JThA 8:00 am–10:00 am Room 327

Joint Session on Laser Based Particle Acceleration

Bill White, *Lawrence Livermore National Laboratory, Presider*

JThA1 (Invited) 8:00 am

Overview of laser-based particle accelerators

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The proposed use of lasers to accelerate particles to ultrahigh energies has been motivated by the very high electric fields associated with focused laser beams. A number of conceptually different schemes have been proposed for this purpose and are under very active investigation. In the last couple of years significant results have been obtained on four of these schemes: the inverse-Cherenkov accelerator,[1] the inverse-free-electron laser accelerator,[2] the laser-plasma beat-wave accelerator,[3] and the self-modulated laser wakefield accelerator.[4] Of these, the first two are an example of what is known as far-field accelerators, that is, the acceleration of charges takes place far away from any solid surfaces. On the other hand, the latter two are an example of acceleration by a space charge wave that is induced by a laser beam in an ionized medium: a plasma.

To effectively use the electric field of a laser to accelerate particles, one has to somehow obtain a component of the field in the direction of the particle and slow the electromagnetic wave down so that this electric field can interact with the particle over a long distance. In the inverse-Cherenkov scheme, the wave is slowed down by introduction of a gas at the focus of the laser beam. A radially polarized laser beam is focused into this gas such that the particles to be accelerated interact with the laser field at the Cherenkov angle. This accelerator employs the Cherenkov mechanism: If a particle moves faster through a medium than light travels in the same medium, then it will radiate. The inverse-Cherenkov accelerator (ICA) simply runs this effect backward. Recently a proof-of-principle experiment has been carried out at Brookhaven National Laboratory's Advanced Accelerator test facility,[1] which shows acceleration of a relativistic electron beam that uses a CO_2 laser in the ICA mode.

In the inverse free electron laser (IFEL) scheme, the particles are accelerated by the ponderomotive bucket formed by the beating of the laser light with a static magnetic wiggler. The synchronism condition is maintained by bending the electron orbits continuously and periodically by the wiggler field such that the particle traverses one wiggle period just as one period of the electromagnetic wave passes by the particle. Very encouraging results on acceleration by the IFEL scheme have recently been obtained.[2]

Finally, relativistic space charge waves excited in a plasma by intense laser beams have shown dramatic results. Coherent space charge waves have accelerated electrons to about 30 MeV in just 1 cm using the laser beat-wave technique.[3] Electrons have been shown to gain up to 100 MeV of energy in about a millimeter with use of the so-called self-modulated laser wake-field acceleration[4] scheme. These accelerating gradients are thus by far the largest terrestrial accelerating gradients for charged particles obtained to date.

1. W. Kimura *et al.*, Phys. Rev. Lett. **74**, 546 (1995).
2. A. van Steenbergen *et al.*, Phys. Rev. Lett. **77**, 2690 (1996).
3. M. Everett *et al.*, Nature **368**, 527 (1994).
4. A. Modena *et al.*, Nature **377**, 606 (1995).

JThA2 (Invited) 8:30 am

An ultrashort-duration relativistic electron beam accelerated by an intense laser

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Because of recent advances in laser technology, there is much current interest in the interactions of high-intensity and ultrashort-duration laser pulses with plasmas. Applications include advanced fusion energy, x-ray lasers, and ultrahigh-gradient electron accelerators. In the latter case, a plasma wave is driven by the displacement of plasma electrons by the ponderomotive force of the laser light. Because of their greater mass, the ions remain stationary, providing an electrostatic restoring force. The electrons will then oscillate and create regions of net positive and negative charge. This forms an electrostatic wake field that propagates with the laser pulse at nearly the speed of light, which can trap and accelerate hot electrons.

In this talk we primarily discuss the self-modulated laser wakefield regime, where the laser pulse duration is much longer than a plasma period. It is shown that the field gradient of a plasma wave exceeds that of an RF linac by four orders of magnitude ($E \geq 200$ GV/m) and accelerates electrons with over 1-nC of charge per bunch in a low-emittance beam (1 mm-mrad).[1] The plasma wave was measured with Thomson scattering to have a duration of 1.5 ps or 100 plasma periods.[2]

We also demonstrate electron acceleration beyond the current limitation of laser-plasma accelerators, the natural diffraction length of the laser. At high laser power, the index of refraction in a plasma varies with the radius, since the laser intensity varies with radius and the plasma frequency changes with the relativistic mass factor. Under these conditions, the plasma acts like a positive lens and focuses the beam (relativistic self-focusing). A relativistically self-guided channel was found to increase the laser propagation distance (by a factor of four), decrease the electron beam divergence (by a factor of two), and increase the energy of the accelerated electrons.

Finally, to create monoenergetic femtosecond electron bunches, we discuss a new concept for laser injection of electrons using the plasma itself as the cathode.[3] It is shown by use of a 2-D particle-in-cell numerical code that it will produce 2-fs electron bunches with energy spread at the percent level.

1. D. Umstadter, S.-Y. Chen, A. Maksimchuk, G. Mourou, R. Wagner, Science **273**, 472 (1996).
2. S. P. Le Blanc, M. C. Downer, R. Wagner, S.-Y. Chen, A. Maksimchuk, G. Mourou, D. Umstadter, Phys. Rev. Lett. **77**, 5381 (1996).
3. D. Umstadter, J. K. Kim, E. Dodd, Phys. Rev. Lett. **76**, 2073 (1996).

JThA3 9:00 am

Propagation of intense femtosecond pulses in plasma waveguides

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We have synchronized a Nd:YAG laser system (1.064-μm, 100-ps pulse duration, up to 500-mJ output) with a Ti:sapphire laser system (780-nm, sub-100-fs pulse duration, ~1-mJ output). The plasma waveguide is formed by focusing the Nd:YAG pulses with an axicon in a backfill gas target. Details on the plasma waveguide formation as well as the Nd:YAG system were published in Refs. 1 and 2. The output of the Ti:sapphire laser system is then synchronously injected into the waveguide. The Ti:sapphire system is based on a CPA scheme and generates <100-fs pulses at a 10 Hz repetition rate. We are in the process of setting up additional multipass amplifiers to further amplify pulses up to ~100 mJ.

The typical plasma waveguide formation time scale is of the order of nanoseconds, which is known from both experimental observations and computer simulations. Subnanosecond time synchronization of the two laser systems is obtained with use of a piezo-driven translator on one of the Ti:sapphire oscillator mirrors. A phase comparator observes the phases of the Ti:sapphire output and a reference signal from the modelocker of the Nd:YAG system and drives the PZT mount to tune the Ti:sapphire cavity length to match that of the Nd:YAG oscillator. The shot-to-shot stability of the guided pulse spot size is evidence that the synchronization of the two systems is sufficient for these experiments.

The spatial profile of a guided sub-100-fs pulse at the output of the plasma waveguide is shown in Fig. 1. For this experiment 500-mJ pulses generated by the Nd:YAG system were focused with a 35° base angle axicon to an ~1-cm line focus in a backfill of 100 torr N_2O. Approximately one nanosecond later, a femtosecond pulse at 0.1 mJ energy level was injected into the plasma waveguide using *f*/25 optics. The output plane of the plasma waveguide was then imaged onto a CCD camera to observe the spatial mode of the guided pulse.

To diagnose changes of the laser pulse we use a FROG technique based on polarization gating.[3] A typical FROG trace of the injected