Development of LWIR-based Advanced Acceleration Technology to Serve the Next Generation of Colliders

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The development of intense, sub-ps lasers in the long-wave infrared (LWIR) region of the electromagnetic spectrum will have significant implications for advanced acceleration techniques for generating lepton, ion, and photon sources. The compact plasma-based accelerators that are enabled by LWIR sources represent a potentially revolutionary capability for future e-/e+ linear colliders. Additionally, the interaction of an electron beam and an intense laser can be used to generate intense γ sources.

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 compact accelerators. Intense LWIR sources such as CO_2 lasers provide a number of unique advantages compared to the near infrared (NIR) lasers, which are commonly used for this research. Primarily, LWIR lasers excite large, stably propagating, fully blown-out bubbles far more efficiently in low-electron-density ($n_e \sim 10^{16}$ cm^{-3}) plasma than NIR lasers [1]. With the large bubble sizes of an LWIR driver as a target, high-quality electron bunches can be injected 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 may ultimately enable the acceleration of ultra-short spin-polarized electron bunches with sub-% energy spread, a goal that has evaded NIR-LWFA for a quarter century.

The CO_2 laser at the Accelerator Test Facility (ATF) of Brookhaven National Laboratory (BNL) is expected to provide the high-intensity sub-ps laser pulses needed for the exploration of basic physics of this interaction. Another unique advantage provided by the ATF is the presence of a high-brightness, linac-produced electron beam [2, 3], which can be injected into the wakefield in order to experimentally study the evolution of energy spread and emittance qualities of the LWFA during acceleration. The quality preservation of an externally injected electron bunch is of great interest because this process is an important component of realizing the cascading stages of LWFAs required to reach collider-scale particle energies for high energy physics (HEP) experiments. This ATF electron beam can additionally be used to directly measure the fields inside an LWFA by transverse probing of the plasma wakefield. Moreover, the recent addition of a short-pulse Ti:Sapphire laser to the interaction point has opened up the possibility of generating ultralow emittance electron beams (tens of nanometer normalized emittance [4]) via an all-optical, two-color ionization injection scheme [5]. Such collider-quality electron beams are of great interest to HEP applications and could be used, for instance, as an injector into any collider linac.

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 [6,7]. 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 ultrashort positron beams of tunable properties using laser wakefield acceleration [7,8]. *First*, the electron beam enables the controlled production of positron-electron showers or jets. *Second*, these positrons are captured in a quasi-nonlinear

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CO_2 LWFA. This scheme has already been proposed for 1 μm lasers [9], but the large size of the LWIR-driven plasma structure is expected to enable a much higher coupling efficiency between the two steps to produce positron beams. This type of positron source is currently at the conceptual stage and will need extensive development in simulations as well as validation in experiments.

An LWIR laser coupled with the large electron charge provided by an LWFA at low plasma density provides the opportunity for creating a path towards all-optical $\gamma\gamma$ colliders by converting these electrons to photons via inverse Compton backscattering. $\gamma\gamma$ colliders are considered valuable extensions to lepton colliders with distinct advantages. For example, the cross sections for production of charged scalar, lepton, and top pairs are higher in $\gamma\gamma$ collisions by nearly an order of magnitude compared with e^-/e^+ collisions. For WW production, this factor could even be up to 20 [10]. Moreover, the control of polarization of the Compton photons will allow for the verification of the circularly polarized nature of Higgs bosons. With the large number of photons produced per unit of laser energy, an LWIR source interacting with an electron beam whose beta function was optimized for the Rayleigh range of the laser can create significantly more Compton photons than an NIR-based source. The ATF holds the record for highest number of x-ray photons generated from inverse Compton Scattering at 10^9/shot [11]. Using an LWIR laser also leads to the suppression of pair production during Compton collisions since the applicable criteria $\lambda[\mu m] > 4.2\, E_e[TeV]$ implies that a laser with $\lambda = 9.2\,\mu m$ is needed for an electron beam with $E_e = 2.2\,TeV$. Efficient conversion of an electron beam with 2.2 TeV of energy to a photon beam with $\mathcal{E} \approx 1.6\,TeV$ can be realized using a CO_2 laser with τ~70 ps and ~27 J per pulse ($a_0^2 = 0.1$), which is presently obtainable.

Laser-driven ion accelerators (LDIAs) present a possibility of producing dense (around 10^{10} ions per bunch) ultra-short (picosecond scale) ion bunches with 100s of MeV of energy per nucleon in millimeter-scale targets. In LDIAs, an intense laser pulse interacts with a near “critical density” plasma, where the laser frequency ω_o matches the local plasma frequency ω_{pe}. Under the right conditions, a significant amount of the laser’s 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 via an electrostatic shockwave that is able to reflect plasma ions [12]. LWIR-driven shockwave acceleration has delivered proton beams with up to 22 MeV of energy, a narrow energy spread ($\Delta E/E$~1-10%), and a geometrical emittance of $\leq$ 5 mm-mrad [13]. Simulations show the possibility of extending proton energies to ~200 MeV with at a laser intensity of $I = 10^{18}$ W/cm^2 [12, 14]. The use of the LWIR laser in the LDIA experiments presents two primary benefits. First, the hot electron yield is significantly increased. 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 $\lambda \approx 10\,\mu m$) can be achieved by using supersonic gas targets as opposed to a solid target, which is required for a NIR laser. The use of a gas target instead of a foil is very attractive because it can be run at a high-pulse repetition rate, and the density of the plasma can be controlled easily in the neighborhood of the critical plasma density [15].

To serve the mission of research and development for the next-generation particle accelerators, the ATF provides the community with access to three classes of experimental facilities: LWIR high power laser at ~ 9.2 µm, a high-brightness linac-driven electron beam, and near-IR laser sources. A majority of the research directions highlighted above require an LWIR laser pulse with high power (>10 TW) and a short pulse (< 1 ps). The ATF itself has provided a platform for the state-of-the-art research of high-power CO_2 pulses, achieving a pulse power of ~5 TW in 2 ps [16]. Recent CO_2 laser R&D effort at ATF has also demonstrated the potential of using material nonlinearity for pulse compression [17], a key technology that can provide a practical path towards LWIR laser pulses with pulse duration of hundreds of femtoseconds, which will enable LWFA experiments in the bubble regime. The ATF along with its partners around the world continue to advance the development of emerging technologies needed to bridge the gap between the existing capabilities and those demanded by the experiments described above.

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