1 GeV Electron Beams from a Laser-Driven Channel-Guided Accelerator

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Abstract: GeV-class electron beams generated from laser wakefield accelerator with 40 TW laser pulses using a 33 mm hydrogen-based capillary discharge waveguide. Stable 0.5 GeV e-beams can produce bright radiation from THz to x-rays.

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1. Introduction

Modern particle accelerators for radiation sources, high-energy physics, and other applications are typically limited to accelerating gradients ~50 MV/m to avoid material breakdown, resulting in large, expensive machines. A different technology for generating intense energetic electron beams and synchronized femtosecond radiation sources relies on plasma acceleration using high-peak power, ultrashort-pulse, high energy lasers. The radiation pressure of an intense laser pulse drives a space charge wave in a plasma [1], producing acceleration gradients on the order of 100 GV/m and micron-wavelength accelerating structures for femtosecond beams. To drive such structures, short pulse lasers are used (40 fs, 40 TW, $I \geq 10^{18}$ W/cm^2), so that the ponderomotive force resonantly drives the plasma wave ($L_{laser} \sim c/\omega_p$) in cold, low-density plasmas ($T_e \sim 10$ eV, $n_e \sim 10^{18}$ cm^{-3}). Structured plasmas (channels) are used to guide this drive pulse, maintaining the accelerating field beyond the intrinsic diffraction range of the laser beam.

2. Monoenergetic electron beams from Laser Wakefield Accelerators (LWFAs)

Experiments have rapidly progressed beyond the initial demonstration of high accelerating gradients. Electron beams of narrow energy spread and good emittance have been produced at several facilities [2-4], by extending the acceleration distance to match the dephasing length over which the accelerated electrons outrun the plasma wave.

Recently, the acceleration distance has been extended to cm-scale at LBNL, using channels in a capillary discharge developed at University of Oxford [5], and resulting in energies up to 1 GeV [6], see Figure 1.

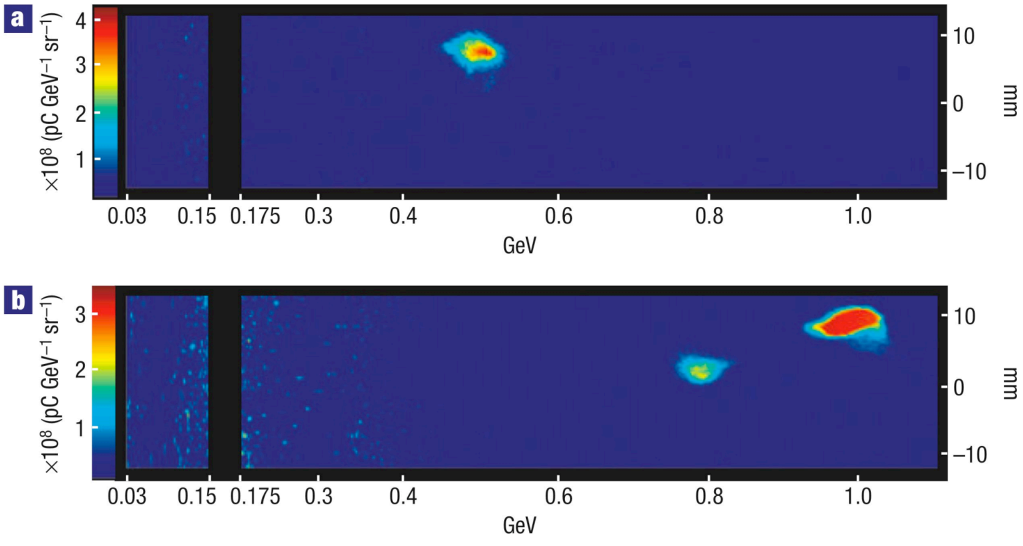

Fig.1. Single-shot e-beam spectra of the capillary-guided accelerator. (a): 12 TW input laser power, 225 µm capillary diameter with a density of 3.5×10^{18} cm^{-3}, (b): 40 TW input laser power, 310 µm capillary diameter with a density of 4.3×10^{18} cm^{-3}. Electron charge is in the tens of pC.

After the successful demonstration of GeV-class electron beams, generated directly from a LWFA, an important next step is the detailed search for optimal plasma and laser parameters for reliable operation of the accelerator [7]. Both the development of longer plasma channels for higher electron beam energies, and the need for improved beam parameters (i.e., narrow energy spread, small longitudinal and transverse emittances, etc.), require detailed understanding of such plasma processes as electron beam loading, laser pump energy depletion and radiation losses/radiation generation in the channeled plasma wake environment. Production of THz [8] and x-ray [9] radiation has also been observed from these laser plasma accelerators. The emitted THz radiation has been used to verify the electron bunch-length to be in the order of ~50 fs [8]. With these advances, laser accelerators are of increasing interest for a variety of applications. Challenges include control and reproducibility of the electron beam, scaling to higher energies, and detailed modeling to understand what optimizations are available. In particular, injection of particles into the wave must be accurately controlled, and shot-to-shot variation must be reduced.

3. Radiation generation

The electron bunches produced by a laser-plasma accelerator can be used to generating radiation ranging from the THz to x-ray regimes. The laser-plasma-accelerated electron bunches are ultra-short, containing 100s of pC of charge. These electron bunches can be used to emit high-peak-field coherent THz radiation. Coherent THz radiation has been generated via transition radiation from the plasma-vacuum boundary at LBNL. Single-cycle THz pulses have been measured (in the temporal and spatial domains) using electro-optic sampling, and peak electric fields up to 0.4 MV/cm have been observed [8]. The spectra of the coherent THz radiation indicate sub-50 fs (rms) electron bunch durations.

Incoherent broadband x-rays result form betatron emission, produced when accelerated electrons propagate in a plasma channel powered by an intense laser beam. The betatron radiation mechanism can be understood as synchrotron radiation emitted as the accelerated electrons undergo betatron oscillations within a plasma channel [9]. As an example, consider a LWFA producing a narrow energy spread electron beam, such as in the recent experiments on the channel-guided LWFA [2]. The high energy part of the electron spectrum is assumed to exhibit a narrow peak at 100 MeV (3 percent energy spread) with a total charge of 0.3 nC and a bunch radius of 3 μm. The plasma is assumed to be 1 mm long with a density of 2×10^{19} cm^{-3}. For these parameters the undulator strength parameter characterizing the betatron radiation is $K \sim 26$. At the peak of the spectrum (10 keV), the number of photons is 2×10^4 photons/shot and the brightness is 6.3×10^6 photons/shot/0.1%BW/mm^2/mrad^2, assuming a 3 mrad detection angle and 0.1% bandwidth.

The high quality laser-plasma-accelerated electron beams can also be used to drive a free-electron laser (FEL) producing a compact source of ultra-fast, high-peak-flux soft x-rays. This ultrafast (tens of fs) source would be intrinsically synchronized to the drive laser, enabling pump-probe studies in ultrafast science. For example, a 0.5 GeV electron beam interacting with a 2 cm period undulator can produce radiation on the order of 10 nm. Owing to the high current (>10 kA), saturation output fluxes are on the order of 10^{13} photons/pulse. Replacing a conventional RF accelerator by a GeV-class laser-plasma accelerator (cm scale length) would greatly reduce the size and cost of such light sources.

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