STABLE, MONOENERGETIC 50-400 MeV ELECTRON BEAMS WITH A MATCHED LASER WAKEFIELD ACCELERATOR*

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Abstract

High-power, ultrashort laser pulses have been shown to generate quasi-monoenergetic electron beams from underdense plasmas. Several groups have reported generating high-energy electron beams using either supersonic nozzles or a capillary based system to guide the laser pulse. While, significant progress has been achieved in the last several years, many issues still remain, with respect to pointing and energy stability of the beam, charge in the monoenergetic component, energy spread, and robustness. Our results demonstrate for the first time the generation of $300 - 400$ MeV electron beams with 600 pC of charge, using self-guided laser pulses and a stable, high-quality laser pulse. Fluid simulations show that matching the laser to the plasma is crucial for stable operation since there is minimal nonlinear evolution of the pulse. The beam is highly reproducible in terms of pointing stability and energy - with parameters superior to those previously obtained using optical injection. The stability and compactness of this accelerator make it possible to conceive of mobile applications in nondestructive testing, or long-standoff detection of shielded special nuclear materials. Scaling laws indicate that with a longer plasma and higher laser powers it should be possible to obtain stable, GeV class electron beams.

INTRODUCTION

Laser systems based on chirped pulse amplification are extremely compact devices capable of producing simultaneously ultra-high peak power, >100 TW, ultra-short duration pulses, <30 fs, at 10-Hz repetition rate. The development of robust high-power laser systems has been accompanied by similar progress in laser-based particle accelerators [1]. Early breakthroughs in laser-based electron acceleration resulted in the generation of MeV energy electron beams with mm-sized accelerators. While these beams had extremely low transverse emittance, the acceleration mechanism led to a Boltzmann-like distribution in energy that resulted in poor longitudinal emittance and would severely limit the brightness of any radiation source constructed with these electron sources. However, in the last couple of years, this problem has been partially overcome by the discovery of a new mechanism, the so-called ”bubble regime,” and quasi-monoenergetic beams [2, 3] have been produced. The energy of these beams is also significantly larger than that obtained using longer laser pulses[4], and opens up the possibility of generating γ-rays, for long-standoff detection as well as a table-top source of bright, ultrafast x-rays for the study of real-time dynamics in chemical and biological systems.

WAKEFIELD ACCELERATOR

In order to generate quasi-monoenergetic electron beams, a high-power laser pulse is focused onto a supersonic jet. The laser pulse as it propagates through the medium, ionizes it and drives a highly nonlinear wake. Electrons are subsequently injected into the wake and accelerated to high-energies. In order to determine the precise conditions under which the acceleration process is optimized, it is necessary to accurately characterize the laser pulses. The high laser power involved made this process extremely challenging. Empirical observations indicate that it is not correct to extrapolate measurements done at low power with one or more amplifiers turned off, to actual laser performance at high power. The laser system was fully characterized with respect to pulse parameters (energy, spectrum, pulse duration, spatial profile, and nanosecond contrast) and reliability (fluctuations in energy and pointing from minutes to hours) while operating at full 100 TW output and nondispersive beam sampling. Contrast measurements on the femtosecond and picosecond time scale required a scanning third-order autocorrelator and were, therefore, performed periodically. The laser system is also equipped with an acousto-optic spectrum modulator (DAZZLER) which permits optimization of the spectral characteristics at the output to compensate for gain narrowing and red shifting during amplification, and control of the temporal pulse profile.

In order to access the relativistic intensity needed to drive a nonlinear wake, it was necessary to focus the beam. The spatial characteristics of the laser pulse are greatly degraded during the amplification process. Without any correction, and using a 1-meter focal length paraboloid, a focal spot of $25 - 30$ microns containing $30 - 40\%$ of the incident energy could be obtained. In this mode, measurements indicated an electron beam with a large divergence, low-energy and poor shot-to-shot reproducibility. This largely arose from the fact that the intensity accessed, even with the relatively large energy available, was quite low and close to the threshold for wakefield acceleration. A large aperture (4-inch) dielectric deformable mirror integrated with a wavefront sensor was implemented to improve the spatial quality of the laser beam. The use of adaptive optics to correct the beam leads to a dramatic improvement in the focusability of the laser and a corresponding improvement of the electron beam. The Strehl ratio of the pulse could be

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improved to 0.95, which indicated a nearly perfect beam in terms of the spatial intensity and phase. In practical terms, this implied a beam which could be focused to the diffraction limit. Direct measurement of the focus with a 1-m focal length paraboloid demonstrated a focal spot with a diameter of 16 μm, for an incident beam of 2.7 inches diameter with a top-hat profile containing $75 - 80\%$ of the incident energy.

EXPERIMENTAL RESULTS

The setup used to study laser-wakefield acceleration is shown in Fig. 1. A high-intensity laser pulse was focused onto the supersonic nozzle using a 1-meter focal length paraboloid. The resulting intensity in vacuum per Joule of laser energy was $I{\sim}10^{19}$ W cm^{-2}. This corresponded to a normalized vector potential of $a_0 = 2.1$. In order to obtain the best electron beam, it was necessary to position the nozzle precisely with respect to the focus. Experiments indicated that the best electron beams were obtained when the focal spot was placed at the gas-vacuum interface, the beam propagated along the middle of the nozzle, and the focal spot was $300 - 400$ μm above the nozzle. This requirement is significantly relaxed when the laser pulse is precisely matched to the plasma. During actual experiments, the laser intensity and plasma density were scanned and the supersonic nozzle was moved along the laser propagation direction to optimize the channeling of the laser beam through the plasma, obtaining the best electron beam. It can be concluded on the basis of this investigation that the best monoenergetic electron beams were produced for pulse duration of ${\sim}30$ fs, Strehl ratio of 0.9 and laser power > 30 TW. Additionally, the nanosecond contrast of the beam needed to be at least 10^{-7}-7 of the main pulse. Any degradation of laser parameters from these values resulted in electron beams with low charge, large divergence angle, large energy spread or no beam at all.

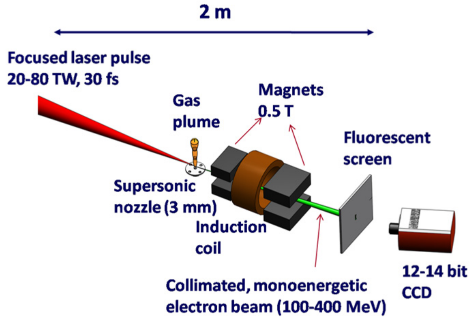

Figure 1: Schematic of device to produce energetic electron beams. A high-power laser pulse is focused onto a supersonic helium nozzle and drives a nonlinear wake. Electrons injected into the wake are accelerated and exit the plasma as a well-collimated high-energy electron beam. The spatial and energy profile of the electron beam are measured using a fluorescent screen imaged by a CCD.

Under optimal laser conditions, the dependence of electron beam parameters on the plasma condition was studied. This was varied by adjusting the backing pressure, which resulted in a change of the plasma density, or by using supersonic nozzles with different lengths which effectively altered the acceleration length. Electron beam characteristics for electron densities in the range $2{\times}10^{18}$-$2{\times}10^{19}$ cm^{-3} and for acceleration lengths in the range $1 - 4$ mm. As a result of the optimization process, very high quality electron beams were obtained. The best electron beams were obtained for laser power of $40-70$ TW, with $3-4$ mm nozzles and resonant density. The resonant density corresponded to the case where the plasma period equaled the temporal duration of the laser pulse. At high-density (self-modulated regime), the electron beam had large divergence and Maxwellian energy distribution. As the density was lowered, the energy distribution became more monochromatic. These experiments were done at relatively low powers: $20 - 30$ TW. Use of higher laser power at high plasma density was not beneficial, as beam filamentation became significant, and the electron beam actually degraded as the power level was increased.

In order to better understand and control the process of wakefield acceleration and obtain high-brightness, high-energy electron beams with low longitudinal and transverse emittance, it was necessary to consider the process of wakefield acceleration. The ponderomotive force of the laser expels electrons along the propagation axis. The ions however, are relatively immobile and the resulting field distribution corresponds to an electron plasma wave moving at a speed governed by the density of the medium, which in the underdense regime is close to the speed of light. Energetic electrons are produced when the free electrons in the plasma are trapped and accelerated by the wave. The ideal situation for generating the most stable and highest amplitude wakes is to have the plasma resonant with the laser [5]. The resonance condition is set by the pulse duration of the laser, τ_L. The largest plasma wave is obtained when the laser pulse is shorter than the plasma wavelength, λ_p [6]. The maximum accelerating field is obtained when the laser pulse length L=(cτ_L) is equal to half the plasma wavelength i.e. cτ_L=λ_p/2. For the most efficient propagation with minimum filamentation, the transverse length of the pulse needs to equal the plasma wavelength. Thus, the most efficient electron acceleration is achieved when the laser pulse is focused down to a ${\lambda_p}^3$ spot. With the availability of short pulse lasers, it has now become possible to fulfill this resonance condition and obtain energetic electron beams. Previous experiments with longer pulse lasers achieved resonance by self-modulation of the pulse or forced laser wakefield acceleration. When a short pulse is used, only one period of the plasma is excited leading to a monoenergetic beam [7]. For a 30 fs laser pulse corresponding to a pulse length of 9 microns plasma wavelength needs to be 18 μm.

Close to resonant density and high peak power (40 TW), highly monoenergetic beams were obtained with extremely low divergence. With further lowering of the plasma density and a 3mm nozzle with a peak power of 45 TW, the highest energy electron beams were produced. A typical spectrum is shown in Fig. 2. The beam had energy of 320 MeV, a spread of 10% (limited by the spectrometer resolution) and an angular divergence of 6 mrad. At these high energies, even with magnetic fields of 1 T from a combination of two permanent magnets, the deflection of the beam was small and it was required to know the undeflected position of the beam very precisely. This was accomplished by having the magnets mounted on motorized stages that moved the magnets into and out of the beam. An interesting result obtained was that the electron beam position did not exactly correspond with the position of the laser beam in vacuum.

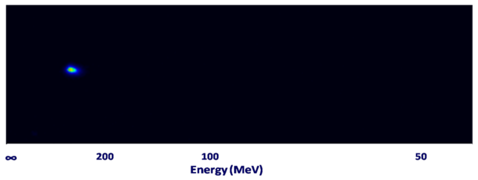

Figure 2: Monoenergetic, low-divergence beam with 45 TW of laser power at a plasma density of 7×10^{18} cm^{-3}. The energy is peaked around 320 MeV with a spread of 10%. The angular divergence of the beam (vertical axis) is 6 mrad.

The stability and reproducibility of the accelerator was also investigated in detail. The pointing and angular stability of the electron beam was found to sensitively depend on the laser contrast. Preliminary experiments done in a low-contrast mode, corresponding to a nanosecond pedestal of 3×10^{-7}, produced electron beams with a shot-to-shot angular variation of $\sim$10 mrad. The location of the monoenergetic peak was found to vary by approximately $20-30\%$ shot-to-shot. In order to stabilize the accelerator, the contrast of the laser system was improved to 2×10^{-8}. In the high-contrast mode, the stability of the system was $1-2\%$ in angle and angular spread, while the energy fluctuated by 10%shot-to-shot.

DISCUSSION

Preliminary simulations of the laser plasma interaction have been performed to determine the conditions leading to the production of these high-energy electron beams.A fluid code has been used to study the evolution of the laser pulse in the plasma. When a 40 TW pulse is allowed to propagate in a plasma with density 8×10^{19} cm^{-3}, it is found that the pulse evolves to its final form after propagating only 340 μm which equals only 10% of the acceleration length. The minimal evolution of the laser leads one to conclude that the pulse is matched with the plasma and explains the high energy and high stability obtained with the accelerator as well as the relatively insensitivity of the nozzle relative to the precise position of the focus. With the laser and plasma matched, the pulse is rapidly evolving due to relativistic self-focusing and the inefficient conditioning phase is unnecessary. Not only does this lead to higher beam energies (due to the greater acceleration distance), the fact that the bubble forms quickly means that the particles forming the bunch are quickly swept up from the background plasma leading to spatial-temporal localization of source of beam electrons. Once enough charge has been accumulated to give the bunch a large wake of its own, beam loading reduces the total wake field and halts trapping. Accomplishing this process quickly (in our case due to rapid pulse evolution), limits the beam energy spread and divergence. As the density is lowered, the pulse length, relative to the plasma period decreases. At the higher density the laser pulse extends into the bubble region and can interact directly with the trapped bunch, scattering the beam leading to an increase in divergence. At lower density, only the low intensity trailing edge of the laser pulse extend into the bubble, which has significantly less effect on the trapped bunch than in the high-density case. Furthermore, at lower density, the pulse is much closer to resonance and a larger wake field is produced and results in faster bubble formation and more rapid trapping leading to the exceptional stability observed experimentally.

CONCLUSION

We have demonstrated a source of stable high-energy electron beams using a compact short-pulse laser system. Scaling laws indicate that the use of a cm-scale plasma and higher laser power permits the generation of GeV-energy electron beams [8]. Preliminary experiments indicate that it is possible to generate $600-800$ MeV electron beams using $5-10$ mm long plasmas and $80-90$ TW laser power.

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