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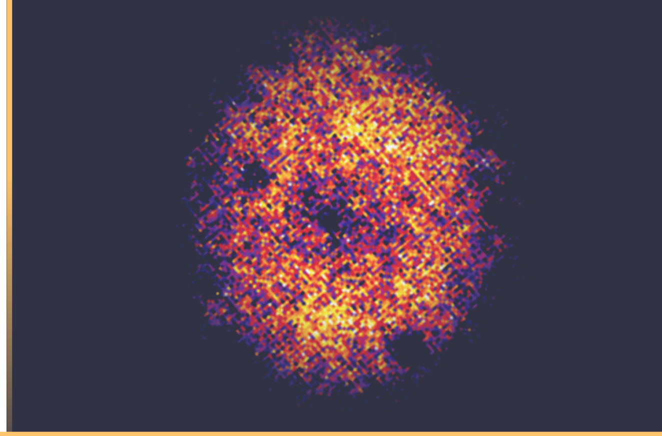

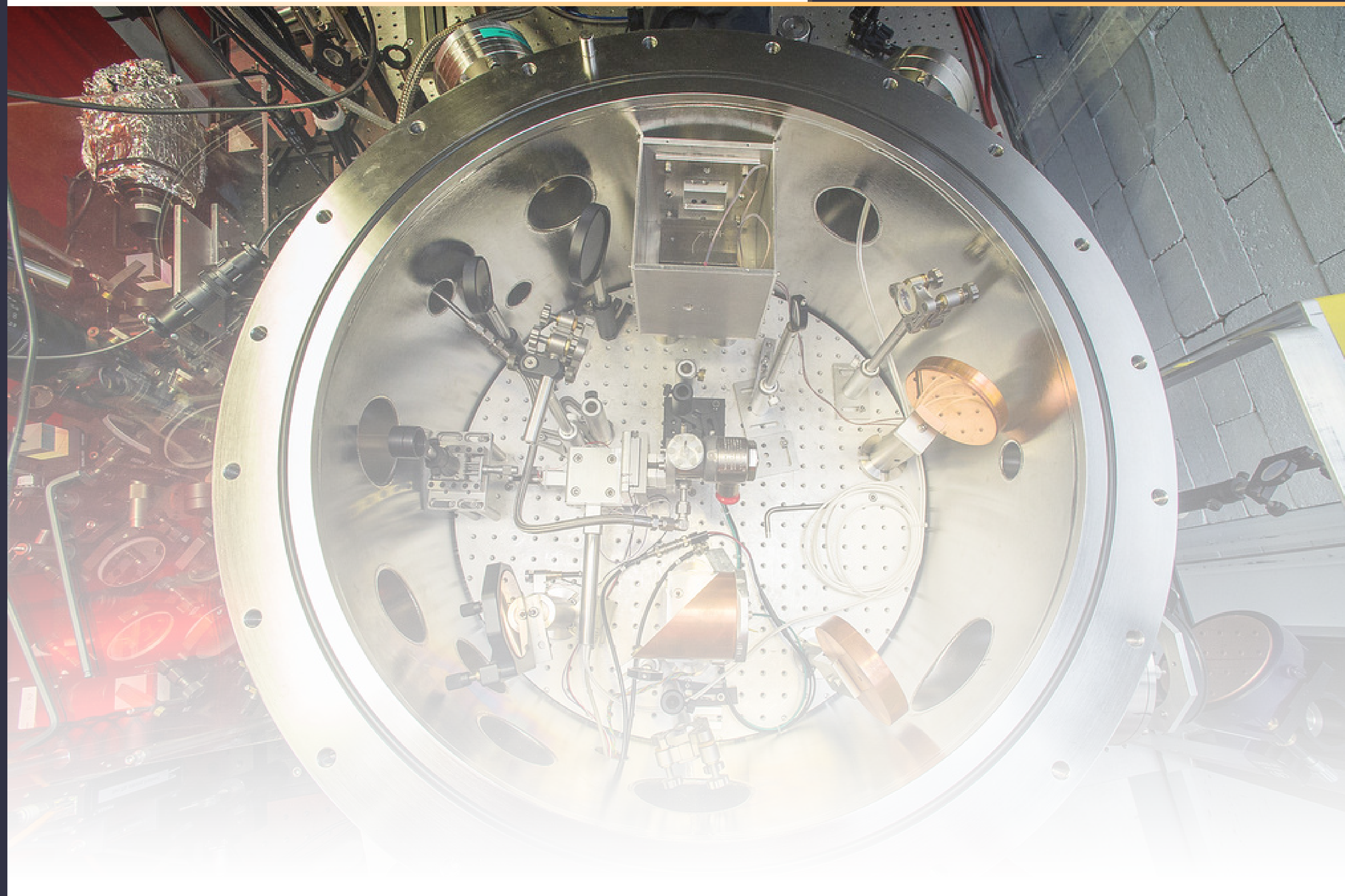

High-Impact Advanced Accelerator Research and Development Using Extreme-Power Mid-IR Lasers for Future Needs

Report of the Accelerator Test Facility Scientific Needs Workshop

November 2017

NATIONAL USER FACILITY ORGANIZATION

The ATF is the DOE Office of Science National User Facility for the High Energy Physics Accelerator Stewardship Program.

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High-Impact Advanced Accelerator Research and Development Using Extreme-Power Mid-IR Lasers for Future Needs:

Report of the Accelerator Test Facility Scientific Needs Workshop

Bruce Carlsten, Chair
11-21-2017

Scientific Needs Workshop Review Panel

- **Topics in Mid-IR Laser Research**
    - Jeffrey Moses (CU)
    - Daniel Gordon (NRL)
    - Yu-hsin Chen (NRL)

- **Topics in Laser-Plasma Interactions and Laser Wakefield Acceleration**
    - Stuart Mangles (ICL)
    - Jean-Pierre Delahaye (CERN)
    - Navid Vafaei Najafabadi (SUNY-SB)
    - Aakash Sahai (ICL)

- **Topics in Laser-Electron Beam Interactions**
    - Felicie Albert (LLNL)
    - Bruce Carlsten (LANL)
    - Gerard Andonian (Radiabeam/UCLA)

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Executive Summary

A team of 39 expert laser and accelerator scientists and engineers met at Brookhaven National Laboratory to evaluate the scientific promise of the planned upgrade of the Accelerator Test Facility (ATF), known as the ATF-II, and to provide comments on the upgrade migration plan. The first impact of the ATF-II will be due to the development of a new 10-20 TW CO_2 laser. The primary goal of this workshop was to identify priority research directions (PRDs) enabled by this novel laser source, as a frontier for experiments, once this capability becomes available. PRDs were found in three areas: 10-TW class mid-IR laser research, laser plasma wakefield acceleration (LPA) research with 10-TW class lasers, and experiments requiring both a 10-TW laser and a high-brightness electron beam. A summary of these PRDs follows:

- 10-TW class mid-IR laser research
    - PRD 1: High-power CO_2/Mid-IR laser development
    - PRD 2: Laser filamentation and propagation in the atmosphere
    - PRD 3: Secondary sources and expansion of CO_2 versatility based on nonlinear optics
- LPA research
    - PRD 1: Electron acceleration
    - PRD 2: Ion acceleration
- Research using both a 10-TW laser and a high-brightness electron beam
    - PRD 1: Inverse Compton Scattering
    - PRD 2: Inverse Free Electron Laser Acceleration
    - PRD 3: Dielectric Laser Acceleration
    - PRD 4: Precision electron beam phase space manipulation on the femtosecond time scale

Specific details and objectives of each of these PRDs are described in the sections below. Together, they represent a significant and robust collection of cutting edge accelerator and technology research. The urgent completion of this research is crucial to support national and international advanced accelerator thrusts. The first two research areas can be studied with only the CO_2 laser migration to the ATF-II. It is important to stress that the third set of PRDs will need to wait until the electron accelerator is also migrated. While, in principle, PRD 1 of the LPA research area (electron acceleration) can eventually lead to a usable electron beam, it is the consensus judgement of the Scientific Needs Workshop review committee that using an LPA-generated beam for the third area PRDs is not credible at the predicted level of LPA maturity over the next decade.

1 Summary of the ATF/ATF-II Capabilities and Plans

The ATF at Brookhaven National Laboratory has served as a community advanced accelerator test facility for many years. It is presently a National User Facility funded by the Accelerator Stewardship Program of DOE/SC/HEP[1]. Over the last two decades, the ATF has become the destination for hundreds of users from different institutions worldwide, both academic and private. These users have conducted world leading research in:

- Accelerator beam physics
- Particle sources and beam instrumentation
- Novel acceleration techniques
- Novel radiation sources

As an example of the ATF's historic impact, research carried out at the facility was critical to the advent of X-ray Free Electron Lasers (FELs). This included first demonstrations of very high-brightness electron beams from a photocathode RF gun, self-amplified spontaneous emission at visible wavelengths and a seeded high gain harmonic generation. These ATF developments laid the foundation for the $B-class Linac Coherent Light Source (LCLS). Additionally, pioneering experiments at the ATF have been done on LPA and beam-driven plasma wakefield acceleration (PWA). Examples of this and other pioneering high-impact research done at the ATF are in the following reference section.

The co-location of a high-brightness test electron beam and a TW-scale picosecond test laser at the ATF is unique and enables experiments that cannot be done at other DOE/SC/HEP facilities such as BELLA, AWA, or FACET-II, as shown pictorially in Figure 1.1. As a result, the ATF has a compelling and unique niche for the national and international advanced accelerator community. Currently, the laser system is based on a 2 TW peak-power CO_2 laser operating at wavelength of 9-11 μm. Its energy per pulse is about 6 J with a 3 psec pulse width and can operate with a 0.05 Hz repetition rate. The current electron accelerator energy has 80 MeV maximum energy, with an emittance of about 1 μm and energy spread of 0.1% for charges of 1.5 nC. The bunch length can be varied from 1 to 8 psec and the accelerator supports multi-bunch trains operating at 1.5Hz.

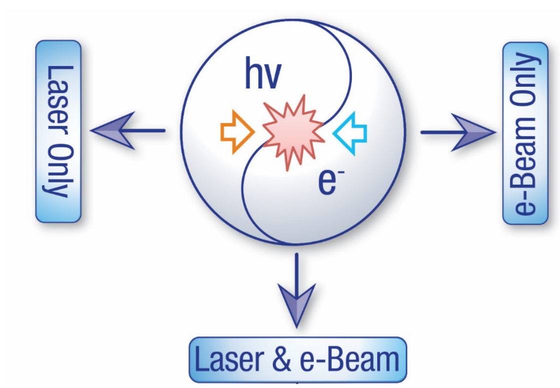

Figure 1.1- The unique combination of a TW-laser with a high-brightness electron beam enables experiments with the laser along, the electron beam alone, and the combination of the laser and the electron beam.

These unique tools enable the following list of the ATF research areas:

[1] https://science.energy.gov/hep/research/accelerator-stewardship/

- Novel particle acceleration techniques - R&D for smaller, more cost-effective accelerators including:
  - Plasma and dielectric wakefield acceleration
  - Direct laser acceleration
  - Inverse free-electron lasers and more...
- High-brightness radiation sources - new techniques to produce electromagnetic radiation from THz to X-rays:
  - FEL R&D
  - Inverse Compton scattering
  - THz radiation from dielectric structures and more...
- Beam manipulation and beam instrumentation - sophisticated longitudinal and transverse beam manipulation capabilities
  - Wide range of beam parameters enabling development and testing of advanced accelerator hardware, beam diagnostics and detectors
- Ion generation and acceleration
  - Experimental hardware for producing supersonic hydrogen gas jets provides capabilities for generating mono-energetic multi-MeV proton beams
- Ultrafast Electron Diffraction/Microscopy - techniques for characterizing materials that are complementary to x-ray sources
  - Developmental beamline and experimental station for diffraction and imaging studies with MeV-class electron beams

It should be emphasized that the CO_2 laser has a longer wavelength than lasers at other advanced accelerator facilities. This leads to the ability to perform different, and often better diagnosed, LPA and other laser-beam experiments. Also, it need to be emphasized that the ATF is the only facility that experiments requiring both a TW-class laser and a high-brightness electron beam can be performed.

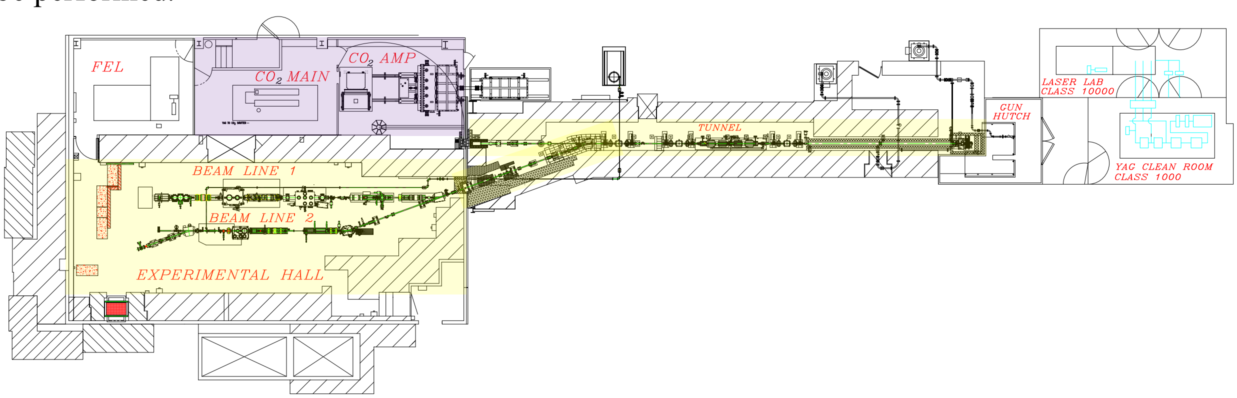

Figure 1.2- The current ATF configuration in building 820 at Brookhaven National Laboratory.

Over two decades ago, the ATF pioneered the concept of a user facility for studying new methods of accelerating electrons and ions. Its experimental program operates through an established, proposal-driven, peer-review process. The ATF provides free facility access to qualified researchers and a highly trained staff to support a broad array of user experiments

The ATF is currently undergoing an upgrade to the ATF-II. The ATF facility, in Brookhaven building 820, is shown in Figure 1.2. The future ATF-II facility, in building 912, is shown in Figure 1.3.

The ATF-II upgrade will provide for roughly three times the total floor space, four times the experimental halls, and seven times the shielded area of the ATF. The electron beam will be upgraded from 80 MeV to 100 MeV and the CO_2 laser will be upgraded from 2 TW to 10TW, and eventually targeting up to 100 TW. Moving user capabilities for mid-IR lasers into the 10s of Terawatts and sub-ps pulse regime will:

- Enable scientific exploration of the benefits of longer-wavelength laser systems for accelerator applications;
- Provide a platform for the development of high peak power laser technologies, including concepts and participation from the broader user community.

In combination with expanded electron beam capabilities, the ATF-II plan can provide world-leading user capabilities for decades to come.

At the beginning of FY16, DOE/SC/HEP requested that the ATF-II plan be re-baselined, including a full and complete re-evaluation of all scope that had been presented in the 2013 proposal, scope from all funding sources, and changes in scope due to the proposed addition of new capabilities to the ATF portfolio.

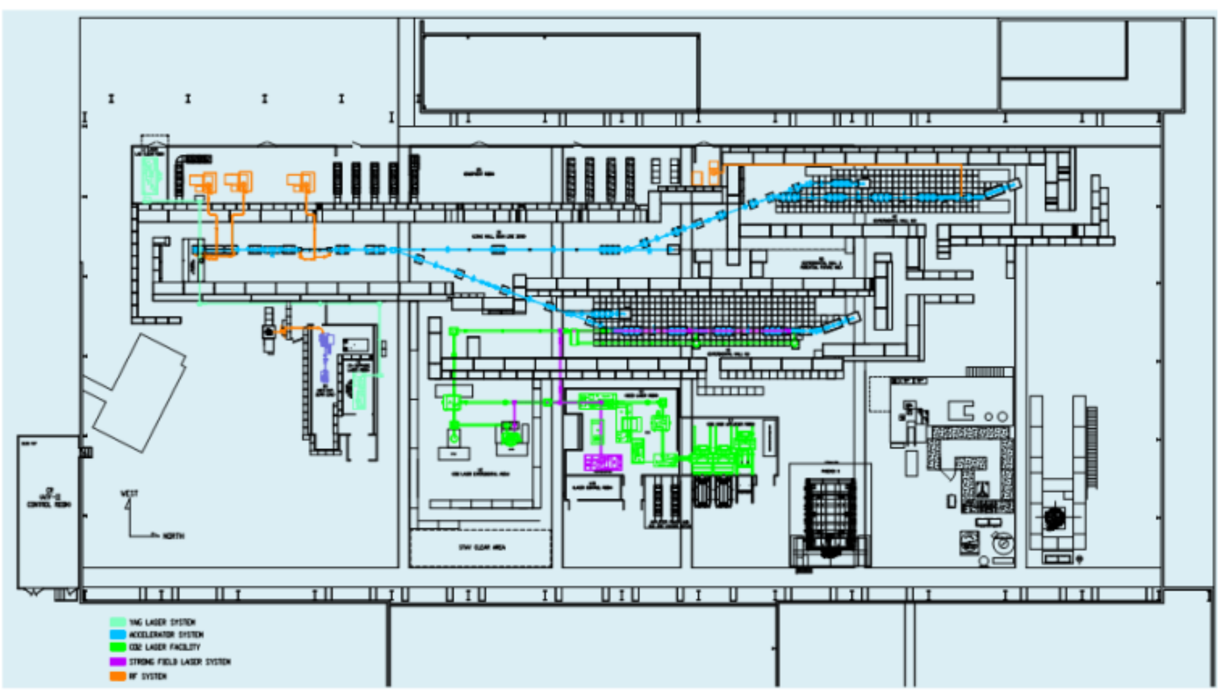

Figure 1.3- The planned ATF-II configuration in building 912 at Brookhaven National Laboratory. The 100-MeV accelerator and beamline is outlined in blue and the 10-100 TW CO_2 laser system is outlined in green. The RF driving the accelerator is shown in orange.

A Scientific Needs Workshop was held in July 2017 to identify and document the scientific need of the ATF-II capability, specifically for the initial step of a higher power laser. At the time of this report, the baseline upgrade schedule is that a standalone 10-20 TW CO_2 laser capability will first be developed at the ATF-II, while a robust user program at the ATF with joint electron beam and TW CO_2 laser operation will continue through FY21. The high-power user laser program will commence at the ATF-II in FY20 and the electron-beam accelerator migration to building 912 will be completed by FY23 (including its increase to an energy of 100 MeV), with about 12 to 15 months of electron beam down-time during the migration. The consensus of the Scientific Needs review committee is that this schedule is appropriate and balanced considering the likely available resources to complete the ATF-II migration.

In addition to evaluating the upgrade schedule, this report documents the assessment made by the Scientific Needs review committee of the scientific needs of the community for mid-IR (9-11 μm regime) laser capabilities. This assessment included reviewing the present experimental efforts, future research directions, and potential paths to achieving the necessary technological infrastructure to enable advanced accelerator research. To capture the future promise of the science enabled by the laser upgrade, the review committee formed three panels at the workshop. These panels focused on ~10-TW mid-IR laser research, LPA research with 10-TW class lasers, and experiments requiring both a 10-TW laser and a high-brightness electron beam. Specific PRDs were identified by the workshop in these three areas to clarify science directions and to help guide Brookhaven and DOE/SC/HEP investment priority decisions.

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2 Panel 1: Topics in Mid-IR Laser Research

2.1 Introduction

Panel 1 developed this report based on the responses of several dozen laser scientists who participated in the Mid-IR Laser Scientific Needs Survey and the ATF Scientific Needs Workshop, as well as the judgment of our three panel members engaged in laser science in the mid-infrared wavelength range. Several scientific communities are represented, including the accelerator/high-energy-density/relativistic plasma physics community, the strong-field laser physics community, and scientists engaged in the development of atmospheric propagation applications.

In order to manage the scope of the discussion, we considered only sources and applications of pulsed mid-IR radiation that are relevant to strongly nonlinear light-matter interaction.

2.2 Science Drivers

There has been strong interest from both research communities and funding agencies in developing and utilizing high-power mid-IR sources for various scientific needs. DOE HEP is supporting research in mid-IR laser-based accelerator technologies. DOD is interested in strong-field laser-matter interactions at mid-IR wavelengths, and is currently providing funds through the Multidisciplinary University Research Initiative (MURI) program in various topics, including atmospheric propagation, development of high-power mid-IR lasers, strong-field physics, particle acceleration, and extreme nonlinear optics. Basic AMO research relying on mid-IR sources is also funded by NSF and DOE BES.

2.3 Current Research Status and Future Directions

Presently, mid-infrared laser research is increasingly represented by a wide range of scientific and technological fields and aims. In addition to the accelerator science community's traditional engagement in research at 10-micron wavelength, using the ATF CO_2 facility, there is growing interest and investment in atmospheric propagation applications in the long-wave infrared (LWIR), such as directed energy, LIDAR and remote sensing, as the LWIR range is marked by low atmospheric absorption. The recently awarded DOD MURI program in LWIR laser science has invested $7.5M in the investigation of nonlinear optics at LWIR wavelengths to further the these aims. Moreover, the strong-field optical physics community has in recent years aimed for longer and longer infrared wavelengths to drive extreme nonlinear optical processes (*e.g.*, to generate shorter X-ray wavelengths with shorter attosecond pulse duration via high harmonic generation (HHG) and to achieve finer resolution in laser-induced electron diffraction [1–6]). This intersection of interests now brings together scientists of myriad backgrounds to explore laser development and fundamental aspects of intense LWIR propagation and optical engineering.

In the last decade, research by both the strong-field physics and physical chemistry communities has led to the development of optical parametric amplification (OPA) systems pumped by titanium sapphire lasers and optical parametric chirped pulse amplifier (OPCPA) systems pumped by ytterbium doped solid-state lasers, delivering tunable infrared pulses at the millijoule level, which have reached a high level of maturity. Typically, the tuning range is between 1 and 3 microns (*e.g.*, the commonly used TOPAS system from Light Conversion tunes from 1.1 to 2.6 microns). Longer wavelengths are accessible by mixing signal and idler in a difference frequency generation (DFG) crystal, but deep in the mid-IR (~10 micron wavelength), the pulse energy is limited to ~10 microjoules. At these longer wavelengths, the efficiency of conversion of the pump radiation is only 0.1%. Since the pumping titanium sapphire laser is itself inefficient, the overall wall plug efficiency is extremely poor. For this reason, research into solid state laser materials that directly support mid-IR wavelengths has been undertaken. For example, thulium and holmium doped materials support a wavelength near 2 microns, with bandwidth suitable for generation of ultra-short pulses, and are already widely used in high average power fiber lasers (*e.g.*, [7]). Commercial systems are typically high repetition rate (MHz) or CW systems with correspondingly low peak power. More exotic materials such as iron-zinc-selenide can in principle push the operating wavelength beyond the 4 micron range [8], but are not yet in widespread use.

Given efficient, high energy, ultra-fast solid state sources in the few micron wavelength regime, OPA and OPCPA becomes viable as a source of high energy LWIR pulses (the efficiency improves if the pump wavelength is closer to the LWIR wavelength). A number of researchers have already made significant progress in this regard, highlighted by the recent work of the Biegert group at ICFO, Spain, which demonstrated ~1 GW at 7 μm [9], with the opportunity to further increase the peak power to ~100GW (see Existing Capabilities below). Pumping such a system with erbium:ZBLAN fiber arrays is a concept being pursued as part of a recent ONR MURI pertaining to long wavelength lasers.

For the present, the peak power and pulse energy that can be accessed using OPA/DFG, or other commonly available solid state systems, is insufficient or marginal for a number of important applications. Self-guided optical filaments can only occur for pulse powers above the critical power for self-focusing, which in the atmosphere may be as high as a terawatt for 10 micron radiation. In order to study multiple filamentation, powers well beyond the critical power are typically required. Ultra-short pulse carbon dioxide (CO_2) lasers appear to be the only technology at present that delivers ultra-short, terawatt class pulses, in the mid-to-long wavelength infrared. There are currently only two such systems in the world, the Neptune laser at the University of California, Los Angeles, and the Accelerator Test Facility (ATF) at Brookhaven National Laboratory. The Naval Research Laboratory and Air Force Research Laboratory are collaborating to build another terawatt class CO_2 laser, but this is not yet operational.

Due to the high operating pressure that CO_2 lasers require in order to achieve the bandwidth necessary to support terawatt peak power, it is often the case that actual experimental pulse format has considerable non-ideal structure. Apart from mechanical constraints, achieving a stable, uniform discharge in a high-pressure gas is difficult. The overall engineering constraints typically lead to a single-shot system with large footprint and considerable weight. This motivates the need for further research into techniques to increase the bandwidth of the gain medium for fixed pressure or to devise nonlinear compression methods. For example, the gain bandwidth may be increased by using isotopic gas mixtures. Engineering the laser to take advantage of power broadening may also improve the pulse format, but this is difficult at the upstream stages in the laser chain where the pulse energy is low. Adapting techniques from solid state lasers, such as OPCPA, is an approach that has been proposed by UCLA. The ATF team is developing a nonlinear pulse compressor based on Kerr self-focusing. Plasma compression via backward Raman amplification has also been considered.

Based on our assessment of community needs, we identified the following priority research directions:

- **CO_2/mid-IR laser development**. As there is strong interest in these lasers from a wide community, current investment in laser development along multiple routes may deliver a high reward.
- **Laser filamentation and propagation in atmosphere**. The DOD-led interest in this topic for atmospheric propagation applications will lead to synergy with the aims of the DOE accelerator community.
- **Secondary sources and expansion of CO2 versatility based on nonlinear optics**. We see high potential long-term reward in the investment of CO_2 laser resources towards increasing the versatility of CO_2 facilities through nonlinear optics. As this will serve both the accelerator community and other scientific communities, it would potentially increase the scientific demand for the ATF and spur-on collaborative solutions to technological problems.

2.4 Existing Capabilities

Currently, the ATF and the Neptune CO_2 laser at UCLA are the only two facilities capable of reaching multi-TW peak power and few-picosecond pulse duration at 10 μm wavelength. We believe it is of particular significance that while Europe is leading the U.S. and other countries in infrastructure for high peak power lasers (ELI-NP, currently projected to multiple tens of PW at near-IR wavelengths), the U.S. has remained the leader in high power mid-IR facilities through the development of the CO_2 laser at BNL and UCLA. The continued investment in the CO_2 laser would help to maintain our competitive advantage.

As mentioned above, another approach to high-power mid-IR wavelengths is nonlinear frequency conversion of near-IR sources through OPA/OPCPA and DFG. The community of strong-field physics and extreme nonlinear optics is actively developing such light sources with emphasis on few optical cycle duration, high peak power, and high repetition rate. For example, the collaboration between the Kapteyn and Murnane group at University of Colorado and the Baltuska group at Vienna University of Technology resulted in a 90 GW source at $\lambda = 3.9$ μm [10]. Recent work by a Russia/Austria/U.S. collaboration at 3.9 μm further increased the peak power to 375 GW [11]. The Biegert group at ICFO, Spain demonstrated ~1 GW at 7 μm [9], with the opportunity to further increase the peak power to ~100GW. Unlike ATF, these mid-IR facilities are in universities and are not open to external users.

Free electron lasers can be designed to operate at mid-IR with broad tuning range of wavelength but lower peak power. For example, the FEL at Fritz Haber Institute, Berlin is capable of delivering ~ 10 MW picosecond pulses at wavelengths between 4 – 48 μm [12]. Another FEL facility at Tokyo University of Science covers 5 – 14 μm with similar pulse duration and peak power [13].

In contrast, the solid-state-based near-IR laser technologies are relatively mature, and there are many 100 TW – 1 PW user facilities worldwide, such as, to name a few, Titan (LLNL), MEC (SLAC), Vulcan (UK), ELI (Europe), and J-KAREN-P (Japan).

2.5 ATF/ATF-II PRDs

2.5.1 PRD 1: CO2/Mid-IR Laser Development

Technology Challenges

A critical challenge for CO_2 laser development at the ATF and the ATF-II remains overcoming the bandwidth limitations of the gain medium [14,15]. The practical limitation appears to come in at about the one picosecond time scale, which assumes that either very high pressure is maintained, isotopic gas composition is employed, power broadening is effective, or that some combination of all three conditions pertains. In order to generate sub-picosecond pulses, some nonlinear processes must be exploited. The solution proposed by the ATF utilizes Kerr self-focusing to map a temporal structure onto a transverse structure, which is then spatially filtered to extract the short pulse components. If successful, this scheme opens up an entirely new regime of LWIR laser-matter interactions. Technological challenges include characterization of the Kerr effect at long wavelengths in gases and solids, suppressing multiple filaments, and control of longitudinal pulse dynamics in the nonlinear medium. The ATF laser may also be well suited for plasma compression via backward Raman amplification (BRA) [16]. Due to the fact that the ATF pulse is fairly short from the outset (~3 ps), parasitic processes that typically plague BRA may be less of a concern. Technological challenges include generation of a suitable seed pulse, control of plasma instabilities, and development of suitable plasma sources.

Due to the historical lack of high pulse energy, ultra-short pulse, long wavelength sources, the nonlinear optical properties of most materials in the long-wavelength regime is not well characterized, yet such knowledge is clearly important for the future of mid-IR laser research. From a diagnostic point of view, most ultra-fast pulse measurement techniques, such as autocorrelation of Frequency Resolved Optical Gating (FROG) rely on some nonlinear effect. Furthermore, source concepts that rely on nonlinear optics, such as OPA/DFG or OPCPA, will tend to push the materials to a point near the damage threshold. Characterization of the damage mechanisms that are relevant to various optical elements is an important challenge and opportunity. Elements of interest include nonlinear crystals, lenses, mirrors, and gratings. Clearly, the ATF CO_2 laser is a candidate for such studies at the 10 micron wavelength. Secondary sources driven by the CO_2 laser could be useful for studying wavelength scaling.

Finally, improving the repetition rate, size, and efficiency of a terawatt class CO_2 laser is a major challenge. The ATF could be a test-bed for advanced CO_2 laser concepts that ultimately lead to an improvement in these parameters. For example, as solid state sources evolve near the 4 micron wavelength, it may be interesting at some point to reconsider optical pumping of the CO_2 gain medium [17]. Alternatively, amplifier configurations that take advantage of power broadening to lower the required gas pressure may have potential for higher repetition rates. In general, researchers developing a novel amplifier concept might gain significant advantage by carrying out testing at the ATF facility.

<u>Research Thrusts</u>

1. **Sub-ps, TW, mid-IR pulses**: Pushing the CO_2 laser technology into new paradigms of pulse duration and peak power is an important goal of the ATF - II. The current pulse duration is typically a few picoseconds. Accessing the sub-picosecond regime, while maintaining terawatt peak power, would be a major milestone for mid-IR laser development. It appears that the only practical way to approach this problem is by employing a nonlinear process to expand the bandwidth of the pulse after the last CO_2 amplifier and further compress the pulse. The ATF has developed their own concept to accomplish this goal, but users might be interested in using the ATF to test alternative concepts, such as plasma compression.
2. **Solid state sources driven by CO_2**: Solid state source development can benefit from the availability of a short CO_2 pulse, either as a pump or seed. In the case of OPA/DFG, the CO_2 pulse could be used as an idler to generate shorter wavelengths in conjunction with a solid state pump, or as a pump to generate longer wavelengths pushing into the THz regime. In the case of OPCPA, it is likely that a much longer CO_2 laser pulse than what the ATF typically delivers would be most interesting, but proof of concept experiments could still be considered.
3. **Mid-IR materials research**: The availability of high peak power 10 micron pulses opens up many possibilities for important mid-IR materials research. Apart from characterization of perturbative nonlinearities, damage thresholds in the mid-IR are not well known. This involves many physical processes such as multi-photon absorption and electron-hole pair creation, excitation of phonons, and strong field effects. Wavelength scaling can be studied, in

principle, by exploiting secondary radiation driven by the CO_2 laser fundamental wavelength.

4. **Novel CO_2 amplifier concepts**: New CO_2 laser concepts can be tested at the ATF. For example, a new CO_2 amplifier design could be brought to the ATF, saving researchers the considerable effort required to produce an injection pulse. An example of a concept that might evolve in the near future is an optically pumped CO_2 amplifier.

2.5.2 PRD 2: Laser Filamentation and Propagation in Atmosphere

Technology Challenges

Nonlinear propagation and filamentation of high-power lasers in various optical media, including air, has been studied extensively with high-power near-IR lasers at 0.8 μm wavelength (see Figure 2.1 a survey of previous study parameters). The measured self-focusing critical power P_{cr} in air varies between 5 – 10 GW depending on the pulse duration. P_{cr} scales with λ^2 assuming the nonlinear refractive index n_2 has no significant dependence on the wavelength. Therefore, P_{cr} should reach 50 – 100 GW at $\lambda = 2.5$ μm and could exceed 1 TW at 10 μm. Recently, mid-IR laser filamentation in air has been demonstrated with P ~ 50 GW at 2.1 μm (SWIR) [18] and with P ~ 200 GW at 3.9 μm (MWIR) [11].

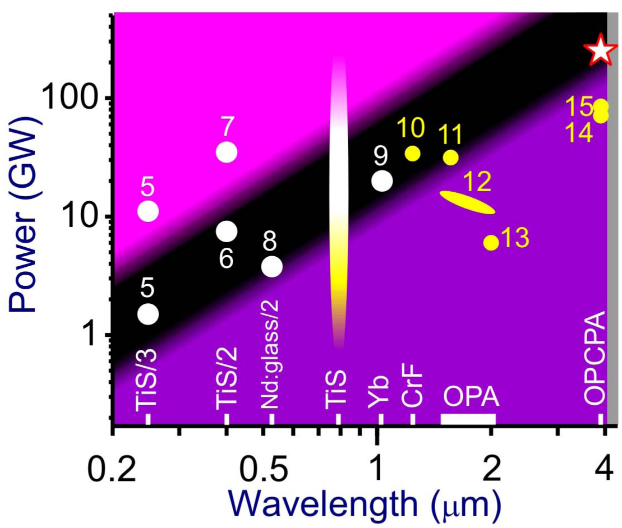

Figure 2.1- Survey of filamentation experiments in gas media, from Ref. 11 [see references within]. A laser power of 200 GW at 3.9 μm has allowed demonstration of atmospheric filamentation in the mid-wave IR. A demonstration within the long-wave IR atmospheric transparency window at 10 μm wavelength is anticipated to require a laser power at least in excess of 1 TW, but long-range filamentation may require significantly higher power, owing to the uncertainty of the nonlinear optical response and predicted spatiotemporal effects [19].

For NLO-based mid-IR laser technologies, it is generally more difficult to reach high peak power due to reduced conversion efficiency. To access the ~10 μm LWIR regime of nonlinear propagation in atmosphere, CO_2 lasers appear to be the best candidate. With the existing configuration, the ATF CO_2 laser is capable of ~ 0.5 – 1 TW. A series of upgrades planned in FY 17 – 18 will increase the peak power to ~2.4 – 4 TW with a single ~2 ps pulse, which should enable experimental study of LWIR filamentation in air. Owing to the uncertainty of nonlinear optical response and thus P_{cr} at 10 μm, the ATF-II with P > 10 TW would provide greater versatility for the experiment. It may also be possible to study nonlinear propagation at other mid-IR wavelengths (5, 3.3, and 2.5 μm) with harmonic generation. Other major technical challenges include excellent laser beam quality and shot-to-shot stability, which are generally required for investigations of nonlinear optical properties and long-range nonlinear propagation in a medium. In addition, the proposed nonlinear compression stage of the ATF-II will overcome the intrinsic limitation of CO_2 laser bandwidth and is expected to reach femtosecond pulse duration. It may enable experimental investigation of the spatiotemporal effects associated with a new paradigm of long-range filamentary propagation, recently predicted by the University of Arizona group [19]. However, nonlinear pulse compression tends to degrade beam uniformity and to magnify shot-to-shot fluctuations, with the possibility of introducing undesired spatiotemporal coupling to the laser pulse.

Research Thrusts

1. **Observation of self-guiding:** One of the most dramatic effects in nonlinear propagation is the formation of optical filaments that guide the optical energy within a tight radius over multiple Rayleigh lengths. It is generally accepted that such phenomenon is the dynamic equilibrium between Kerr-like self-focusing, ionization with plasma defocusing, and diffraction. Filamentation in air is routinely produced with ultrafast lasers at $\lambda = 0.8 - 1$ µm but the peak power (energy) guided within a channel is generally limited to a few GW (mJ). With CO_2 lasers, filamentary propagation is expected to occur at TW (J) level in atmosphere. It is also predicted that the length and the diameter of the mid-IR filament could be much larger than that produced at ~ 1 µm wavelength [20].

2. **Characterization of plasma:** Plasma generation through multiphoton ionization is the signature of femtosecond near-IR laser filamentation in air. Interactions of the optical field with both free and bound electrons lead to complicated spatiotemporal evolution of the laser pulse, including multiple defocusing-refocusing cycles, intensity clamping, continuum generation, conical emission, pulse steepening and splitting, and energy reservoir [21]. Depending on the initial laser conditions, the electron density in the femtosecond NIR filament in atmosphere is typically in the range of $\sim 10^{14} - 10^{17}$ cm^{-3}. The extended plasma channel is potentially useful in some applications such as guiding electrical discharges.

   In LWIR, plasma production in the filament could be very different from the near-IR regime. The effect of the free electrons on the change of refractive index scales with λ^2. Furthermore, in femtosecond and picosecond pulse durations, tunneling ionization would be the dominant mechanism of plasma generation. On the other hand, recent theoretical works suggested that weak ionization below the single-atom threshold due to many-body effects could have significant effect on filamentation in the LWIR range [22].

3. **Measurements of nonlinear optical properties of air in LWIR:** The nonlinear optical properties of air are sparsely studied at mid-IR wavelengths so far. A recent time-resolved measurement on N_2 and O_2 gas showed that the Kerr component of nonlinear optical response is nearly dispersionless between

$\lambda = 0.8 – 2.4$ µm [23]. Later, another experiment with four-wave mixing near 10 µm was reported, and the effective n_2 at long pulse limit was extracted [24]. It may not only benefit the research in nonlinear propagation, but also the whole NLO and AMO communities, if more measurements can be carried out using different methods in the mid-wave-IR – LWIR range.

4. **Femtosecond pulse dynamics:** Femtosecond CO_2 lasers were first demonstrated in 1980s [25] but did not become popular in the research community due to the emergence of dye- and solid-state-based short pulse technologies. With the femtosecond, few-cycle capability of the ATF-II, it will be possible to investigate the new regime of mid-IR laser filamentation proposed in Ref. [19], where arrest of beam collapse occurs through walk-off of harmonics instead of plasma refraction.

2.5.3 PRD 3: Secondary Sources and Expansion of CO2 Versatility Based on NLO

<u>Technology Challenges</u>

Historically, nonlinear optical frequency conversion, amplification and spectral broadening methods have developed around existing lasers. For example, by far the greatest knowledge base for practical laser expansion and secondary source methods based on nonlinear optics is at the 800-nm wavelength range, where the Ti:sapphire laser has provided a workhorse for the community. Nonlinear pulse compression, supercontinuum generation, sum- and difference-frequency generation, parametric amplification, and secondary source (e.g., THz generation and extreme ultraviolet generation) methods are widely explored at this wavelength. This is not at all true at CO_2 laser wavelengths, where very few high intensity sources have been available. Moreover, as discussed in PRD 2, above, fundamental properties of nonlinear light-matter interactions at 800 nm are well understood, but they are assumed to scale according to theory with Miller's Rule to the LWIR, and contradictory evidence exists [23,24].

Meanwhile, the community studying "extreme nonlinear optics", known widely as strong-field physics, but which we might call non-relativistic laser plasmas within the accelerator community, has had increasing interest in mid-IR sources HHG, LIED, and other scientific or technological applications [1–6]. Such applications typically employ few-cycle pulses.

THz generation through four-wave mixing of filamentation processes is a growing application, and has been demonstrated by the UCLA group using CO_2 lasers, producing record THz peak power [26]. As noted by the SNW, THz is currently believed to be a promising wavelength for direct laser acceleration.

Still, very little work has been done in basic frequency conversion, including second-harmonic generation, third-harmonic generation, Raman shifting, and supercontinuum and nonlinear pulse compression methods. As should be reported by the other workgroups reporting on the ATF SNW, accelerator science applications would benefit from access to wide range of different wavelengths, either as a primary or a secondary beam (for use as a diagnostic, for example), and also for shorter durations.

In our workgroup's opinion, if the nonlinear optics community gains interest in using ATF for secondary source development (given the synergy developing between researchers in the accelerator, strong-field physics, and laser science communities), this will lead to an amplification of efforts in creating future technologies for use in accelerator science at the ATF. The future scale of the ATF may make a big difference in this occurring. For example, upgrading the ATF to ~10 TW might make ~1 TW sources with other characteristics (color, duration, etc.) achievable through nonlinear optical methods. Moreover, for future aims of the accelerator community, evaluation of opportunities for generating secondary beams synchronized to the primary CO_2 10-micron beam (*e.g.,* EUV, short-wave IR, near-IR, visible, THz, and electron beams, which were all mentioned in surveys and during the SNW workshop).

Research Thrusts

1. **Secondary source generation:** e.g., EUV/soft X-ray generation via HHG and THz generation via four-wave-mixing in gases. This topic overlaps with scientific aims of the AMO physics community exploring ultrafast strong-field light-matter interactions in gases (*i.e.*, non-relativistic laser plasmas), including the physics of strong-field ionization and collisions (*e.g.*, HHG, LIED, strong-field processes with $\lambda_{laser} \sim \lambda_{vib}$).

2. **Basic NLO properties of materials in LWIR range:** not only is little known about nonlinear optical properties of gases in the LWIR range, as mentioned in PRD 2, but little is known about many solid state materials, including those used for nonlinear optical technologies.

3. **Frequency conversion:** e.g., perturbative harmonic generation, Raman shifting, difference- and sum-frequency generation, and parametric amplification.

4. **Bandwidth expansion**: e.g., spectral broadening, continuum generation, and nonlinear pulse compression.

2.6 Conclusions

The key conclusions of our workgroup are as follows:

- Funding agencies and scientific communities covering a wide range of disciplines have recognized the development of mid-IR sources and mid-IR laser science as key to growth.
- The characteristics of mid-IR sources desired by the strong-field physics community and for DOD-funded efforts in atmospheric propagation applications are strongly convergent with those desired by high energy physics and accelerator applications. Thus, a synergy can be developed along several lines through:
    - continued development of CO_2 lasers towards shorter pulse duration,
    - exploration of nonlinear optics using a CO_2 front end that may lead to secondary sources (through harmonic generation, electron beam generation, THz generation, etc.) of interest either as primary or diagnostic beams,
    - development of alternative approaches to intense mid-IR waves, such as through OPA/OPCPA pumped by mid-IR solid-state lasers, which would make use of the ATF investments in mid-IR optics and technologies.
- In terms of laser light sources for high energy physics, the U.S. has remained the leader in high power mid-IR facilities based on CO_2, while Europe has invested heavily in high peak power infrastructure at other wavelengths. Continued research and development at these CO_2 facilities is key to maintaining U.S. leadership.

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3 Panel 2: Topics in Laser-Plasma Interactions and Laser Wakefield Acceleration

3.1 Introduction

Laser-plasma interactions are an exciting route to producing compact particle accelerators. The very high, transverse fields of a laser pulse can be converted into useful accelerating fields via the ponderomotive force acting on a plasma; this is the non-linear force on a charged particle caused by spatial variations in the laser field strength. The ponderomotive force scales with the laser intensity and the square of the laser wavelength, $F_p \propto I\lambda^2$ which means that long wavelength laser drivers have a clear advantage over more conventional near infrared (NIR) systems: they can achieve the same strength ponderomotive force at lower laser intensity.

Long wavelength drivers have clear advantages in at least two areas of laser-plasma accelerator research: ion acceleration, where the laser interacts with a high-density plasma which is nearly opaque to the drive laser; and electron acceleration, where the laser travels through a low-density plasma at near light speed, producing an accelerating structure in its wake.

One of the leading advanced accelerator concepts for electron acceleration is laser plasma wakefield acceleration (LPA). In LPA, the ponderomotive force of a high intensity short-pulse laser expels the plasma electrons outwards and creates an ion cavity. The resulting space charge between this ion cavity (i.e. blowout region) and the expelled electrons pulls the expelled electrons back towards the axis of the laser and establishes a plasma density wave with a phase velocity equal to the group velocity of the drive laser pulse as shown in Figure 3.1(a) [1]. The linear focusing force created in this structure and the high accelerating force (both of which scale as $n_0^{1/2}$) create the ideal conditions for this structure to accelerate an electron beam to ultra-relativistic energies if the electrons can ride these fields over significant distances. Furthermore, the accelerating electrons can oscillate transversely in the linear focusing force of this cavity, generating femtosecond bursts of hard x-rays with energies in the tens of keV range [2], which are of interest in a wide range of applications [3].

Laser driven ion acceleration can be achieved by focusing an intense laser pulse onto a nearly opaque (high-density) plasma. The laser can only propagate into the plasma until it reaches the "critical density surface" (where the laser frequency ω_L matches the local plasma frequency ω_p), where some of the laser energy is coupled into the plasma. A long wavelength laser offers the advantage of being able to use gas-targets for attaining critical density and thus overcome unwanted debris produced with solid targets. At moderate intensities, this energy is predominantly coupled into fast electrons which then stream through and thermalize on the rear of the target, creating very strong electric fields in a thin sheath on the rear surface, which then accelerate ions. This sheath acceleration technique was first observed using NIR lasers [4-6], and now accelerates 10s of MeV proton beams with a high flux. Narrow energy spread beams can be produced using a variety of methods [7,8]. If sufficient energy is rapidly deposited at the critical surface forming an electron-ion double layer then an electrostatic shock can be driven through the target that accelerates ions from the bulk of the target. At even higher intensities the "radiation pressure" regime is reached, where the light pressure of the laser pulse effectively moves the bulk plasma target and can even produce narrow energy spread proton beams [9].

3.2 Science Drivers

Compact particle accelerators have a range of potential applications which could address scientific needs across various communities, agencies and industries, including: DOE/SC/HEP, NP, and BES; other US Government agencies; industry; fundamental accelerator science and technology research. Additionally, laser-driven acceleration technology is seen as a potentially revolutionary capability which will enable future multi-TeV e+/e- linear colliders. The interaction of an electron beam and an intense laser can even be used to study laboratory-based astrophysics. As a result, both the US, through DOE/SC/HEP and European funding agencies are investing ~ \$100M/year in developing this technology. The leading US laboratory doing laser-based accelerator research is the BELLA facility at the Lawrence Berkeley National Laboratory. The related work that can

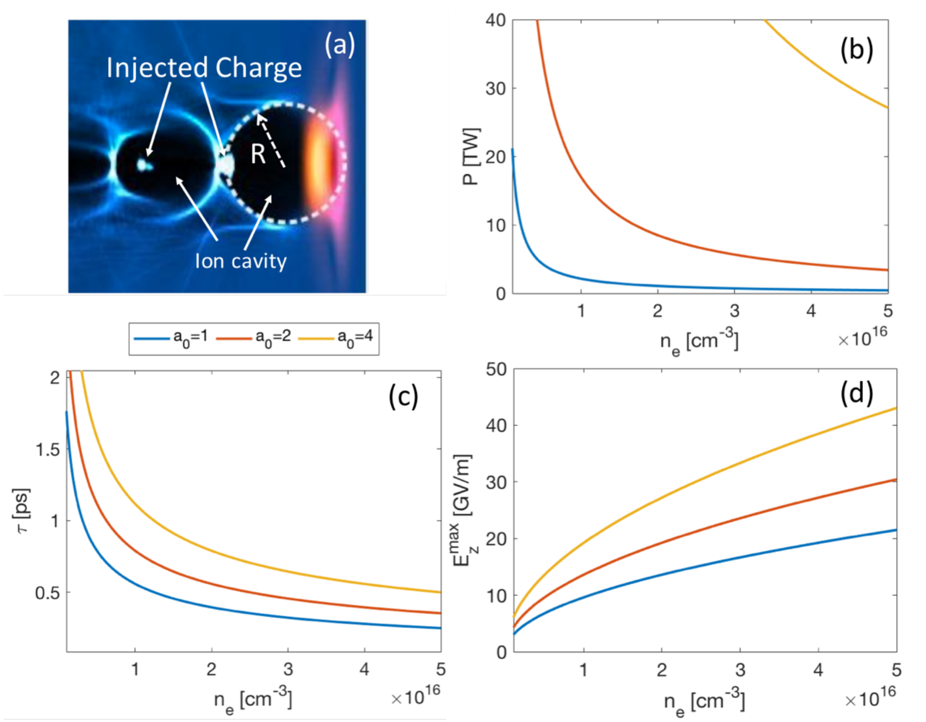

Figure 3.1- (a) Particle-in-cell simulation of laser wakefield accelerator, reproduced from [1]. The laser travels to the right, producing a density wave and an ion cavity of radius R in plasma. Injected electrons can be observed inside the cavity. (b) Power required for a matched laser pulse to drive a wakefield in ideal bubble regime as a function of density for a_0=1 (blue), a_0=2 (red), a_0=4 for λ = 10 µm. (c) Laser pulse length that will occupy half the radius of blowout region as a function of density. (d) Peak accelerating field for the same conditions as a function of density

be done at the ATF/ATF-II is complementary, not a duplication (as described below), and can lead to a very high, and leveraged, impact.

3.3 Current Research Status and Future Directions

3.3.1 Electron Acceleration

Laser wakefield acceleration has reached many milestones over the last two decades. These have, for the most part been achieved using near infrared drivers based on Ti:Sapphire, though we note that much of the earliest work in the area was achieved using long wavelength CO_2 lasers [10]. Major milestones include the initial reports of high amplitude plasma wave production [11,12], first demonstration of narrow energy spread electron beams [13-15] extending the energy gain to the multi-GeV range [16], as well as demonstrations of controlled injection via various techniques [17-19] and demonstrations of multi-stage operation that will needed for future high energy colliders [20]. Given the success of NIR driven laser wakefield accelerators, it is perhaps reasonable to ask where long wavelength drivers can contribute. The answer is clear, laser wakefield accelerators are driven by the ponderomotive force and so long wavelength drivers, which have a larger ponderomotive force than a NIR driver with the same peak power, afford a range of interesting and important opportunities.

One of the major future directions for long wavelength drivers is to reach the bubble regime of laser wakefield acceleration. To access the bubble regime, the ponderomotive force has to be strong enough to expel virtually all of the electrons from a spherical region just behind the drive laser. The bubble has linear focusing and accelerating fields and therefore can accelerate high quality electron beams. Ideal performance is expected when the laser wakefield accelerator operates in the so-called "matched" mode, where the physical dimensions of the laser pulse are approximately equal to the dimensions of the plasma wave it drives. Theoretical calculations based on non-linear theory show that the ideal bubble regime is reached when $a_0 \geq 4$, the plasma density is matched such that $P/P_c = (a_0/2)^3$, and the laser pulse length is less than the diameter of the bubble ($P_c[GW] = 17(\omega_0/\omega_p)^2$ is the critical power for self-focusing, ω_0 is the laser frequency and ω_p is the plasma frequency). This places stringent requirements on the laser parameters and can be used to estimate the threshold at which bubble regime operation will be possible (P > 20 TW for a 10 μm driver with a pulse duration of 0.5 ps). Alternatively, a "mismatched regime" can be used to rely on plasma self-focusing to increase the a_0 and access the bubble regime. Intermediate milestones prior to reaching the bubble regime include: observation of the self-modulated laser wakefield regime (where a laser pulse longer than the plasma wavelength break up into a series of pulselets that resonantly drive a plasma wave, this requires $a_0 \approx 1$ and $c\tau > \lambda_p$); generation of non-linear plasma waves (this requires $a_0 \approx 1$ and $c\tau < \lambda_p$) and observation of the onset of blow-out, i.e. when the electron plasma density inside the first ion cavity drops to near zero (this requires cavitation $P > P_c$, $a_0 \approx 2$

and $c\tau < \lambda_p$). For a 0.5 ps laser pulse the plasma densities and laser powers that will be required with a 10 μm driver are shown in Table 3.1 below:

Table 3.1- Milestones for reaching experimental parameters for LPA in nonlinear blowout regime. The pulse length for all three is considered to be 500 fs.

a_0	**Regime**	**Laser power (TW)**	**Plasma density (10^{16} cm^{-3})**
1	self-modulated	0.2	80
1	non-linear	2	1.2
2	blowout	7	2.5
4	bubble	27	5.0

Perhaps one of the major advantages of long wavelength drivers is that, for a given laser power, the size of the wakefield structure is much larger than that driven by a MIR laser system for the same intensity. This presents two significant opportunities: diagnosis of the wakefield acceleration process and controlled injection.

The first advantage concerns the diagnosis of the plasma wave amplitude and shape. This is an active area of research in the field [21-23], once again currently predominantly using NIR drivers. Accurate diagnosis of the wake structure and evolution is playing a crucial role in our understanding of this intrinsically non-linear phenomenon [24]. However, diagnostics are currently limited by in spatial resolution due to the small (~ 10 μm) size of the bubbles produced by 0.8 μm lasers. The ability to diagnose the much large bubbles (~100 μm) driven by 10 μm drivers will enable the fine structures of plasma waves in a laser wakefield accelerator to be observed for the first time.

The second advantage concerns controlled injection. Much of the research in LPA still uses the highly non-linear process of self-injection to place charge into the bubble to be accelerated. While this is very useful for the production of high charge electron beams suitable for radiation generation (e.g. synchrotron X-ray radiation from betatron oscillations of the beam inside the bubble, or the production of gamma rays using a bremsstrahlung convertor target) the quality of electron beams it produces is below that currently required for the beam to be injected into an undulator and drive a free electron laser. One obvious solution to this is to inject high quality (low energy spread, low emittance) bunches produced by a conventional accelerator into a plasma wakefield. However, for the beam to retain its initial high quality after it is accelerated in the plasma wave, the spatial extent of the injected bunch must be significantly smaller than the dimensions of the bubble and the small bunch must be accurately placed inside the plasma bubble. For the small bubbles produced by 0.8 μm drivers at comparable intensities to long-wavelength, this mean that the bunch size and alignment tolerances are at the sub-micrometer level. This has so far proved too great of a technological challenge.

Moving to the large bubbles produced by 10 μm drivers significantly reduces these constraints and opens the possibility of a paradigm shift in the quality of the electron beams produced by laser wakefield accelerators. This requires the colocation of high quality conventional electron beams with long wavelength high power laser drivers. The possibility of exquisite control over the injection of a high-quality electron bunch into a large plasma bubble opens up the opportunity to control X-ray generation via whole beam betatron oscillations of the bunch, and the eventual demonstration of an ion channel laser [25].

Long wavelength driven wakefield acceleration also opens up the possibility of performing highly controlled all optical injection using a scheme based on two color ionization injection [26]. In "standard" ionization injection [27,28], impurities are added to the gas that can only be ionized near the peak of the drive pulse. This allows some electrons to be "born" inside the bubble. Such electrons are more easily trapped and this scheme can produce higher charge, higher quality electron beams. A significant drawback of single pulse ionization injection is that electrons are always "born" in the front half of the bubble (before the drive laser reaches peak intensity) and therefore have to drift back through the bubble before they can be accelerated to the maximum energy. The two-color scheme overcomes this by using two laser pulses. A long wavelength pulse has a high ponderomotive force but low electric field strength. This means it is possible to drive a large amplitude plasma without the drive pulse ionizing the impurity species. A second short wavelength pulse, which has a low ponderomotive force but high electric field strength can then be used to cause localised ionization injection at a specified location behind the drive pulse. The advantages of developing this technique for long wavelength drivers is clear – the large bubble size will allow the second pulse to be focused to a size that is significantly smaller than the bubble diameter. This results in the injected bunch occupying a smaller phase space volume and so opens up the exciting potential of generating FEL quality electron bunches from an all optical technique.

3.3.2 Ion Acceleration

Laser ion acceleration presents a possibility of major advancement of ion-sources for producing dense (around 10^{10} ions per bunch) ultra-short (picosecond scale) ion bunches with 100s of MeV energy per nucleon, with a possibility of extending beyond the GeV scale, in millimeter-scale targets. While these ion sources may not yet demonstrate a major size advantage over cyclotrons due to the size of the high-intensity laser systems, they still prove to be indispensable as they outweigh all advantages of conventional sources by overcoming the requirement of a 100-ton scale gantry-based transport system for routing a beam onto the target. The laser beam can be pointed in an arbitrary direction along which the millimeter-scale plasma system that produces ion beams.

Current ion acceleration mechanisms work when an intense laser pulse is incident on a plasma which is opaque, i.e. one which is above the critical density. For 0.8

μm lasers this usually means that ion acceleration targets need to be solid density. Since the critical density, $n_c = 4\pi^2 m_e \epsilon_0/(\lambda^2 e^2)$ is inversely proportional to the laser wavelength squared, it is possible to perform ion acceleration experiments in gaseous targets with 10 μm lasers. This has a number of significant advantages, including the potential to operate such targets at high repetition rate, as well as the ability to select ion species. Indeed, significant milestones have already been reached in this field using 10 μm laser drivers [29,30]. As mentioned previously, various acceleration mechanisms are possible, but all scale favourably with increases in laser power.

New acceleration schemes based on relativistically induced transparency (RITA) [31], magnetic vortex enabled acceleration (MVEA) [32] and laser radiation pressure benefit from using gas targets because it is much easier to shape their density profiles. Importantly, longer wavelength lasers are able trap and accelerate ions at lower, easier to achieve, gas densities. As the lasers reach higher powers they can be focused to higher intensities and the effectiveness of radiation pressure acceleration decreases due to target transparency and the scaling of radiation pressure driven energies, $E \sim I_0/n_t$, with n_t being the target density. Increasing the power of long wavelength laser drivers will therefore result in increases in ion energy, opening up the possibility of developing capability in areas such as proton radiography, neutron production as well as allowing testing of the therapeutic effectiveness of laser driven ion beams. With long wavelength drivers, laser powers of 1 TW, few MeV proton beams have been produced [29]; with laser powers of ~10 TW 10 – 20 MeV protons beams can be produced [30]; with laser powers of ~25 TW it is expected that ion beams with > 100 MeV are possible.

3.4 Existing Capabilities

In this section, we briefly review the existing capabilities of laser drivers for laser plasma accelerators:

In the near IR regime, i.e. λ~0.8 μm lasers, there are a number of lasers around the world with over 100 TW of power that are engaged in plasma-based particle acceleration experiments. In the US, there are only a handful of short-pulse (<100 fs) laser systems in this class that are used for electron acceleration experiments. These systems are the 300 TW Hercules system at the University of Michigan, the 400 TW Scarlet laser at Ohio State University, the 1000 TW BELLA laser at Lawrence Berkeley National Laboratory, and the 1000 TW Dioclese system at University of Nebraska. These systems are used to explore the energy frontier of laser-driven plasma wakefield accelerators, as well as exploring the applications of this technique, especially plasma-produced x-rays for medical, security, industrial, and other applications. For ion acceleration, the emphasis is on low prepulse level and surface quality rather than the pulse length. Thus, high energy lasers with picosecond pulse length at larger facilities such as the Omega-EP at the Laboratory for Laser Energetics, the Titan laser at Lawrence Laser National Lab and until recently, the Trident laser at Los Alamos National Lab have been used for ion acceleration experiments.

In addition to these large systems, there are a number of smaller 10-40 TW systems that are used for the study of various phenomena related to laser-plasma interactions. In Europe, there are over two dozen active research programs investigating plasma acceleration of electrons using laser systems that scale from 50 TW to 10,000 TW, with the highest power lasers being currently under construction by the ELI project.

In the mid-IR regime, because of the $I\lambda^2$ scaling of the ponderomotive force, the laser powers producing equivalent effects scale roughly with the wavelength of the laser. Therefore, a 100 TW Ti:Sapphire laser is roughly equivalent to a CO_2 laser with tens of TW of power. Once upgraded to this regime, the ATF CO_2 laser therefore is expected to explore the regime of electron acceleration accessible currently only to >100 TW Ti:Sapphire lasers with the benefit of the favourable scaling of parameters with wavelength; for instance, the much larger bubble radius at higher wavelength that produces an equivalent interaction (see above). It is important to note the other unique feature of the ATF laser: it is a user facility, providing an experimental platform for the research groups without an institutional laser centre.

Aside from the ATF laser, there is only one other TW scale CO_2 laser used for laser acceleration of particles and that is the Neptune Laboratory at UCLA. The Neptune laser has been used in the past to demonstrate 20 MeV acceleration of a proton beam with <1% energy spread using a train of pulses with ~4TW of peak power and > 100J of laser energy [30].

Finally, short-pulse (20 fs) low-energy (20 mJ) MIR laser systems (λ~2-3 μm) have been under construction in US and UK. Much of the focus of these systems has been on the production of high harmonic attosecond light sources, but as the power of these systems increases they are expected to be used for laser wakefield acceleration experiments in the near future.

3.5 ATF/ATF-II Priority Research Directions

Taking into account the survey results and the discussions that took place at the Scientific Needs Workshop, the working group has identified the following Priority Research Directions for long wavelength driven laser-plasma interactions:

3.5.1 PRD 1: Electron Acceleration

Technology Challenges

While the amplification of the CO_2 laser pulse to over 10 TW is an important challenge, the primary concern will be the ability to reduce the pulse length to below 1 ps, such that the laser pulse does not overlap the accelerating electrons within the plasma wakefield. The ATF team has designs to address these challenges and it will be important to support these efforts to a successful conclusion.

Another challenge is to be able to synchronize multiple laser pulses with the linac electron beam with sub-picosecond accuracy, so that their interactions overlap within the physical space of the plasma wakefield.

Research Thrusts

1. **Accessing highly non-linear wakefield regime**: Because of the favorable scaling of the ponderomotive force with wavelength, the ATF has the opportunity to access the highly nonlinear wakefield regime of LPA (a_0>4), which in the case of a CO_2 laser requires lower laser powers than the traditional 0.8 µm Ti:Sapphire lasers. Therefore, we feel that this should be ATF's primary experimental priority with regards to the laser wakefield acceleration of electrons. This regime of laser wakefield is characterized by production of self-injected electrons beams with low energy spread.
2. **High quality electron beams from large bubbles**: A key priority in the field of laser wakefield acceleration is to improve the quality of the produced beam, particularly the quality of the beam in the transverse direction. This will be an important avenue to explore at the ATF as well. Particularly, the two-color injection scheme would be of interest. This method relies on the ionization injection mechanism, which has been shown in simulations to produce highly desirable transverse qualities [1]. In a two-color scheme, the lower intensity, higher wavelength CO_2 laser drives a plasma wake, while a short pulse higher intensity laser is used to ionize elements (such as impurities) within the fully formed wake. The newly ionized electrons will form into a low emittance beam at the back of the wake, and be accelerated by it.
3. **External Injection**: The simultaneous use of the linac capability at the ATF along with a CO_2 laser pulse creates the opportunity for the first-time demonstration of external injection of a high-quality beam into a laser produced plasma wakefield. Although challenging to implement experimentally, the combination of the large bubble size produced by a CO_2 laser and the availability of an independently controlled, high quality electron source makes the ATF a unique facility for such an important experiment. Furthermore, the proof-of-principle experiments demonstrating successful injection of an electron beam to plasma wave will enable the ATF to be a pioneer in solving physics challenges related to staging of plasma-based accelerators.
4. **Probing of large wake structure**: The larger wake structure generated with a long wavelength laser provides an opportunity to probe this structure with unprecedented detail and resolution. The probing of the wake structure will be possible using longitudinal and transverse laser induced Thomson scattering, or via transverse probing using an electron beam.

3.5.2 PRD 2: Ion Acceleration

Technology Challenges

The key challenge for ion acceleration is controlling the contrast ratio at high-power and shaping the laser pulse of a high-power, CO_2 driver (> 10 TW).

Research Thrusts

1. **Higher energy hole-boring acceleration:** Extend hole-boring radiation pressure ion acceleration to higher energy (10-20 MeV with 10 TW, 100 MeV with > 25 TW).
2. **Investigate applications of ion beams**: Evaluate therapeutic effectiveness, proton radiography, and security and lithography applications.
3. **Investigate shaped gas density and laser intensity profiles**: Develop new ion acceleration schemes by using shaped gas density and laser intensity profiles (e.g. RITA / MVEA), including the use of mixed-Z gases.

3.6 Conclusions

The working group wants to emphasise that there is currently no long wavelength laser laboratory pursuing laser wakefield acceleration. Increasing the power of long wavelength drivers to the ten terawatt level and beyond will allow this field to develop rapidly, allowing some of the significant advantages that long wavelength drivers have over MIR systems to be exploited. We also stress that there is currently no *user facility* capable of performing experiments in laser wakefield acceleration in the USA.

An upgraded ATF at BNL will therefore provide some important and unique opportunities. In the areas of laser wakefield acceleration and laser-plasma driven ion acceleration, we have identified a number of key future directions which the ATF upgrade is ideally positioned to address. These include:

- The generation of large plasma bubbles ideal for advanced injection schemes, both all-optical and external injection. This will allow the production of FEL quality electron beams from a laser wakefield accelerator.
- Radiation generation schemes such as controlled betatron oscillations in the large bubble, the development of ion channel undulators and first steps towards the first ion channel lasers.
- Radiation pressure dominated ion acceleration mechanism using shaped gas targets, including the development of new acceleration mechanisms uniquely suited to long wavelength laser driven experiments.

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4 Panel 3: Topics in Laser-Electron Beam Interactions

4.1 Introduction

Panel 3 was tasked with investigating experimental conditions for electron-photon interactions, such as for Compton scattering experiments and inverse free electron laser acceleration. The report comments on what is achievable with present facilities and what capabilities will be needed to support research efforts over the next decade at the ATF-II. They focused primarily on identifying the key experimental deliverables and milestones as opposed to the laser R&D required to support those deliverables. This working group had four user community presentations to help with the discussions:

- Yusuke Sakai, UCLA: *Nonlinear Compton Scattering*
- Gennady Shvets, Cornell University: *Beam-driven Surface Wave Accelerator Based on Silicon Carbide*
- Aakash Sahai, Imperial College London: *Scaling of Plasma-based Ion Acceleration Using Multi-TW Mid-IR Lasers*
- Pietro Musumeci, UCLA: *IFEL Research Needs at ATF and ATF-II*

4.2 Science Drivers

Three science drivers were identified for this working group, which were kept in mind when drafting recommendations for the ATF-II facility:

- Accelerator Stewardship Program (DOE – HEP): to enable particle accelerators to provide transformational capabilities in the fields of energy and environment, medicine, industry, national security, and discovery science.
- Future light sources (DOE – BES): new light sources should provide high repetition rate, ultra-bright, transform limited, femtosecond x-ray pulses over a broad photon energy range with full spatial and temporal coherence. Stability and precision timing will be critical characteristics of the new light source.
- Future electron sources (DOE – BES): the peak and average electron beam brightness of new electron sources will expand the scientific capabilities of X-ray and electron scattering instruments, as well as open up new applications such as shorter wavelength FELs, single shot ultrafast electron microscopy, femtosecond nano-diffraction, high average flux Compton scattering sources, and compact light sources.

4.3 Current Research Status and Future Directions

The current research conducted at the ATF and presented for the ATF-II during the workshop can be grouped into four main topics:

4.3.1 Inverse Compton Scattering (ICS)

In ICS, optical laser photons scatter off a relativistic electron beam to produce Doppler up-shifted radiation, in most cases in the few eV to MeV spectral range. For an electron beam relativistic factor $\gamma = 1/\sqrt{1 - v^2/c^2}$, where v is the electron beam velocity and c is the speed of light, and a laser photon energy E_L, the photon energy of the scattered radiation is (neglecting radiation reaction):

$$E_x = \frac{2\gamma^2(1 - Cos(\phi))}{1 + \gamma^2\theta^2} E_L$$

Here, θ is the angle of observation, and ϕ is the angle between the colliding laser and electron beams. In most cases, ϕ = 180° (head on collision) and θ = 0° (observation on axis), which means that E_x roughly scales as $4\gamma^2 E_L$. Several experiments on this topic have been conducted at the ATF, notably for applications in EUV lithography (presented in the talk of Y. Sakai from UCLA), and to study nonlinear Compton scattering effects [1,2]. A longer laser wavelength is advantageous to study nonlinear ICS effects. Indeed, it means that electrons can undergo a typical "figure 8" motion, where they have a longer acceleration length, as opposed to purely transverse oscillations. At the ATF, up to 10^9 photons where produced at 65 keV in this nonlinear regime [3], shown in Fig. 4.1. The use of two laser wavelengths (10 μm and 1 μm) allows the short wavelength laser to impose an additional rapid, small amplitude oscillation to the electrons, which allows for better control of the ICS photons [4]. ICS driven only by shorter wavelength lasers (as in most facilities) produce harder ICS photons, which makes detailed spectra measurements less practical than at ATF.

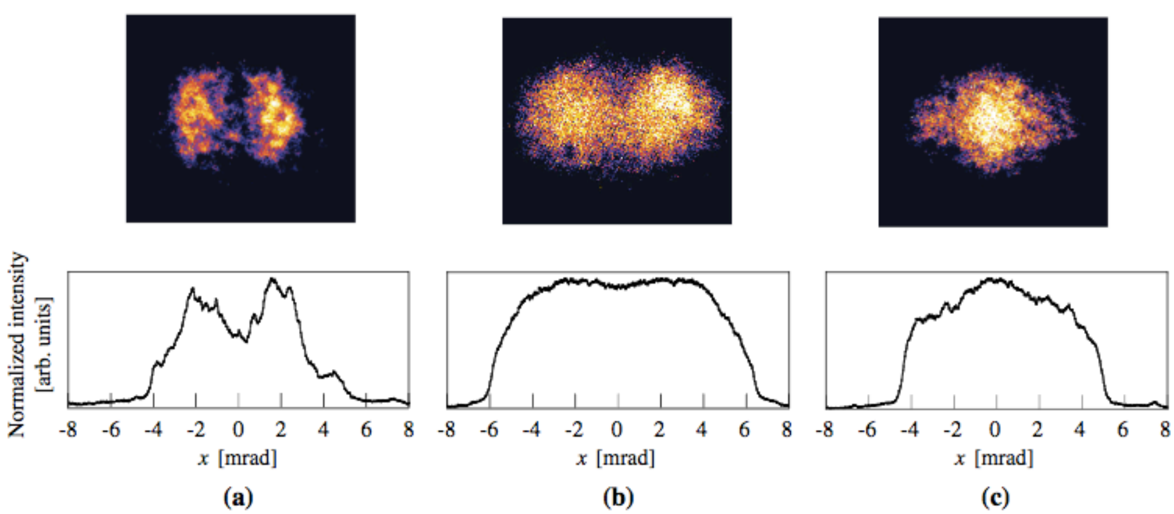

Figure 4.1 - Observation of nonlinear Compton scattering spatial profiles at ATF for laser normalized vector potentials between 0.5 and 0.7 [Sakai 2015]. (a) 2nd harmonic, (b) 2nd and 3rd harmonics, and (c) 3rd harmonics only.

4.3.2 Inverse Free Electron Laser (IFEL)

The inverse free electron laser accelerator [5] uses a magnetic undulator to couple transverse electromagnetic waves from a laser to electron motion. Therefore, there is net energy transfer from the radiation wave to the electrons. For optimum energy transfer, the resonance condition $\lambda_r = \frac{\lambda_u}{2\gamma^2}\left(1 + \frac{K^2}{2}\right)$ must be satisfied. Here λ_r and λ_u are respectively the radiation and the undulator period, and K is the undulator strength. Hence, the undulator period must be tapered to match the increasing electron energy. The ATF is currently a flagship facility for IFEL research. The RUBICON experiment demonstrated acceleration from 50 to 93 MeV with 400 GW of CO_2 laser power, and 54 cm long tapered helical undulator [6] (Figure 4.2), and the same setup was later used to demonstrate energy extraction from the electron beam with a 30 % efficiency [7].

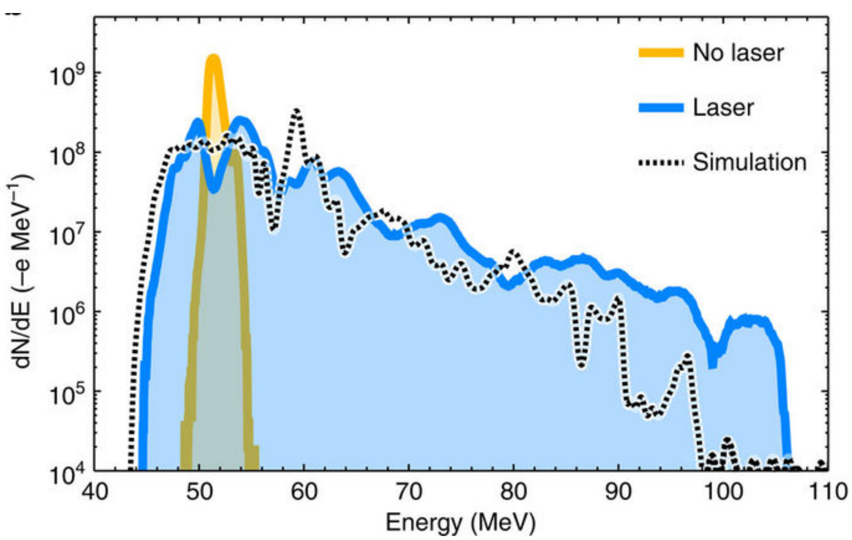

Figure 4.2- Electron beam spectra obtained during the RUBICON experiment at ATF with a helical undulator [6]

4.3.3 Dielectric Laser Acceleration and Acceleration in Structures

Dielectric laser acceleration (DLA) uses a laser pulse to accelerate electrons in a dielectric waveguide. The dielectric structure can guide an electromagnetic traveling wave mode, and serves as a confining structure for the electron beam. The long wavelength of the ATF's CO_2 laser is attractive for DLA, because to achieve high coupling efficiency (on the order of 50 %), the channel's transverse dimensions must be on the order of the laser wavelength. Also, in order for successive bunches to sit in the accelerating phase of the wave, the bunch duration must be on the attosecond scale, with intrabunch spacing equal to an integer multiple of the laser wavelength. Another proposed topic is to develop a surface wave accelerator based on silicon carbide. The surface waves concentrate in the middle of the channel, where they can be luminous (they resonantly interact with electrons), or sub-luminous [8]. The current wavelength of the ATF's CO2 laser (10.3 µm) does not permit luminous surface waves.

4.3.4 Electron Beam Phase Space Manipulation

Precision phase space manipulations of the electron beam are critical in experiments for high brightness light source generation and advanced acceleration. Electron beam – laser interactions in an undulator, resonant at the laser wavelength combined with dispersive elements, generate femtosecond scale modulation of the electron beam with a high degree of precision. Such modulations have direct application to the increased efficiency of IFELs, to inject as many particles into the accelerating bucket [7], and in "double bunching" configuration [9] to further optimize electron capture. Similar interactions occurring for higher-order laser modes (e.g. TEM_{10}) can lead to the possibility of sub-fs modulation of the electron beam phase space, which has application as ultrafast bunch length diagnostics [10] as shown in Figure 4.3. Electron beam laser applications generally rely on high power, high quality laser delivery. The ATF high power CO_2 laser, coupled with the high-brightness electron beam, provides a unique tool for experiments requiring controlled beam bunching, and higher-order interactions.

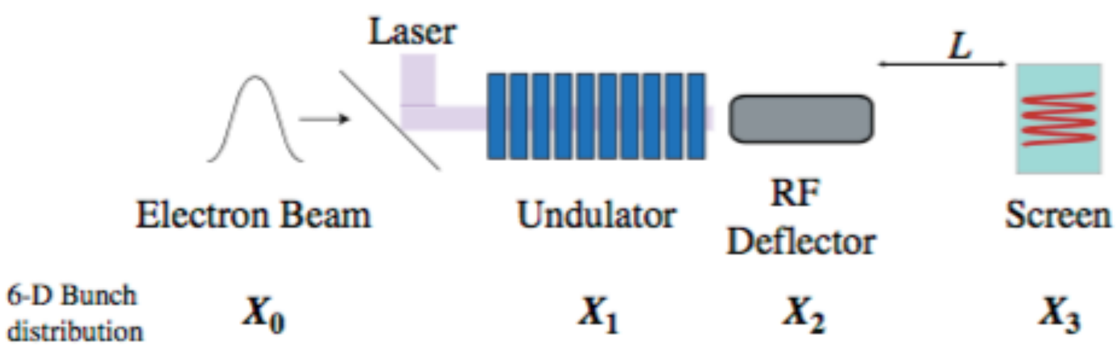

Figure 4.3- Conceptual scheme for electron beam longitudinal profile diagnostic with sub-fs resolution [10]

4.4 Existing Capabilities

Besides the ATF, there are a few facilities that have both a laser and electron beam capability. These facilities are summarized in Table 4.1. The majority of them are dedicated to inverse Compton Scattering sources, with applications to nuclear physics. We note that in this landscape, the ATF and ATF-II are the only facilities offering a 10 µm long wavelength laser.

Table 4.1- Overview of combined electron beam/laser facilities for science research

Facility	Accelerator	E beam (MeV)	Laser	Laser power (W)	Application	Year operation
FACET II	S band linac	10000	Ti:Sapphire	10^{12} (50 fs)	High gradient e- acceleration	2019-
HIGS	Storage ring	1200	FEL		ICS, N. Phys	1996-
PLEIADES	S band linac	55	Ti:Sapphire	10^{12} (55 fs)	ICS	2000-2004
T-REX	S band linac	120	Nd:Yag	10^{10} (20 ps)	ICS, N. Phys	2005-2008
Compton	X band linac	30	Ti:Sapphire		ICS	2015-
NewSUBARU	Storage ring	1000	Nd: YVO4	5 (CW)	ICS	2003-
THOMX	Storage ring	70	Fiber		ICS	
PHOENIX	Superc. linac	22.5	Ti:Sapphire		ICS	2013-
ELI-NP	S/C band linac	19500	Ti:Sapphire	10^{11} (1.5 ps)	ICS, N. Phys	

4.5 ATF/ATF-II PRDs

During the workshop, we identified four priority research directions for the ATF/ATF-II, listed below. For each of them we have also highlighted the technological challenges and research thrusts.

4.5.1 PRD 1: Inverse Compton Scattering (ICS)

Technology Challenges

Multiple laser wavelengths (1 and 10 µm) should be available at the electron/laser interaction point. 10 µm laser light is used to drive the ICS source, whereas a shorter wavelength can impose smaller amplitude electron oscillations to better control the output of the source. CO_2 laser recirculation will enable a higher photon flux and thus a higher conversion efficiency. Controlled polarization of the CO_2 laser is desirable to produce polarized x-rays and gamma-rays, useful for certain nuclear physics and condensed matter science applications.

Research Thrusts

1. **A nonlinear ICS source at 100 keV and above**: Such source could enable compelling medical and nuclear physics applications.
2. **Low energy ICS source:** EUV ICS sources should be used for lithography applications

4.5.2 PRD 2: Inverse Free Electron Laser (IFEL)

Technology Challenges

The undulator technology (tapering) limits high electron energies achieved with a 10 μm laser. To satisfy the resonance condition, the undulator period needs to be γ^2 times the laser wavelength. While a 10 μm laser is attractive because it allows for a lower initial electron energy (25-30 MeV), it prevents IFEL acceleration from reaching electron energies beyond 1 GeV because the period would become too large. IFEL with a 10 μm laser will still be very attractive as a light source driver. CO_2 laser recirculation will enable a higher IFEL efficiency. In order to increase the acceleration gradients (currently about 100 MeV/m at ATF demonstrated with the RUBICON experiment), a high power/short pulse CO_2 laser is desirable (25-100 TW) at ATF-II.

Research Thrusts

1. **Recirculated IFEL:** A recirculated IFEL would allow an increased repetition rate.
2. **250 MeV IFEL**: With the 2 TW CO_2 laser upgrade, this is feasible by adding a 2^{nd} ~ 50 cm long helical undulator to the original RUBICON experiment configuration.
3. **Waveguide IFEL:** A waveguide IFEL could compensate for the laser diffraction limit. This requires short pulse CO_2 to enable efficient coupling of high power pulses [11].
4. **Demonstrate light sources based on IFEL accelerated electron beams**: Examples of such light sources include an ICS-based gamma-ray source and a compact mode-locked soft x-ray FEL.

4.5.3 PRD 3: Dielectric Laser Acceleration

Technology Challenges

For DLA, a small beam aperture is needed and thus beam transport will be an issue, particularly for high beam powers (it is important to note that the electron beam aperture must be on the order of the laser wavelength, so a CO_2 laser at the ATF-II is attractive for that purpose as compared to beam transport in structures built for shorter wavelength lasers). Also, staging of DLAs and high efficiency beam loading are both critical technology steps.

Research Thrusts

1. **Injection with external pre-bunched beams:** An IFEL can be used to pre-bunch the beam.
2. **Staging multiple acceleration sections**
3. **Demonstrating high efficiency**
4. **Demonstrating low interception**
5. **Surface wave acceleration**: A strong preference for this application is to operate the CO_2 laser between 10.7 and 11.4 μm, with a different isotope mixture than what is presently used for the CO_2 amplifiers. During the

workshop, it was suggested that users at the ATF/ATF-II could bring their own gas mixtures.

4.5.4 PRD 4: Precision Electron Beam Phase Space Manipulation on the Femtosecond Timescale

Technology Challenges

When laser-electron beam interactions occur in undulator fields, they scale with laser power (typically ~ $P_{Laser}^{1/2}$). The technology challenge of this PRD is thus to provide both high brightness electron beams simultaneously with a high laser power. The beam properties (spot size and emittance) are demanding, and sometimes may require beam collimators, which can reduce the detectable signal. Additionally, since sub-fs electron beam modulations are the result from laser-electron beam interactions for higher order laser modes, it will be critical to demonstrate such modes (TEM_{10}) at high power as well, while suppressing the fundamental laser mode.

Research Thrusts

1. **Sub-fs modulation of electron beam**. Laser-electron interactions occurring for higher-order laser modes (e.g. TEM_{10}) in an undulator can lead to the possibility of sub-fs modulation of the electron beam phase space.
2. **Microbunching on laser wavelength scale**. This has applications to the increased efficiency of IFELs as it allows injection of many particles into the accelerating bucket and the use of a “double bunching” configuration optimize electron capture.
3. **Applications to e-beam diagnostics,** such as bunch length and profile measurements. Most techniques (coherent radiation interferometry, electro-optical sampling, RF deflectors) are currently limited to 10 fs temporal resolutions. A better temporal resolution is needed for a number of applications including: (i) Compression techniques to generate sub-ps pulses with high current; (ii) Characterization of sub-fs electron modulations; (iii) Benchmarking of theoretical and computational models; (iv) understanding beam variations in emittance and current.

4.6 Conclusions

In conclusion, the ATF (and in the future the ATF-II) is one of the only user facilities in the US where a linear electron accelerator providing a high-brightness electron beam and a high-power laser are co-located. We want to emphasize that in the list of coupled laser and accelerator facilities, the ATF and ATF-II are the only facilities offering a 10 μm long wavelength laser. This enables four main research areas, in which the unique capabilities of the ATF’s long wavelength CO_2 laser will be a clear benefit:

- Inverse Compton scattering, for x-ray and gamma-ray source development. Here the long wavelength laser will permit the production of slightly lower energy x-rays than at other facilities (for example the upcoming ELI-NP in Europe), which is an advantage to study finer structures of the ICS radiation spectral properties. Two color ICS experiments (with 1 μm and 10 μm lasers) will also allow better control of the source output for application experiments.

- Inverse free electron laser acceleration, which uses a magnetic undulator to couple transverse electromagnetic waves from a laser to electron motion. For this purpose, a 10 μm laser is attractive because it allows for a lower initial electron energy (25-30 MeV).
- Dielectric laser acceleration, which uses a laser pulse to accelerate electrons in a dielectric waveguide. Here, the 10 μm wavelength of a CO_2 laser is attractive because it relaxes the constraints on the transverse waveguide dimensions (on the order of the laser wavelength).
- Electron beam phase space manipulation, which is critical in experiments for high brightness light source generation and advanced acceleration.

4.7 References

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5 Transformative Research Capabilities

The ATF and ATF-II will support a very broad portfolio of very high impact advanced accelerator research. In order to identify the truly transformative ATF/ATF-II capabilities, we note that the ATF/ATF-II configuration provides two unique capabilities as compared to other US facilities. First, a high-power, long-wavelength laser capability (2 TW to eventually 100 TW at 9-11 μm) is only available for experiments at the ATF/ATF-II. Also, the combination of this long-wavelength laser light with a high-brightness electron beam is unique. The ATF/ATF-II transformative research capabilities identified below are centered around these unique tools.

High-power laser development: As pointed out earlier, the US leads the world in high-power mid-IR laser research and the ATF-II laser upgrade represents a new major, and transformative, step. Two high-impact specific experiments that would be enabled by the ATF-II capabilities include laser beam filamentation and self-guide fields for transport in the atmosphere. Also, the opportunity for synergy with the strong-field physics community, especially for secondary source development, is highly attractive.

Plasma wakefield acceleration: The larger wavelength of a mid-IR laser (as compared to the near IR lasers used at other LPA research facilities) provides transformative research opportunities. The promising bubble region can be more easily achieved with a longer wavelength; additionally, the longer wavelength supports more detailed diagnosis of the wakefield (allowing observation of the wakefield's fine structure) and eases controlled injection of electrons (including possible two-color injection). Also, with the closure of the TRIDENT facility at Los Alamos, the ATF-II will be the premiere ion acceleration field world-wide. With the higher CO_2 laser powers at the ATF-II, acceleration to 20-100+ MeV will be possible.

Laser-electron beam interactions: The importance of a co-located high-power laser and a high-brightness electron beam cannot be overstated. The lack of a high-brightness electron beam at the ATF-II would cripple the US advanced accelerator program. The most transformative possible research in laser-beam interactions include studying nonlinear inverse Compton scattering; higher efficiency and brightness electron acceleration with the IFEL mechanism (including as a driver for other optical acceleration schemes such as LPA and DLA); and DLAs with improved beam transport, staging, and higher efficiencies.

Importantly, the ATF CO_2 upgrade satisfies nearly all of the near- to mid-term laser research requirements described in this document, including both laser-only and laser-electron beam experiments. The following table, Table 5.1, cross-walks key experiments with laser requirements and identifies that the ATF-II laser upgrade will meet essentially all requirements.

Table 5.1- Overview of near- to mid-term laser experimental requirements by topical area

Experiment	Requirement	ATF-II Laser Upgrade
Nonlinear Kerr effect	1-10 TW	Yes
Non-linear LPA	~2 TW	Yes
Blow-out LPA	5-10 TW, 0.5 psec	Yes
Bubble LPA	25-30 TW, 0.5 psec	Yes
Ion acceleration	25-100 TW; long-term circ. polar.	Yes (power); No* (circ. polar.)
IFEL	25-100 TW	Yes
DLA	10-100 GW, lin. polar.	Yes
ICS	2-10 TW	Yes
ICS OAM	Circ. polar.	No*
Phase space manipulation	~ TW	Yes

** Circularly polarized laser light is not currently part of the proposed project plan*

Additionally, the ATF-II laser upgrade addresses essentially all the desired laser parameters identified by the Mid-IR Laser Scientific Needs Survey provided to the ATF users and potential users. Table 5.2 summarizes the match between the desired parameters and the planned CO_2 upgrade parameters. Together, these tables show that the ATF-II laser upgrade planning is aligned with anticipated future research needs. The Scientific Needs Workshop review panel endorses the technical goals of the CO_2 laser upgrade as being well matched to the scientific needs identified in this report.

Table 5.2- Comparison of the desired laser parameters from the Mid-IR Laser Scientific Needs Survey and ATF-II Laser Upgrade parameters.

Parameter	Requirement	ATF-II Laser System
Power	1-100 TW	Yes (>20 TW is longer term development direction)
Energy	1-100 J	Yes (up to 70 J)
Pulse length	3 psec down to <500 fsec	Yes (<1 psec is longer term development direction)
Stability	< 10% (1%)	Possible. ATF laser system currently achieves tens of % (rms); ATF-II laser system should show significant improvements
Pulse number	Single pulse	Yes
Temporal profile	Pulse shaping	Possible. Some interest in control of pulse shaping
Spatial profile	$M^2 < 1.2$	Good at lower power; transverse shaping responsibility of user
Rep rate	0.1 – 10 Hz	Current design is <0.1 Hz at full power, up to 3 Hz at lower power
Polarization	Circ., lin.	Current design only circular polarization at lower power

Appendix I: Agenda

ATF Scientific Needs Workshop
May 31- June 1, 2017
Brookhaven National Laboratory

Wednesday, May 31, 2017		
09:00-10:00	**Workshop Introduction**	
	09:00 Laboratory Welcome	
	09:10 Accelerator Stewardship Program Comments	Eric Colby (DOE)
	09:25 Workshop Opening	Mark Palmer (BNL)
	09:45 Scientific Needs Survey Highlights	Christina Swinson (BNL)
10:00 –12:45	**Topic #1: Topics in Mid-IR Laser Research**	
	10:00 Working Group Survey Results	Christina Swinson (BNL)
	10:15 User Community Presentations	
	• AE:74 Long-range Self-Channeling of Multi-TW CO2 Laser Pulses in Air	Eric Welch (UCLA)
	10:45 *Coffee Break*	
	11:00 User Community Presentations	
	12:15 Discussion	
12:45-14:00	*Lunch (On your own)*	
14:00-17:15	**Topic #2: Topics in Laser- Plasma Interactions and Wakefield Acceleration**	
	14:00 Working Group Survey Results	Christina Swinson (BNL)
	14:15 User Community Presentations	
	• Plasma-based Particle Acceleration Using Synchronized Mid-IR and Near-IR Laser Pulses	Gennady Shvets (Cornell University)
	• Mid-IR Laser-driven Plasma-based Insertion Devices for Compact Coherent X-ray Production	Aakash Sahai (Imperial College London)

	• Mid-IR Driven Laser Wakefield Acceleration	Christina Swinson (BNL) / Mike Downer (University of Austin Texas)
	15:15 *Coffee Break*	
	15:30 User Community Presentations	
	• Laser Wakefield Acceleration in the Bubble Regime	Navid Vafei-Najafabadi (SBU)
	16:00 Discussion	
18:00-21:00	*No Host Dinner- Bistro 72*	
Thursday, June 1, 2017		
08:30-09:30	**Committee Executive Session**	
09:30-12:45	**Topic #3: Topics in Laser-Electron Beam Interactions**	
	09:30 Working Group Survey Results	Christina Swinson (BNL)
	09:45 User Community Presentations	
	• Compton Scattering	Yusuke Sakai (UCLA)
	• Beam-driven Surface Wave Accelerator Based on Silicon Carbide	Gennady Shvets (Cornell University)
	• Scaling of Plasma-based Ion Acceleration Using Multi-TW Mid-IR Lasers	Aakash Sahai (Imperial College London)
	• IFEL Research Needs at ATF & ATF-II	Pietro Musumeci/ Nichols Sudar (UCLA)
	• TBD	Yu-shin Chen (NRL)
	12:15 Discussion	
12:45-14:00	*Lunch (On your own)*	
14:30-17:00	**The ATF-II Facility Plan and Response to Community Needs**	
	14:30 Overview of the Facility Plan	Mark Palmer (BNL)
	14:50 Addressing the Needs of WG#1	Mikhail Polyanskiy (BNL)
	15:10 Addressing the Needs of WG#2	Igor Pogorelsky (BNL)
	15:30 Addressing the Needs of WG#3	Mikhail Fedurin (BNL)
	15:50 *Coffee Break*	
	16:05 User Community Discussions	