations for two-color ionization injection LWFA; a) transverse injection in the Tsinghua scheme; b) longitudinal injection in the LBNL scheme.

Bernhard Hidding (University of Strathclyde), who represented a broader international collaboration of interested users presented an enthusiastic forecast on the ATF-II as a testbed for reproducing a variety of space radiation conditions including broadband electron-, ion- and photon- beams pertinent to space missions.

The meeting confirmed once more the underlying idea that the ATF-II upgrade undoubtedly will move the ATF to forefront of advanced accelerator- and radiation-source-research, so supporting the most innovative ideas in this field and prompting the emergence of new ones.