BNL-104414-2014-CP

Brookhaven National Laboratory's Accelerator Test Facility – Research Highlights and Plans

I.V. Pogorelsky and I. Ben-Zvi

Presented at the Laser & Plasma Accelerator Workshop 2013 (LPAW 2013)
Goa, India
September 2-6, 2013

Collider-Accelerator Department
Brookhaven National Laboratory

U.S. Department of Energy
Office of Science

Notice: This manuscript has been authored by employees of Brookhaven Science Associates, LLC under Contract No. DE-AC02-98CH10886 with the U.S. Department of Energy. The publisher by accepting the manuscript for publication acknowledges that the United States Government retains a non-exclusive, paid-up, irrevocable, world-wide license to publish or reproduce the published form of this manuscript, or allow others to do so, for United States Government purposes.

This preprint is intended for publication in a journal or proceedings. Since changes may be made before publication, it may not be cited or reproduced without the author's permission.

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, nor any of their contractors, subcontractors, or their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or any third party's use or the results of such use of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof or its contractors or subcontractors. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

Brookhaven National Laboratory's Accelerator Test Facility - Research Highlights and Plans

I. V. Pogorelsky and I. Ben-Zvi

Accelerator Test Facility, Collider Accelerator Dept., BNL, Upton, NY 11973

igor@bnl.gov

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 fulfilling this mission, the ATF offers the unique combination of a high-brightness 80-MeV electron beam synchronized to a 1-TW picosecond CO_2 laser. We unveil herein our plan for considerably expanding the ATF's floor space with upgrading the electron beam's energy to 500 MeV and the CO_2 laser's peak power to 100 TW. This upgrade will propel the ATF even further to the forefront of researches on advanced accelerators and radiation sources, supporting most innovative ideas in this field. We discuss emerging opportunities for scientific breakthroughs that include the following ones: Plasma Wakefield Acceleration (PWFA) studies, in research direction already active at the ATF, Laser Wakefield Acceleration (LWFA) where the longer laser wavelengths expectedly will engender a proportional increase in the beam's charge, while our linac will assure, for the first-time, the opportunity for undertaking detailed studies of seeding and staging of the LWFA, for proton acceleration to the 200-MeV level as is essential for medical applications, and others.

1. Introduction: The ATF past and present

Deepening our insight into matter rests on our pushing the energy frontiers of particle accelerators. As known accelerator technology is being driven to its limits, we therefore must explore revolutionary new methods of acceleration, for example, wakefields in plasmas and dielectric structures driven by electron- or laser-beams. Simultaneously, this exploration promises economical solutions for compact particle accelerators that are essential for many applications in industry, medicine, and other civil ventures. Much of the U.S. work in accelerator science and engineering is conducted in the Department of Energy's National Laboratories, but researchers from universities and small businesses also play an important role. How can all these diverse groups undertake cohesive experimental research to explore bold new ideas, test new techniques, and prove theoretical models? The answer is clear: In user facilities. User facilities are the mainstay of many sciences, and, by hosting a free service to users, they deter waste and duplication of efforts. Invaluably, they enable investigators with a small research budget to carry out their experimental work using high-performance accelerators and lasers. Over a quarter of a century ago, the Brookhaven Accelerator Test Facility (ATF) pioneered the concept of a user facility for advanced accelerator research. Established by two visionaries of accelerator science, Bob Palmer and Claudio Pellegrini, the ATF has served American researchers and scientists worldwide by affording incomparable opportunities for studying the complex properties of modern accelerators and new techniques of particle acceleration using lasers, electron beams, and beam/plasma interactions.

In fulfilling this mission, the ATF offers its users a unique choice, viz., a high-brightness 80-MeV electron beam synchronized to a 1-TW picosecond CO_2 laser, both of which are very versatile tools for various applications. Used separately, or in combination, they support a diverse scope of user research that covers multiple areas of accelerator R&D and applications, as is illustrated in figure 1.

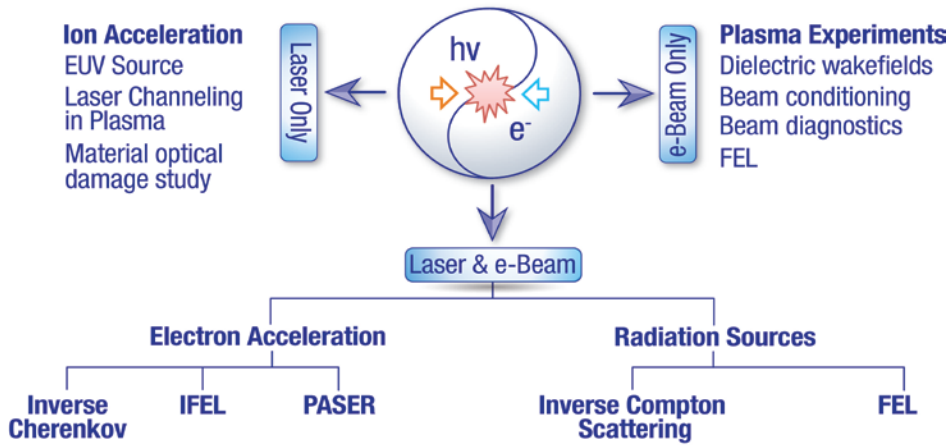


Figure 1. Classification of user experiments accomplished over the 20 years of the ATF's history.

Studies of electron-beam-driven plasma wakefields was a notable part of the ATFs' research program conducted throughout the last decade. Following our first introduction of a capillary discharge as a plasma source imbedded in the electron beamline [1], we experimentally demonstrated phasing between the longitudinal- and transverse-components of the wakefields acting on a drive electron bunch [2]. This research verified the added ATF capability for supporting beam-driven plasma wakefield experiments in a compact user-friendly setup, as immediately was recognized by the ATF's users. Proposals for a series of plasma-based studies quickly followed, such that the ATF's plasma source, combined with a high-brightness linac beam, became a test-bed for comprehensive studies of a wide variety of the electron bunch's modulation effects - longitudinal, transverse, and in electron momentum. These encompassed the following first experimental demonstrations and observations:

The demonstration of the high-gradient, controlled acceleration of a short electron- bunch trailing the driver electron-bunch in high-density plasma [3];

The observation of current filamentation instability of an electron beam propagating in plasmas at various densities [4];

the demonstration of the seeding of the self-modulation instability [5], resulting in the periodic modulation of the electron bunch, an effect that will be used in electron-acceleration experiments in the planning phase at SLAC-FACET and CERN;

and, the demonstration of the resonance multi-bunch PWFA as well as a masking technique to generate multiple bunches [6].

From its very inception, the ATF steadfastly has continued its quest to offer new opportunities for user experiments by elevating the CO_2 laser's peak power. Figure 2 presents a historical perspective of the evolution of the ATF's laser over the last 20 years: it shows the dramatic increase in power of nearly three orders-of-magnitude that we have realized from early years to the present. Every step up in the laser's power enabled a new series of user experiments, as this figure illustrates.

This sequence of successes attests the advantages of using a long-wavelength 10-μm CO_2 laser beams for certain classes of experiments. We list these benefits below, together with examples of their experimental exploitation:

- Favorable scaling of accelerating structures, better electron-phasing into the field
    - Inverse Cherenkov acceleration [7]
    - Staged Electron Laser Accelerator (STELLA) Inverse Free-Electron Laser (IFEL) [8]

- Stronger electron-quiver motion and ponderomotive effects at the same laser intensity
    - Ion acceleration (TNSA) [9]
    - Nonlinear Inverse Compton Scattering (ICS) [10,11]
- Tenfold more photons per Joule of laser energy
    - ICS [12]
- A hundredfold lower critical-plasma density
    - Shock wave ion-acceleration [13]

Some very recent examples of successful user experiments based on combining a CO_2 laser with an e-beam include the record energy-gain (50 MeV) and acceleration gradient (100 MeV/m) realized in the IFEL RUBICON experiment [14], and the observation of the mass-shift effect and up to the 3rd harmonic in the inverse Compton scattering (ICS) spectrum [11].

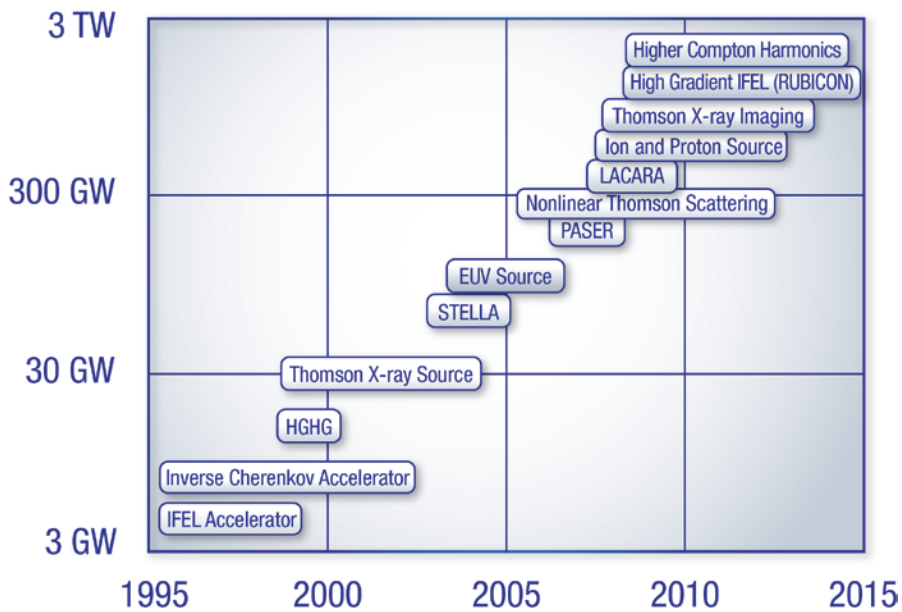


Figure 2. ATF User's experiments enabled by our continuing upgrades of the power of the CO_2 laser.

2. Upgrade plan for the ATF

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 capabilities, its science reach, and its value via simultaneously upgrading the parameters of the e-beam and laser. This plan covers an increase in the e-beam's energy from 80- to 500-MeV and a hundredfold increase in the laser's peak power. The 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. Users' access to these novel research opportunities will be much facilitated due to the concurrent major expansion in the ATF's floor space, and by our implementing multiple experimental halls. Figure 3 is a diagram of the future ATF facility. The radiation-shielded experimental area will be increased sevenfold compared to the present space. Three experimental halls will accommodate four beam lines, offering a selection of energies ranging from 100- to 500-MeV. At least one experimental hall will be assigned to research on e-beam/laser interactions, with another one dedicated to "laser only" experiments (such as ion

acceleration from gas jets and foils). We anticipate that the new layout of the ATF will have ample space for the expanding the laser system, along with a bigger control room, and the enlargement of other technical areas.

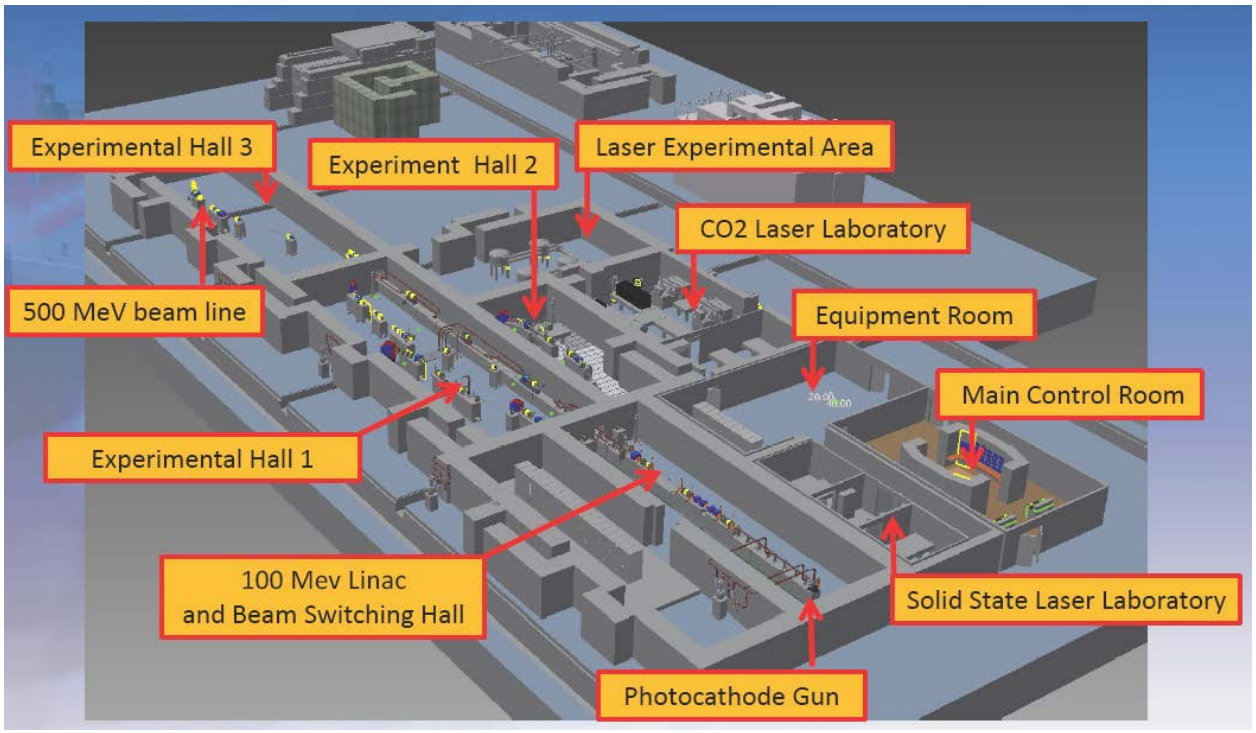


Figure 3. Layout of future ATF.

2.1. CO_2 laser upgrade

The justification for developing a new ultra-fast CO_2 laser technology rests on those same arguments that prioritized an IR laser for several classes of experiments throughout the ATF's history. Similar advantages will be attained at the higher laser powers we plan to deliver. Furthermore, this ultra-high power IR laser will offer ATF's users unique opportunities to explore *wavelength scaling* of strong-field physics phenomena to the laser-strength parameter a_0=10 at λ=10μm.

The power sweep of the ATF's picosecond CO_2 laser up to the present, illustrated in figure 2, was achieved by building up the system, that is, adding components and features that qualify as *evolutionary* upgrade. Further progress towards hundredfold higher peak powers will require devising next-generation ultra-fast CO_2 laser technology and implementing new, *revolutionary* methods never employed previously with gas IR lasers. At the core of our laser upgrade plan are three major innovations: All-solid-state, femtosecond, optical parametric amplifier (OPA) front end; chirped pulse amplification (CPA); and, using multiple CO_2 isotopes in the expanded chain of laser amplifiers. These developments somewhat parallel similar revolutionary betterments made years ago in solid-state laser technology where ultra-fast terminology now is applied conventionally to lasers of 100 fs pulse-length or shorter.

2.1.1. Optical Parametric Amplifier. After thorough consideration, we selected and now are commissioning a new front end of the ATF CO_2 laser system, i.e., an OPA, based on nonlinear mixing crystals pumped with a Ti-sapphire laser. This all-solid-state seed-pulse generator manufactured by Quantronix Co. produces 35-μJ, 350-fs (FWHM), 10-μm pulses. The natural bandwidth of the 350-fs injection pulse is about threefold broader than that of a CO_2amplification band. Hence, the spectrum of the pulse will narrow upon amplification, whilst its duration simultaneously with rise to 1.5-2ps. This affords us a two-to-three-fold improvement over the current configuration wherein the injection pulse's

minimum duration is limited at ~5ps by the speed of optical switches used for generating it. Another improvement reflects the fact that the broadband injection pulse simultaneously will extract excitation energy from a manifold of ~10 rotational sub-levels, compared to the interaction of only ~3 rotational sub-levels with a 5-ps pulse. We estimate attaining an order-of-magnitude higher gain in the peak power due to pulse shortening (a factor of 3), combined with better energy extraction (again, a factor of 3).

2.1.2. Chirped Pulse Amplification (CPA). The invention of CPA was a dramatic breakthrough in the field of solid-state laser technology, and we expect that its effect on gas lasers will be equally invaluable. Although the nonlinear indices of the gaseous active media are smaller by orders-of-magnitude than those of the solid-state materials, in the presence of transmitting optics and long beampaths the nonlinear effects (Kerr lensing, self-phase modulation) also become a problem for high-peak-power CO_2 lasers. Resolving this dilemma is vital for stepping up in the peak power. We consider that CPA is an obvious advantageous way to go for next-generation CO_2 lasers. We can assure high-energy extraction from the active medium and its undistorted transmission through the amplifier windows provided that a CO_2 seed-pulse is stretched to 100-200 ps with diffraction gratings. Hence, we plan to introduce a stretcher after the OPA.

2.1.3. Amplifier chain. We will expand the amplifier chain of the existing ATF CO_2 laser system, aiming primarily at boosting the laser's energy. It will encompass the following three steps:

We will extract more energy from the first regenerative amplifier. Presently, this amplification stage (SDI Co., UV-pre-ionized discharge, 10-atm, 12-mm aperture, isotopic regenerative amplifier) is limited to ~5 mJ due to nonlinear distortions on the intra-cavity optical elements. Pulse stretching will suppress those nonlinearities and assure efficient utilization of the energy stored within the amplifier's active medium, so lifting the output to 100 mJ.

We will purchase a new high-repetition rate UV-preionized CO_2 laser amplifier, similar to the one currently used in the initial regenerative amplification stage (SDI Ltd., RSA). We note that SDI amplifiers are configured to operate at a 10 Hz repetition rate. Combining two such amplifiers of gradually increasing aperture with an OPA allows us to assemble a complete terawatt-class laser system operated at a 10-Hz repetition rate. The detailed performance of such system will depend upon design choices, such as upgrading the possible OPA output, on implementing pulse-stretching before amplification and compression afterwards, and on attaining the optimum balance between the regenerative and multi-pass amplification schemes. Estimates indicate the possibility of our reaching up to 5TW output at 10 Hz repetition rate with an efficiently configured system. Such a regime will benefit the driving of high-average-power THz and x-ray radiation sources.

As the next step in adding to the amplifier chain, we will build an additional x-ray pre-ionized amplifier with 10 cm aperture that finally raise the output energy to 50-75 J in a stretched 100-ps pulse.

The diffraction grating compressor will be housed in vacuum chamber, and sited before the final focusing parabola at the applicable experiment location (ion acceleration- or laser/e-beam- interaction point). After recompressing the pulse to ~2ps, the combination of CPA with the improved energy output from the amplifier chain will produce a 25-TW peak laser power (figure 4). Our projection is supported by simulations of the CO_2 CPA regime demonstrating that despite noticeable narrowing and modulation of the laser pulse's spectrum during amplification, we still can achieve efficient recompression (figure 5).

2.1.4. Femtosecond compression. The simulations shown in figure 5 are based on using a single band in the CO_2 gain spectrum that results from the narrowing of an initially broad spectral envelope of an amplified laser pulse around the band's central frequency. However, there are additional options for reducing the narrowing of the spectrum by combining several CO_2 isotopes and their amplification bands (figure 6). Properly engineered spectral filtering allows our blending multiple isotopic bands into the super-continuum of the 10 THz spectral-width, thus amplifying our initial 350 fs seed pulses without spectral narrowing.

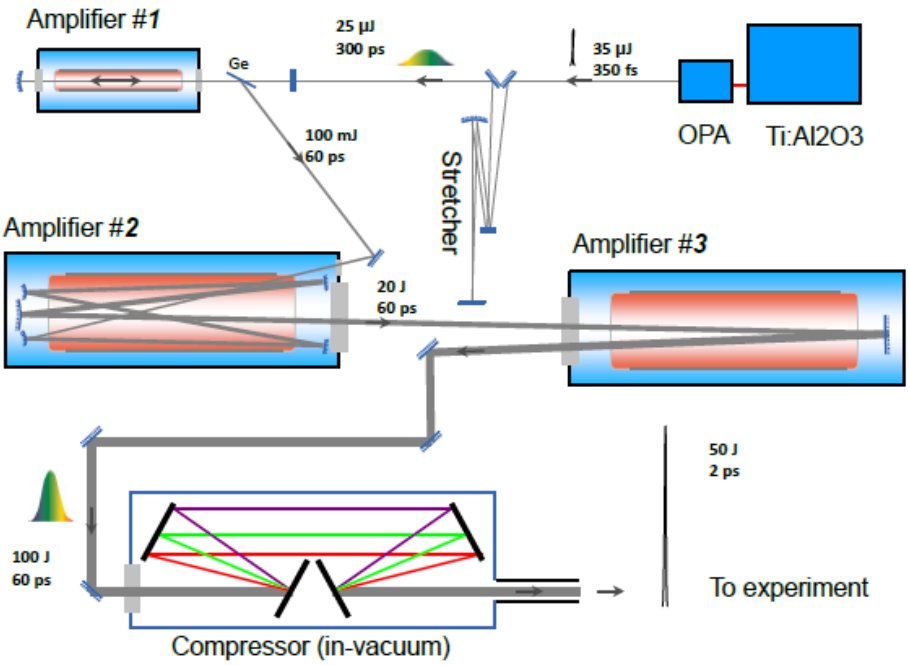


Figure 4. Optical diagram of the proposed ATF CO_2 laser.

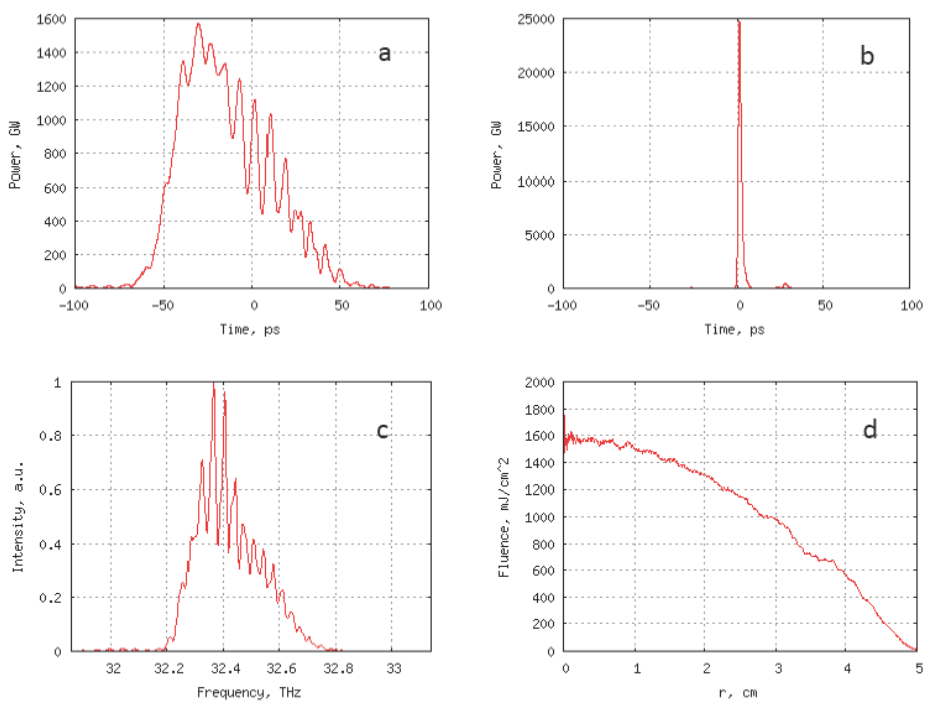


Figure 5. Simulation of the multi-TW CO_2 laser system shown in figure4. a –Laser pulse after the last amplification stage; b – Pulse after a compressor; c – Output spectrum, and d – Beam's profile.

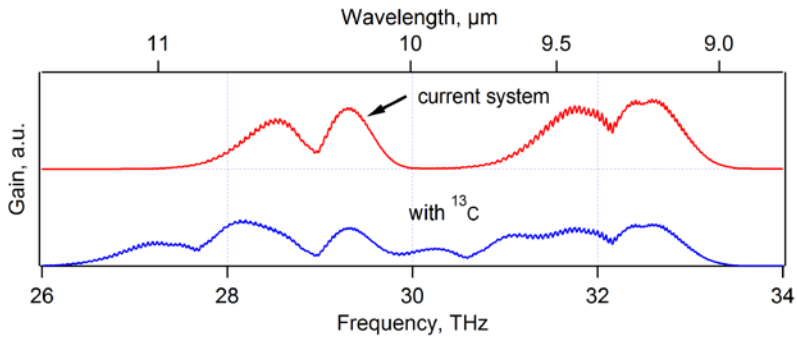


Figure 6. CO_2 molecule gain spectrum at 10atm pressure; top (red) – regular CO_2 with admix of ^{18}O, the operating band is marked with an arrow; bottom (blue) – the same mixture with an additional admix of ^{13}C.

Another interesting possibility of compressing a CO_2 pulse down to 3-4 cycles is opened via nonlinear self-chirping induced by the Kerr effect, and post-compression with diffraction gratings or via material with anomalous dispersion, such as sodium chloride. Figure 7 shows considerable expansion of the laser pulse's bandwidth after passing a nonlinear element (a 0.5-mm Ge plate). After filtering out the central spectral component with a spatial filter, the residual radiation has a quasi-linear spectral chirp that supports efficient pulse compression. Our simulations show the possibility of attaining 100 TW peak power in a 100-fs CO_2 laser pulse when this method is used.

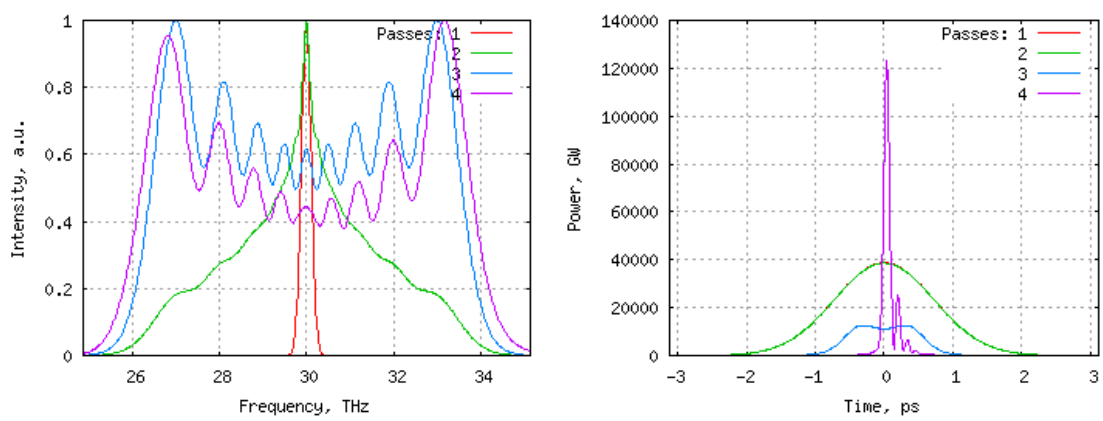


Figure 7. Simulated tripling of the laser's peak power upon self-chirping in Germanium; red – pulse after grating compression before the Germanium; green –after passing 0.5 mm of Ge; blue – after passing a spatial filter; purple – after compression with an NaCl window.

2.2. Upgrade of Electron beam

We propose to improve the electron beam's quality, stability, and energy at the ATF through a new electron gun and a UV photocathode laser system, state-of-the-art engineered beam lines that have laser-tracker alignment and reduced temperature induced motion, and through adding linac sections.

The ATF's low-emittance electron beam, ε_n=1.4 mm.mrad, and low energy spread, 0.1%, will be improved to ε_n=0.8 mm.mrad after installing the next-generation photocathode gun.

Upgrading to higher electron energy has the following clear consequences:

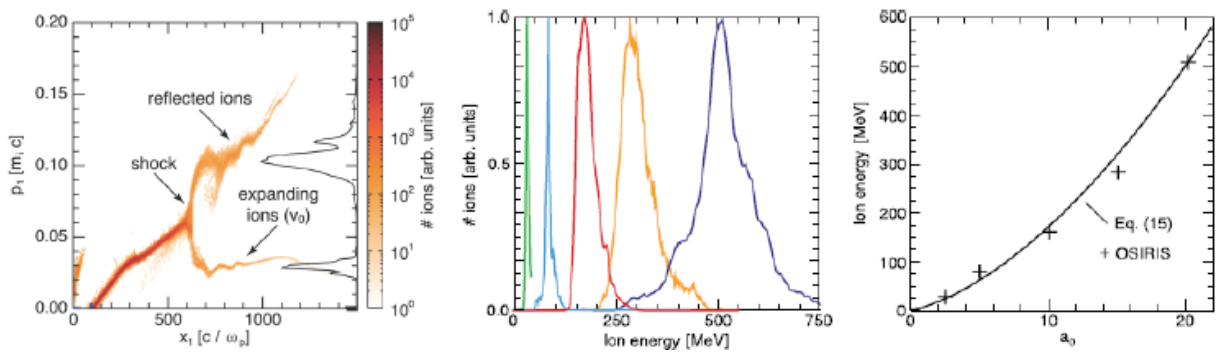
First, for a given normalized emittance, the size of the beam can be reduced in inverse linear proportion to the γ increase. The ATF beam is already very small. We demonstrated that we could focus the electron

beam to about 6μm (standard deviation) spot sizes with a charge of 300pC. Following the energy upgrade to 500MeV, the spot size will be reduced to 2μm. This size is less than the CO_2 laser wavelength of 10 μm, and is sufficiently small for a variety of advanced accelerator techniques, including structure-based laser acceleration where the transverse decay distance of the evanescent electric field is of the order of the laser's wavelength. To increase the beam's density, the bunch length can be shortened below 30 fs via an additional bunch compressor installed in the linac line before last accelerator sections.

3. Science case

3.1. Anticipated opportunities due to laser upgrade.

3.1.1. 200 MeV proton accelerator. An important argument for developing multi-terawatt CO_2 laser technology is to empower research in ion acceleration, motivated by pressing applications, such as radiation therapy. The method of Laser Shock Wave Acceleration (LSWA) recently demonstrated with the CO_2 laser promises to become one of the leading candidates to achieve the goal of attaining 200 MeV proton beams with parameters very suitable for medical treatments. The major distinctive features of this methodology include the production of monoenergetic ion beams, and the close-to-linear scaling of the ion energy with the laser's intensity. Such accomplishments allow us to project that the 200 MeV goal can be met at ~10^{18}W/cm^2 of the CO_2 laser intensity, attainable at 100 TW peak power. The recent simulations shown in figure 8 support these arguments.



a **b** **c**

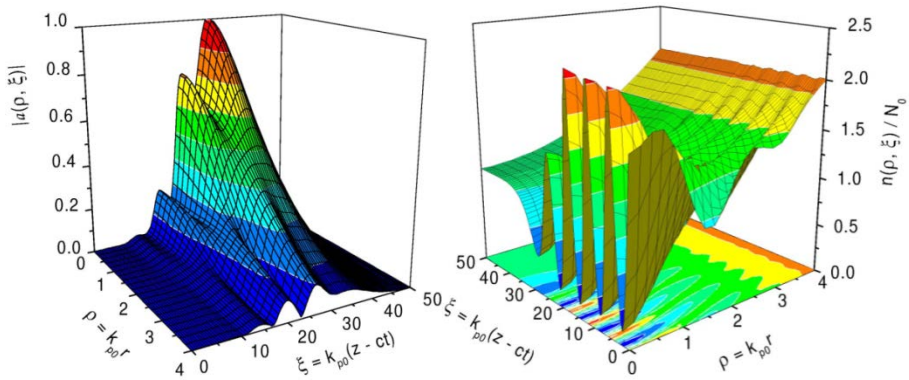
Figure 8. Shock-wave simulations showing (a) the distribution of proton momentum as a function of position in units of plasma inverse wavenumber , (b) ion spectra at different laser a_0 with red corresponding to a_0=10 , and (c) the dependence of maximum proton energy on $a_0$from an approximate parabolic equation and simulation [15].

3.1.2. Laser Wakefield Accelerators (LWFAs) wherein a high-intensity laser pulse creates a plasma wake that can accelerate electrons, have demonstrated very high acceleration gradients up to 100 GV/m. Most experiments used near-infrared laser sources (λ=0.8-1μm) that offer multi-terawatt peak-powers and femtosecond pulses. It was noticed that longer laser wavelengths have certain advantages due to wavelength scaling in the electrons' ponderomotive potential that is crucial in launching the collective plasma-electron motion, so causing wakes. These advantages have not been fully explored because of the lack of long-wavelength multi-TW mid-IR laser sources with a pulse length sufficiently short to drive a plasma wake to a competitively high field-gradient.

The parameters soon to be achieved with the ATF CO_2laser open up the possibility to perform LWFA experiments at 10 μm. In addition, the ATF has undertaken capillary-discharge experiments where channeling of the CO_2 laser light was demonstrated. Thus, the ATF not only possesses a viable laser driver for LWFA, but has a verified means to confine it over many Rayleigh lengths.

The so-called resonant LWFA normally requires the length of the laser pulse, τ, to be comparable to or less than half of the plasma wake's period, π/ω_p , where $\omega_p \propto n_e^{1/2}$. At the plasma density of

$n_e = 10^{16}$ cm^{-3}, considered close to the low limit for a meaningful high-gradient LWFA, this corresponds to $\tau \approx 0.4$ ps. An amplified 2-ps CO_2 laser pulse, soon to be attained by our implementing a new OPA as a front end for an upgraded ATF CO_2 laser, still would be too long for optimally generating a plasma wake in the resonant LWFA. However, simulations reveal that even though the 2-ps duration of the laser pulse is several times longer than that for ''resonant'' LWFA, a very strong wake can be attained. This achievement reflects the nonlinear evolution of the laser pulse upon coupling with the plasma. The laser pulse's envelope (figure 9a) is modulated, with the peak intensity over 50% higher than its initialvalue.



a **b**

Figure 9. The normalized laser field (a), and electron plasma density (b), after 6.7 cm propagation in plasma [16].

More important for wake generation is the nonlinear steepening of the pulse, which is caused by two effects: 1) Self-focusing at the peak of the laser pulse; and, 2) a modulation growing near the pulse's trailing edge. Such a modulated pulse falls into resonance with the plasma, so producing a strong wake. Simulations predict a wake amplitude >1 GV/m for a 2-ps, and a relatively low 2.5 TW laser pulse. In addition, the wake is very regular, as illustrated in figure 9b. We plan to probe the accelerating gradient with a femtosecond electron bunch from the ATF linac. After installation into the ATF's linac beam line, this experiment will become a test-bed for exploring seed-bunch phasing into the wake, and beam-loading effects.

The LWFA experiment at the ATF will progress in concert with the upgrade of laser power finally reaching the condition for assuring the bubble LWFA regime at the following CO_2 laser parameters:

Laser peak power	P = 100 TW
Laser pulse duration	τ = 500 fs
Laser pulse energy	E_L = 50 J

We took the following considerations into account for attaining the bubble regime:

The laser power should exceed the threshold value for the blow-out regime:

$$P > P_{\text{bubble}} \approx P_{\text{rel}}(\omega_0\tau)^2 \approx \left(\frac{\tau[\text{fs}]}{\lambda[\mu\text{m}]}\right)^2 \times 30 \text{ GW},$$

Where, $P_{\text{rel}} = m^2c^5/e^2 \approx 8.5$ GW, and $\omega_0\tau = 2\pi c\tau/\lambda \approx 1.9\tau[\text{fs}]/\lambda[\mu\text{m}]$.

For the laser parameters above, $P_{\text{bubble}} \approx 75$ TW is slightly below the laser's power at the laser pulse's duration $\tau =$ 500 fs.

There are additional key conditions for the bubble regime:

The radius of the laser pulse, R, should scale as

$$k_0 R \approx \left(\frac{n_{\mathrm{cr}}}{n_{\mathrm{e}}} a_0\right)^{1/2}$$

And, its duration should be short compared with its radial size

$$\tau \leq \frac{R}{c} \text{or} \quad \tau \leq \frac{\lambda}{2\pi c}\left(\frac{n_{\mathrm{cr}}}{n_{\mathrm{e}}} a_0\right)^{1/2}.$$

These condition relates the plasma density with the laser intensity, that for $a_0 = 8$ (at $R \approx 75$ μm) gives

$$n_{\mathrm{e}} \approx 5 \times 10^{15} \mathrm{cm}^{-3}.$$

The length of acceleration

$$L_{\mathrm{acc}} \approx 0.7 \frac{c\tau}{\lambda} Z_{\mathrm{R}} \approx 3 \text{ cm},$$

where Z_{R} is the Rayleigh distance.

The energy of the quasi-monoenergetic peak in the spectrum of accelerated electrons is

$$E_{\mathrm{mono}} = 0.65 mc^2 \left(\frac{P}{P_{\mathrm{rel}}}\right)^{1/2} \frac{c\tau}{\lambda} \approx 600 \text{ MeV}.$$

In Table 1, we compare the possible parameters of the bubble electron accelerator with the 2-GeV accelerator recently demonstrated with the Texas Petawatt Laser [17].

Table 1. Comparative parameters for bubble accelerator driven with 1-μm and 10-μm lasers. The parameters were derived using the expressions in the text above.

Parameter	Unit	1-μm laser	10-μm laser
λ	μm	1	10
P	TW	1100	100
a_0	-	8	8
τ	fs	170	500
n_{e}	cm^{-3}	$5\mathrm{x}10^{17}$	$5\mathrm{x}10^{15}$
P_{bubble}	TW	900	75
P_{cr}	TW	43	43
L_{ph}	cm	20	200
L_{PD}	cm	10	30
E_{max}	GeV/cm	2	0.2
L_{a}	cm	1	3
N_{mono}	-	10^{10}	10^{11}
V_{bubble}	mm^3	0.0001	0.1

Moreover, a relatively low plasma density, in combination with bigger laser spots, both features that are typical for a CO_2 laser-driven LWFA, open the possibility for increasing the size and charge of the electron bunch.

The number of accelerated electrons in the monoenergetic peak is

$$N_{\mathrm{mono}} \approx \frac{1.8}{k_0 r_{\mathrm{e}}}\left(\frac{P}{P_{\mathrm{rel}}}\right)^{1/2} \approx 10^{11}$$

that is, about 16nC. A bubble a thousand fold bigger in volume compared with one obtained in solid-state laser facilities (in proportion to the plasma wavelength) undoubtedly will relieve the problem of space charge and simplify electron injection into the acceleration stages.

These features, in combination with the available femtosecond electron injector, make the ATF's experiment a viable complement to the LWFA research ongoing at world-class PW laser facilities. The experiment will provide a platform for directly comparing different methods of electron seeding into the bubble, such as via a conventionally produced electron bunch from a linac, or an all-optical method with direct photoionization from an external Ti:sapphire laser that soon will become available at the ATF according to the upgrade plan.

3.1.3. THz Radiation Source. Different physical mechanisms are being explored with the goal of accessing high-power THz radiation sources desirable for emerging applications ranging from material studies, to work for Home Land Security. Arguably the most powerful sources of such radiation are based on the collective motion of electrical charges induced by an intense laser.

Efficient energy conversion from a laser beam to THz radiation recently was reported as a by-product of experiments on Target Normal Sheath Acceleration (TNSA) wherein a laser was focused onto a thin foil [18]. Hot electrons escape the laser focus at several-MeV energy; then, they are stopped by the foil's positive charge. This violent change of the electron's motionon the picosecond time-scale produces a single-cycle THz radiation that can be collected and collimated by a coin-sized parabolic mirror focused at the foil's rare surface.

CO_2 lasers are well known for their high efficiency in producing hot electrons. Indeed, as the ponderomotive energy of the electrons escaping the laser focus scales as $\Phi = I/4\omega^2$, a hundred times higher intensity is required from a 1-μm laser to induce the same electron-energy as does the long-wavelength CO_2 laser. This wavelength scaling was demonstrated at the ATF where we needed only 10^{16}W/cm^2 of CO_2 laser intensity to produce the same ion acceleration via the TNSA mechanism as with 10^{18}W/cm^2 by the solid-state laser used elsewhere (figure 10).

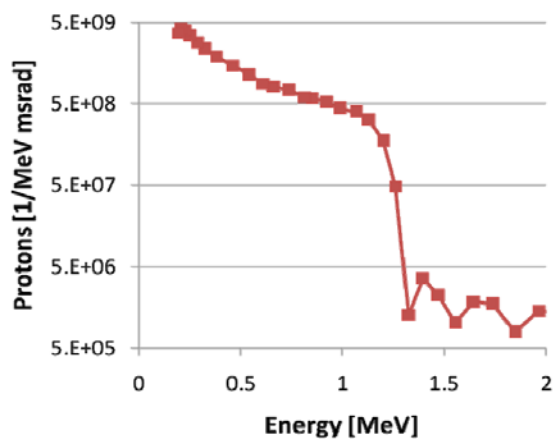


Figure 10. Proton energy spectrum obtained with a 3-J CO_2 laser of the 10^{16}W/cm^2 intensity [19].

Furthermore, λ=1 μm permits up to a tenfold tighter focus at the diffraction limit. This way, the same ponderomotive electron energy can be realized with a 1-μm laser of the same peak power as a CO_2 laser, but notably, in a hundredfold smaller surface area; this might well result in a corresponding drop in the integral hot-electron yield. Therefore, we can safely predict that a 100-TW CO_2 laser could be up to 100 times more efficient in producing hot electrons than a 100-TW solid-state laser. In other words, a 10-PW

solid-state laser will be required to match the 100 TW CO_2 laser in rates of production of hot-electrons and offspring effects, such as THz radiation. Considering that up to 50% of the CO_2 laser's energy can be routed into generating hot electrons, and that a considerable portion of these electrons end up with forming a rear-surface sheaf cloud while radiating THz photons in the process, we can predict that the proposed method may become an efficient source of the single-cycle THz radiation.

Importantly, the radiation process has a low laser-intensity threshold and can be studied with the already available 1-TW ATF CO_2 laser. Therefore, the ATF is in a unique position for facilitating this type of research that will be a natural continuation of our successful TNSA ion-acceleration studies, and may culminate in a record-breaking demonstration of a high-intensity THz source when we further upgrade our laser power.

3.2. Science enabled by upgrading the electron beam's energy to 500 MeV

Increasing the top electron energy from 80- to 500-MeV by adding linac sections also would secure a smaller geometric emittance, so potentially resulting in a smaller beam, a feature that is very important for applications such as ultra-high-gradient structure-based accelerators, beam-plasma R&D, and higher-energy beam-produced radiation like Compton-generated gamma rays, or Free-Electron Lasers. Several already approved and active ATF users' experiments on dielectric wakefields will become the first direct beneficiaries. A simultaneous increase in the wakefield's intensity and confining the beam over longer distances through the test structure will significantly enhance (×50-100) the anticipated effect, such as electron acceleration by a wakefield, energy chirp compensation, and the yield of THz radiation yield, among other benefits.

As another concrete example, we consider the nonlinear regime of PWFA. The smaller beam at a higher energy will increase the current's density. This will be achieved via focusing the beam more tightly, combined with shortening the length of the electron bunch via installing an additional bunch compressor in the linac, just before the final accelerator sections. Presently, the available energy, charge, and emittance of the ATF's electron beam are close to satisfying the basic requirements for driving the PWFA in the nonlinear blowout ("bubble") regime, which are

$$n_b/n_0 > 1, \qquad \sigma_r \ll \lambda_p \ , \qquad N_b/n_0\,\lambda_p^3 \gg 1,$$

where N_b and n_b are, correspondingly, the beam charge and density, σ_r is the beam rms size, n_0 the plasma density, and λ_p is the plasma wavelength.

Tight e-beam focusing below σ_r=5 μm is required to satisfy blowout conditions at plasma density $n_0 = 10^{16} cm^{-3}$. Such focusing already was achieved at the ATF. An available 17-mm long capillary discharge provides not only the plasma source; its parabolic radial-density profile helps to confine the tight-focused e-beam over the entire length of the capillary. With a calculated transformer ratio of 1.5, a 150 MeV/m accelerating gradient is expected from the ongoing ATF PWFA experiment.

The planned 500-MeV ATF energy upgrade with an additional bunch compressor, combined with better emittance of a new ATF photocathode electron gun, further will facilitate our meeting the blowout PWFA conditions and ensure the establishment of efficient beam confinement and plasma wake excitation over an extended capillary length.

Further upgrade of this experiment to the resonance wakefield excitation using properly tailored train of electron bunches produced by a "mask technique" perfected at the ATF, can lead to transformer ratio of 4.5, with a corresponding larger energy gain per stage. Thus, the ATF will become an effective test-bed of different aspects of PWFA physics, including electron-injection mechanisms, such as optimizing laser injection for the Trojan Horse scheme [20], studies of beam matching for injection into a plasma bubble as well as the release of the beam from a bubble, leading to staging of plasma accelerators.

High repetition rates in plasma channels are crucial for plasma acceleration in high-luminosity applications. Given that the plasma is a volatile medium, and it has to be refreshed between shots, this is a

study that has to be done. The ATF photo gun has a unique feature: It can be operated in multi-bunch mode, with over 200 pulses separated by 24.5 ns with charge of ~300 pC/pulse. Thus the ATF will allow observing the emergence of instabilities in the process at maximum repetition rates of 40 MHz.

Higher energy enables access to shorter wavelength radiation through inverse Compton Scattering (ICS). The photon beam is contained in a small cone with the opening angle determined by the electron energy and the selected bandwidth of the emitted radiation. The ICS photons observed along the axis of the e-beam are mono-energetic ones, with a spectral bandwidth dictated by the energy spread and emittance of the electron beam, and the interaction length between the laser and the electron bunch. All of these parameters can be controlled to a large extent by the optics of the electron beam. .

The CO_2- and Ti:sapphire- laser beams will be transported to the 500-MeV electron beamline, so enabling continuing research towards gamma sources applicable to electron-gamma and gamma-gamma colliders as well as for producing polarized positrons for e^+-e^- colliders.

These are just few examples out of more than twenty proposed researches that will be carried out the ATF's upgraded parameters for the electron beam and laser.

4. Conclusions

The ATF is the only facility worldwide having a terawatt CO_2 laser synchronized to a high-brightness electron beam and dedicated for user's experiments. Unlike most ultrahigh-power laser systems based on solid-state active media and operating at ~1μm wavelength, the ATF's laser provides a powerful beam at 10-micron wavelength. This increase in wavelength is desirable for multiple applications, including certain aspects of research on advanced particle accelerators.

The next upgrade of the ATF's CO_2 laser to multi-TW peak power and electron energy to 500 MeV will open new research programs at BNL. By our offering a unique, compact and powerful laser, new scientific missions will be enabled including the following: Ion acceleration of the radiotherapy relevance; creation of ultra-bright sources of monochromatic X-rays through inverse Compton scattering off electron beams; novel opportunities in investigating laser wakefield acceleration of electrons, and other strong-field applications that complement cutting-edge projects conducted or planned with the most powerful solid-state lasers worldwide.

Acknowledgements

This work is supported by the US DOE contract DE-AC02-98CH10886. The authors are grateful to all who contributed to the ATF Upgrade Proposal, the success of user experiments reviewed in this paper, and helpful discussions. Our special thanks go to V. Platonenko, V. Gordienko, J. Osterhoff, N. Andreev, W. Kimura, P. Muggli, M. Babzien, M. Fedurin, K. Mirabella, R. Rock, C. Swinson, J. Skaritka, C. Joshi, Z. Najmudin, P. Dover, O. Tresca, and C. Maharjan. We also thank the ATF Program Advisory Committee, W. Leemans, K. Harkay, V. Yakimenko, J. Rosenzweig and K. Krushelnick, and the ATF CO_2 Laser Advisory Panel, C. Barty, P. Corkum, L. Dimauro, H. Kapteyn, S. Tochitsky and W. White.

References

[1] Pogorelsky I V *et al* 2003 Transmission of high-power CO_2 laser pulses through a plasma channel *Appl. Phys. Lett*. **83** 3459

[2] Yakimenko V *et al* 2003 Cohesive acceleration and focusing of relativistic electrons in overdense plasma *Phys. Rev. Lett*. **91** 014802

[3] Kallos E, Katsouleas1 T, Kimura W D, Kusche K, Muggli P, Pavlishin I, Pogorelsky I, Stolyarov D and Yakimenko V 2008 High-gradient plasma-wakefield acceleration with two subpicosecond electron bunches *Phys. Rev. Lett.* **100**0 74802 Cite

[4] Allen B, Yakimenko V, Babzien and M, Fedurin M 2012 Experimental study of current filamentation instability *Phys. Rev. Lett.* **109** 185007

[5] Fang Y *et al* 2013 Self-modulation instability *Phys. Rev. Lett. (submitted)*

[6] Muggli P, Yakimenko V, Babzien M, *et al* 2008 Generation of trains of electron microbunches with adjustable subpicosecond spacing *Phys Rev Lett.* **101** 054801

[7] Kimura W D, Kim G H, Romea R D, Steinhauer L C, Pogorelsky V, Kusche K P, Fernow R C, Wang X and Liu Y 1995 Laser acceleration of relativistic electrons using the inverse Cherenkov effect *Phys.Rev. Lett.* **74** 546

[8] Kimura W D *et al* 2001 First staging of two laser accelerators *Phys. Rev. Lett.* **86** 4041

[9] Pogorelsky I V, Yakimenko V, Polyanskiy M, Shkolnikov P, Ispiryan M, Neely D, McKenna P, Carroll D, Najmudin Z and Willingale L 2010 Ultrafast CO_2 laser technology: Application in ion acceleration*Nucl.Instrum.Methods Phys. Res.* A **620** 67

[10] Babzien M *et al* 2006 Observation of the second harmonic in Thomson scattering from relativistic electrons *Phys. Rev. Lett.* **96** 054802

[11] Sakai Y *et al* 2013 Observation of red-shifting and harmonic generation in nonlinear inverse Compton scattering *Phys. Rev. Lett. (submitted)*

[12] Pogorelsky I V *et al* 2000 Demonstration of 8×10^{18} photons/second peaked at 1.8 Å in a relativistic Thomson scattering experiment *Phys. Rev. ST Accel. Beams* **3** 090702

[13] Palmer C A J *et al* 2011 Monoenergetic proton beams accelerated by a radiation pressure driven shock *Phys. Rev. Lett*. **106** 014801

[14] Duris J P *et al* 2013 High energy gain in high gradient helical inverse free electron laser *Phys. Rev. Lett. (submitted)*

[15] Fiuza F *et al* 2013 Ion acceleration from laser-driven electrostatic shocks *Phys. of Plasmas* **20** 056304

[16] Kimura W D *et al* 2005 Pseudo-resonant laser wakefield acceleration driven by 10.6-μm laser light *IEEE Trans. Plasma Sci.* **33** 3

[17] Wang X *et al* 2012 Quasi-monoenergetic laser-plasma acceleration of electrons to 2 GeV *Nature Comm.* **4:1988** | DOI: 10.1038/ncomms2988 | www.nature.com/naturecommunications

[18] Gopal A *et al* 2013 Observation of gigawatt-class THz pulses from a compact laser-driven particle accelerator *Phys. Rev. Lett.* **111** 074802

[19] Pogorelsky I V, Yakimenko V, Polyanskiy M, Shkolnikov P, Ispiryan M, Neely D, McKenna P, Carroll D, Najmudin Z and Willingale L 2010 Ultrafast CO_2 laser technology: Application in ion acceleration *Nucl. Instrum. and Methods in Phys. Res*. A **620** 67

[20] Hidding B, Pretzler G, Rosenzweig J B, Königstein T, Schiller D, Bruhwiler D L 2012 Trojan horse laser electron injection and acceleration in a beam-driven plasma blowout *Phys. Rev. Lett.* **108** 035001