Laser-Plasma Accelerators for High-Energy Physics and Light Source Applications

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Abstract: Laser-plasma accelerators are able to produce ultra-high accelerating fields, enabling compact accelerators, and to generate high-peak current, ultra-short beams, with applications for next-generation colliders and compact light sources. The operational plasma density and laser parameters for future colliders based on laser-plasma accelerators are examined. Experiments to demonstrate a 10 GeV laser-plasma accelerator will be discussed. The prospects for driving a free-electron laser with a laser-plasma accelerated beam is considered, and paths to lasing using presently demonstrated laser-plasma accelerator beams are examined.

1. Introduction

Laser-plasma accelerators [1] have attracted significant interest as an accelerator technology because of their ability to sustain extremely large acceleration gradients, enabling compact structures. Laser-plasma acceleration is realized by using a short-pulse, high-intensity laser to ponderomotively drive a large electron plasma wave (or wakefield) in an underdense plasma. The plasma wave has relativistic phase velocity, and can support large fields, several orders of magnitude above conventional accelerators, in the direction of propagation of the laser. Rapid progress in the field of laser-plasma acceleration, and in particular the demonstration of high-quality GeV electron beams using cm-scale plasmas [2], has increased interest in laser-plasma accelerators as compact sources of high-energy, high-brightness beams for collider and light source applications.

2. High-energy physics applications

Advanced acceleration techniques are required to expand the energy frontier of future colliders, and laser-plasma acceleration is actively being considered as a possible technology for realization of a TeV-class electron-positron linear collider. Realization of a future collider, using any accelerator technology, requires minimization of both construction costs (size of machine) and operational costs (required power). The basic plasma density and laser wavelength scalings for a possible future laser-plasma-based collider have be derived [3]. Evaluation of laser-plasma physics considerations and collider interaction point constraints (e.g., final focus limitations and beamstrahlung) [4] suggest operation of the laser-plasma accelerator at a density of the order of 10^{17} cm^{-3} for a collider. Such a laser-plasma-based linac would consist of many ~10 GeV laser-plasma accelerator stages combined to reach high-energy; each stage requiring a relativistically-intense, short-pulse laser system containing tens of Joules of energy, coupled to a tailored plasma channel.

To develop a (single-stage) 10 GeV laser-plasma accelerator, Lawrence Berkeley National Laboratory is undertaking the BELLA (Berkeley Lab Laser Accelerator) project [5]. Commissioning of the BELLA laser system (40 J on target, with maximum compression <40 fs, at 1 Hz) is underway, with experiments to demonstrate generation of 10 GeV electron beams expected to begin late 2012.

3. Light source applications

Collider applications are a long-term goal of laser-plasma accelerator research and development. One of the most discussed near-term applications of laser-plasma accelerators is as drivers for light sources, and, in particular, free-electron lasers (FELs). Because laser-plasma accelerators are intrinsic sources of fs, high-peak current beams, it is natural consider laser-plasma-accelerated beams for high-peak brightness, ultrafast, light source applications, such as driving an FEL. Although this application has been actively pursued in the last several years, FEL lasing has not yet been demonstrated, and the large relative beam energy spread (few percent) has hindered FEL applications. Present laser-plasma accelerators are able to generate high-quality electron beams at the hundreds of MeV to GeV-level in centimeter-scale plasmas. Such a beam coupled to a conventional undulator would produce XUV to soft-x-ray wavelengths [6]. Laser-plasma-accelerated electron beams typically contain kA peak currents (tens of pC of charge in several fs duration), and recent measurements using betatron spectra have indicated the beam transverse normalized emittance is of the order 0.1 mm mrad [7], less than that produced in conventional RF photocathodes. With these recent measurements of the laser-plasma-accelerator beam characteristics, the 6D beam brightness of the laser-plasma-accelerated electron beam can be estimated and shown to be comparable to state-of-the-art conventional sources of electron beams (e.g., LCLS).

Although triggered injection techniques (e.g., colliding pulse injection [8] or density gradient injection [9]) are actively being pursued to control the electron beam phase space characteristics for improved beam brightness and to improve the shot-to-shot stability and tunability of the beam parameters, the experimentally demonstrated 6D brightness is sufficient for FEL lasing, provided one considers a re-distribution of the beam phase space.

Several paths to FEL lasing are possible using present experimentally-demonstrated laser-plasma accelerator beams. Beam decompression may be considered [10], which has the advantage of potentially mitigating both beam energy spread and slippage effects. Alternatively, a correlation between energy and transverse position may be introduced, coupled with a transverse gradient undulator, to satisfy the resonant condition for all energies [11]. Although requiring a more complicated canted-pole undulator design, the use of a transverse gradient undulator has potentially a number of advantages, including generation of ultrashort radiation, removing wavelength fluctuations due to beam energy jitter, and higher peak power.

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