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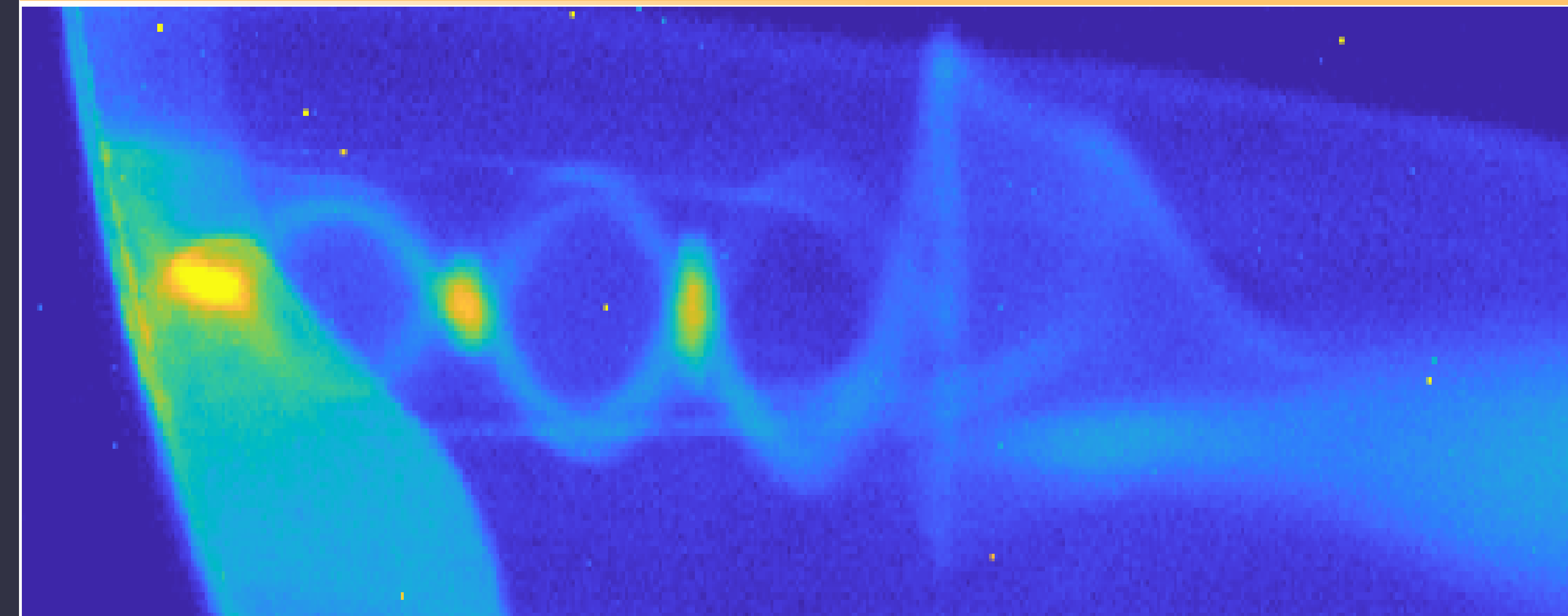

Report of the Accelerator Test Facility Science Planning Workshop

October 2019

NATIONAL USER FACILITY ORGANIZATION

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

Cover Image Credit:

I. Petrushina, et al: Presentation at 23rd Annual ATF Users' Meeting,
AE93 - "Direct Measurements of Fields and Radiation in the Self-Modulated Plasma Wakefield Regime"

Accelerator Test Facility Science Planning Workshop Report

(October 2019)

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Executive Summary

The Accelerator Test Facility (ATF) at Brookhaven National Laboratory, supported by the U.S. DoE's Office of Science Stewardship program in advanced accelerator physics and technology, is a unique resource supporting a broad range research and development activities by users from universities, national laboratories and industry in the U.S. and internationally.

Because the ATF is highly focused on cutting edge research, it is necessary to periodically review present and future facility capabilities to ensure that the evolving user needs will continue to be met and expanded in concert with future research directions. Consequently, on October 15 - 17, 2019 the ATF convened a meeting of experts in the fields of research relevant to the ATF science programs to identify priority research directions consistent with the ongoing operations and upgrade plans at building 820. The previous Scientific Needs workshop, held in 2017, was centered on an assessment "of the needs associated with the mid-IR laser capabilities" as were expected to be implemented at the ATF II facility (Building 912)[1]. Since that workshop, significant program and budget redirection by the DOE Office of High Energy physics coupled with an internal BNL reevaluation with respect to the long term and realistic direction of the ATF facilities, concluded that the expansion into building 912 was not feasible. Therefore, new planning must be undertaken to reassess the scientific needs of the community of users on a broader scale at the Building 820 facility. It is the purpose of the present workshop to carry out that reassessment.

As guidelines for that reassessment, the following goals were established based on the existing capabilities and planned short term facility upgrades presented at the workshop:

- Determine or reaffirm the set of parameters that will support the currently planned program and enable the exploration of new Physics,

- Determine the priority research directions that can be leveraged to establish a priority based upgrade path.

In preparing this report we have focused in each scientific area on using a combination of the technical and scientific presentations from the workshop to develop:

- A summary of scientific needs for the parameters for the ATF facilities to pursue to enable the exploration of new physics,

- A summary of capability upgrades required for enabling new key research

In presenting these results we have chosen to follow generally the structure of the 2017 report, since much foundational material from it remains relevant. Thus the report is again organized around a set of Scientific Research areas. However, we have modified the list

[1] The full report can be accessed at https://www.bnl.gov/atf/docs/atf_snw_report_final.pdf

to three areas to be consistent with the focus of the current workshop on a Building 820 based program. Originally, there was to have been a fourth section on the needed diagnostics, but after some reflection, we have chosen to fold these into the detailed discussion of each research area in a way that shows relevance to the proposed research directions.

The primary goal of this workshop remains, as it was for the 2017 workshop, to identify priority research directions (PRDs) within each Research Area that are enabled by the present research infrastructure and near-term upgrade plans at building 820. After reviewing the workshop presentations and summaries, and folding in proposal information from the recent (Dec. 13, 2019) User meeting, we have developed the following PRD's in each of the three principal research areas:

A. Long-Wave Infrared (LWIR) Driven Science.

    1. LWIR Laser-Driven Plasma Ion Acceleration
    2. LWIR Laser-Driven Plasma Electron Acceleration
    3. Basic Plasma Physics Research in Novel Regimes
    4. LWIR Laser Technology Development

B. Electron Beam Driven Science

    1. Advanced Acceleration Research
    2. Beam Phase Space Optimization
    3. Low Emittance Source Development
    4. Novel and Efficient Terahertz Radiation Generation

C. Laser Electron Beam Interactions

    1. Basic Research of Laser-Plasma Charged-Lepton-Beam Production
    2. Electron Acceleration Techniques Driven by the Combination of Electron Beam and LWIR Laser
    3. Radiation Generation

Specific details and objectives of each of these PRDs, including basic research thrusts, are described in relevant sections. For each topic presented, we have endeavored to focus on the uniqueness/advantage of the ATF facilities to the science proposed and on the required LWIR/electron beam parameters needed for the science proposed. Together, the topics represent a significant and robust collection of cutting-edge accelerator and technology research. We believe that the urgent completion of this future research is crucial to support continued progress on our national and international advanced accelerator thrusts.

1 Introduction and Technical Summary

1.1 Introduction

The Accelerator Test Facility (ATF) at Brookhaven National Laboratory, supported by the U.S. DoE's Office of Science Stewardship Program, is a unique resource supporting a broad range of research and development activities by users from universities, national laboratories and industry from all over the world. The ATF research has included accelerator beam physics, particle sources, novel acceleration techniques, novel radiation sources, and laser and charged-particle-beam instrumentation.

Because the ATF is highly focused on cutting edge research, it is necessary to periodically review present and future facility capabilities to ensure that the evolving user needs will continue to be met and expanded in concert with future research directions. Consequently, on October 15 - 17, 2019 the ATF convened a meeting of experts in the fields of research relevant to the ATF science program to identify priority research directions consistent with the ongoing operations and upgrade plans at building 820. The previous Scientific Needs Workshop (SNW), held in 2017, was centered on an "assessment of the needs associated with the mid-IR laser capabilities" as were expected to be implemented at the ATF II facility (Building 912)[1]. Since that workshop, significant program and budget redirection by the DOE Office of High Energy physics coupled with an internal BNL reevaluation with respect to the long term and realistic direction of the ATF facilities concluded that the expansion into building 912 was not feasible. Therefore, new planning must be undertaken to reassess the scientific needs of the community of users based on a broader scale at the Building 820 facility. It is the purpose of the present workshop to carry out that reassessment.

Background

The ATF provides the community with access to three classes of source driven experimental facilities:

- Long-wave IR (LWIR) High Power Laser at ~ 9.2 µm
- Electron Beams
- Near-IR laser sources

The capabilities of these facilities and the expected R&D path for the mid-term (roughly the next 3 years) are as follows:

1. LWIR High Power Laser Facility: The ATF is pursuing an R&D plan with the goal of delivering 10-20 TW of CO_2 laser power with sub-ps pulse length to the users in the mid-term. Currently, the facility is capable of producing a 5 TW CO_2 pulse with a 2 ps pulse length. However, with the current air transport line, the delivered energy to the users is kept below ~2.5 TW to avoid nonlinear distortions in the pulse. A vacuum transport upgrade is planned to be completed within a year,

[1] The full report can be accessed at https://www.bnl.gov/atf/docs/atf_snw_report_final.pdf

which will enable the full 5 TW to be delivered to users. ATF's R&D effort encompasses the realization of two more capabilities in the mid-term: First, modification of the gain profile is a potential route to enable the delivery of 10 TW, 1 ps pulses. Second, a recent proof-of-principle demonstration of the nonlinear pulse compression (NLPC) technique has confirmed the feasibility of a sub-picosecond pulse. These preliminary results show that ~0.5 ps pulse lengths may become possible with this technique in the near future. To achieve this path, additional R&D and upgrade funding will be required over the course of the next 3 years.

2. Electron Beam Facility: Currently the facility is capable of delivering an electron beam with an energy of 50-65 MeV, 0.1-2 nC in charge, a pulse-length down to 100 fs, and a normalized emittance of 1 μm at a 1.5 Hz repetition rate. The ATF staff presented several upgrade thrusts in the e-beam energy and pulse duration in order to gain feedback on the potential interest in these upgrades:

a. With respect to the electron energy, a second klystron powering the existing two linac sections would result in an increase in the beam energy up to 125 MeV. The increased $\gamma \sim 250$ will be very advantageous for the physical processes that scale nonlinearly with e-beam energy, such as inverse Compton scattering (ICS). Additionally, the increased energy will result in significant gain in the pump depletion length for experiments that use the electron beam as a driver (e.g. of plasma waves). Therefore, the increased energy is expected to be an enabling factor for more advanced beam-driven experiments.

b. Several schemes exist for improving the bunch compression. Two of these schemes, which were discussed at the previous user meeting[2] involve the use of a double chicane or a chicane-dechirper combination. The choice between these two methods involves the tradeoff between the energy spread and the compression. Another novel, double-chicane, bunch compression technique uses a particular ratio between the R56 of the two chicanes so as to remove the need for any beam optics between the two chicanes, while minimizing the coherent synchrotron radiation effects[3]. This method has been shown in simulations to be able to reduce the bunch length to 30 fs and is expected to be implemented once tested and demonstrated experimentally.

c. The diagnosis of the electron beam's longitudinal phase space can be enabled by installing and commissioning an additional transverse deflector cavity at end of the second beam line where the electron beam can be delivered (a cavity currently exists on one of them).

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[2] See https://indico.bnl.gov/event/6651/ for the archived presentations

[3] Y. Jing, et al. in *Proc. IPAC'19*, Melbourne, Australia, May 2019, pp. 382-385. doi:10.18429/JACoW-IPAC2019-MOPGW112 (2019)

The high-power CO_2 laser and electron beam capabilities can be combined at the interaction point (IP), but the pursuit of applications driven by the electron beam – independent of the LWIR laser – is also highly desired.

3. Near IR Facilities: The ATF is in the process of significantly expanding its near IR capabilities. Currently, a Nd:YAG laser with 1-15 ps and 1-5 mJ in energy can be delivered to the IP. The expansion of the near IR capabilities encompasses the integration and the delivery of a short-pulse (≤ 100 fs), terawatt-class Ti:Sapphire laser pulse to the IP. This expanded capability is consistent with the interest expressed by the community at the 2017 Scientific Needs Workshop. Further upgrades to the laser power are possible, but will depend on the interest of the scientific community and availability of funding.

Goals of the Workshop

The purpose of the workshop was to obtain the guidance of the user community in the following areas in order to prioritize the upgrades planned for the facilities described above in the *Background* section:

- Determine or reaffirm the set of parameters that will support the currently planned program and enable the exploration of new physics,

- Determine the priority research directions that can be leveraged to establish a priority-based upgrade path.

The priority research directions identified in the 2017 SNW resulted in the table of required parameters presented in Table 5.1 of the workshop report and reproduced as Table 1.1 below. It shows that a laser power of >25 TW is needed to enable several key research areas, such as the laser plasma acceleration (LPA) in the bubble regime, ion acceleration, and IFEL. The LPA in the bubble regime is particularly of interest as the combination of the upgraded near-IR capability with the CO_2 laser pulse creates a path for an all-optical electron beam injector via ionization injection. A primary goal of the present workshop is to revise or reaffirm these parameters.

Since the focus of the 2017 Workshop was on LWIR laser systems, the novel physics enabled by the linac-produced electron-beam was not discussed. In the present workshop, however, the intent is to focus on novel physics enabled by all ATF capabilities, including those specifically driven by the electron-beam facility as well as those enabled by the integration of the electron beam with the laser facilities interacting with a structure (plasma or otherwise).

The second goal, determination of Priority Research Directions (PRD), requires the identification of particular research areas and the facility directions needed to reach the parameters that enable these areas. For the CO_2 facility in particular, ATF is interested in a discussion of relative merits of various technologies for reaching above 25 TW of delivered energy, including the commonly used electrical discharge pumping, as well as new approaches such as optical pumping or diode pumping.

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

Table 1.1. Overview of experimental requirements by topical area, reproduced from the "report of the accelerator test facility scientific needs workshop 2017". Page 48

This Report

Using a combination of the technical and scientific presentations from the workshop, we have developed

- A summary of scientific Priority Research Directions targeted at the facilities available at ATF for pursuing the exploration of new physics, and

- A summary of capability upgrades required for enabling new these PRDs.

In presenting these results we have chosen to follow generally the structure of the 2017 report, since much foundational material from it remains relevant. Thus the report is again organized around a set of Scientific Research areas. However, we have modified the list to three areas to be consistent with the focus of the current workshop on a Building 820 based program as described in the *Background* section above.

The primary goal of this workshop remains, as it was for the 2017 workshop, to identify priority research directions (PRDs) within each Research Area that are enabled by the present research infrastructure and near-term upgrade plans at building 820. After reviewing the workshop presentations and summaries, and folding in proposal information from the recent (Dec. 13, 2019) User meeting, we have developed the following PRDs in each of the three principal research areas:

A. Science Enabled by LWIR High Power Laser
   1. LWIR Laser-Driven Plasma Ion Acceleration
   2. LWIR Laser-Driven Plasma Electron Acceleration
   3. Basic Plasma Physics Research in Novel Regimes
   4. LWIR Laser Technology Development

B. Electron Beam Driven Science
   1. Advanced Acceleration Research
   2. Beam Phase Space Optimization
   3. Low Emittance Source Development
   4. Novel and Efficient Terahertz Radiation Generation

C. Laser and Electron-Beam Interactions.
   1. Basic Research of Laser-Plasma Charged-Lepton-Beam Production
   2. Electron Acceleration Techniques Driven by the Combination of Electron Beam and LWIR Laser
   3. Radiation Generation

Specific details and objectives of each PRD is structured through the following three sections constituting the body of the report. Within each PRD we provide an *introduction* section that describes the context of the PRD at ATF within its respective science area and any related prior R&D. Then the *status of the current research and future directions* are presented. This section addresses, as appropriate, present status of the ATF R&D as well as the proposed experiments that will pursued in the context of each specific PRD. A summary of the specific research thrusts is also provided in this section. Finally, in the *enabling technologies* section, the beam requirements and upgrades to enable the research thrusts are identified, including the required supporting diagnostic, instrumentation, and simulation or other software support as appropriate.

For each topic presented we have endeavored to focus on the uniqueness/advantage of the ATF facilities to the science proposed and on the required laser/electron beam parameters needed for the proposed science. Together, the topics represent a significant and robust collection of cutting-edge accelerator and technology research. We believe that the urgent completion of this research is crucial to support national and international advanced accelerator thrusts.

1.2 Scientific and Technical Summary

What follows here is a summary of the PRDs described in the report, including the relevant research thrusts as well as the facility requirements.

A. Long-Wave Infrared (LWIR) Driven Science

PRD A.1: LWIR Laser-driven Plasma Ion Acceleration

In Laser-driven ion accelerators (LDIAs), an intense laser pulse interacts with a near "critical density" plasma. Under the right condition, significant amount of the laser energy can be coupled to the forward motion of a large population of hot electrons in the plasma. The displacement of these electrons (generally in a forward direction) creates a strong electric field that can accelerate ions directly or create a slowly moving electrostatic shockwave that is able to reflect plasma ions.

The use of the LWIR laser in the LDIA experiments presents two primary benefits: first, the hot electron yield is significantly increased with the use of an LWIR laser. This is an important advantage because these electrons play a critical role in creating the space charge that will accelerate ions. The second advantage of using an LWIR laser is the fact that the critical density for such a laser pulse ($n_e \sim 10^{19}$ cm^{-3} for $\lambda = 10$ µm) can be achieved by using supersonic gas targets as opposed to a solid target, which is required for a near infrared (NIR) laser. The use of a gas target instead of a foil is very attractive because it is a clean source of protons and ions; it can be run at a high-pulse repetition rate, and the density of the plasma can be changed easily in the neighborhood of the critical plasma density. Based on the current research and future research directions, the future thrusts are as follows:

1. **Higher energy acceleration using collisionless electrostatic shock acceleration (CESA):** CESA has been an ongoing experiment at ATF with very promising results. These results should be extended to higher energies. In particular, the ultimate goal of 200 MeV at $a_o \sim 10$ should be pursued as the primary goal.
2. **Investigate the potential benefits of using LWIR laser ion acceleration mechanisms other than CESA, particularly in RPA and RITA**: Both RPA and RITA are examples of so-called coherent techniques, where thin plasma surfaces are directly driven by the high-intensity laser to co-propagate with it. The exploration of radiation pressure acceleration (RPA) requires the development of ultrathin gaseous targets and controlling the laser pre-pulse energy. The relativistically induced transparency acceleration (RITA) mechanism requires further investigation of mixed-Z gas targets apart from shaping of gas targets. Other acceleration mechanisms, such as Magnetic Vortex Enabled Acceleration (MVEA) also remain largely unexplored in the LWIR regime.

In addition to the required laser parameter (shown in Table 1.2 below), an ion accelerator requires diagnostics for laser and plasma profiles, as the details of both can have significant impact on the physics of these interactions. In particular, prepulse contrast diagnostics better than 4 orders of magnitude and diagnostics for determining the precise longitudinal density profile of the plasma will be required.

PRD A.2: LWIR Laser-Driven Plasma Electron Acceleration

A laser wakefield accelerator (LWFA) that is driven by an LWIR source was discussed as a priority research direction in the SNW 2017 and it continues to be a priority experiment for ATF. In this scheme, the ponderomotive force of the laser expels the plasma electrons out of its path. The space charge between the expelled electrons and the remaining ions, which are much heavier than the electrons, creates a plasma wave in the wake of the laser pulse. The accelerating and focusing fields in such wave can reach a magnitude of tens of GV/m. LWIR lasers provide a number of unique advantages that make the related work at ATF facility a complementary effort to the NIR LWFA research that can lead to high, leveraged, impact. In particular, the LWIR laser is ideal for operating the LWFA in the blowout regime at low densities of 10^{16}-10^{17} cm^{-3}. The hundreds-of-μm-radius bubbles that can be driven in this regime, combined with low dark current and ATF-based opportunities for pinpoint external injection, open new pathways for LWFA of electron bunches with sub-% energy spread, a goal that has evaded NIR-LWFA for a quarter century. Based on the current research and future research directions, the future thrusts are as follows:

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 LWFA (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. The unique features of LWIR-driven LWFA in this regime, such as lack of dark current should be experimentally confirmed
2. **High quality electron beams from controlled two-color injection**: Using the lower-intensity, higher wavelength CO_2 laser to drive a plasma wake, the short-pulse higher intensity NIR laser can be used to ionize elements (such as impurities) within the fully formed wake. This two-color scheme is expected to result in FEL-quality electron bunches.
3. **High quality electron beams from controlled external injection**: The injection of the e-beam generated by the ATF linac into the large bubble driven by the LWIR laser is a primary research thrust for ATF. Since this research thrust leverages both LWIR laser and the ATF e-beam, its detailed discussion is done in PRD C.1.
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. The latter will be discussed in more detail in PRD C.1.

In addition to the laser parameter shown in Table 1.2 below, successful LWFA experiments will require advanced laser-plasma diagnostics. Because of the integral role of the electron beam to diagnose the fields of LWFA, the discussion of the diagnostics for LWFA is carried out below in PRD C.1. The two-color optical injection experiment requires yet more specialized diagnostics, particularly for achieving accurate alignment and synchronization. Methods such as using semiconductor switch, self emission, as well as shadowgraphy can be used for spatial and temporal alignments.

PRD A.3: Basic Plasma Physics Research in Novel Regimes

Unique aspects of the LWIR laser should be leveraged for the exploration of the basic physics of laser plasma interactions (LPI) in this region of the electromagnetic spectrum. For instance, a plasma generated via optical field ionization with an LWIR laser has a known anisotropic electron velocity distribution at very high temperatures. This anisotropy can be used for the study of phenomena such as the electron Weibel instability, which is an important mechanism for self-generating magnetic fields in both laboratory and space plasmas. Application-driven basic plasma physics research is another important component of this PRD, where the investigation of the basic physics of LPI can lead to improved capabilities of the LWIR lasers, which will then benefit a wide array of experiments in return. The two examples of the application-driven plasma-physics research presented in the workshop were the plasma optics, and backward Raman amplification (BRA). "Plasma optics" refers to use of plasma medium to manipulate the state of a laser pulse, including focusing, guiding, and compression. The chief advantage of a plasma optic is that since it avoids material damage altogether, it represents an important alternative for a final-focus optic, which is usually the largest, most expensive and most damage-prone optical element in a beam delivery system. BRA is a method for amplification of short pulses, and it consists of a low-energy, femtosecond seed pulse and a high-energy, long-duration, counter-propagating pump pulse in the plasma. Energy is transferred from pump to seed when the frequencies of two pulses match the resonant condition $\omega_{pump} - \omega_{seed} = \omega_p$, where ω_p is the plasma frequency. The relevant research thrusts in these areas were summarized as follows:

1. **Weibel Instability:** Using the ATF CO_2 laser, carry out the first detailed measurements on the growth rate and k-spectrum evolution of electron Weibel instability.
2. **Plasma Optics:** Develop the physics of plasma focusing optics and investigate the possibility of implementation as a final focusing optics. This thrust will require the investigation of the challenges as they relate to dispersion and plasma nonlinearities
3. **Backward Raman LWIR Amplification:** Investigate the potential application of the backward Raman amplification technique to ATF laser, including the design and demonstration of a particular viable configuration

The laser parameters required for the study of the Weibel instability are shown in Table 1.2. In addition, ultrafast electron radiography using ATF's linac-produced electron beam will be used to measure the growth of the magnetic fields in this experiment. The required electron beam parameters are also shown in Table 1.2. For the plasma lens and backward Raman amplification, no facility upgrades specifically were requested. Rather, it was emphasized that the development of these technologies at ATF creates an opportunity for developing such novel approaches to focusing and amplification of a high-power LWIR laser, which in turn can only be tested at the ATF CO_2.

PRD A.4: LWIR Laser Technology Development

A majority of the research directions highlighted in this report require an LWIR laser pulse with high power (>10 TW) and a short pulse (≤ 1 ps). Because bridging the gap between the existing capabilities and those demanded by the experiments described above requires the development and emergence of new technologies, research in this area merits consideration as an independent PRD at ATF. The unique LWIR infrastructure as well as the significant institutional experience and memory in CO_2 technology development make ATF an ideal place for this development. The LWIR technologies discussed during the workshop can be categorized as belonging to two general areas:
(1) CO_2 beam manipulation technology, including laser micro-fabricated components;
(2) Advanced optical pumping of the CO_2 laser-amplifier, aimed at improving the rep-rate, efficiency and compactness of terawatt CO_2 lasers;

Based on the current research and future research directions, the future thrusts are as follows:

1. **Advanced CO_2 beam manipulation:** Characterize optics developed via femtosecond laser micromachining and determine if they can be implemented as a replacement for conventional optical components
2. **Advanced laser amplifier technology:** Investigate issues surrounding the transition from electrical discharge sources to optical pumping, which includes the development of more energetic 4.3 μm pump sources, understanding the physics of excitation and relaxation, and gain tailoring via isotope mixing.

It is noteworthy that the planned CO_2 laser upgrades drive the demand for large aperture, high power components, which in turn can only be tested at the ATF CO_2. Such ATF-CO_2-centric development is extremely valuable for the community, because availability of the high-power components in turn will drive the development of high power industrial CO_2 lasers.

B. Electron Beam Driven Science

PRD B.1: Advanced Acceleration Research

The current research thrusts in the field of beam-driven advanced acceleration at the ATF include wakefield acceleration in dielectrics, plasmas, and metallic structures. The presence of high-quality electron beams as well as the capability to deliver single bunch and multi-bunch configurations to users coupled with state-of-the-art diagnostics make ATF an ideal facility for carrying out the basic research in these fields to answer fundamental questions about the physics of these interactions.

In a dielectric wakefield accelerator (DWA), a relativistic drive beam traverses a dielectric-lined waveguide establishing a wakefield, which is then sampled by a trailing witness beam. The high-brightness beam delivered by ATF has allowed this facility to play a major role in the history of experimental demonstration of key components of DWA research in recent years. In the metallic-structure-based wakefield acceleration, the proposed work consists of developing a class of novel cavity designs with unconventional spatiotemporal distributions using multi-harmonic mode superposition (e.g. TM010 and TM012) to suppress pulsed heating and RF breakdown. The future thrusts for these areas are as follows:

1. **Dielectric wakefield acceleration:** The continued programs on dielectric wakefield acceleration (DWA) are aimed at extending interaction lengths by measuring the effects of beam breakup due to transverse forces, investigation of high transformer ratios by beam phase space tailoring, and material and geometry advances to combat structure breakdown limitations.
2. **Exploration of Multi-mode Harmonic Cavities (MHCs):** the goal is to incorporate the MHC concepts for the realization of a beam-driven high gradient two-beam accelerator (TBA) with low breakdown probability and a reliable acceleration gradient in an X-band structure to reach 200 MV/m, without exceeding the empirical limits. The transformer ratio for this scheme and for an inductively detuned structure is expected to be larger than 10, resulting in the high beam-to-beam efficiency of energy transfer.

In addition to the beam parameters described in Table 1.2, the research thrusts described above require state of the art diagnostics. These include the transverse deflective cavity (T-CAV), 2 THz interferometry from coherent transition radiation (CTR), coherent diffraction/edge/Cerenkov radiation (CDR/CER/CCR), with a number of these diagnostics having been pioneered at ATF. The development of novel diagnostics for the characterization of the spectral information contained in the emitted Cherenkov radiation, as well as the beam diagnostics for energy and longitudinal profile measurements will also be important and extendible to other experimental endeavors.

PRD B.2: Beam Phase Space Optimization

The precision control of the beam longitudinal phase is important for current profile tailoring for high transformer ratios, coherent synchrotron radiation (CSR) suppression, and other applications for advanced accelerators. The extensive control over the parameters of the ATF electron beam as well as the ready availability of the state-of-the-art diagnostics for measuring beam properties makes ATF an important contributor to the study of tailoring methods for high brightness beams. Previous measurements have already demonstrated ancillary applications of DWA and corrugated metallic structures in place of traditional accelerator components, such as de-chirpers, passive deflectors or beam bunchers and shapers. In addition, using the high-power laser provides additional opportunity to use inverse-free-electron laser interactions in an undulator to also manipulate the longitudinal phase space of the beam. The present PRD is based on the extension of these methods for optimizing the beam phase space for particular applications with the future thrusts as follows:

1. **Dechirpers and shapers** Continued exploration of broadband, multimode structures to remove residual energy chirp inherent in beam compression stages. Also, by prudent choice of excited frequencies in the structure, and the addition of a compression element such as a chicane, the beam longitudinal profile can be bunched (short wavelength) or ramped (long wavelength)
2. **Sub-fs modulator:** a higher-order IFEL interaction in conjunction with the x-band deflecting cavity creates beam angular modulations correlated to the longitudinal

beam coordinate. The modulations in turn can be useful as a high-resolution beam diagnostic for precision features on the electron beam. The proposed method will be capable of measuring bunches with the power to resolve features on the sub-fs scale

In addition to the beam parameters described in Table 1.2, full longitudinal phase space diagnostics are required, which consists of a transverse deflecting cavity and dipole spectrometer, with associated beam optics for establishing imaging criteria for the quantities of interest.

PRD B.3: Low Emittance Source Development

Generally speaking, the experimental efforts at ATF will either benefit greatly by having access to ultralow emittance electron beams, or their aim is to develop new sources with enhanced performance over existing sources. Currently, there is no user accelerator facility where these new sources could be tested. The ATF has the required infrastructure and expertise for testing new injectors and schemes, albeit nontrivial issues must be addressed to realize this effort, including addressing spatial limitations at the linac front-end and possible downtime to accelerator operations. Based on the current research and future research directions, the future thrusts for the ultra-low emittance source development are as follows:

1. **Field Emission Cathodes:** laser-driven field-emission cathodes have demonstrated generation of fs microbunches with the potential for ultralow emittance. In this scheme, the laser beam is directed across the tip of the cathode rather than illuminating the cathode as done in laser-driven photocathodes. This particular scheme is also conducive to using non-traditional cathode materials, in particular, carbon nanotubes (CNTs). The development of this method with such novel material as CNTs will facilitate achieving ultralow emittance.
2. **Diamond Electron Amplifiers:** In a DEA, the primary electrons from, say, a thermionic cathode impinge upon a diamond wafer, which generates >200 secondary electrons for every primary one. These secondary electrons emerge from the backside of the diamond wafer with low emittance and low energy spread. Thus, further development of DEA will allow for the conversion of a low-quality e-beam from a conventional cathode into a high-quality e-beam with higher charge.
3. **Optical Bessel Beams***:* optical Bessel beam (OBB), which may be formed for instance by focusing a radially-polarized laser beam using an axicon, could be used to help guide the electrons emitted from advanced electron sources. The electrons counter-propagate through the center of the OBB and oscillate within the potential well formed by the electric field distribution in the center of the OBB. This guiding process is analogous to usage of a solenoid magnet, but requires no magnetic hardware around the e-beam. It also avoids the problem of magnetic field leakage onto the cathode, which can spoil the emittance. Thus, the development and integration of OBBs with advanced sources will lead to higher quality beams.

In terms of required diagnostics, there is a clear need for the ability to test advanced electron sources as injectors on an existing and high-performance accelerator. Ideally, having access to the front-end of the ATF accelerator would allow testing the injectors by sending their emitted electrons into the RF accelerating cavities. This might be accomplished by using, for example, a side port connected to the front-end and a bending magnet. The existing beam diagnostics for emittance at the ATF are adequate to diagnose the emittance of the generated beams, and would additionally enhance core capability allowing other experiments valuable cross-checking and calibration.

PRD B.4: Novel and Efficient Terahertz Radiation Generation

The THz range is one of the regions in the electromagnetic spectrum where FELs are particularly attractive both because solid-state-based sources are scarce and because electron beam and undulator parameters needed are relatively easily achievable. Long wavelength free-electron lasers have been efficiently operated using a waveguide to compensate the effects of diffraction. By controlling the dispersion properties of the wave it is possible to obtain simultaneously group and phase velocity matching, enabling a very long interaction region. The parameters at ATF are particularly well suited to explore the 1-10 THz range, which are of interest to a variety of applications

The main thrusts in this area are the first test of the physics of the zero-slippage FEL in a tapered undulator with high gain. This allows validating analytical and simulation models and studies of the spectral properties of the amplified radiation, as well as the effects of space charge, wakefields and multi-modal emission. Second, a record-high 10% conversion efficiency, mJ-level THz pulse energy and GV/m THz fields are achievable with the ATF beam. In the waveguide zero-slippage configuration, by strongly tapering the undulator, we can further prolong the interaction until the limit where the electron beam energy is depleted, and achieve in single-pass systems record high efficiencies in the conversion of the e-beam energy into THz pulse energy

C. Laser Electron Beam Interactions

PRD C.1: Basic Research of Laser-Plasma Charged-Lepton-Beam Production

With accelerating gradients that are orders of magnitude higher than those of the conventional accelerators, the laser wakefield accelerators (LWFAs) represent a critical avenue of investigation for future of HEP physics. One significant milestone, which is required for achieving high beam quality in an LWFA, is the accurate understanding of the fields and the interaction of the electron beams with these fields. ATF is in an ideal position to significantly contribute to this research because ATF is the only facility in the US (and one of only a handful of facilities in the world) where a linac-produced electron beam with a nanocoulomb of charge and high quality is available for experiments with a high-power, short-pulse laser system. Because of the stability, high-quality, and the flexibility in properties of the electron beam produced at ATF, the injection and acceleration of this electron beam in an LWIR-driven LWFA allows for the investigation of the impact of the plasma wakefield on the quality of the electron beam. Moreover, the electron beam can be propagated perpendicular to the plasma wakefield, and in this way be used as a probe for direct measurement of LWFA's field structures. This latter capability provides a direct method for investigating the basic physical properties of the fields in LWFA.

In addition to the potential of LWIR plasma-driven wakefields to contribute to electron acceleration, BNL-ATF's unique combination of linac-produced, sub-picosecond, nanocoulomb electron beam tightly synchronized with sub-picosecond multi-TW CO_2 laser pulse can enable breakthrough experiments in producing ultra-short *positron* beams of tunable properties using laser wakefield acceleration. *First*, the electron beam enables the controlled production of positron-electron showers or jets. *Second*, these positrons are captured in a quasi-nonlinear CO_2 LWFA. This scheme has already been proposed for 1-μm lasers, but the large size of the LWIR-driven LWFA is expected to enable a much higher coupling efficiency for the shower positrons to produce positron beams. This positron source is currently at the conceptual stage and will need extensive development in simulations as well as validation in experiments. Based on the current research and future research directions, the future thrusts are as follows:

1. **Electron beam injection experiments:** injecting the electron beam longitudinally in a wakefield will enable the following objectives:
   (a) Acceleration of the injected beam at high efficiency, while preserving a low energy spread and emittance
   (b) Investigating the physics of transverse instabilities, including transverse instability growth and mitigation strategies; e.g. impact of ion motion
2. **Transverse electron probe development:** The transverse probing of the plasma wakefield should be developed for direct measurement of the fields in linear and nonlinear plasma wakes, particularly at densities $<10^{17}$ cm^{-3}.
3. **Confirm the scaling of positron generation physics for LWIR driver through simulations and preliminary experiments:** The properties of the electron positron showers generated by the ATF e-beam and high-Z target including characterization of the spatial and temporal properties as well as the energy distribution of the positrons need to be verified in simulations first as well as in dedicated experiments. Once the properties of positrons are well-established, the ability of the LWFA to capture and accelerate these positrons, including the demonstration of low-energy-spread "quasi-monoenergetic" production of positron beams, will need to be investigated and verified in simulations and experiments.

The laser and electron beam parameters needed to enable this research is shown in Table 1.2 below. In addition to these parameters, the two beams must be synchronized with great precision, with the jitter between the two much less than the size of the bubble. Computer-based optimization technologies will likely be required to achieve repeatable and high-precision synchronization. The effective use of these computer-based optimization methods requires a high rep-rate for both laser and electron beam. Thus, a focus at ATF on building capabilities to increase the repetition rate of the TW CO_2 lasers as well as implementing computer optimization and machine learning into the beam line, electron sources, RF and laser sources are essential to the practical realization of tightly synchronized electron and laser beams as required by these experiments. Beyond precision alignment, the integration of machine-learning algorithms as a standard part of the research infrastructure available to ATF users will greatly improve research efficiency. In addition to an increase in the rep rate of operations, better instrumentation for digitizing data and better computer-friendly control elements and improved machine-learning strategies and software are also required.

With respect to the required diagnostics, the groundbreaking experiments in this PRD demand innovative e-beam and plasma diagnostics, even beyond those developed for standard laser-wakefield accelerators (LWFAs) over the past 3 decades. The ultrafast electron radiography experiments, which profile internal electric fields of wakes using transverse fs e-bunches, appear promising for visualizing low-density wakes. However, additional e-beam diagnostics will need to be developed at ATF to characterize plasma accelerated e-beams with the expected fractional percent energy spread and spin-polarization. Full e-trajectory recovery within the spectrometer's energy-dispersion plane using for example tandem screen detection or fiducial grids will be essential. E-beam polarimeters based on Møller e-e scattering from polarized ferromagnetic targets, which are standard equipment at many research electron accelerators, will have to be adapted for the first time to the unique challenges of LWFA beams. Finally, the potential of large-bubble LWFAs for producing low-emittance e-bunches must be verified. Coherent transition radiation (CTR) methods — including multi-octave spectroscopy, imaging, and interferometry — show promise for high-resolution 6D profiling of plasma-accelerated e-bunches outside of the accelerator. Computational advances in reconstructing e-bunch profiles from CTR data are also needed. ATF is well-positioned to become a leader in diagnosing ultrashort, narrow-energy-spread, spin-polarized electron bunches from advanced plasma accelerators.

Advanced simulation capabilities constitute another tool required for understanding the physics of interactions at ATF as well as improving results. These include particle-in-cell (PIC) codes such as WarpX, FBPIC, OSIRIS, VSim, and SPACE for modeling fields and charged particles self-consistently; magnetohydrodynamic codes (FLASH) for modeling plasma evolution e.g. in plasma lenses, ionized gas jets and discharge capillaries; machine-learning tools for beam diagnostics and steering; parallel codes for computing Lienard-Wiechert fields from particle trajectories (LW3D), to model e.g. undulator or betatron radiation; and other codes available through RadiSoft's Sirepo cloud-based interface. There is a strong desire to make realistic simulations of ATF experiments available to users without requiring them to devote significant resources to simulation development. Commercial codes, such as VSim, provide many ease-of-use features (e.g. graphical user interface, complete online documentation) so that researchers who are not simulation experts can get started quickly. Additionally, ATF initial conditions, such as laser pulse profiles and electron phase space distributions, could be built into simulation codes and be updated as the facility evolves. For example, users could simply select "ATF laser" in a code's interface without having to input specific pulse parameters themselves. Common ATF setups could be provided as ready-made examples. ATF should collaborate with computational experts from the workshop to meet this need.

PRD C.2: Electron Acceleration Techniques Driven by the Combination of Electron Beam and LWIR Laser

A primary role for ATF as a premier Accelerator Stewardship facility is to cultivate novel and emerging particle acceleration concepts. Recently, several new acceleration mechanisms have emerged, which use a laser and an electron beam to accelerate electrons at higher gradients than conventional accelerators. Because of the combination of the

LWIR laser and high-quality electron beam collocated at ATF, this facility uniquely provides the tools needed for cultivating these ideas. Development of these methods may in turn give rise to fundamentally new technological approaches with potentially transformative ramifications. The two examples of such research presented in this report were the Dielectric Laser Acceleration (DLA1) experiments and Direct Laser Acceleration (DLA2) experiments.

A dielectric laser accelerator (DLA1) is a compact accelerator for charged particles based on micron scale photonic structures driven with laser light – a fundamentally new technological approach with accelerating fields of 1-10 GV/m, a factor of 100 larger than current state-of-the-art conventional accelerators. The availability of ATF's unique combination of 10 μm CO_2 lasers and high-brightness photoinjector-based electron beam would allow for several significant experimental advantages, including a factor of 100 higher charge throughput, reduced requirements on external focusing, and factor of 10 relaxation in tolerances on structure fabrication and co-alignment of successive structures.

The direct laser acceleration (DLA2) refers to a process where electrons inside an ion column gain energy from a co-propagating laser pulse. This method is proposed as a way to replenish the energy of an electron beam driving a plasma wakefield in a *synergistic Electron-bunch/Laser-pulse Wakefield Acceleration (ELWA)*. Under the right conditions for example, Driver Beam (DB) electrons can gain energy from the laser at a rate that is the same or higher than the rate they lose energy to the wakefield. In addition to the direct HEP application, EWLA concept can be used for such key accelerator stewardship applications as the generation of copious high-energy X- and γ−rays.
The relevant research thrusts in the two areas discussed above are summarized as follows:

1. **Dielectric laser acceleration (DLA1):**
   a. Proof of principle demonstration of GeV/m acceleration in specialized structures
   b. Key demonstrations to study beam dynamics, wakefield effects, and acceleration over centimeter-scale distances with multi-MeV energy gains.
2. **Direct laser acceleration (DLA2):** Demonstration of the synergistic increase of acceleration length under the combined effect of the ATF electron beam and LWIR laser:
   a. In single-bunch, high charge configuration, the electron beam will extend the propagation length of laser in plasma.
   b. In two-bunch configuration, the trailing electron beam will experience higher energy gain due to the synergistic increase in acceleration length.

The beam requirements for demonstrating the key physics of these two techniques are shown in Table 1.2.

PRD C.3: Radiation Generation

Generating short, intense x-rays is one of the primary applications of particle accelerators. Such devices generally work by wiggling relativistic electrons transversely with respect to their direction of propagation. The transverse oscillation can be provided by an intense laser pulse, where the tremendous transverse fields of the laser are coupled to the transverse motion of the electrons, either in vacuum or in the presence of a plasma wave. The first method, called Inverse Compton Scattering (ICS), has been an active area of research at ATF for the last two decades. The second method known as direct laser acceleration (DLA2 in PRD C.2 above) encompasses a set of experiments, which are just beginning to be developed, leveraging the coupling between the transverse field of the laser and the oscillating motion of electrons in the focusing force of plasma structures (the so called betatron oscillations), to generate radiation from these electrons.

The ATF facilities provide capabilities that can enable unique contributions to the research in this area. With respect to ICS for instance, compared to the commonly-used, broadband Ti:S sources at wavelengths from 750-850nm, the LWIR laser at ATF enables the study of narrowband ICS sources with high photon flux, which enables unique studies such as nuclear resonance experiments for eventual gamma-ray applications in the emergent nuclear photonics community. While the LWIR-driven ICS sources generate lower energy x-rays (~10 keV rather than 100 keV using NIR sources), this is advantageous because the lower energy photons relax the demands on the diagnostics allowing for precision-controlled experiments to investigate the basic physics of these interactions, which can then be scaled to higher energies for numerous applications. The LWIR at ATF also enables the study of ICS sources in the nonlinear regime with high photon flux, useful for exploration of basic photon science.

A dedicated, tunable, high quality electron beam source such as the one provided by ATF is another great advantage because it increases the flexibility of the experimental parameter space, which allows for the exploration of novel methods such as polarized x-ray generation. Additionally, the presence of two high power laser sources at different wavelengths at ATF (1µm and 10µm), allows for novel hybrid schemes to investigate bi-harmonic energy production and modulation of ICS x-ray pulses at the sub-femtosecond scale. Generating an x-ray bunch-train from the recirculation of the laser and multiple interaction with the electron beam is another unique capability enabled by ATF's independent control over laser and electron beam source, which enables control over the bandwidth of the radiation.

With respect to DLA 2, the electrons will have a larger transverse momentum and a higher radius of oscillation compared to the situation where they are not overlapped with the drive laser. The increased transverse momentum and oscillation amplitude of electrons in DLA 2 are expected to significantly increase the gamma-ray yield of electrons in the plasma. The possibility of exquisite control over the injection of a high-quality electron bunch into a large plasma bubble at ATF also 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.

The future thrusts for this PRD are as follows:

1. **<u>Developing ICS sources in novel regimes</u>**
   a. Developing high flux ICS spectral radiation on a single shot basis
   b. Bi-harmonic (dual wavelength mixing) ICS Experiment, using the NIR lasers (Nd:YAG/Ti:S lasers) in conjunction with the multi-TW CO_2 laser

c. Linear ICS Source <100 keV for certain medical applications and hard x-ray optics development
d. The combination of an ICS source driven by an inverse free-electron laser accelerator enables an all-optical system for high average flux photons.

2. **Investigate the radiation generated from LWFA**
a. Injecting the electron beam longitudinally in the SM-LWFA and investigating the resulting radiation
b. Characterizing the betatron radiation from an injected electron in an LWFA driven in the blowout regime
c. Exploring novel radiation mechanisms such as ion channel laser.

In addition to the laser parameter shown in Table 1.2 below, the following diagnostics are required: General area detectors, including KBr, MCPs, x-ray CCDs, and CsI scintillators with CCD are used for single shot observation of the radiation distribution, or for measurement of the double-differential spectrum at the screen location. Each of these detectors have a different sensitivity, and spectral responsivity, and are matched to the corresponding x-ray characteristics of each specific experiment. Additionally, flux measurements with CdTe or Si based photodetectors are needed to measure the integrated flux of the photons over the full solid angle. Liquid scintillator detectors in combination with single photon count PMT, and Compton magnet spectrometer are also needed for high-energy gamma-ray measurement. In addition, the emission of a bunch train of x-rays demands to measure the micro bunching by the x-band deflector or an x-ray streak camera.

The required parameters for the PRDs described above are summarized in the table below:

Experiment	LWIR Laser	e-beam
PRD A.1: Ion Acceleration	10 TW: ~ 10 MeV ions 25 TW: ~ 100 MeV ions Circ. Pol. For advanced methods (RPA, etc)	
PRD A.2 e-Acceleration	10 TW, 1ps: Blowout regime 20 TW, 0.5 ps: Bubble regime Integrated intense NIR: two color injection	
PRD A.3 Weibel	1 TW, ~3 ps, circ. Pol.	
PRD B.1 Dielectric Wakefield Acceleration (DWA)		$\epsilon_n \sim 1-2\ \mu m$, $Q > 300$ pC, $\sigma_z < 200\ \mu m, \sigma_r < 50\ \mu m$ r.m.s
PRD B.1 Two Beam Acceleration (TBA)		$Q \sim$ 1nC, $\sigma_z, \sigma_r < 2\ mm$, total peak power> 60 MW

PRD B.2 Structure-based phase space manipulation		$\epsilon_n \sim 1-2\ \mu m.$
PRD B.2 fs beam manipulation	TEM_10 mode	
PRD B.4 THZ Generation		$\epsilon_n \leq 2\ \mu m$, $Q > 400$pC, $\sigma_z < 120\ \mu m$, 6.4 cm period undulator: 1.5 mJ THz pulse
PRD C.1 e- injection into LWFA in blowout	20 TW, 0.5 ps: Bubble regime	$\sigma_r, \sigma_z \ll R_b \sim 100\ \mu m$, $\gamma >$ 200: 100 MeV beam injection $\sigma_r \gg \lambda_p$: ultrafast electron radiography
PRD C.1 e+ beam generation	0.5-5 TW, ~2 ps, spot size w_0~50-100 µm	>60 MeV, $\Delta E/E$ <1%, σ_r<50 µm, Q>250 pC, ϵ_n<10 µm, bunch length σ_z/c<0.2 ps
PRD C.2 Dielectric Laser Acceleration	20 mJ, 2 ps, 10 Hz rep rate	50 MeV, $Q \sim 1$ pC, $\epsilon_n \sim 20\ nm$, $\sigma_r \sim 5\ \mu$m
PRD C.2 Direct Laser Acceleration	20 TW, 0.5 ps: Bubble regime	$\sigma_z/c \sim 0.5$ ps, $Q \sim$ 1nC: Drive beam $\sigma_z/c \sim 30$ fs, $Q \sim$ 10pC: Trailing beam
PRD C.3 Inverse Compton Scattering	$a_0 = 1.5$, Circular polarization: nonlinear ICS $a_0 = 2$, linear polarization: harmonic radiation $a_0 = 10$, any polarization: higher order multiphoton Thomson scattering	50-75 MeV, $\epsilon_n \sim 1\ \mu m$, $\sigma_r \sim 10-30\ \mu m$, $Q \sim 300-500 pC$, rep rate 3Hz

Table 1.2: The laser and electron beam requirement summary for experiments in this report

2 Science Enabled by LWIR High Power Laser

The following priority research directions were identified as areas that are enabled by the multi-tera-watt sub-picosecond long-wave infrared (LWIR) laser at ATF:

1. LWIR Laser-Driven Plasma Ion Acceleration
2. LWIR Laser-Driven Plasma Ion Acceleration electron acceleration
3. Basic Plasma Physics Research in Novel Regimes
4. LWIR Laser Technology Development

The material in this section is derived from contributions by A. Sahai (University of Colorado), N. Vafaei-Najafabadi (Stony Brook University), C. Siders (LLNL), C.J. Zhang, C. Joshi (UCLA), D. Gordon, Yu-hsin Chen (NRL), S. Mirov (UAB), and S. Antipov (Euclid).

2.1 LWIR Laser-Driven Plasma Ion Acceleration

2.1.1 Introduction

Laser-driven ion accelerators (LDIAs) has been demonstrated to produce intense ultrashort bunches of ions with source-size of the order of tens of microns. It 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 of energy per nucleon and with a possibility of extending beyond the GeV scale, in millimeter-scale targets. As the energy and quality of the laser-plasma accelerated ion beams improve, these ion sources have a large number of potential applications including radiotherapy of cancerous tumors [1,2], radiography [3], generation of short-lived isotope needed in positron emission tomography [4], Injection for conventional accelerators [5], and inertial confinement fusion [6].

In LDIAs, an intense laser pulse interacts with a near "critical density" plasma (density at which the laser frequency ω_o matches the local plasma frequency ω_{pe}). While the laser pulse typically gets reflected at the critical surface, under the right condition, significant amount of its energy can be coupled to the forward motion of a large population of hot electrons in the plasma. The displacement of these electrons (generally in a forward direction) creates a strong electric field that can accelerate ions directly or create a slowly moving electrostatic shockwave that is able to reflect plasma ions [7]

The use of the LWIR laser in the LDIA experiments presents two primary benefits: first, the hot electron yield is significantly increased with the use of an LWIR laser. This is because the maximum laser energy transferred to a plasma electron is determined by the ponderomotive force, which scales as $I\lambda^2$ [7]. Moreover, while lasers of different color may end up producing the same ponderomotive force, a laser with ten-times-longer wavelength can do so over a hundred-times-larger area and potentially a thousand-times-larger volume (focus area multiplied by the Rayleigh length or the pulse duration, whichever is shorter), thus exhibiting proportionally higher yield of hot electrons [8]. This is an important advantage because these electrons play a critical role in creating the space charge that will accelerate ions.

The second advantage of using an LWIR laser is the fact that the critical density for such a laser pulse ($n_e \sim 10^{19}$ cm^{-3} for $\lambda = 10\ \mu m$) can be achieved by using supersonic gas targets as opposed to a solid target, which is required for a near infrared (NIR) laser. The solid targets used in NIR LDIA have drawbacks limiting their practical use such as difficulty in maintaining the purity of a target (e.g. carbon targets are accompanied with hydrogen), producing debris, having a limited repetition rate, and sensitivity to laser prepulse, which creates a plasma at the target surface before the arrival of the main pulse [9]. On the other hand, the use of a gas target instead of a foil is very attractive because it is a clean source of protons and ions; it can be run at a high-pulse repetition rate, and the density of the plasma can be changed easily in the neighborhood of the critical plasma density. Another attractive feature of this scheme is the possibility of switching between different ions from H, He to Ne simply by changing the gas, which is of interest to several medical and scientific applications [10].

The CO_2 laser operating at a wavelength of $10\ \mu m$ is currently the only viable candidate for reaching very high intensities in the mid-IR part of the EM spectrum [7]. This has been an active area of research at ATF and the continued development of the ATF LWIR laser towards powers in the range of tens of TW gives this facility an excellent vantage point to contribute to this research.

2.1.2 Status of current research and future directions

Based upon the laser-plasma interaction parameter regime the techniques of ion acceleration can be broadly classified into thermal and coherent. Irrespective of the underlying prominent differences, all the acceleration mechanisms scale favorably with increase in the peak laser power. Whereas thermal mechanisms favor long pulses in order to effectively heat the plasma, coherent mechanisms favor shorter pulses in order to avoid instabilities that can disrupt the orderly interaction. Moreover, coherent mechanisms are highly sensitive to uncontrolled pre-pulse energy in the laser pulse and have to often spend significant experimental effort to understand the pre-pulse structure as well as to increase the contrast ratio of the laser.

The most common technique for laser-plasma ion acceleration uses the interaction between a high-intensity Ti:Sapphire laser and thin metals foil. The pre-pulse of the laser ablates the foil forming a relatively long-scale length pre-plasma. A high-intensity laser drives ponderomotive energy gain of pre-plasma electrons. As the laser is tightly focused and shot at nearly normal direction to the metal foil, most of the ponderomotively driven pre-plasma electrons propagate through the thin foil. However, their inability to escape the Coulombic field of the foil results in the pile-up of hot electrons that form a sheath at the rear of the foil. This target normal sheath acceleration (TNSA) thermal acceleration technique was first observed using NIR lasers [11-13], and now accelerates 10's of MeV protons with a high flux. Narrow energy spread beams can be produced using TNSA by controlling the interaction [14,15] mechanism so that a significant fraction of the laser energy penetrates to the back of the target due to relativistic transparency and results in laser-sheath coupling in the rear of the target. This can lead to the enhancement of ion energies in the so-called "breakout afterburner" mechanism [16].

Other thermal techniques of ion acceleration have also been proposed using the understanding developed from the studies of the TNSA mechanism. One such alternative thermal technique that has gained momentum in the last decade is referred to as collisionless electrostatic shock acceleration (CESA). If sufficient energy is rapidly deposited at the critical surface, an electron-ion double layer electrostatic shock can be driven. This shock propagates through the target and accelerates ions from the bulk of the target. CESA ion acceleration experiments have been successfully performed using gaseous target driven by 10 μm CO_2 lasers [16,17,18]. 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 the ion species to be accelerated.

Coherent techniques utilize plasma surfaces that are directly driven by the high-intensity laser and co-propagating with it. One such coherent technique is the “radiation pressure” acceleration (RPA) regime where the pressure exerted by a laser pulse effectively moves a thin plasma target [19,20]. It is critical to control the thickness of the target in order to balance out the photon energy density and the thin plasma momentum flux. As the laser intensities increase at higher powers, that are favorable for scaling to higher speeds of the thin plasma foil, it becomes important to understand target transparency from relativistic effects.

The relativistically induced transparency (RITA) regime [21] utilizes these relativistic effects to drive a thin layer of electrons ahead of the laser in a near-critical density target. The co-propagating electrostatic field at the head of the laser accelerates the plasma ions. The relativistically induced transparency effect has been experimentally verified [22] but is yet to be experimentally utilized for ion acceleration. Under ultrahigh intensity conditions, the TNSA mechanisms is also expected to experience a relativistic transparency phase where the laser does not simply reflectively exchange energy with the critical layer electrons but also drives a relativistically induced transparency (RT) front [23].

Another scheme which uses the laser to drive a magnetic vortex in near critical density target to magnetically trap and accelerate ions has also been proposed and is referred to as magnetic vortex enabled acceleration (MVEA) [24]. It also benefits from using gaseous targets because it also requires shaping the density profile which is much more effective in gaseous plasmas.

Of the mechanisms described above, the CESA method has been investigated exclusively using LWIR lasers. Proton beams with up to 22 MeV of energy, a narrow energy spread ΔE/E~1-10%, and a geometrical emittance of better than 5 mm-mrad have been observed in experiments using a hydrogen gas jet [18]. At ATF, monoenergetic ion beams with energies on the order of 1 MeV have been experimentally produced by this method as well [17]. Particle-in-cell simulations show that it is possible to produce the ~200 MeV proton beams required for medical applications at an $a_0 = 10$ or at an intensity, $I = 10^{18}$ W/cm^2 for a CO_2 laser [7, 25].

In the experiments mentioned above, hydrodynamic plasma shocks were initiated by an earlier weaker laser pulse preceding the main CO_2 laser [26, 27]. Taking advantage of the larger degree of control in a gaseous target, a subsequent experiment used an auxiliary Nd:YAG laser to launch a controlled hydrodynamic blast by focusing it on a metal foil at the edge of the supersonic gas nozzle [28]. This hydrodynamic front expended into the hydrogen gas produced by the gas jet, creating a sharp and stable density spike at about 6 times the local density over the length of $< 30\ \mu m$. The deliberate generation of this shock front greatly improved the reproducibility and consistency of the proton spectra, with the energy at ~ 1 MeV [8].

Other promising LDIA mechanisms such as RPA and RITA have so far remained largely unexplored in the LWIR regime. Research into these methods in the LWIR regime will depend on the future development of the plasma targets that are thin enough to enable the critical physics of these methods. Simulations must be performed to determine the conditions where these methods become applicable in LWIR regime, so that the experiments can take advantage of the high yield of the hot electrons facilitated by the LWIR laser.

Summary of Future Research Thrusts:

1. **Higher energy acceleration using collisionless electrostatic shock acceleration (CESA):** The current promising results of CESA should be extended to higher energies. In particular, the ultimate goal of 200 MeV at $a_0 \sim 10$ should be pursued as the primary goal.
2. **Investigate the potential benefits of using LWIR laser ion acceleration mechanisms other than CESA, particularly in RPA and RITA**: The exploration of radiation pressure acceleration (RPA) requires the development of ultrathin gaseous targets and controlling the laser pre-pulse energy. The relativistically induced transparency acceleration (RITA) mechanism requires further investigation of mixed-Z gas targets apart from shaping of gas targets. Other acceleration mechanisms, such as Magnetic Vortex Enabled Acceleration (MVEA) remain largely unexplored in the LWIR regime.

2.1.3 Enabling Technology

Beam Requirements and upgrades:

To reach the goal of ultimately producing 200 MeV protons, the laser vector potential should be steadily increased to $a_0 \sim 10$. Laser power of over 10 TW is required to achieve ion energies of over 10 MeV, with 100 MeV ions expected to be generated at powers of over 25 TW. Generating multi-TW LWIR laser pulse is a common requirement for a number of PRDs in this section. Moreover, circular polarization at high power provides a significant advantage for certain ion acceleration schemes such as RPA. Furthermore, the repetition rate of CO_2 laser should be increased to fully take advantage of the high-repetition rate provided by the gaseous targets.

During the workshop, several methods were presented for amplifying the laser power. Development of high-power amplification for an LWIR laser represents a priority research direction itself and it is discussed in section 2.4 below.

Required Diagnostics:

Prepulse: As mentioned above, preionization of targets before the arrival of the main pulse can significantly alter the plasma length scale and the interaction itself. Therefore, it is important for the structure of the prepulse to be known with accuracy, particularly as the peak power is increased to beyond 10 TW. Since the targets used in the LWIR regime are gaseous targets, the intensity of the prepulse should be kept below 10^{14} Wcm^{-2} (approximate tunnel ionization threshold for hydrogen). Since the ultimate goal of 200 MeV proton will require an intensity on the order of $I = 10^{18}$ W/cm^2, the ability to accurately measure the prepulse contrast of better than 4 orders of magnitude will be required.

Plasma diagnostics: Since the outcome of the LDIA experiments is strongly dependent on the structure of the plasma density, the ability to accurately characterize the plasma density is required. Methods such as Michaelson/Mach-Zehnder interferometry, frequency domain interferometry [29], or angular filter refractometry (AFR) [30] can be used to characterize the plasma density profiles with accuracy. Moreover, transverse electron beam radiography (using the ATF linac e-beam as a transverse probe) can be used to characterize the fields generated by hot electrons, which is a necessary component of LDIA experiments. The latter diagnostic is discussed in the Sec. 4.1 of this report.

2.2 LWIR Laser-Driven Plasma Electron Acceleration

2.2.1 Introduction

Compact plasma-based electron 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; and fundamental accelerator science and technology research. Additionally, laser-driven acceleration technology is a potentially revolutionary capability for 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 [31-33].

Nearly all US laboratories engaged in laser-plasma electron acceleration experiments use NIR laser drivers. LWIR lasers provide a number of unique advantages that make the related work at ATF facility a complementary effort to the NIR LWFA research that can lead to high, leveraged, impact. In particular, as will be discussed below, the LWIR laser is ideal for operating the LWFA in the blowout regime at low densities of 10^{16}-10^{17} cm^{-3}. The hundreds-of-µm-radius bubbles that can be driven in this regime, combined with low dark current and ATF-based opportunities for pinpoint external injection, open new pathways for LWFA of electron bunches with sub-% energy spread, a goal that has evaded NIR-LWFA for a quarter century.

2.2.2 Status of current research and future directions

A laser wakefield accelerator (LWFA) that is driven by an LWIR source was discussed as a priority research direction in the SNW 2017 and it continues to be a priority experiment for ATF. In this scheme, the ponderomotive force of the laser expels the plasma electrons out of its path. The space charge between the expelled electrons and the remaining ions, which are much heavier than the electrons, creates a plasma wave in the wake of the laser pulse. The accelerating and focusing fields in such wave can reach a magnitude of tens of GV/m.

One primary experimental regime of interest in LWFA is the blowout or bubble regime, where the ponderomotive force of the laser is strong enough to expel all electrons, forming an "ion cavity" that travels behind the laser pulse at the group velocity of the laser in the plasma [34]. The linear focusing force and the high accelerating force created in this structure (both of which scale as $n_0^{1/2}$) provide the ideal conditions for the acceleration of 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 [35], which are of interest in a wide range of applications [36].

Major milestones in LWFA include the initial reports of high amplitude plasma wave production [37,38], first demonstration of narrow energy spread electron beams [39-41], extending the energy gain to the multi-GeV range [42], as well as demonstrations of controlled injection via various techniques [43-45] and demonstrations of multi-stage operation that will needed for future high energy colliders [46]. Most of this work was carried out 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 [47].

One of the major goals for LWIR-driven LWFA is reaching the bubble regime at plasma densities in the range $10^{16} < n_e < 10^{17}$ cm^{-3}. To access this 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.

Ideal performance is expected when the laser wakefield accelerator operates in the so-called "matched" mode, where the transverse and longitudinal dimensions of the laser pulse are approximately equal to the dimensions of the plasma wave it drives. Theoretical calculations based on non-linear theory [34] show that the transverse size of the laser is matched to the diameter of the bubble when

$$\frac{P}{P_c} = \left(\frac{a_0}{2}\right)^3.$$

Here,

$$P_c[GW] = 17\left(\omega_0/\,\omega_p\right)^2$$

is the critical power for self-focusing, ω_0 is the laser frequency, ω_p is the plasma frequency, and

$$a_0 = 8.6 \times 10^{-10}\sqrt{I[\mathrm{Wcm}^{-2}](\lambda[\mu\mathrm{m}])^2}$$

is the normalized peak value of the vector potential of the laser.

Longitudinally, a matched laser pulse will have a pulse length equal to the radius of the bauble. The ratio between the pulse length and the length of the nonlinear plasma wavelength can be characterized by a dimensionless pulse length parameter [48]:

$$T_p = \frac{c\tau_{laser}}{\Lambda_{wake}} = \frac{\omega_p \tau_{laser}}{2\pi a_0^{1/2}}.$$

Here, τ_{laser} is the pulse length and $T_p = 1$ characterizes the condition where the laser fills the entire bubble. The matching condition therefore occurs for $T_p = 1/2$, which ensures that the accelerating electrons do not significantly overlap with the laser fields before they reach their dephasing length, thus maintaining their transverse quality.

The value of a_0 provides a good indicator for determining the regime of interaction. The ideal bubble regime (with a spherical ion column) is reached when a_0 is larger than 4, and the transition to blowout regime (full expulsion of electrons from the axis) occurs for a_0 between 2 and 4.

These matching criteria place stringent requirements on the laser parameters and can be used to estimate the threshold at which bubble regime operation will be optimal. For instance, for a 10 μm driver with a pulse duration of 0.5 ps, a laser power is 27 TW is required to reach $a_0 = 4$ in a matched configuration [49]. Alternatively, a "mismatched regime" can be used to increase the a_0 when the required power for a matched configuration is not available. For instance, the transverse matching condition for P = 20 TW requires a spot size of $117\ \mu m$ for a plasma density of 2×10^{16} cm^{-3}, resulting in the matched a_0 value of 2.4. Because of the low value of a_0, the blowout regime *is not* reached in this configuration as can be observed in Fig. 2.1 (a). The blowout regime is reached by deviating from the matched condition by reducing the focus spot size such that the value of a_0 is raised to above three (a simulation with $a_0 = 3.8$ is shown in Fig. 2.1 (b).

Other simulations indicate that longitudinally mismatched laser pulses can also reach the blowout regime when $a_0 \sim 4$. Figure 2.1 (c) shows the result of a simulation also with a P = 20 TW, but with a pulse length of 1 ps. The spot size of $74\ \mu m$ results in an $a_0 = 3.8$ at a density of 2.3×10^{16} cm^{-3}, resulting in the blowout regime. Similarly, blowout regime is reached for a laser pulse with 10 TW peak power and 1ps pulse length once the laser pulse is focused tightly (spot size of $50\ \mu m$) to reach an a_0 value of 4 (Fig. 2.1 (d)). It is important to note however that this scaling does not hold if the pulse length is much longer than the plasma wavelength. For a 2 ps laser pulse at 7.5×10^{17} cm^{-3} with $a_0{\sim}4$, the laser pulse is in the self-modulated regime, where the plasma bubble is disrupted after a few plasma periods [50,51]. Therefore, in addition to an appropriately high a_0 value, it is important for the laser pulse to be on the order of the bubble size, which for $\sim 2 \times 10^{16}$, it means the pulse length should be less than 1 ps.

The use of an LWIR laser source such as the CO_2 provides a significant advantages over the commonly-used $1\ \mu m$ laser sources for LWFA experiment: they excite bubbles far more efficiently in low-electron-density ($n_e \sim 10^{16}$ cm^{-3}) plasma than NIR lasers [8]. This is because they smoothly self-focus to $a_0 \sim 5$ at peak power ~10 TW in $n_e \sim 10^{16}$ cm^{-3} plasma, creating a large, stably propagating, fully blown-out bubble, whereas for an equivalent result their NIR counterparts would require petawatt power, a technology that is restricted to lower repetition rate and is more prone to shot-to-shot fluctuations.

Today's best NIR-laser-driven plasma accelerators produce un-polarized electrons with ~10% energy spread, thus inhibiting the most important applications of plasma-based accelerators. For example, driving tabletop X-ray free-electron lasers [52] or observing resonant particle creation processes with an electron-positron collider demands ~0.1% energy spread. Similarly, probing parity-violating interactions and nuclear spin-states requires spin-polarized electron beams, a need that has so far received almost no attention in the laser-plasma accelerator community. Producing electron bunches of narrow energy spread and high spin-polarization has become one of the most intractable problems in plasma-based electron acceleration.

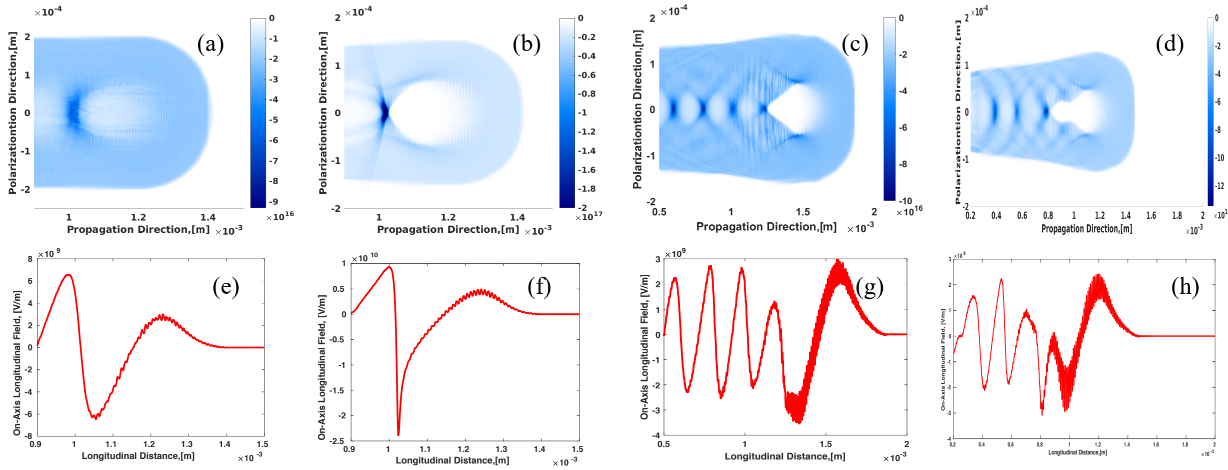

Figure 2.1 Simulations for different regimes of LWFA using the code SPACE [53]. (a) $a_0 = 2.4$: laser power P=20 TW, pulse length $\tau = 0.5$ ps, spot size $w_0 = 117$ μm, plasma density $n_e = 2 \times 10^{16}$ cm^{-3}. (b) $a_0 = 3.8$: P=20 TW, $\tau = 0.5$ ps, $w_0 = 74$ μm, $n_e = 2 \times 10^{16}$ cm^{-3}. (c) $a_0 = 3.8$: P=20 TW, $\tau = 1$ ps, $w_0 = 74$ μm, $n_e = 2.3 \times 10^{16}$ cm^{-3}. (d) $a_0 = 4.0$: P=10 TW, $\tau = 1$ ps, $w_0 = 50$ μm, $n_e = 2.3 \times 10^{16}$ cm^{-3}. (e-h) Accelerating electric fields corresponding to the wakefields generated in (a-d)

With the large bubbles sizes of an LWIR driver as a target, external sources can inject high-quality *e*-bunches into a tiny fraction of the bubble's volume with pinpoint precision, avoiding internal field gradients that otherwise depolarize and energy-broaden accelerating electrons, as happens in much smaller NIR-laser-driven accelerators. As a result, these super-sized bubbles preserve spin-polarization and energy-spread as they accelerate injected *e*-bunches to GeV energy within a few centimeters [54, 55], ultimately enabling the acceleration of ultra-short spin-polarized electron bunches (*e*-bunches) with sub-% energy spread that is synchronized to the LWIR driver. ATF provides a co-located linac producing tens-of-MeV, 0.1 nanocoulomb, ~1 ps, un-polarized *e*-bunches with <1% energy spread. Currently these are synchronized to the CO_2 laser with 100 fs jitter, and compressed to 200 fs. But ATF plans to synchronize [56] and compress [57] these bunches to the 10 fs level, so that they can be injected into a CO_2-laser-driven plasma bubble with precision. The external injection experiment will be further discussed in detail in Sec. 4.1.

Furthermore, simulations of the LWIR-driven blowout regime with beam parameters described here ($a_0 \sim 4$, $n = 2 \times 10^{16}$ cm^{-3}) do not result in self-injection. This is likely because the spot size of the LWIR (74 μm) is within a factor of two of the matched spot size for this density (117 μm). Therefore, the strong transverse evolution of the laser spot and the bubble radius that result in injection in NIR scenarios are absent in these cases. The lack of self-injected electrons, sometimes referred to as "dark current", were confirmed in 3D SPACE simulations of up to 2.5 mm, and at densities in the range of $2 - 8 \times\ 10^{16}$ cm^{-3}.

The lack of dark current in the LWIR-driven wakefield acceleration also opens up the possibility of performing highly controlled all optical injection using a scheme based on two color ionization injection [58]. In "standard", single-pulse ionization injection [59,60], 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 than self-injection schemes. 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 laser field before they can be trapped and 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 that it is possible to drive a large amplitude plasma without the drive pulse fully 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 localized 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.

Finally, scaling the LWFA driver to longer wavelengths may provide significant advantages from the standpoint of efficiency and overall accelerator system design [61].

Summary of Future 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 LWFA (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. The unique features of LWIR-driven LWFA in this regime, such as lack of dark current should be experimentally confirmed
2. **High quality electron beams from controlled two-color injection**: Using the lower-intensity, higher wavelength CO_2 laser to drive a plasma wake, the short-pulse higher intensity NIR laser can be used to ionize elements (i.e. impurities) within the fully formed wake. This two-color scheme is expected to result in FEL-quality electron bunches.
3. **High quality electron beams from controlled external injection**: The injection of the e-beam generated by the ATF linac into the large bubble driven by the LWIR laser is a primary research thrust for ATF. Since this research thrust leverages both LWIR laser and the ATF e-beam, its detailed discussion is done in Sec. 4.1.
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. The latter will be discussed in more detail in Sec. 4.1.

2.2.3 Enabling Technology

Beam Requirements and upgrades:

From the discussion in Sec. 2.2.2 it follows that the most critical goal for reaching the blowout regime requires a laser pulse that can reach an $a_0 \sim 4$ with a pulse length $\tau \leq 1$ ps. Intermediate milestones prior to reaching this 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 $a_0 > 1$ and $\tau > 1$ ps); generation of non-linear plasma waves (this requires $a_0 \sim 2$ and $\tau \sim 1$ ps); 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 $P > P_c$, $a_0 \leq 4$ and $\tau \sim 1$ ps).

The two-color injection scheme requires the availability of a second, short-wavelength pulse (e.g. Ti:Sapphire or other NIR laser) that can be tightly focused to produce higher electric fields than the driver and therefore ionize impurity species, which then form the accelerating electron beam. Significant challenges for this latter scheme are synchronization and spatial alignment of the two lasers. High-repetition-rate sources (1 Hz or greater) will be a tremendous asset for enabling this alignment process, which may otherwise be prohibitively difficult.

Required Diagnostics:
Successful LWFA experiments will require advanced laser-plasma diagnostics. The femtosecond NIR laser at ATF as well as the linac-produced electron beam will both have a significant role as diagnostics in these experiments. Because of the integral role of the electron beam to diagnose the fields of LWFA, the discussion of the diagnostics for LWFA is relegated to Sec.4.1.3

The two-color ionization injection experiment requires more specialized diagnostics, particularly for achieving accurate alignment and synchronization. Alignment of LWIR and NIR lasers are usually accomplished by using a semiconductor "switch". In this technique, a semiconductor such as Ge, which is normally transparent to CO_2 laser become opaque when its valence electrons are excited to the conduction band by the NIR laser. Additionally, since both laser pulses are expected to have the intensity to create a plasma, self-emission as well as shadowgraphy can be used for spatial and temporal alignments.

2.3 Basic Plasma Physics Research in Novel Regimes

2.3.1 Introduction

The unique facilities at ATF enable the exploration of the basic physics of laser plasma interactions (LPI) in the LWIR regime. The study of electron Weibel instability is one example that greatly benefits from the unique properties of the ATF LWIR laser. Electron Weibel instability (EWI) is driven by anisotropic velocity distributions and is an important mechanism for self-generating magnetic fields in both laboratory and space plasmas. The use of LWIR lasers for this research is highly beneficial because a plasma generated via optical field ionization with an LWIR laser has known anisotropic electron velocity distributions at very high temperatures [62], ($T_e \sim$ 10s keV)), particularly when compared with NIR lasers (see Table 2.1 below).

Another unique advantage that ATF facilities bring to the research of EWI is the availability of the linac-produced ultrashort relativistic electron bunches, which can be used as a probe to record the spatiotemporal evolution of the self-generated Weibel magnetic fields. By taking a series of snapshots of the magnetic fields at different times, wave vector spectrum evolution and growth rate of the EWI can be deduced and compared with kinetic theory. The electron probing of plasma fields is discussed in more detail in Sec. 4.1.

The other two research areas discussed in this section are the plasma lens and backward Raman amplification. These two areas represent application-driven basic plasma physics research, where

Table 2.1 Comparison between the properties of photoionized plasma generated by a CO_2 laser (λ ~10 μm) and a NIR laser (λ ~0.8 μm). T_ ⊥ and $T_{\parallel}$ are the plasma temperatures perpendicular and parallel to the direction of laser propagation and γ is the growth rate of the Weibel Instability

	λ=10 μm, τ=3 ps, a_0=0.86, n_e=1e17 cm^{-3}	**λ=0.8 μm, τ=60 fs, a_0=0.2, n_e=5e18 cm^{-3}**
$T_{\perp}$	**28 keV**	**0.5 keV**
$T_{\parallel}$	**15 keV**	**0.04 keV**
γ	**0.06 ωp**	**0.02 ωp**
γ^{-1}	**0.9 ps**	**0.36 ps**

the investigation of the physics can lead to improved capabilities of the LWIR lasers, which will benefit a wide array of experiments such as those discussed in Sec. 2.1 and 2.2.

Finally, a unique aspect of LWIR lasers, which was not explored in great detail in this workshop, is the accessibility of plasma with a near-critical density, which allows for research into near-critical laser-plasma interaction, and is of potential interest to particle acceleration (e.g. laser filamentation, nonlinear self-focusing, and hole-boring processes [18, 26, 63]) or other areas of research. In particular, the much lower critical density (compared to NIR lasers) allows *gaseous targets* to be used with LWIR lasers to explore the LPIs in near critical-density regimes. These gaseous targets provide a great degree of flexibility experimentally, particularly with respect to control and tunability of plasma density scale lengths as well as the implementation of diagnostics.

2.3.2 Status of current research and future directions

Three presentations at this workshop covered a range of topics in basic plasma physics research in LWIR regime: the electron Weibel instability, the plasma lens, and backward Raman amplification.

***Electron Weibel instability in CO_2-ionized plasmas (UCLA)*:** Weibel instability was first discovered theoretically in 1959 [64]. It is a kinetic instability that grows in plasmas with anisotropic velocity distributions or temperatures. As an important mechanism responsible for self-generation of magnetic fields in anisotropic plasmas, Weibel instability is relevant to many important physical phenomena such as collisionless shocks [65], gamma-ray bursts [66], and cosmological magnetic fields generation [67] and therefore has been extensively studied in theory and simulations. However, the experimental study of Weibel instability is challenging due to the difficulties of initializing anisotropic distributions in a controllable manner and of probing the magnetic fields with high spatiotemporal resolution. This is especially the case for electron Weibel instability due to the much larger growth rate ($\gamma \sim \omega_{pe} \gg \omega_{pi}$) and smaller dimensions ($k^{-1} \sim \frac{c}{\omega_{pe}} \ll \frac{c}{\omega_{pi}}$) compared to ion Weibel instability.

Existing experiments have shown filamentary structures of either magnetic fields [68,69] (captured by proton radiography or Faraday rotation) or the electron beam that has passed through a background plasma but these have been attributed to relativistic filamentation instability [70]. Thus, there are no detailed measurement on the most fundamental parameters, namely, the growth rate and k-spectrum evolution of electron Weibel instability to our knowledge.

More recently, it has been shown that it is possible to initialize plasmas with known electron velocity distributions via optical-field-ionization using ultrashort but intense lasers [62]. The anisotropy of the optical field ionized (OFI) plasma can be controlled by changing the polarization, wavelength and intensity profile of the laser or by using different type of gas. We have also shown that the intense electric (or magnetic) fields in the plasma can be probed by an ultrashort bunch of relativistic electrons [71]. By combining these two concepts, we propose to develop a laboratory platform at ATF which will enable us to carry out the first detailed measurements on the growth rate and k-spectrum evolution of electron Weibel instability. These measurements will be compared to the predictions of kinetic theory and simulations to verify their validity.

This experiment is ideally suited to the ATF facility because ATF alone has the necessary infrastructure carry out this research: a joule-class CO_2 laser to generate highly anisotropic plasmas on the one hand, and an ultra-short, relativistic electron beam to probe the instability on the other. The unique laser facility at ATF can be used to perform the first measurements of the growth rate and k-spectrum evolution of electron Weibel magnetic fields. Due to its long wavelength, the CO_2 laser can produce much hotter (Te~10s keV) plasmas which may allow us to explore the electron Weibel instability in astrophysical relevant plasmas, which cannot be done elsewhere.

In the Weibel experiment, the ATF CO_2 laser will be used to initialize plasmas with known anisotropic electron velocity distributions. 3D PIC simulation carried out by UCLA shows that the helium plasma ionized by a 3-ps (FWHM), 0.8 TW, w_0=50 μm, circularly polarized CO_2 laser has temperatures in the transverse and the longitudinal directions of $T_{\perp} \approx 28$ keV and $T_{\parallel} \approx 15$ keV, respectively. Such a plasma will drive electron Weibel instability with a growth rate of $\gamma \sim 0.1\omega_{pe}$. The strength of the magnetic fields is on the order of one Tesla, with spatial scales of $\sim c/\omega_{pe}$ which for a 10^{17} cm^{-3} plasma is about 15 microns. Simulations show that these magnetic fields can be probed by the ~50 MeV electron beam available at ATF.

Plasma optics (Gordon, NRL): "Plasma optics" refers to use of plasma to manipulate the state of a laser pulse, including focusing, guiding, and compression. The chief advantage of plasma optics is that it avoids material damage altogether. This is especially important for a final-focus optic, which is usually the largest, most expensive and most damage-prone optical element in a beam delivery system. Since a plasma withstands higher intensity than solid materials, plasma optics can be more compact. Moreover, its focusing properties can be adjusted *in-situ*. The challenges of plasma optics for intense, ultrashort pulses are to manage plasma dispersion, which stretches ultrashort pulses, and to control plasma nonlinearities. ATF provides a unique test bed for plasma optics designed for *intense*, *short* pulses at *10 μm* wavelength. At this wavelength, the plasma approaches critical density (needed for high index of refraction) at lower atomic density (~10^{19} cm^{-3}) than for shorter wavelength light. Intense, ultrashort pulses enable ultrafast ionization. As a result, plasma profiles of optical elements are very similar to the gas profile before ionization, which can therefore be shaped entirely through gas dynamics.

Backward Raman LWIR Amplification (NRL): Recently the ATF CO_2 laser has achieved a peak power of 5 TW with a pulse duration of 2 ps, by employing several techniques including chirped pulse amplification (CPA), pressure broadening, and isotopic gain media. To further increase the laser peak power without additional amplification stages, ATF is currently exploring possibilities such as nonlinear pulse compression, which is extensively used in visible – NIR wavelength range by researchers [72]. In order to adopt this technique for ATF, significant R&D efforts are required because the nonlinear optical properties of LWIR materials are relatively less studied.

Another approach to generating intense ultrashort LWIR pulses is backward Raman amplification (BRA) [73]. The apparatus of BRA consists of a low-energy, femtosecond seed pulse and a high-energy, long-duration, counter-propagating pump pulse in the plasma, as shown in Fig. 2.2. Energy is transferred from pump to seed when the frequencies of two pulses match the resonant condition $\omega_{pump} - \omega_{seed} = \omega_p$, where ω_p is the plasma frequency. BRA was previously studied in the hope of producing extreme peak power without restrictions imposed by the damage threshold of optical elements in the laser system. However, the highest energy conversion efficiency achieved in the NIR BRA experiment so far is ~ 6% [74], which is not ideal for the purpose of ultra-intense NIR pulse generation. On the other hand, with the existing broadening techniques, the shortest pulse duration that the CO_2 laser can reach is ~ 1 ps. BRA may be able to produce high-power, ultrashort LWIR pulses by overcoming the limitation of the CO_2 laser gain bandwidth, which cannot be achieved by any other known methods. Preliminary simulation results (Figs. 2.3(a)-2.3(c)) show that by employing a microjoule, femtosecond LWIR seed pulse and a 3 J, 3 ps CO_2 pump pulse, multi-terawatt peak power with a few times of power enhancement can be obtained after interacting in a 1-mm-long plasma with a density $n_e = 10^{18}$ cm^{-3}.

The planned femtosecond Ti:Sapphire laser system at ATF will be used to generate seed pulses through two-color ionization and filamentation in air [75]. Electrons from tunneling ionization produce an overall drift current under the symmetry-broken laser field containing fundamental and second harmonic frequencies, resulting in a broadband radiation covering the spectral range from terahertz to LWIR [76]. This technique is relatively simple and low cost compared with nonlinear $\chi^{(2)}$-based methods such as parametric generation.

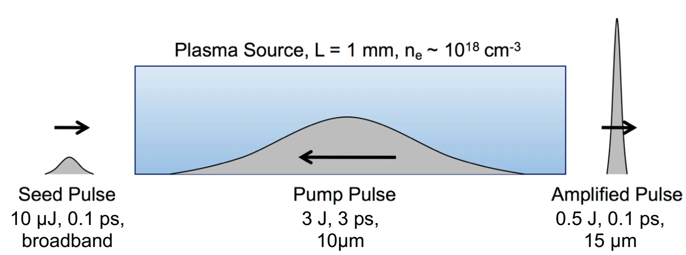

Fig. 2.2. Schematic of backward Raman amplification.

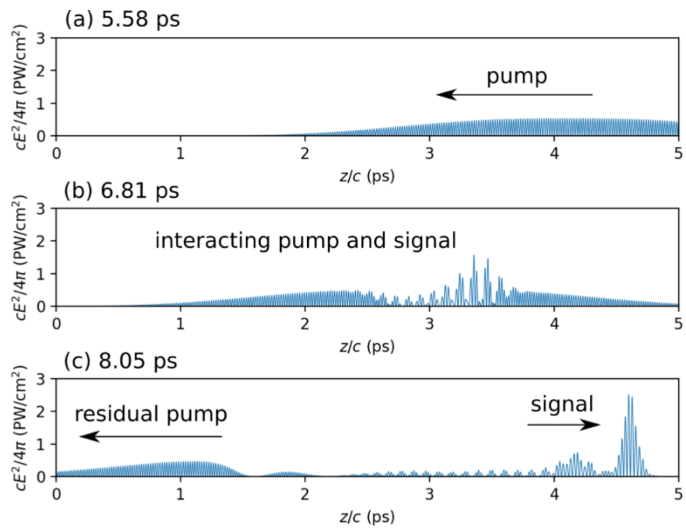

Fig. 2.3. 1D relativistic fluid simulation of BRA, showing the instantaneous intensities (a) before, (b) during, and (c) after interaction of pump and seed in the 1-mm-long plasma with ne = 1018 cm−3.

<u>Summary of Future Research Thrusts:</u>

The research thrusts for the plasma physics areas identified in the workshop are as follows

1. **Electron Weibel Instability (EWI):** Using the ATF CO_2 laser, carry out the first detailed measurements on the growth rate and k-spectrum evolution of electron Weibel instability.
2. **Plasma Optics:** Develop the physics of plasma focusing optics and investigate the possibility of implementation as a final focusing optics. This thrust will require the investigation of the challenges as they relate to dispersion and plasma nonlinearities
3. **Backward Raman LWIR Amplification:** Investigate the potential application of the backward Raman amplification technique to ATF laser, including the design and demonstration of a particular viable configuration

2.3.3 Enabling Technology

<u>Beam Requirements and upgrades:</u>

For the EIW, the CO_2 laser should be intense enough to be able to fully ionize helium or hydrogen. Based on simulation parameters described above, a 3-ps (FWHM), P~0.5-1 TW, spot size w_0~50-100 µm, circularly polarized CO_2 laser would be desired.

For the plasma lens and backward Raman amplification, no facility upgrades specifically were requested. Rather, it was emphasized that the development of these technologies at ATF creates an opportunity for developing such novel approaches to focusing and amplification of a high-power LWIR laser, which in turn can only be tested at the ATF CO_2.

<u>Required Diagnostics:</u>

Ultrafast electron radiography using ATF's linac-produced electron beam will be used to measure the growth of the magnetic field in the electron Weibel instability. The electron beam will need to have the following properties: energy ~50 MeV, energy spread <1%, charge >50 pC, emittance ε_n<10 μm, spot size σ_r~1 mm, pulse duration τ<0.2 ps. Moreover, the time jitter between CO_2 laser and e- beam will need to be below 0.2 ps

2.4 LWIR Laser Technology Development

2.4.1 Introduction

A majority of the research directions highlighted above require an LWIR laser pulse with high power (10-25 TW) and a short pulse (≤ 1 ps). Currently, ATF itself has provided a platform for the state of the art research of high-power CO_2 pulses, with the most recent results yielding a pulse with power of ~ 5 TW in 2 ps [77]. Because bridging the gap between the existing capabilities and those demanded by the experiments described above requires the development and emergence of new technologies, research in this area merits consideration as an independent PRD at ATF. The unique LWIR infrastructure as well as the significant institutional experience and memory in CO_2 technology development make ATF an ideal place for this development. Moreover, the development of these technologies is well aligned with the ambitious parameters demanded of ATF by the experiments, and the lack of LWIR sources in the US and around the world means that these capabilities will likely not be developed from without.

The LWIR technologies discussed during the workshop can be categorized as belonging to two general area:
(1) CO_2 beam manipulation technology, including laser micro-fabricated components;
(2) Advanced CO_2 laser-amplifier technology, aimed at improving the rep-rate, efficiency and compactness of terawatt CO_2 lasers;

It is also worth noting that as technologies such as plasma-based focusing and backwards Raman amplification mature, they will be able to contribute to LWIR technology development. In their current state however, these technologies are in the early stages of research and development, and therefore the "basic plasma physics research in novel regimes" section (Sec 2.3) was considered a more appropriate placement for these topics in the present report.

2.4.2 Status of current research and future directions

(1) Advanced CO_2 beam manipulation technology: Researchers from Euclid pointed out that the ATF CO_2 laser provides a unique motivation and test-bed for advanced laser beam manipulation technologies based on laser micro-machining.

Laser micro-fabrication (Antipov, Euclid). A high-power, long-wavelength-infrared (LWIR) laser system such as the ATF CO_2 laser requires large area optical elements such as compression gratings, large-area dispersive mirrors, and power samplers that are resistant to optical damage. Since damage thresholds and physics are not well characterized or understood at this wavelength, there is a need for a manufacturing approach that can rapidly and inexpensively prototype optical elements for testing. Computer-numerically-controlled (CNC) machining is too coarse to control features in the one to tens-of-microns range required for LWIR optics, while nano-lithography as used in semiconductor manufacturing is too fine and expensive. Femtosecond laser micromachining can fill this gap. It can rapidly prototype high-power LWIR components, and has made impressive advances in recent years in accuracy, scalability and surface finish quality. Micromachining of μm-scale rounded edges can mitigate optical damage.

(2) ***Advanced CO_2 laser-amplifier technology:*** Two methods were described in the workshop for CO_2 laser amplification. The first, stimulated Raman amplification of a CO_2 laser pulse in plasma, was presented by NRL and discussed in Sec. 2.3 as discussed above, and second, amplification of CO_2 laser pulse using optical pumping, was presented by University of Alabama at Birmingham and will be discussed here.

Optical Pumping (Mirov, UAB). Grand challenges of terawatt CO_2 laser technology are to increase repetition rate and efficiency, and to decrease amplifier size. Switching from electrical discharge to optical pumping of a high-pressure centimeter-scale CO_2 cell could increase rep-rate from .05 Hz to 10-100 Hz, while decreasing the master oscillator- power amplifier (MOPA) size and pulse length 10-fold. ATF could be a test-bed for advanced CO_2 laser concepts that ultimately lead to such improvements. Fe:ZnSe generates energetic pump pulses at 4.3 – 4.8 μm [78,79], which pump the upper laser level in 10-μm lasing channel directly from the ground state with 0.3 optical conversion efficiency, as recently demonstrated [80,81]. Numerical simulations show multi-pass amplification of 10 μJ seed pulses to GW peak power in a 20 atm, "palm-size" CO_2 cell is feasible [80]. Scaling to TW, 300 fs pulses requires: (1) more energetic (1-1.5 J), pulsed (100-150 ns), narrow-band (< 1 nm), tunable (4.1-4.4μm) Fe:ZnSe pump sources; (2) better understanding of physics of CO_2 excitation at 4.3 μm, especially the role of self-focusing of the pump, CO_2 relaxation processes, and optimization of upper level lifetime at high pressure; (3) gain tailoring via isotope mixing to increase bandwidth.

Summary of Future Research Thrusts:
While in many cases, ATF is the end user of the research discussed in this PRD rather than a direct participant, ATF's partnership with the respective principle investigators could significantly accelerate their development. The primary research thrusts discussed in this section were

1. **Advanced CO_2 beam manipulation:** Characterize optics developed via femtosecond laser micromachining and determine if they can be implemented as a replacement for conventional optical components
2. **Advanced laser amplifier technology:** Investigate issues surrounding the transition from electrical discharge sources to optical pumping, which includes the development of more energetic 4.3um pump sources, understanding the physics of excitation and relaxation, and gain tailoring via isotope mixing.

2.4.3 Enabling Technology

Beam Requirements and upgrades:
(1) Advanced CO_2 beam manipulation technology. The ATF CO_2 laser provides a unique facility for testing advanced beam manipulation technologies based on laser-micromachining. Existing ATF laser parameters appear to be adequate for testing proposed laser-micro-machined components in which the community is interested. Thus no facility upgrades specifically for this research direction are recommended. Rather, these researchers emphasize that CO_2 laser upgrades planned for other applications drive the demand for large aperture, high power components, which in turn can only be tested at the ATF CO_2. Such ATF-CO_2-centric development is extremely valuable for the community, because availability of the high power components in turn will drive

the development of high power industrial CO_2 lasers. This research direction will contribute to CO_2 laser development, to design and manufacture of structure-based THz wakefield accelerators, and to beam manipulation research.

(2) Advanced CO_2 lasers-amplifier technology. Several near-term research efforts are needed to advance optically pumped CO_2 laser-amplifier technology. First, large-scale Fe:ZnSe gain elements (e.g. by post-growth thermal diffusion of Fe in poly-crystalline ZnSe) must be fabricated. Second, methods must be developed to co-dope these media with a 4-5μm absorber in order to suppress transverse amplified spontaneous emission (ASE). Third, methods must be developed to suppress optical damage of gain crystal facets. Chemically-assisted plasma etching and/or femtosecond laser micro-machining (see Sec. 2.4.2) may play a role in this development. Finally, high-damage-threshold anti-reflection (AR) coatings must be developed. ATF is well positioned to collaborate with university-based groups in furthering this research.

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3 Topics in Electron Beam Driven Science

The ATF has a long and acclaimed history in the development of high-quality electron beams for various applications. Over its near 40 years in operation, the ATF has devoted many resources to improving beam brightness and hosted numerous experiments utilizing high-quality electron beams. The concentration of beam-based experimental activity at the ATF is focused on advanced accelerator concepts in structures and plasmas, novel diagnostic innovations, radiation sources based on coherent emission, and investigations in 6D phase space manipulations. Experiments utilizing the state-of-the-art electron beams prepared at the ATF are abundant and have yielded high-impact results spanning across various scientific communities. This section examines the continued significant opportunities in research based on the high quality electron beams achievable with the current, and upcoming upgraded, ATF parameter space.

The material in this section includes contributions from G. Andonian, P. Hoang, P. Musumeci, Y. Sakai, J. Rosenzweig (UCLA), E. Snively (SLAC), S. V. Shchelkunov, X. Chang, Y. Jiang, J. L. Hirshfield (Omega-P R&D, Inc., Yale University), W. Kimura (STI Optronics) and L. Schacter (Technion Israel Institute of Technology).

3.1 Advanced Acceleration Research

3.1.1 Introduction

The current research thrusts in the field of beam-driven advanced acceleration at the ATF include wakefield acceleration in dielectrics, plasmas, and metallic structures. The presence of high-quality electron beams as well as the capability to deliver single bunch and multi-bunch configurations to users coupled with state-of-the-art diagnostics (see below) make ATF an ideal facility for carrying out the basic research in these fields to answer fundamental questions about the physics of these interactions.

The high-brightness beams produced by the ATF allow for beam-driven wakefield acceleration in sub-mm structures, providing access to high-frequencies (up to THz scale)
which is essential to reach ultra-high longitudinal gradients, and ultimately high energy gain in a compact footprint.

The ATF has a long history in beam-driven dielectric wakefield acceleration (DWA), including numerous publications in the last decade. The continued programs on wakefield acceleration are aimed at extending interaction lengths by measuring the effects of beam breakup due to transverse forces, investigation of high transformer ratios by beam phase space tailoring, and material and geometry advances to combat structure breakdown limitations.

In other metallic-structure wakefield acceleration, the goals are to demonstrate the high acceleration gradient and RF-breakdown-suppression features of a detuned-cavity two-beam accelerator (TBA). In this case, one would measure the energy gain/loss of high intensity relativistic drive beams after propagating through the structure, and study the statistics of RF breakdown events. There is no other user-facility in the United States that could provide the required high-current/charge-per-bunch, long drive-bunch train of relativistic beams to excite the accelerator structure to reach steady state.

3.1.2 Status of Current Research and Future Directions

Dielectric Wakefield Acceleration: The pursuit for higher accelerating gradients naturally suggests using higher frequency structures, and has led to the extensive research in dielectric wakefield acceleration (DWA). The advantages of DWA include attaining higher fields before the onset of breakdown at high frequency. In the DWA, a relativistic drive beam traverses a dielectric-lined waveguide establishing a wakefield, which is then sampled by a trailing witness beam. The witness beam is accelerated or decelerated depending on its relative phase with respect to the wakefield. The amplitude of the longitudinal component of the wakefield is dependent on the drive beam parameters, while the operating wavelength depends on the structure geometry and materials [1]. With modern advances in micro-fabrication techniques, access to novel materials, and the availability of high-brightness drive beams, terahertz frequencies and sub-mm wavelengths are attainable in DWA structures [2,3]. The generated wakefields can be utilized for high-gradient acceleration, beam phase space manipulations, and radiation generation. Recently, a milestone demonstration of >GV/m wakefields was achieved in DWA at SLAC [4].

The high-brightness beams produced by the ATF are ideal for use with sub-mm scale structures. As such, the ATF has played a major role in the history of experimental demonstration of key components of DWA research in recent years. The results have provided impactful insight into the beam dynamics in the presence of wakefields, important for many advanced acceleration techniques. Recent experimental highlights in DWA research at the ATF include:

- the first demonstration of resonant mode operation in a cylindrical DWA structure using a multi-bunch train at THz frequency [5]. The results showed selective mode excitation by tuning the driver bunch spacing to the appropriate frequencies supported by the structure. Novel spectral characterization techniques based on interferometry of emitted Cherenkov radiation were also developed for use in the THz range.

- the demonstration of acceleration of witness beam particles in a planar slab-symmetric DWA [6], where significant charge in the tailing beam was accelerated, and novel diagnostic techniques in frequency characterization using coherent Cherenkov radiation interferometry were deployed.

- the detailed mapping of accelerating and decelerating phase of the wakefield in diamond structures [7], where a near full-cycle of the trailing wakefield was characterized by varying the delay between the drive and witness beams. Careful modeling of the wakefield showed agreement with simulations.

- excitation of narrowband THz frequency in a DWA structure with Bragg-reflecting boundaries [8], where a novel fabrication method is used to construct a reflective layer with alternating dielectric materials. The alternating layers re-enforce a constructive interference condition for a single mode supported by the DWA. The results showed a very narrowband excitation at 210 GHz with high spectral purity.

- further advances in micro-fabrication techniques allow the use of a fully 3D photonic-like DWA structure, which was first characterized spectrally in a woodpile geometry [9] at THz frequencies at the ATF. Using woodpile structures is important for addressing issues of

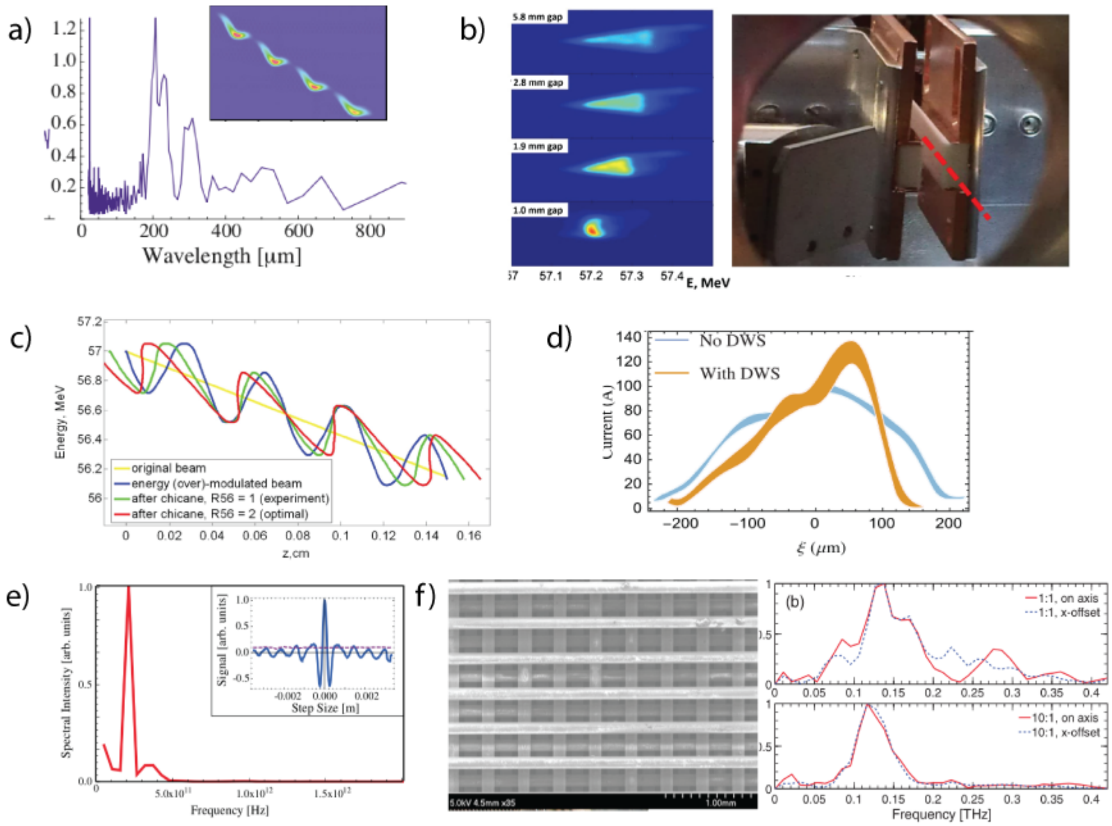

Figure 3.1: Potpourri of DWA results obtained at ATF in recent history. Some highlights include a) selective higher-order mode excitation using bunch trains; b) energy de-chirper with variable gap DWA; c) micro-bunching in beam from energy modulation in DWA and density modulation in chicane, d) ramped beam generation using DWA energy modulations; e) narrowband mode excitation in Bragg-reflector DWA; f) DWA based on woodpile geometry for 3D wakefield characterization.

field concentration in the vacuum gap and field exclusion in the dielectric, with further implication on transverse instability mitigation.

The DWA research portfolio at the ATF is very rich and has established a strong foundation for continued efforts. The development of novel diagnostics for the characterization of the spectral information contained in the emitted Cherenkov radiation, as well as the beam diagnostics for energy and longitudinal profile measurements is important and extendible to other experimental endeavors.

Metallic Structure-Based Accelerations: RF breakdown poses fundamental limitations to achieve a working acceleration gradient approaching 200 MeV/m or greater in conventional metallic accelerator structures, as is considered desirable for a multi-TeV machine that could be built on a practical real-estate footprint. Surface RF pulsed heating is considered as one of the major causes which trigger the onset of RF breakdown. Recently, the Omega-P/Yale collaboration proposed a class of novel cavity designs with unconventional spatiotemporal distributions using multi-harmonic mode superposition to suppress pulsed heating and RF breakdown [10, 11]. A multi-harmonic cavity (MHC) can support the fundamental mode (TM010) as well as the higher mode, e.g. the TM012 mode with the eigen-frequency equal to the harmonic (e.g. the third one) of the fundamental mode. Both are the acceleration modes. The time varying nature of RF fields with multiple-frequency mode superposition introduces a possibility to suppress RF breakdown [12, 13]. As additional constraints are imposed on the cavity design optimization, certain characteristic quantities, such as quality factor or shunt impedance, of each individual mode might be inferior to the designs without such constraints; however, with two-mode superposition, the overall performance can be superior to that of a single mode, in terms of effective acceleration gradient and RF breakdown suppression. The common accepted argument is that the two-beam accelerator (TBA) configuration is more appealing for a large-scale high-gradient accelerator [14]. The limitation due to the paucity of high power RF sources can be overcome using beam-driven excitation of a cavity or accelerator structure. A novel two-beam accelerator consisting of detuned cavities [13, 15] was proposed recently to allow the drive beam and test beam to propagate collinearly through the structure, without need for a sophisticated and costly waveguide system and transfer structure which can provide sites for RF breakdown [14]. Incorporated with the MHC concepts, realization of a beam-driven high gradient TBA structure with low breakdown probability is conceivable, allowing a reliable acceleration gradient in an X-band structure to reach 200 MV/m, without exceeding the empirical limits [16]. The transformer ratio (for an inductively detuned structure) is also expected to be larger than 10, resulting in the high beam-to-beam efficiency of energy transfer. Another compelling reason to use bimodal cavities in a TBA structure is that the short length for electron bunches that is dictated by the need for high luminosity automatically implies high magnitude harmonic frequency components in the beam current. The ability to extract energy carried in higher harmonic components—in addition to that in the fundamental--should boost energy efficiency of the TBA.

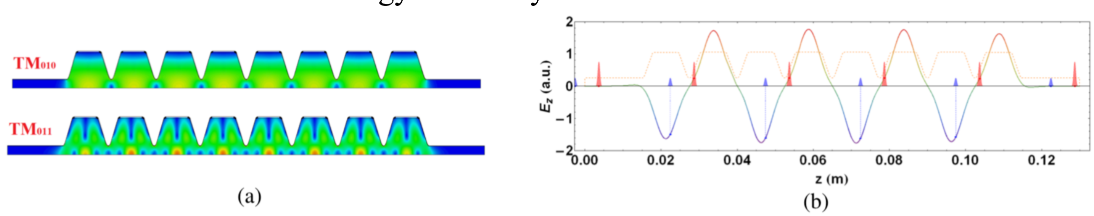

Figure 3.2: a) Electric fields for each mode in the TBA structure; (b) axial electric field experienced by the test bunches (blue) and drive bunches (red).

While the particular example above is about beam-driven structures that are built using conventional materials (copper), a multi drive-bunch operation is desired, and will be largely beneficial for a variety of other structures, for instance, beam-driven dielectric-lined wakefield structures, and plasma wakefield beam-driven structures. Thus, a facility such as the ATF, that has a plethora of experience and expertise with bunch characterization, diagnostics, transport and manipulation, but at the same time, implements a multi-bunch capability will serve better for the future needs of the advanced accelerator studies.

The future thrusts for these areas are as follows:

1. **Structure-based wakefield acceleration:** The continued programs on structure-based wakefield acceleration (including dielectric and corrugated metallic structures) are aimed at addressing outstanding issues including extending interaction lengths, quantifying the effects of beam breakup due to transverse forces, investigating high transformer ratios by beam phase space tailoring, and material and geometry advances to combat structure breakdown limitations.

2. **Exploration of Multi-mode Harmonic Cavities (MHCs):** the goal is to incorporate the MHC concepts for the realization of a beam-driven high gradient two-beam accelerator (TBA) with low breakdown probability and a reliable acceleration gradient in an X-band structure to reach 200 MV/m, without exceeding the empirical limits. The transformer ratio for this scheme and for an inductively detuned structure is expected to be larger than 10, resulting in the high beam-to-beam efficiency of energy transfer.

3.1.3. Enabling Technology

For electron beam driven DWA, the ATF provides a prime opportunity to study THz-scale (sub-mm) structures. For such experiments a low transverse emittance (~1-2 μm) with reasonable charge (>300pC) is needed to conduct spectral characterization using THz interferometry techniques developed at ATF. In addition, to study higher harmonic content, i.e. multi-modal structures, the variability of the bunch length is important. In the case of THz studies, bunches < 300 μm r.m.s. would provide the needed spectral content to access higher order modes. In the case of longer structures, the beam beta function should be appropriate (ranged from 5-15cm), with appropriate spot size (<50 μm) to ensure complete transmission. For the case of transverse wakefield studies, the beam transverse distribution should also be variable to generate beams with high aspect ratio (elliptical or flat bunch distributions). In addition, a complete longitudinal phase space diagnostic, consisting of a high-resolution deflecting cavity and a dipole energy spectrometer is needed to measure time-resolved wake-effects from the DWA.

For TBA studies, a detuned version that supports modes at 11.4 and 34.2 GHz such as the one in [17] and is excited by a bunch train spaced at 2.856GHz requires high charge (>16nC). However, a proof-of-principle prototype without detuning can operate at drive bunch charges below 1nC. Yet, to reach steady-state, the number of drive (relativistic) bunches should be in excess of 350. The structure without detuning is intrinsically low-efficiency in the beam-loaded regime; however, it can support high accelerating gradient (> 200 MV/m), and thus serve as a vehicle to investigate break-down effects and their suppression as predicted for bimodal configurations. The other requirements will be: the bunch transverse size < 2 mm in diameter at the interaction point (IP); the bunch length < 2 mm at IP; the bunch energy ~ 10 MeV, with the energy spread as needed for transport to IP. It can be estimated that the total peak power in slight excess of 60 MW may be required, thus suggesting that a conservative number of klystrons, each at 20 MW, to support operations will be 3.

In addition to the described beam parameters, the research thrusts described above require state of the art diagnostics. Temporal diagnostics for beam bunch length and bunch profile information include the transverse deflective cavity (T-CAV) which can provide nearly 2 fs temporal resolution and THz interferometry from coherent transition radiation (CTR), coherent diffraction/edge/Cerenkov radiation (CDR/CER/CCR), which also yields spectral information about the emitted radiation. A number of these diagnostics were pioneered at the ATF and subsequently adopted by other facilities. The development of novel diagnostics for the characterization of the spectral information contained in the emitted Cherenkov radiation, as well as the beam diagnostics for energy and longitudinal profile measurements is extendable to other experimental endeavors. In addition, for small aperture structures, the ATF has developed a high resolution transverse profile monitor, imaging the surface of an optical transition radiation foil, with near μm level resolution [18].

3.2 Beam Phase Space Manipulations

3.2.1 Introduction

The precision control of the beam longitudinal phase is important for current profile tailoring for high transformer ratios, coherent synchrotron radiation (CSR) suppression, and other applications in advanced accelerators. The extensive control over the parameters of the ATF electron beam as well as the ready availability of the state-of-the-art diagnostics for measuring beam properties makes ATF an important contributor to the study of tailoring methods for high brightness beams. Previous measurements have already demonstrated ancillary applications of DWA and corrugated metallic structures in place of traditional accelerator components, such as de-chirpers, passive deflectors or beam bunchers and shapers. In addition, using the high power laser provides additional opportunity to use inverse-free-electron laser interactions in an undulator to also manipulate the longitudinal phase space of the beam.

3.2.2 Status of Current Research and Future Directions

***Dechirpers and shapers*:** Dielectric and corrugated metallic structures have been used in ATF experiments to both dechirp and to longitudinally shape the electron drive beam. Broadband, multimode structures are convenient methods of removing residual energy chirp [Fig. 3.1 (b)] from the drive beam inherent in beam compression stages. Also, by prudent choice of excited frequencies in the structure, and the addition of a compression element such as a chicane, the beam longitudinal profile can be bunched (short wavelength) or ramped (long wavelength) as shown in Fig. 3.1 (c) and (d) respectively. These experiments, which were carried out the ATF, take full advantage of the low emittance beams propagating through sub-mm aperture in structures:

- the demonstration of energy-chirp suppression using a variable gap planar dielectric structure [19]. In this study, the collective wakefield effects in a heavily-moded structure were enhanced by reducing the gap size, and thus increasing the wakefield amplitude, to linearize the beam energy correlation. The parametric study showed optimal configurations for de-chirping and introduced novel analytic methods applicable to other structures.
- novel longitudinal shaping of the drive beam with a ramped current profile, using a single-mode dielectric structure followed by a compact chicane [20]. The demonstration is important for high transformer ratio in beam driven wakefield schemes, and is attractive because there is no loss of charge that is typical of other beam shaping methods employing masks.
- generation of a micro-bunched beam in a dielectric structure and compact permanent magnet chicane [21] at THz frequency. The fundamental wavelength is much greater than the drive beam bunch length, leading to an energy modulation of the beam, which is then converted to density modulation after passing through a high-field chicane. The resultant output is a beam micro-bunched at sub-mm spacing.

***Sub-fs modulator*:** The ATF is a unique facility as it employs a high quality electron beam and a synchronizable high-power mid-IR laser at the same location. The interaction with the laser allows for electron beam phase space manipulations for myriad purposes such as inverse free electron laser (IFEL) studies. One such example is the sub-femtosecond diagnostic that incorporates a higher-order IFEL interaction in conjunction with the x-band deflecting cavity to provide beam angular modulations correlated to the longitudinal beam coordinate. The modulations in turn can be useful as a high-resolution beam diagnostic for precision features on the electron beam. The proposed method will be capable of measuring bunches with the power to resolve features on the sub-fs scale (Fig. 3.3) [22]. The angular modulation of the electron beam is enhanced when interacting with the TEM10 Hermite-Gaussian laser mode in the presence of a planar undulator field resonant at the laser wavelength. This (transverse) angular modulation is resolvable on a distant screen, producing a sweeping pattern, where each sweep corresponds to half the laser wavelength. For use with the high-power CO_2 laser, the sweep corresponds to a half-period of 15fs. Depending on beam parameters and choice of optics, this is equivalent to a resolution on the order of ~200as.

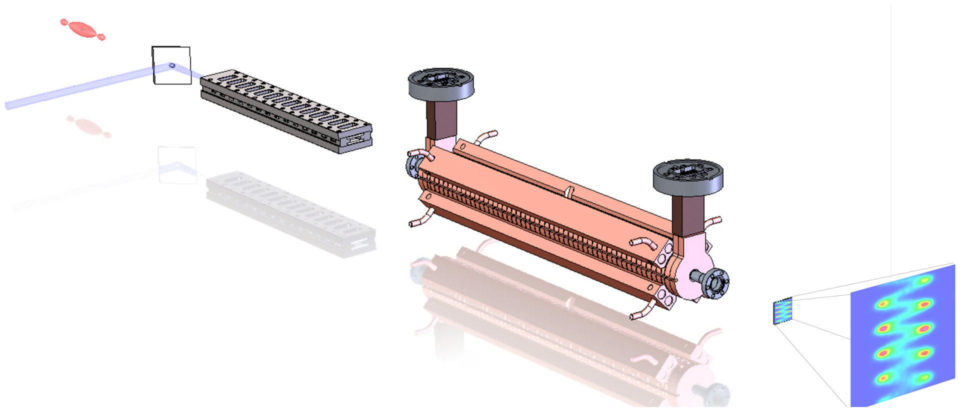

Figure 3.3: Layout of the sub-femtosecond streaking experiment at the ATF including the higher-order laser mode generation, resonant undulator for energy modulation, and x-band deflecting cavity. The image shows a sinusoidal pattern that is directly correlated to beam longitudinal extent after manipulation.

The present PRD is based on the extension of these methods for optimizing the beam phase space for particular applications with the future thrusts as follows:

1. **Dechirpers and shapers** Continued exploration of broadband, multimode structures to remove residual energy chirp inherent in beam compression stages. Also, by prudent choice of excited frequencies in the structure, and the addition of a compression element such as a chicane, the beam longitudinal profile can be bunched (short wavelength) or ramped (long wavelength)
2. **Sub-fs modulator:** a higher-order IFEL interaction in conjunction with the x-band deflecting cavity creates beam angular modulations correlated to the longitudinal beam coordinate. The modulations in turn can be useful as a high-resolution beam diagnostic for precision features on the electron beam. The proposed method will be capable of measuring bunches with the power to resolve features on the sub-fs scale.

3.2.3 Enabling Technology

For structure-based phase space manipulations, i.e. using beam generated wakefields to provide correlations to the beam phase space, the ATF beam emittance allows the employ of sub-mm scale structures (dielectric, corrugated pipe, etc.). A low transverse emittance (~1-2 μm) is required for observable changes in the beam phase space. Similar to the bunch shaping experiments, beta functions should be chosen based on structure length and vacuum channel dimensions.

For the sub-femtosecond beam manipulation studies, the CO_2 laser is required to operate in the TEM10 mode, requiring additional laser optics (beam splitters, combiners, pyroelectric imagers, and associated diagnostics).

In addition, full longitudinal phase space diagnostics are required, which consists of a transverse deflecting cavity and dipole spectrometer, with associated beam optics for establishing imaging criteria for the quantities of interest.

3.3. Low Emittance Source Development

3.3.1 Introduction

While the experimental efforts at the ATF are quite diverse in their technologies, they do share an important commonality. They either would benefit greatly by having access to ultralow emittance electron beams, or their aim is to develop new sources with enhanced performance over existing sources. Currently, there is no other user accelerator facility where these new sources could be tested. The ATF has the required infrastructure and expertise for testing new injectors and schemes, albeit nontrivial issues must be addressed to realize this effort, including addressing spatial limitations at the linac front-end and possible downtime to accelerator operations.

While nearly all accelerator applications would love to have access to ultralow emittance beams, certain experiments would especially benefit, for example dielectric laser accelerators (DLA) [23] and two-beam accelerators (TBA) that utilize solid-state excited dielectrics [24, 25]. DLAs feature microstructures whose dimensions are of order the laser wavelength. Indeed, the width of the DLA channel that the electrons must traverse through is only approximately one wavelength wide. This means for IR wavelengths ranging from 1-10 µm the electrons must be focused into a gap that is only a few µm wide. (Note, 10 µm wavelength corresponds to a CO_2-laser-driven DLA, which, as will be discussed in Sec. 4.2, has certain advantages compared to using NIR solid-state lasers, including higher charge throughput). Moreover, the length of the channel can be a few centimeters long; hence, the channel length-to-width aspect ratio is very large. This implies the electron beam must remain tightly focused over relatively long distances.

A similar situation arises with TBAs where the e-beam passes through a small evacuated bore in the center of the active medium. In TBAs, a drive electron bunch traverses through the bore to generate a Cherenkov wake that is amplified by the active medium. A witness electron bunch propagating behind the drive bunch is accelerated by the amplified Cherenkov wake. Since the witness bunch extracts energy from the Cherenkov wake via an evanescent wave, it is imperative the electrons travel as close as possible to the surface of the dielectric, preferably within a few periods. If the active medium is, say, Nd:YAG corresponding to 1.06 µm wavlength, then the bore diameter should be ideally ~1-2 µm. For efficient energy extraction, the length of the TBA should be of order 10 centimeters; thus, it has an even higher aspect ratio than DLAs. (10-µm bore diameters have been fabricated in Nd:YAG fibers [26]).

Source development to attain ultra-low emittance drive beams is critical to advance the fields of TBAs and DLAs, and the ATF has the necessary infrastructure to tackle cutting-edge work in this area.

3.3.2 Status of Current Research and Future Directions

Field Emission Cathodes: There are various efforts being pursued whose aim is to develop the next- generation of electron sources. For example, laser-driven field-emission cathodes have demonstrated generation of fs microbunches with the potential for ultralow emittance [27, 28, 29]. In this scheme, the laser beam is directed across the tip of the cathode rather than illuminating the cathode as done in laser-driven photocathodes. The laser field, i.e., polarization, is oriented along the same direction as the DC field applied across the anode-cathode (A-K) gap. Quasi-monoenergetic e-beams are possible by controlling the A-K gap spacing such that the transit time of the electrons crossing the gap equals a multiple number of laser periods [30]. This particular scheme is also conducive to using non-traditional cathode materials, in particular, carbon nanotubes (CNTs). CNTs can have very high enhancement factors (e.g., β = 2,500-10,000 [31]), which means high emission is possible at relatively low applied DC and AC fields, where the latter is provided by the laser beam. A CNT cathode can also have a very small diameter that is flat and not a needle point as used by others, thereby, facilitating achieving ultralow emittance.

Diamond Electron Amplifiers: BNL was one of the pioneers in developing diamond electron amplifiers (DEAs), where >200 times electron gain was demonstrated [32]. In a DEA, the primary electrons from, say, a thermionic cathode impinge upon a diamond wafer, which generates >200 secondary electrons for every primary one. These secondary electrons emerge from the backside of the diamond wafer with low emittance and low energy spread. Thus, the DEA essentially converts a low-quality e-beam from a conventional cathode into a high-quality e-beam with higher charge.

Optical Bessel Beams: Although not directly related to generating ultralow emittance e-beams, optical Bessel beams (OBBs), formed by focusing a radially-polarized laser beam using an axicon, could be used to help guide the electrons emitted from these advanced electron sources [33, 34]. The electrons counter-propagate through the center of the OBB and oscillate within the potential well formed by the electric field distribution in the center of the OBB. This guiding process is analogous to usage of a solenoid magnet, but requires no magnetic hardware around the e-beam. It also avoids the problem of magnetic field leakage onto the cathode, which can spoil the emittance. Since the amount of charge the OBB can guide is affected by the width of its potential well and this width is directly related to the laser wavelength, using a long wavelength laser, such as the ATF CO_2 laser, would permit guiding more charge than using a 1-μm laser wavelength. In addition, creation of a radially polarized CO_2 laser beam has already been demonstrated at the ATF [35].

Based on the current research and future research directions, the future thrusts for the ultra-low emittance source development are as follows:

1. **Field Emission Cathodes:** laser-driven field-emission cathodes have demonstrated generation of fs microbunches with the potential for ultralow emittance. This particular scheme is also conducive to using non-traditional cathode materials, in particular, carbon

nanotubes (CNTs). The successful development of this method with such novel material as CNTs will facilitate achieving ultralow emittance beams.

2. **Diamond Electron Amplifiers:** In a DEA, the primary electrons from, say, a thermionic cathode, impinge upon a diamond wafer, which generates >200 secondary electrons for every primary one. These secondary electrons emerge from the backside of the diamond wafer with low emittance and low energy spread. Thus, further development of DEA will allow for the conversion of a low-quality e-beam from a conventional cathode into a high-quality e-beam with higher charge.
3. **Optical Bessel Beams***:* optical Bessel beam (OBB), which may be formed for instance by focusing a radially-polarized laser beam using an axicon, could be used to help guide the electrons emitted from advanced electron sources. The electrons counter-propagate through the center of the OBB and oscillate within the potential well formed by the electric field distribution in the center of the OBB. This guiding process is analogous to usage of a solenoid magnet, but requires no magnetic hardware around the e-beam. It also avoids the problem of magnetic field leakage onto the cathode, which can spoil the emittance. Thus, the development and integration of OBBs with advanced sources will lead to higher quality beams.

3.3.3 Enabling Technology

There is a clear need to be able to test advanced electron sources as injectors on an existing and high-performance accelerator. In particular, it is important to accelerate the emitted electrons as quickly as possible to relativistic energies (e.g., with a gradient ≥5 MV/m) in order to combat space charge effects. This also permits measuring the beam characteristics, such as the emittance and energy spread, using conventional accelerator diagnostics. Ideally, having access to the front-end of the ATF accelerator would allow testing the injectors by sending its emitted electrons into the RF accelerating cavities. This might be accomplished by using, for example, a sideport connected to the front-end and a bending magnet. The assumption is that the electrons emitted by the injector would need to have the proper pulse format to match the RF structure. One convenient way to ensure this is if the same laser that currently drives the ATF photocathode is used to instead drive a CNT field emitter.

The ATF has demonstrated a normalized emittance of 0.8 μm at 500 pC and a beam waist size of 5 μm. For 50-MeV, the beam radius will expand to ~10 μm in 5 mm. To transmit the e-beam through a 10-cm long bore will require either a much larger bore diameter, e.g., ~100 μm, or much smaller beam emittance. While the former may be acceptable for a proof-of- principle demonstration, the large bore diameter greatly decreases the efficiency of accelerating all the electrons in the e-beam; therefore, a lower emittance is much preferred. Existing beam diagnostics for emittance at the ATF are adequate to undertake the low-emittance beam generations methods discussed here, and would additionally enhance core capability allowing other experiments valuable cross-checking and calibration.

3.4 Novel and Efficient Terahertz Radiation Generation

3.4.1 Introduction

Long wavelength free-electron lasers have been efficiently operated using a waveguide to compensate the effects of diffraction. By controlling the dispersion properties of the wave it is possible to obtain simultaneously group and phase velocity matching, enabling a very long interaction region [36, 37]. The beam parameters at ATF are particularly well suited to explore the 0.1-10 THz range, which are of interest to a variety of applications. The main thrusts in this area are the first test of the physics of the zero-slippage FEL in a tapered undulator with high gain. This allows to validate analytical and simulation models and study the spectral properties of the amplified radiation, as well as the effects of space charge, wakefields and multi-modal emission. Second, a record high 10 % conversion efficiency, mJ-level THz pulse energy and GV/m THz fields are achievable with the ATF beam

3.4.2 Status of Current Research and Future Directions

As mentioned above, the main thrust in this area is the first test of the physics of the zero-slippage FEL in a tapered undulator with high gain. The THz range is one of the regions in the electromagnetic spectrum where FELs are particularly attractive both because solid-state-based sources are scarce and because electron beam and undulator parameters needed are relatively easily achievable. Many FELs operate using long (many wavelength) electron bunches with relatively low peak current and a small gain per undulator pass, and use an oscillator to build up power in an optical cavity. Higher brightness (high peak current, low transverse emittance) electron beam sources allow for tighter beam focusing in the undulator and stronger coupling to the radiation fields to attain high gain. Nevertheless, high current densities are typically achieved using shorter electron beams and unfortunately at long wavelengths, compressing the beam longitudinally to increase the current is detrimental for efficient FEL-based THz generation. This occurs due to the fact that when the coherent bandwidth of the beam spectrum becomes much larger than the intrinsic FEL bandwidth, the interaction is degraded by the slippage effects.

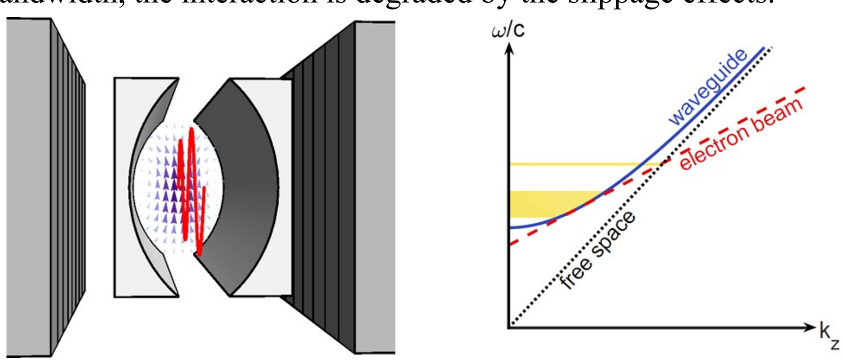

Figure 3.4: left) Cartoon of curved parallel plate waveguide FEL. right) Dispersion relation for EM waves in vacuum and in waveguide. Coupling with e-beam occurs at intersection points. For tangential intersection the zero slippage condition is satisfied.

Recently, experiments have renewed interest in the possibility of using a waveguide inside the undulator to modify the dispersion of electromagnetic waves in vacuum so that the group velocity matches the average longitudinal electron beam velocity (so-called zero-slippage condition) [38 , 39]. In this case, the peak of the envelope of the electromagnetic radiation pulse does not slip forward by one wavelength each undulator period (as in a regular FEL), but remains aligned with the electron beam during the entire interaction. This situation is very advantageous for THz-FEL generation as strong coupling can now occur over much longer interaction regions. In the waveguide zero-slippage configuration, by strongly tapering the undulator, we can further prolong the interaction until the limit where the electron beam energy is depleted, and achieve in single-pass systems record high efficiencies in the conversion of the e-beam energy into THz pulse energy [40, 41]. Furthermore, pre-seeding the interaction either optically (using an optical rectification or non-linear optics based source or by prebunching the electron beam at the cathode) has the potential to dramatically shorten the undulator.

3.4.3 Enabling Technology

The specific beam parameters required depend on the THz frequency targeted and efficiency depending on the undulator fabrication. For example to achieve a fundamental frequency of 5 THz, in a 6.4 cm period undulator, a 50 MeV beam with sub-2μm transverse emittance and 400 pC charge (400 fs FWHM pulse length) yielding an 1.5mJ THz pulse with 8% efficiency. Extending the range to 10 THz, and a 3.2 cm period undulator, with similar beam parameters would double the efficiency.

The experimental requirements for THz radiation generation studies include electron beam, laser beam, and THz diagnostic capabilities, including beam energy, bunch length, and THz pulsed energy and spectral measurements.

In summary, The ATF provides a fertile environment for cutting-edge studies in beam-driven research enabled by high brightness beams. The science encompasses advanced acceleration techniques, beam phase space manipulations, radiation generation, and novel source development and characterization. The efforts in these regards have led to a slew of experimental demonstrations and pioneering publications. Moreover, the existing capabilities are further strengthened by the continuing addition of innovative beam diagnostics such as the high-resolution x-band deflecting cavity, further enabling the possibilities in beam-driven research.

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4 Topics in Laser and Electron-Beam Interactions

ATF is the only facility in the US (and one of only a handful of facilities in the world) where a linac-produced electron beam with a nanocoulomb of charge and high brightness is available for experiments with a high-power, short-pulse laser system. Moreover, the wavelength of this laser is in the long wave infrared (LWIR) regime, which makes ATF one of the only two laser facilities in the US with such a laser source. This unique combination enables a number of research areas with accelerator and radiation generation applications. The LWIR laser is ideally suited for research in these areas because, as will be discussed, the size of the structures used in this research scale nonlinearly with wavelength. The following areas were identified as priority research directions that are enabled by the combination of the laser and electron beam sources at ATF:

- Basic research of laser-plasma charged-lepton-beam production
- Electron acceleration techniques driven by the combination of electron beam and LWIR laser
- Radiation generation

4.1 Basic Research of Laser-Plasma Charged-Lepton-Beam Production

4.1.1 Introduction

With accelerating gradients that are orders of magnitude higher than those of the conventional accelerators, the laser wakefield accelerators (LWFAs) represent a critical avenue of investigation for future of HEP physics. While the ability of LWFAs to generate and accelerate electrons at high gradients has been well established, the beam quality must improve to meet the requirements for HEP applications. This includes both the transverse quality (measured as emittance) as well as longitudinal quality (measured as energy spread). Accurate understanding of the field in LWFA and the interaction of the electron beams with these fields is required as a milestone in achieving high beam quality. So far, the exploration of the physics of LWFA has been accomplished by investigating the properties of self-generated electron beams. Since these beams form within the plasma, the initial quality of the beam is unknown, and therefore the capability of LWFA in preserving the beam quality during acceleration cannot be experimentally established. There is therefore a need for direct experimental investigation of the interaction of the fields in an LWFA with the accelerating electron beam and the impact of this interaction on the beam's final quality. Understanding of this interaction in turn is critical to improving the quality of the electron beam for the future HEP applications.

ATF is in an ideal position to significantly contribute to this research because ATF is the only facility in the US (and one of only a handful of facilities in the world) where a linac-produced electron beam with a nanocoulomb of charge and high brightness is available for experiments with a high-power, short-pulse laser system. Because of the stability, high-quality, and the flexibility in properties of the electron beam produced at ATF, the injection and acceleration of this electron beam in an LWIR-driven LWFA allows for the investigation of the impact of the plasma wakefield on the quality of the electron beam. Comparing the beam properties, such as emittance and energy spread, in the presence of the plasma wakefield will allow one to unambiguously characterize the impact of the plasma wakefield on the accelerating beam, and devise methods for its improvement. Moreover, the electron beam can be propagated perpendicular to the plasma wakefield, and in this way be used as a probe for direct measurement of LWFA's field structures. This latter capability provides a direct method for investigating the basic physical properties of the fields in LWFA

A primary HEP application envisioned for plasma accelerators is a collider for elementary particles. This vision is often expressed in terms of an electron-positron collider [1,2]. While significant progress has been made with regards to the application of laser-driven plasma wakefields to the problem of acceleration of an electron beam, previous positron acceleration experiments have almost exclusively been performed with the use of a particle-beam driver [3-5]. There is therefore a significant gap in the study of positron acceleration in laser-driven plasma waves.

Moreover, besides the HEP applications, positrons are also of interest for many areas of material science [6,7], medicine [8] and applied antimatter physics [9]. Such applications have however not had ready access to positron accelerators and have had to rely on alternative sources such as radioactive-decay [10], (p,n) reaction [11] and pair- production [12] of MeV-scale photons from—fission reactors [13], neutron-capture reactions [14] or MeV-scale electron beams impinging on a high-Z target [15]. A tunable positron source will thus pave the way for innovation in a wide range of pre-existing as well as future, HEP applications.

BNL-ATF offers the unique capability of a stable sub-picosecond electron beam tightly synchronized with sub-picosecond multi-TW CO_2 laser pulse that can make possible the breakthrough of producing ultrashort positron beams of tunable properties using laser wakefield acceleration [16,17]. This breakthrough demonstration of a laser positron accelerator will be accomplished using controlled interaction between distinct plasma states: positron-electron showers or pair plasmas and laser-driven plasma wakefields.

Firstly, the RF-linac-accelerated sub-picosecond nano-Coulomb electron beam that is available at BNL-ATF enables reproducible and controlled production of positron-electron showers or jets with a high degree of control. *Secondly*, the large size of the 10-micron wavelength CO_2 laser-driven wakefield acceleration structures in plasma enables efficient trapping and manipulation of the properties of shower positrons to produce positron beams. The tunability of the positron beam is accomplished through the variation of the properties of the e-beam, laser and plasma.

The positron source development proposed here is a forefront idea, still at the conceptual stage, and it will first need to be pursued primarily through simulations aimed at defining and quantifying the advantages of 10 μm LWFA driver as well as the properties of the linac-based pair-shower generation. It should also be noted that while in the short-term our proposal on positron acceleration indeed depends upon the electron beam, an all-optical positron acceleration is envisioned as an ultimate goal (similar to the all-optical LWFA electron source).

4.1.2 Status of current research and future directions

Electron Acceleration Physics

The presence of a high-quality, linac-produced electron beam has created unique research opportunities for the field of LWFA at ATF. With the currently available capabilities, the laser pulse spans tens of plasma wavelengths and therefore the interaction is in the self-modulated laser wakefield acceleration (SM-LWFA) regime. An experimental collaboration consisting of Stony

Brook University, UCLA, and University of Texas at Austin have been exploring the physics of SM-LWFA by using the linac-driven electron beam to transversely probe the fields within the wakefield. In contrast to an optical probe, which is also of great value in this research, an electron beam interacts directly with the electric and magnetic fields inside the plasma. This allows one to obtain a direct measurement of the field structures of an LWFA, rather than projections based on the reconstructed density structure as determined by the plasma index of refraction in the case of an optical probe. Using this so-called ultrafast electron radiography, plasma structures smaller than the bunch length of the electron beam can be resolved. For the current electron beam compression of ~300 fs, this corresponds to structures smaller than ~90 μm.

With the increase in the laser power and higher compression of the electron beam, several areas of research into the basic physics of LWFA will become available at the ATF facility. This includes the ultrafast electron radiography of LWFA in the blowout regime as well as the investigation of beam-quality preservation of an externally injected electron beam into and LWFA in this regime.

e-beam injection experiments: One of the primary experiments of interest enabled by ATF's combination of future capabilities is the external injection experiment, where the electron beam is injected longitudinally into the wakefield and is accelerated at high efficiency while its beam quality is preserved [18, 19]. This demonstration is of great interest to the LWFA community because the process on external injection is an important component of incorporating LWFAs in high energy physics (HEP) applications. While a single LWFA stage may be able to generate an electron beam with an energy on the order of 10 GeV, applications on the frontier of HEP require electron beams with hundreds of GeV in energy. Reaching such high energy requires a cascading of multiple stages of LWFA, where the electron beam's energy is amplified while its quality is preserved in each successive stage.

An example of this process is simulated as shown in Fig. 4.1, where an electron beam compressed down to 30 fs ($\sigma_z \sim 4\ \mu m$) and $\sigma_r = 11\ \mu m$ is injected inside the blowout regime driven by a $9\ \mu m$ laser pulse with 20 TW of power and 200 fs pulse length focused down to a spot size of $80\ \mu m$. This laser creates a blowout regime of $\sim 170\ \mu m$ in length. In this simulation, the electrons are accelerated with a field of nearly 27 GeV/m.

A second experiment enabled by the same configuration is the study of the growth of transverse beam instabilities and their dependence on various beam and plasma parameters. LWIR is uniquely suited for this research because the plasma wake produced by such a laser is significantly larger than those created by the commonly-used near-IR lasers. Therefore, the electron beam can be focused to a waist size that is significantly smaller than the dimensions of the bubble, allowing for accurate placement of the beam inside the plasma wakefield. This level of control over the injection phase and position will allow for the study of conditions under which the beam may be accelerated while retaining its initial high quality. Moreover, because of the independent control over the properties of the electron beam and the LWIR laser, the physics of efficient acceleration of charge in a plasma wakefield and its connection with transverse beam instabilities can be experimentally characterized in detail. This question has been a subject of intense debate recently in the LWFA community [20-24] and ATF's unique combination of laser and electron beam facilities singularly qualifies ATF to address this question.

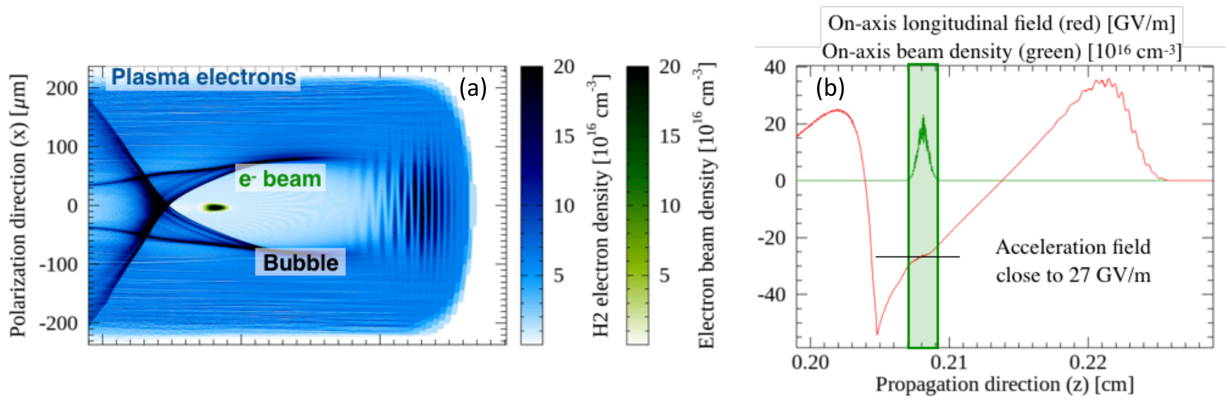

Figure 4.1 Simulation of external injection in LWFA using the code OSIRIS [27]. The laser central wavelength is 9μm, the peak power 20 TW, pulse length 0.2 ps, and the laser is focused to a matched spot size of 80 μm. The electron beam has a charge of 160 pC, bunch length of 30 fs and is focused to a spot size of σ_r=11 μm. The two beams are injected into a preionized plasma with plateau density of 6.1×10^{16} *cm*$^{-3}$ *and 100 micron ramps (a) number density of plasma electrons (blue color scale) and number density of injected electron beam (green color scale). Both color scales are normalized to 10*^{16} *cm*$^{-3}$*. (b) On axis electric field and electron beam density after ~2.1 mm propagation in plasma.*

e-beam as diagnostic: The use of the linac-produced, high-quality electron beam as a diagnostic of the wakefield [25] driven by the LWIR laser (i.e. ultrafast electron radiography) is another unique experimental opportunity at ATF. The availability of this probe is particularly advantageous in the case of an LWIR driver. This is because due to its higher ponderomotive force, a short LWIR laser can create a large blowout radius in the matched regime for densities below 10^{17} cm^{-3}. Operating an LWFA in this regime, where the density is much lower than the typical scenarios with NIR lasers, is of great interest because most of the important limiting parameters such as the dephasing length and pump depletion length scale favorably with reduced plasma density [26]. Since the index of refraction at these densities is very low, it is a significant challenge to incorporate most common optical techniques such as interferometry in this regime. In contrast, the electron probe will allow direct characterization of the fields in the wake, which may not be obtained in other ways.

It is important to note that the development of injection and diagnostic techniques at ATF are not dependent on the progress of laser pulse development because novel experiments may be conducted in various regimes of LWFA, including the self-modulated LWFA regime, which is achievable using the current CO_2 laser pulse parameters at ATF. Figure 4.2 for instance shows a simulation with the laser pulse currently available, but with an electron beam that has been compressed to 30 fs. This simulation which explores the self-modulated regime shows three distinct regions of interactions, each imparting a unique modulation onto the electron beam probe. At the front of the wake (region A), the electron beam (shown in green color table) is modulated on a scale of $\approx \lambda_p$, while at the back (region C), the electron probe beam is modulated on the scale of the laser wavelength (λ_0). To observe the modulation on the smallest scale in the simulation, i.e. the laser wavelength, the bunch length needs to satisfy $\sigma_z \ll \lambda_0$. Achieving this level of compression for the electron beam is challenging, but various beam compression methods are actively under investigation at ATF to yield the desired beam size.

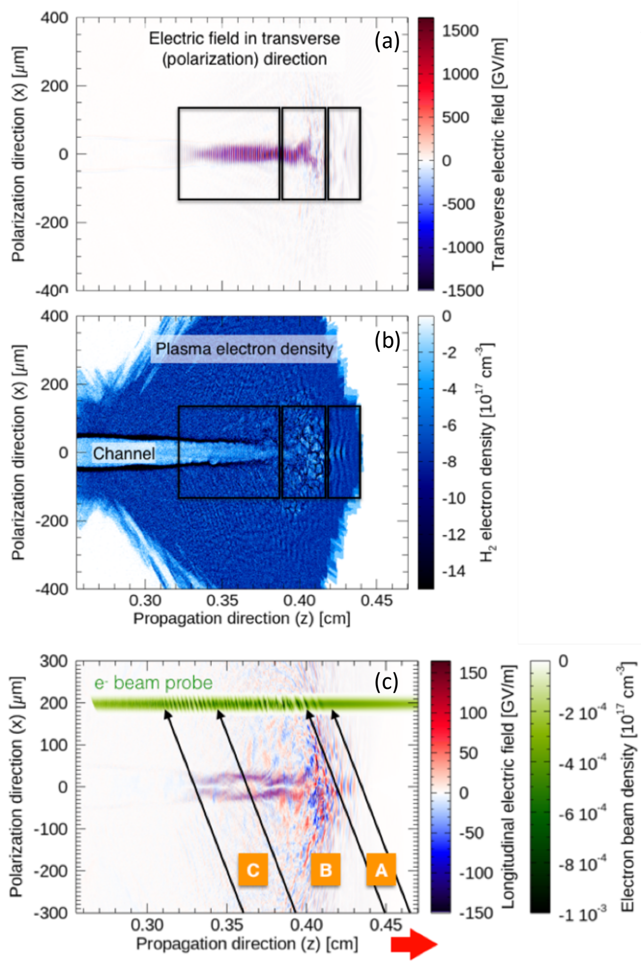

Figure 4.2 2D Simulation of LWIR-driven LWFA in the self-modulated regime using the code OSIRIS [27]. The laser central wavelength is 9.2 μm, the laser energy is 4 J, pulse length 2 ps, and the laser is focused to a spot size of 20 μm. The laser is focused on the upramp of neutral hydrogen with plateau density of 7.5×10^{17} *cm*$^{-3}$ *and 500 micron ramps. Plasma generation process is modelled using the ADK ionization rate. Electron beam probe has a charge of 1 nC, bunch length of 30 fs and is focused to a spot size of* σ_r*=1 mm. Simulation results are shown after laser propagates 4.5 mm into the plasma. (a) Transverse electric field in the simulation in GV/m (b) number density of plasma electrons (blue color scale) normalized to* 10^{17} *cm*$^{-3}$*. (b) Longitudinal electric field shown in red/blue color scale and the number density of electron beam, which shows the modulation of the probe after travelling through the plasma. The three black rectangles in panels (a) and (b) correspond to the three regions in (c) marked as A-C.*

<u>Positron Acceleration Physics</u>

Ultrashort positron-electron showers: When the micron-scale low-emittance sub-picosecond electron beams at BNL-ATF interact with a high-Z target a positron-electron shower is produced [12]. This interaction is dominated by high-energy bremsstrahlung radiation which undergoes pair-production under Coulomb force of the nucleus. Pair shower or plasmas thus produced inherently have micron spatial and temporal scales of the electron bunches which drive their production. Moreover, as the pair plasma production is intermediated by high-energy gamma-ray production, the pair-plasma possess a significant gamma-ray content along with pair particle flux when exiting the high-Z target.

Although positron-electron shower production is a well-known method of obtaining copious quantities of positrons, recent works have demonstrated picosecond scale positron electron jets [28,30]. In this work, a picosecond kilo-Joule laser pulse incident on a Gold target was used to produce MeV-scale positrons in positron-electron jets. In this technique the sheath fields driven by kilo-Joule (kJ) lasers on the rear-side of the metal targets produce quasi-monoenergetic 10 MeV positrons [28] although with inherently high temperatures. Both scaling to higher energies and cooling of positrons using this mechanism is yet unexplored.

Production of positron-electron showers using high-energy electrons from a compact laser-plasma wakefield accelerator has also been reported [29]. However, unlike positron beams, showers are divergent and suffer from innately exponential energy spectra. Moreover, the positron number in showers which peaks around a few MeV, undergoes orders-of-magnitude drop at higher energies. Post-processing of these showers is thus a critical step to convert a positron-electron jet into a usable positron beam with characteristics desired for a variety of applications.

CO_2 laser-wakefield driven post-processing of ultrashort showers: The specific post-processing step in this work is to use a CO_2 laser-driven plasma wave matched to the shower, with inherently Maxwellian energy spectra, for trapping, acceleration or deceleration of a positron beam with peaked energy spectrum. In this scheme, the LWIR laser will drive a quasi-nonlinear plasma wave, where the positrons are captured in the accelerating and focusing phase of the wave and can be accelerated to desired energy. Simulation of positron capture and acceleration using a plasma wave driven by a 1 μm driver shows that a positron beam with around 1 pC of charge and a quasi-monoenergetic spectra (~5% FWHM energy spread) with mrad scale divergence can be generated with this method [17].

The use of an LWIR laser to drive the plasma wave potentially provides significant enhancement of the positron capture, which leads to the ability to accelerate a positron beam with significantly more charge. The promise of the LWIR laser for this research can be demonstrated by the following qualitative argument: For example, experiments in [30] generated an e^+/e^- shower of density $n_b \sim 10^{16}$ cm^{-3}. The volume of the accelerating-focusing bucket of a 1μm-LWFA in a plasma density of $n_e \sim 10^{19}$ cm^{-3} is $\sim 10^{-9}$ cm^3, so one can expect to trap and accelerate $10^7 e^+$, or 1 pC, consistent with the simulation findings [17]. This bunch density $n_b \sim 10^{16}$ cm^{-3} is well below the ambient plasma density, so beam-loading is not serious. The equivalent volume of the accelerating-focusing bucket for 10 μm-LWFA in a plasma density of $n_e \sim 10^{16}$ cm^{-3} is $\sim 10^{-6}$ cm^3, so we could in principle trap and accelerate 10^{10} e^+, or 1 nC. However, the resulting bunch density $n_b \sim 10^{16}$ $cm^{-3} \sim n_e$, will severely beam-load the wake. Therefore, to avoid beam loading, the charge of the injected positrons needs to be reduced to a range of tens of pC.

In short, because LWIR lasers can drive plasma waves far more efficiently in low-electron-density ($n_e \sim 10^{16}$ cm^{-3}) plasma than NIR lasers, the size of the focusing-accelerating region in the quasi-nonlinear regime of an LWIR driver is ~1000X larger in volume than that of a NIR driver. The large size of the 10μm-LWFA should therefore greatly improve coupling between the 1st (e+e- shower generation) stage and the 2nd (e+ trapping and acceleration) stage. This increased coupling efficiency provides an LWIR-driven LWFA with great advantage for this research compared to other high-power NIR sources. Recent efforts have shown that it is conceptually possible to overcome single-stage limits of electron acceleration for instance by using multistage electron laser wakefield accelerators [31].

Amongst several outcomes of the post-processing operation, here we seek a critical one which is tunable positron bunches while optimizing for the trapped positron number through controlled interaction between showers and plasma waves.

Summary of Future Research Thrusts:

1. **Electron beam injection experiments:** injecting the electron beam longitudinally in a wakefield will enable the following research thrusts:
   (a) Acceleration of injected beam at high efficiency, while preserving a low energy spread and emittance: This thrust will include the investigation of energy extraction efficiency at high charge and the preservation of beam quality
   (b) Physics of transverse instabilities: This thrust will include the investigation of transverse instability growth and mitigation strategies; e.g. impact of ion motion, which has been under investigation in LWFA community for its potential of mitigating transverse instabilities [32]
2. **Transverse electron probe development:** The transverse probing of the plasma wakefield should be developed for direct measurement of the fields in linear and nonlinear plasma wakes, particularly at densities $<10^{17}$ cm^{-3}.
3. **Confirm the components of the positron-beam generation physics for LWIR driver through simulations and experiment**
   a. Measure the properties of electron positron shower generated by ATF e-beam and high Z target, including characterization of the spatial and temporal properties as well as the energy distribution of the positrons
   b. Demonstrate capture and acceleration of positrons, including the demonstration of low-energy spread "quasi-monoenergetic" production of positron beams accelerated by LWIR-driven LWFA in a quasi-nonlinear regime

4.1.3 Enabling Technology

Beam Requirements and upgrades:

Laser: The required laser driver properties for driving an LWFA in the blowout regime was discussed in a previous section. In short, the LWIR laser system needs to be upgraded to provide a sufficiently high normalized vector potential ($a_0 \sim 4$).

e-beam: For the injection experiments, the electron beam will need to have dimensions much smaller than the blowout radius. In other words, $\sigma_r, \sigma_z \ll R_b \sim 100\ \mu m$. Additionally, to model an externally injected electron from a previous stage of LWFA, the electron beam will need to be highly relativistic ($\gamma \gg 10$). For the ultrafast electron beam radiography, the electron beam will need to be wide compared to plasma wavelength ($\sigma_r \gg \lambda_p$), but short compared to the wave-like features it is intended to probe. This is because these features and the beam both travel at the speed of light. The electron beam currently satisfies the transverse requirements and can be focused to the required σ_r, but it will need to be further compressed by over an order of magnitude. Moreover, higher energy of the electron beam than what is provided now would be useful to better simulate an injection from a previous acceleration stage.

Finally, the two beams must be synchronized with great precision, with the jitter between the two much less than the size of the bubble. Computer-based optimization technologies will likely be required to achieve repeatable and high precision synchronization. The effective use of computer-based optimization methods requires a high rep-rate. Three researchers at the workshop (C. Geddes, LBNL; Y. Ma, U. Michigan; M. Streeter, John Adams Inst.) presented strong examples of how machine-learning techniques are improving the performance and science coming out of near-infrared LWFA R&D at their respective institutions. Thus, a focus at ATF on developing capabilities to increase the repetition rate of the TW CO_2 lasers as well as implementing computer optimization and machine learning into the beam line, electron sources, RF and laser sources will be highly beneficial to the practical realization of tightly synchronized electron and laser beams as required by these experiments. The present rep rate (1.5 Hz) ATF linac, given its basis on SLAC S-band technology, can be increased more straightforwardly.

In addition to precision alignment, the integration of machine-learning algorithms as a standard part of the research infrastructure available to ATF users will greatly improve research efficiency. In addition to an increase in the rep rate of operations, better instrumentation for digitizing data and better computer-friendly control elements and improved machine-learning strategies and software are also required. Separate, yet synergistic, opportunities exist for applying machine learning to ATF's CO_2 laser, its linac, and its auxiliary laser sources. Here also, ATF is well positioned to team with the national-lab- and university-based groups who have successfully applied machine learning to near-infrared-laser-driven plasma accelerators.

For positron research, an outline of the requirements on the CO_2 laser and the electron beam is as follows:
e- beam: >60 MeV, energy spread <1%, waist-size σ_r<50 μm, charge >250 pC, emittance ε_n<10 μm, bunch length σ_z/c <0.2 ps
CO_2 laser: peak power P~0.5-5 TW, pulse duration τ~2 ps, spot size w_0~50-100 μm
Synchronization: CO_2 laser and e- beam within 100 fs

In the long term, key "enabling technology" for an all-optical positron generation scheme should be considered. This includes splitting the primary LWIR laser pulse into two and delivering the sub-pulses in different regions of the beamline for driving the two stages.

Required Diagnostics:
Advanced laser-plasma acceleration diagnostics: The groundbreaking experiments described in the previous section demand innovative e-beam and plasma structure diagnostics, even beyond those developed for standard laser-wakefield accelerators (LWFAs) over the past 3 decades [33]. The ultrafast electron radiography experiments described above, which profile internal electric fields of wakes using transverse fs e-bunches [34], appear promising for visualizing low-density wakes. However, additional e-beam diagnostics will need to be developed at ATF to characterize plasma accelerated e-beams with narrow energy spread and spin-polarization.

Measuring sub-1% energy spread of GeV e-beams will challenge magnetic spectrometer technology in a way that few-% energy spread beams from mainstream LWFAs have not. The challenge for GeV LWFA beams lies in their mrad-level divergence and pointing fluctuations. Full e-trajectory recovery within the spectrometer's energy-dispersion plane using e.g. tandem screen detection [35] or fiducial grids [36] will be essential. E-beam polarimeters based on Møller e-e scattering from polarized ferromagnetic targets [37], which are standard equipment at many research electron accelerators [38], will have to be adapted for the first time to the unique challenges of LWFA beams. Finally, the potential of large-bubble LWFAs for producing low-emittance e-bunches [39] must be verified. Coherent transition radiation (CTR) methods —

including multi-octave spectroscopy [40], imaging, and interferometry — show promise for high-resolution 6D profiling of plasma-accelerated e-bunches outside of the accelerator. Computational advances in reconstructing e-bunch profiles from CTR data are also needed [41]. ATF is positioned to become a leader in diagnosing ultrashort, narrow-energy-spread, spin-polarized electron bunches from advanced plasma accelerators.

Simulation tools for ATF: Advanced simulation capabilities are required for understanding the physics of interactions at ATF as well as improving results. Several presentations about simulation capabilities for ATF experiments were given at the workshop. These included particle-in-cell (PIC) codes (WarpX, FBPIC, OSIRIS, VSim, SPACE) for modeling fields and charged particles self-consistently, magnetohydrodynamic codes (FLASH) for modeling plasma evolution e.g. in plasma lenses, ionized gas jets and discharge capillaries, machine-learning tools for beam diagnostics and steering, parallel codes for computing Lienard-Wiechert fields from particle trajectories (LW3D), to model e.g. undulator or betatron radiation, and other codes available through RadiSoft's Sirepo cloud-based interface. The main discussion focused on how best to make this wide array of computational tools available to ATF users.

There is a strong desire to make realistic simulations of ATF experiments available to users without requiring them to devote significant resources to simulation development. Commercial codes, such as VSim, provide many ease-of-use features (e.g. graphical user interface, complete online documentation) so that researchers who are not simulation experts can get started quickly. Additionally, ATF initial conditions, such as laser pulse profiles and electron phase space distributions, could be built into simulation codes and be updated as the facility evolves. For example, users could simply select "ATF laser" in a code's interface without having to input specific pulse parameters themselves. Common ATF setups could be provided as ready-made examples. ATF should team with computational experts from the Workshop to meet this need.

4.2 Electron Acceleration Techniques Driven by the Combination of Electron Beam and LWIR Laser

4.2.1 Introduction

A primary role for ATF as a premier Accelerator Stewardship facility is to cultivate novel and emerging particle acceleration concepts. Recently, several new acceleration mechanisms have emerged, which use a laser and an electron beam to accelerate electrons at higher gradients than conventional accelerators. Because of the combination of the LWIR laser and high-quality electron beam at ATF, this facility uniquely qualifies to provide the tools needed for cultivating these ideas. Development of these methods may in turn give rise to fundamentally new technological approaches with potentially transformative ramifications.

4.2.2 Status of current research and future directions

Although there are currently no experiments in this category conducted at ATF, two ideas were presented (one during the workshop and one afterwards) to the editors for consideration as future opportunities:

Dielectric Laser Acceleration (DLA) experiments: A dielectric laser accelerator (DLA[1]) is a compact accelerator for charged particles based on micron scale photonic structures driven with laser light – a fundamentally new technological approach with potentially transformative ramifications in many fields. DLAs open a path to energy-efficient particle acceleration with accelerating fields of 1-10 GV/m, a factor of 100 larger than current state-of-the-art conventional accelerators. Essential elements of a DLA have been proposed decades ago, but only in 2013 was the core DLA acceleration concept verified by two independent experiments conducted at SLAC and MPQ [42, 43]. In the subsequent 5 years, enormous progress has been made under an international research collaboration spanning 3 continents, 9 universities, 4 government laboratories, and 2 commercial partners [44, 45]. Experiments to date have demonstrated near-GeV/m accelerating gradients, laser-driven focusing for particle confinement, compatible miniaturized electron sources, methods for extended interaction and phase control, attosecond microbunching and net acceleration, and integration of the DLA with waveguides and external couplers for laser delivery [46-49]. Groups at Stanford University and Friedrich Alexander University in Erlangen, Germany are working to combine these components into a tabletop demonstration of a 1 MeV accelerator the size of a shoebox. This new approach may lead to revolutionary downscaling of various devices and facilities centered on particle beams, such as cathode ray tubes and accelerators used in materials science, biology and medicine. Furthermore, there is hope that this new approach may benefit larger accelerators such as synchrotron light sources, free electron lasers and particle accelerators for nuclear and fundamental particle physics.

The operating principles of DLA are similar in many ways to those of conventional microwave accelerators, but scaled in frequency by 4 orders of magnitude from radiofrequency (RF) to infrared (IR) wavelengths. Similar to RF accelerators, in a DLA the particles are accelerated inside of a vacuum channel where the accelerating fields are confined by a surrounding static structure. The aperture of the accelerating channel is on the order of the driving wavelength, which is in the range of 0.8 to 2 μm for typical near-infrared lasers. However, these small apertures pose challenges for particle transport, limiting the electron charge that can be efficiently accelerated to a few fC per bunch, and requiring the development of compatible nano-emission sources of extremely low emittance and exceptional brightness. The availability of ATF's unique combination of 10 μm CO_2 lasers and high-brightness photoinjector-based electron beam would allow for several significant experimental advantages, including a factor of 100 higher charge throughput, reduced requirements on external focusing, and factor of 10 relaxation in tolerances on structure fabrication and co-alignment of successive structures. In addition, the availability of optically microbunched beams and laser recirculation, such as used in the recent high-duty-cycle inverse free electron laser (IFEL) experiments at ATF, open the possibility for phase-synchronous net acceleration of pre-bunched beams and high repetition rate operation. These capabilities would facilitate key demonstrations to study beam dynamics, wakefield effects, and acceleration over centimeter-scale distances with multi-MeV energy gains.

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[1] Note: Although Direct Laser Acceleration and Dielectric Laser Acceleration share the acronym DLA, they are unrelated and are based on completely different physical mechanisms of electron acceleration.

Direct Laser Acceleration (DLA) experiments: In the past, plasma-based acceleration concepts have been neatly divided into laser-driven and beam-driven wakefield accelerators known by the acronyms of LWFA and PWFA. While both the laser pulse and the bunch can produce an accelerating plasma bubble on their own, each approach has its inherent limitations. For example, the laser pulse can be self-guided over long distance if its power strongly exceeds the critical power $P_{crit} \approx 17(\omega_0^2/\omega_p^2)$ GW. Therefore, for low-density plasmas relativistic self-focusing requires multiple petawatts of laser power and tens of joules of laser energy assuming tenuous plasma density of order $n_0 \sim 10^{17}\ cm^{-3}$ and the laser wavelength $\lambda_0 \sim 1\ \mu m$. On the other hand, an electron driver beam can create a very similar blow-out plasma bubble with just a fraction of the laser energy. Unfortunately, because of the rapid deceleration of the driver beam by its own wakefield, the bubble cannot be maintained for sufficiently long distance. *ATF presents a remarkable opportunity to expand this artificial division by exploring the physics of synergistic Electron-bunch/Laser-pulse Wakefield Acceleration (ELWA). The basic premise of the ELWA concept, illustrated in Fig. 4.3, is that the propagation distance of both the driver bunch and laser pulse can be extended by the synergistic interaction between the two.*

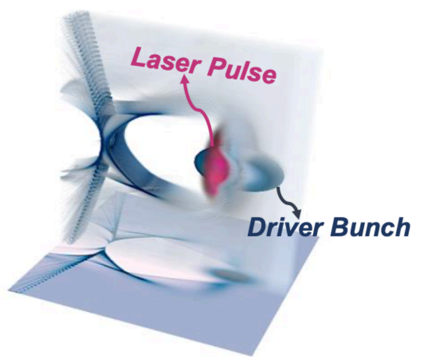

Figure 4.3 Schematic of the Electron-bunch/laser-pulse Wakefield Accelerator (ELWA): the Driver bunch guides the laser pulse while the laser pulse replenishes the energy of the driver bunch via direct laser acceleration.

The physics of the synergistic interaction that can be explored at the ATF is as follows. On the one hand, the electron beam guides the laser pulse by producing the plasma bubble, thereby mitigating the laser diffraction via laser channeling. On the other hand, electrons in the plasma bubble gain energy directly from the laser field through the direct laser acceleration (DLA) mechanism despite their position in the decelerating portion of the plasma wakefield. This phenomenon of "acceleration in the deceleration phase" was discovered last year [50].

Specifically, the Driver Beam (DB) electrons can gain energy from the laser at twice the rate as they lose energy to the wakefield. It has been estimated that in a plasma with density $n_0 \sim 10^{15} cm^{-3}$ the electron DB can gain (and maintain) relativistic energies on a scale of a GeV because the maximum energy gain from the DLA is: $\gamma_{max} \approx (\omega_p/\ \omega_0)^2(E_0/E_\parallel)^4/130$, where E_0 is the amplitude of laser electric field and $E_\parallel$ is the wakefield. Therefore, the propagation distance of the electron beam driver is also extended by the presence of the laser pulse, i.e. the two act synergistically.
Figure 4.4 illustrates the physics of extending the propagation distance of the bubble by using the combination of a laser pulse (LP) and a driver bunch (DB). Laser and beam parameters can be changed as needed; they are merely chosen to explain the physics that can be explored at the ATF. Without the DB, the LP propagates for less than z = 40cm, whereas with the DB it propagates z = 62cm. As a result of this propagation enhancement, the final energy attained by a witness beam (red-colored in Fig. 4.4) is increased from $\gamma_{wit} mc^2 \approx 2.4$GeV to $\gamma_{wit} mc^2 \approx 4.5$GeV: a truly remarkable enhancement given that the total energy contained in the DB is less than 10% of that contained in the LP.

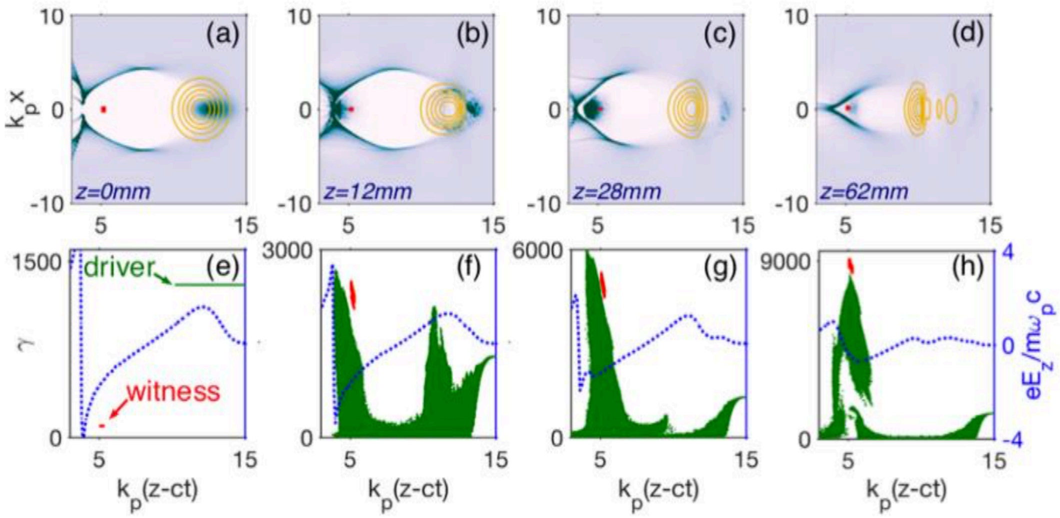

Figure 4.4 ***(a-d)*** *Evolution of the plasma bubble driven by a combination of a laser pulse and an electron beam driver at different distances. Color: plasma density, contours: laser intensity* ***(e-h)*** *Evolution of the wakefield (dotted line) and the phase spaces of the driver (green) and witness (red) electrons. Electron beam drive: τ_b =0.56 ps, Q_b =2.5 nC, $\gamma_{in}mc^2$ =650 MeV. Laser: P_l=380 TW, τ_l =0.7 ps. Plasma: $n_0 = 4\times 10^{15}$ cm-3. Laser/bunch profiles: Gaussian. Acceleration length: to 62 cm*

Therefore, the ELWA concept can be applied to enhancing the energy gain by a trailing ultra-short witness bunch. Because the witness bunch does not overlap with the LP, it does not experience any DLA and its emittance is not increased by it. This makes the testing of the ELWA concept HEP-relevant. An upgraded ATF is a perfect facility for conducting experimental tests of ELWA, either with or without the witness bunch.

Direct HEP applications are not the only accelerator applications of the ELWA concept. In fact, ELWA can be used for such key accelerator stewardship applications as the generation of copious high-energy X- and γ−rays. Such applications do not require the injection of the witness bunch into the back of the plasma bubble. Specifically, DB electrons get significantly accelerated while acquiring large transverse momentum $p_\perp \equiv Kmc$, where K is the undulator parameter. The importance of the undulator parameter is that, for given plasma density, it determines the cutoff frequency $\omega_c \sim \omega_p K\gamma^{3/2}$ of the emitted X-rays. By imparting large undulator parameter and a high relativistic energy γmc^2 to DB electrons, the ELWA concept is a potential enabler of bright X-ray sources that could be tested at the ATF.

The results of the simulations shown in Fig. 4.4(h) demonstrate that, on average, DB electrons gain as much as $\Delta E_{DB} \sim 1.6$ GeV over 6cm, thus turning them into an attractive robust source of high-energy X-rays. Numerical simulations indicate that X-rays with energies of order 1 MeV can be generated for the laser/beam/plasma parameters listed in Fig. 4.4. The betatron radiation can be calculated from electron trajectories using a recently developed [51] highly efficient code.

While the laser power and electron bunch energy parameters presented for the direct laser acceleration in Fig. 4.4 are quite challenging, there are many closely-related experiments that can be carried out with much more relaxed parameters. For example, by lowering the energy of the beam and by increasing the plasma density, it will be possible to reduce the laser power and to produce high-energy X-rays. One such example is shown in Fig. 4.5, where the electron beam is broken into two parts: the leading bunch ("DLA electrons") and the trailing bunch ("non-DLA electrons"). According to Fig. 4.5(c), the DLA electrons gain much larger transverse momentum. As a result, they emit much higher energy X-rays than the non-DLA electrons. While the non-DLA electrons can be injected into the plasma bubble using a wide variety of approaches (e.g., ionization injection), the injection of the DLA electrons can only be external. Therefore, the unique combination of the external electron bunch and a laser pulse pave the way for the efficient generation of high-energy X-rays.

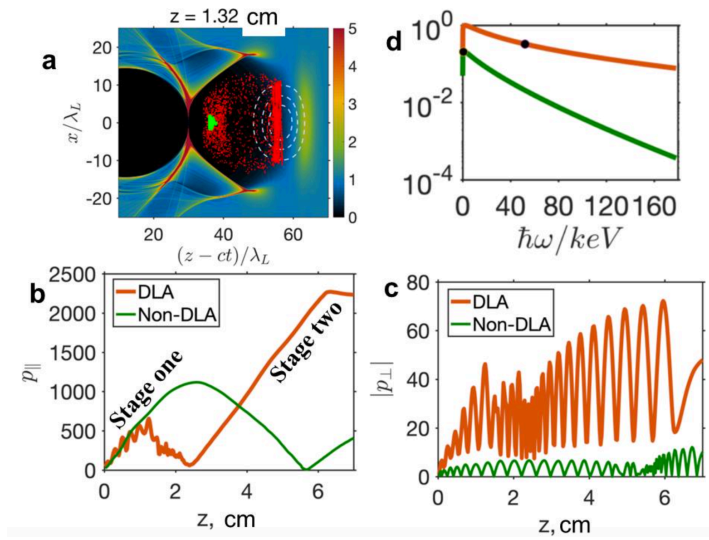

Figure 4.5: X-ray generation using co-injection of the electron bunch and laser pulse. (a) white contours: laser intensity levels, red dots: leading ("DLA") electrons, green dots: trailing ("non-DLA") electrons. (b) Typical forward momentum evolution of DLA and non-DLA electrons. Non-DLA electrons undergo dephasing after 3 cm. (c) Same, but for the transverse momentum. (d) X-ray spectra emitted by DLA and non-DLA momenta. *Electron beam:* $\tau_b = 0.4ps$. $\gamma_{in}mc^2 = 12\ MeV$. *Laser:* P_l=170 TW, τ_l=0.4 ps. *Plasma:* $n_0 = 4.3 \times 10^{16} cm^{-3}$.

Summary of Future Research Thrusts:

ATF can provide the testing ground for the proof-of-principle experiments that will demonstrate the viability of novel acceleration methodologies that combine laser and electron beam as physics drivers:

1. **Dielectric Laser Acceleration (DLA1):**
   a. Proof of principle demonstration of GeV/m acceleration in specialized structures, including optically microbunched beams and laser recirculation
   b. Key demonstrations to study beam dynamics, wakefield effects, and acceleration over centimeter-scale distances with multi-MeV energy gains.
2. **Direct Laser Acceleration (DLA2):** Demonstrating the synergistic increase of acceleration length under the combined effect of the ATF electron beam and LWIR laser:
   a. In single-bunch, high charge configuration, the electron beam will extend the propagation length of laser in plasma.
   b. In two-bunch configuration, the trailing electron beam will experience higher energy gain due to the synergistic increase in acceleration length.

4.2.3 Enabling Technology

Beam Requirements and upgrades:

Laser: In the case of direct laser acceleration, the laser will be required to create the blowout regime with pulse length occupying less than half the bubble. (see section 2.2)

For the dielectric laser acceleration, some general beam and laser parameter requirements are shown in the Table 4.1, below. Except for the required high repetition rate, the laser requirements for proof-of-concept "Demonstration" experiments in the first column are largely compatible with ATF's current experimental capabilities. The "Ideal" column represents the envisioned parameter range for a future fully integrated accelerator system based on the DLA concept and powered by efficient solid-state laser technology.

e-beam: In the case of direct laser acceleration, the drive electron beam needs to have the same length as the laser pulse, charge ~ 1 nC. In addition to the drive beam, a trailing bunch with a charge in tens of pC and a short pulse duration (~30 fs) is desired as beam load into the plasma wakefield. Spacing between the drive and trailing beams should be set based on the size of the blowout regime. Additionally, it will be absolutely essential to have the capability to accurately synchronize these two beams. Laser and electron beam synchronization to less than 100 fs will be required.

For the dielectric laser acceleration, the beam requirement in the Demonstration column of Table 4.1 are largely within the capability of the facility, except for the required emittance, where the current emittance of ATF electron beam is 1 μm.

Table 4.1 Required parameters for dielectric laser acceleration experiments. The left column shows the parameters for demonstration experiments, and the right column shows parameters that are ideally desired.

Parameter	Demonstration	Ideal
Bunch Charge	1 pC	1-5 fC
Beam Energy	50 MeV	-
Emittance (norm)	20 nm	1-5 nm
RMS Spot Size	5 µm	10 to 100 nm
Laser Wavelength	10 µm	1 to 2 µm
Laser Pulse Length	2 ps	0.1 to 1 ps
Laser Pulse Energy	20 mJ	1 to 10 µJ
Rep Rate	10 Hz	10-100 MHz

4.3 Radiation Generation Research

4.3.1 Introduction

Generating short, intense x-rays is one of the primary applications of particle accelerators. Such devices generally work by wiggling relativistic electrons transversely with respect to their direction of propagation. The transverse oscillation can be provided by an intense laser pulse, where the tremendous transverse fields of the laser are coupled to the transverse motion of the electrons, either in vacuum or in the presence of a plasma wave. The first method, called Inverse Compton Scattering (ICS), has been an active area of research at ATF for the last two decades, conducted in collaboration with various institutes including Radiabeam, UCLA, INFN, University of Sassari Italy, University of Tokyo, Tokyo Metropolitan University, and KEK Japan. The second method known as direct laser acceleration (DLA2 in Sec. 4.2) encompasses a set of experiments, which are just beginning to be developed, leveraging the coupling between the transverse field of the laser and the oscillating motion of electrons in the focusing force of plasma structures (the so called betatron oscillations), to generate radiation from these electrons.

While research in this area is primarily carried out using NIR lasers with a wavelength of ~1 μm [52-60], ATF facilities provide capabilities that can enable unique contributions to this research. With respect to ICS for instance, compared to the commonly used, broadband Ti:S sources at wavelengths from 750-850nm, the LWIR laser provides access to different regimes of inverse Compton scattering. Compton sources based on Ti:S lasers are typically all inherently broadband, with no reports below 10% bandwidth (FWHM). Additionally, the NIR-laser energies used in industry are typically below the nonlinear limit to avoid red-shift (see Sec. 4.3.2 below) and they operate at low flux per shot, but aim to have a high repetition rate (near CW) for high total photon flux. In contrast, The LWIR laser at ATF enables the study of narrowband ICS sources with high photon flux, which enables unique studies such as nuclear resonance experiments [61,62] for eventual gamma-ray applications in the emergent nuclear photonics community. While the LWIR-driven ICS sources generate lower energy x-rays (~10 keV rather than 100 keV), this is advantageous because detection of high energy photons requires significantly expensive infrastructure in the feasibility phase of study. Therefore, the lower energy photons relax the demands on the diagnostics allowing for precision-controlled experiments to investigate the basic physics of these interactions, which can then be scaled to higher energies for numerous applications. The LWIR at ATF also enables the study of ICS sources in the nonlinear regime with high photon flux, useful for exploration of basic photon science.

Furthermore, as other high-intensity laser facilities lack a high-quality electron beam source with low emittance, they must generate the relativistic electrons first, commonly through laser-plasma interactions, and then reflect the laser back towards those electrons and generate radiation in an energy efficient way [52-59]. A dedicated, tunable, high quality electron beam source such as the one provided by ATF is a great advantage because it increases the flexibility of the experimental parameter space, which allows for the exploration of novel methods such as polarized x-ray sources. Additionally, the presence of two high power laser sources at different wavelengths at ATF (1μm and 10μm), allows for novel hybrid schemes to investigate bi-harmonic energy production and modulation of x-ray pulses at the sub-femtosecond scale [63]. Generating an x-ray bunch-train from the recirculation of the laser and multiple interaction with the electron beam is another unique capability enabled by ATF's independent control over laser and electron beam source, which enables control over the bandwidth of the radiation.

4.3.2 Status of current research and future directions

Inverse Compton Scattering process (ICS): The process of Inverse Compton Scattering process (ICS) is currently under investigation at ATF, primarily by a collaboration from Radiabeam and UCLA. In ICS, laser photons collide with an electron beam to generate Doppler blue-shifted radiation. In most cases, this radiation extends from a few eV to the MeV range, typically as $4\gamma^2E_l$, where γ is the relativistic Lorentz factor and E_l is the laser energy. Longer laser wavelength at high energy are advantageous to the study nonlinear ICS effects as the obtainable momentum increases along the interaction region. In addition, as the emission occurs at lower photon energy, precision characterization of the x-ray pulses may be carried our using high quantum efficiency detectors. For example, using the ATF parameters, a 50 MeV electron beam interacting with a 10 µm laser produces 1-10 keV photons. The low photon energy allows us to study the basic physics of ICS dynamics without the complications of detectability at higher energies.

The ATF has a multi-decade history in ICS experiments using ATF's LWIR (~10 µm) laser. Initially, the experiments were driven by two motivations: first, generating high photon fluxes and narrow bandwidth from the ATF LWIR laser with applications to polarized electrons for linear colliders and second, to investigate the limits of photon production at LWIR. In fact, the ATF still holds the record for highest number of x-ray photons generated from inverse Compton Scattering at 10^9/shot. This result employed the LWIR CO_2 laser, which contains a higher number of photons than NIR lasers at the same laser power, interacting with an electron beam whose beta function was optimized for the Rayleigh range of the laser (Rayleigh length can be longer than 10 µm) [64-66].

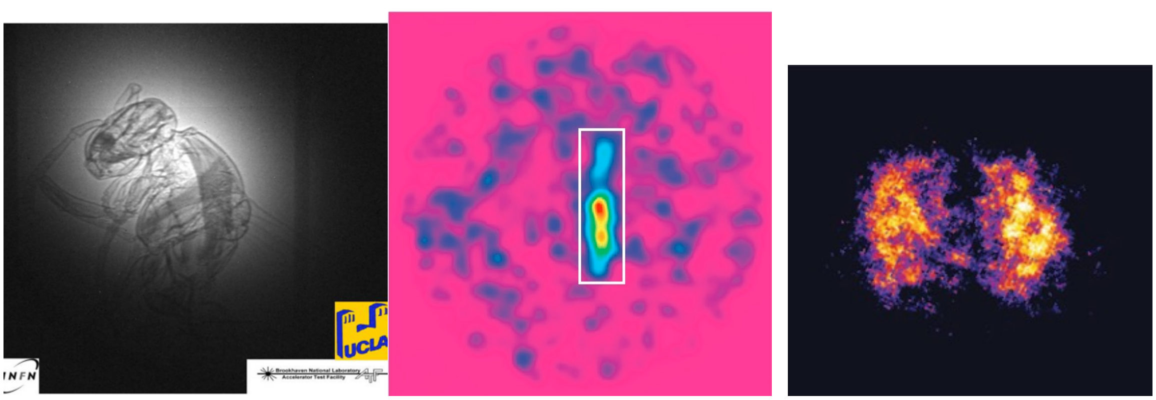

Figure 4.6: left – Wasp imaged via phase contrast imaging with x-rays from ATF ICS source in single shot operation. Center: single shot x-ray diffraction pattern from ATF ICS source. Right: higher order harmonic generation of polarized photons in gold sample.

Some of the recent ATF experiments on ICS include studies of radiation generation, diagnostic development, and improvement on beam and photon distribution. Here we list some relevant milestones accomplished at the ATF:

a) Recirculated ICS interaction in a 40MHz pulse train showing significant increase in output energy flux, efficiently up to 15 pulses [67],
b) Development of K-edge filtering diagnostics for harmonics characterization due to narrowband x-ray radiation [68],
c) Single-shot, phase contrast imaging of biological samples [69],

d) Single-shot diffraction imaging from Silicon wafers [70],
e) Nonlinear ICS effects and spectral characterization, including harmonics in both linear and circular polarization, and the first observation of distinct nonlinear redshift [71]
f) Single-shot double differential spectrum with bent crystal diagnostic, and quantitative investigation of the nonlinear red-shifting, in the strong laser-field regime [72]
g) RUBICONICS: merging IFEL and ICS techniques to boost photon energy up to 12 keV [73]

In particular, the RUBICONICS experiment is extremely notable in the community for a number of achievements including demonstration and application of LWIR laser recirculation, high efficiency capture of the accelerated beam by the inverse free-electron laser (IFEL) process, low emittance beams (at ~1 mm mrad [74]), and narrow band photon production. Since the emission is a bunch train of x-rays, the overall spectrum can be narrowband in principle, which is attractive for future pump probe, or resonant, experiments [75].

Presently, ICS experiments at the ATF are centered on advances to further interrogate the nonlinear regime using LWIR laser, and have opened possibilities to study hard X-ray industrial applications based on short wavelength lasers in collaboration with NSLS II for photon energies of up to 150 keV (using a new super conducting wiggler under construction, with unique hard x-ray optics, at NSLS), with advances on mode characteristics and possible particular applications such as photon activation therapy. One area of study is in the control of mode or laser polarity, which would open new applications on communications and material industries, and motivates the emerging study on orbital angular momentum (OAM) of the photons, with potential applications in nuclear photonics [76,78]. In the elastic case, oscillations induced by the laser field are directly re-scattered, maintaining the original polarization. Therefore, the drive laser light having OAM should produce “twisted” x-rays with OAM as well [79]. In the inelastic case, OAM x-rays can be generated by the nonlinear motion of the emitter electron, such as in a helical undulator [76, 80, 81]. The comparison with FELs provides a particular avenue of interest at ATF since the OAM x-rays generated by an FEL have photon energies of up to ~25 keV, which can be generated by the LWIR-driven ICS source of 3rd order harmonic with 10^7 photons per shot.

In ICS, a strong circular laser field with a_L, ~ 1, where a_L is the normalized vector potential, is strong enough to drive transverse momentum corresponding to a particle rest mass, resulting in the generation of harmonic radiation [76]. The resulting spectra, including the red shift at higher radiation angle, is shown in Fig. 4.7. Additionally, if a multi photon process is considered, the scattered photon will contain different polarization information. For example, if two laser photons are absorbed by a single electron, the photon energy of emission becomes 2 $\hbar\omega_L$. In order to conserve the total OAM of the photons $2\hbar$, the emitted x-rays obtain an OAM of $\hbar$ and spin angular momentum (SAM) of $\hbar$. As a consequence, the n-th order harmonic contains OAM of (n-1)$\hbar$. Observation of the x-ray vortex off axis radiation distribution, is ongoing work within a feasibility study at ATF.

Beyond these polarization studies, there are nonlinear electrodynamic effects revolving around bi-harmonic Compton scattering, extending experimental investigations of nonlinear ICS in a hybrid scheme as a current phase of basic science. According to the experimentally confirmed nonlinear effects, it is possible to control the radiation kinetics of ICS using two wavelengths of laser light [63]. During the Compton interaction experiment in BNL ATF, the CO_2 laser transfers significant momentum to the radiator electrons. Thus the motion of the electron induced by a second Nd:YAG laser is modulated by a large "figure-8" motion super-imposed on the oscillations. The emitted ICS spectrum is then described by a set of bands and its harmonics. This is equivalent to imparting a modulation in the time domain on the hard X-rays on a time scale below the attosecond.

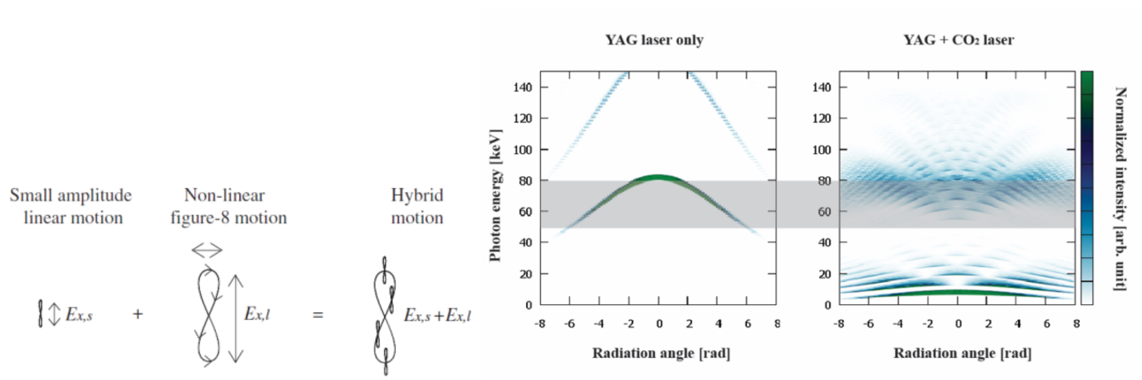

Figure 4.7: Control of radiation kinetics in the "Figure 8"-motion, from bi-harmonic ICS interaction.

The Compton edge of hard x-rays scattered from 68-70 MeV electron beam is in the range of 82-85 keV in near future experiment in ATF. This spectrally rich source can be used in pump-probe experiments that are synchronized to the CO_2 drive laser. Thus one may synchronously strobe systems driven by a high intensity CO_2 laser, opening an entirely new set of possibilities for investigating harmonically pumped systems in condensed matter physics. Of course, bi-harmonic phenomena can be applied to polarization control, and OAM associated study [82].

Laser-Driven Plasma Wakefield experiments: Electrons accelerating in a plasma wakefield undergo betatron oscillations due to the focusing force of the plasma wave. In the blowout regime, this force is linear in the transverse coordinate. When the accelerating electrons overlap the field of the laser, direct laser acceleration (DLA) occurs for those electrons whose momentum is in the same direction as the transverse force due to the laser. This method has been demonstrated in certain conditions to impart more energy to the electrons than the longitudinal force of the plasma structures [83-84]. These electrons will have a larger transverse momentum, and a higher radius of oscillation. These electrons also exhibit other interesting properties such as being bunched with a period corresponding to laser wavelength [84]. The increased transverse momentum and oscillation amplitude of electrons in DLA are expected to significantly increase the gamma-ray yield of electrons in the plasma [85]. The long wavelength of the LWIR laser and the high-quality linac-driven beam create an opportunity for the detailed study of the generation radiation in both self-modulated laser wakefield acceleration (SM-LWFA) as well as the blowout regime at ATF. This exploration is particularly timely given the recent resurgence of interest in the radiation generated in the SM-LWFA regime as a diagnosis for fusion experiments [86-87]. Moreover, 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 [88].

Summary of Future Research Thrusts:

1. **Developing ICS sources in novel regimes**
   a. Developing high flux ICS spectral radiation on a single shot basis
   b. Bi-harmonic (dual wavelength mixing) ICS Experiment, using the NIR lasers (Nd:YAG/Ti:S lasers) in conjunction with the multi-TW CO_2 laser
   c. Linear ICS Source <100 keV for certain medical applications and hard x-ray optics development
   d. The combination of an ICS source driven by an inverse free-electron laser accelerator enables an all-optical system for high average flux photons.
2. **Investigate the radiation generated from LWFA**
   (a) Inject the electron beam longitudinally in the SM-LWFA and investigate the resulting radiation
   (b) Characterize the betatron radiation from an injected electron in an LWFA driven in the blowout regime
   (c) Explore novel radiation mechanisms such as ion channel laser.

4.4.3 Enabling Technology

Beam Requirements and upgrades:

Laser: Reaching the nonlinear ICS regime will require a normalized vector potential of $a_0 > 1$:

- $a_0 = 1.5$ (Circular polarization) will enable x-ray vortices from nonlinear inverse Thomson scattering of circularly polarized light having higher OAM
- $a_0 = 2$ (Linear polarization) will enable harmonic radiation of a relativistic nonlinear inverse Compton scattering using two laser wavelengths
- $a_0 = 10$(Any polarization) will enable High-order multiphoton Thomson scattering in wiggler radiation mode [89]

For the nonlinear ICS, the multi-photon process with various different photon energies, should be observed, typically through K-edge filtering utilizing Au (80.7 keV) and Pb (88.0 keV).

For the biharmonic experiments, Nd:YAG/Ti:S lasers will need to be combined with the CO_2 laser.

In the case of radiation generation from an LWFA, there is significant interest in the characteristics of the radiation in all regimes of LWFA. This research can be conducted in all phases of the facilities upgrade.

e-beam: The electron beam requirements for ICS are described in the table below:

	Parameter Range
Bunch Charge	300-500 pC
Beam Energy	50-75 MeV
Emittance (norm)	1 mm-mrad
Spot Size	10-30 µm
Rep rate	3 Hz

Diagnostics:

ICS Diagnostics

- General area detectors, which include Potassium Bromide (KBr), Micro-Channel Plates (MCPs), x-ray CCDs, and Cesium Iodide (CsI) scintillators with CCDs. These detectors are utilized for single shot observation of the radiation distribution, or for measurement of the double-differential spectrum at the screen location. Each of these detectors have a different sensitivity, and spectral responsivity, and are matched to the corresponding x-ray characteristics of each specific experiment.
- Flux measurements with Cadmium Telluride (CdTe) or silicon (Si) based photodetectors. Crystal Si detectors, or CdTe for optional channeling, are used in average flux energy spectrometers. These detectors integrate over the full solid angle, and measure the total energy flux of photons. Si is sensitive for photons of energy <10keV, while CdTe for photons >10keV.
- Single-shot Double differential diagnostic, and Curved-bent-multi layer or Si & Quartz spectrometer. The curved-bent-multi-layer with lattice spacing of ~nm is ideal for low energy photons (<10keV). Natural crystals with spacing on the 0.1nm range, are suitable for higher energy photons, where curvature and thickness increases efficiency by optimizing the resolution for ICS interactions.
- Gamma-ray detection using a liquid scintillator detector in combination with a single photon count PMT (photo-multiplier tube), and Compton magnet spectrometer. This diagnostic setup is used for measurement of high energy Gamma-ray photons.

In addition, the emission of a bunch train of x-rays demands to measure the micro bunching by the x-band deflector or an x-ray streak camera. Depending on the time scale of the bunch train, microbunching due to the IFEL process at optical wavelengths requires the x-band deflector (~2fs temporal resolution). This was one of the original motivations for the development of the x-band cavity at the ATF for high resolution temporal measurements.

X-ray diagnostics such as radiation stacks [86] are used in NIR experiments to determine the energy and intensity of generated X-rays. Similar diagnostics will need to be implemented for the plasma experiments at LWIR regime for these experiments

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