Staging Laser Plasma Accelerators for Increased Beam Energy

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Abstract. Staging laser plasma accelerators is an efficient way of mitigating laser pump depletion in laser driven accelerators and necessary for reaching high energies with compact laser systems. The concept of staging includes coupling of additional laser energy and transporting the electron beam from one accelerating module to another. Due to laser damage threshold constraints, in-coupling laser energy with conventional optics requires distances between the accelerating modules of the order of 10m, resulting in decreased average accelerating gradient and complicated e-beam transport. In this paper we use basic scaling laws to show that the total length of future laser plasma accelerators will be determined by staging technology. We also propose using a liquid jet plasma mirror for in-coupling the laser beam and show that it has the potential to reduce distance between stages to the cm-scale.

Keywords: laser-plasma accelerators, staging, plasma mirror.
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INTRODUCTION

Laser wakefield accelerators (LWFAs) have achieved remarkable advances over the last decade. Several research groups have now produced electron beams with percent level energy spread, small divergence [1-3] and energies reaching up to 1.1 GeV [4]. Scaling of these results to the 10GeV level is expected as PW class lasers become available. At the same time effects of laser depletion and electron-wake dephasing limit the energy achievable in a single stage (length) of plasma. One can deduce this from the basic scaling laws that govern the process of laser plasma acceleration [5]. The energy gain W_{stage} that can be achieved in a single length of plasma drops with increasing plasma density n as n^{-1}. At the same time, for normalized laser intensities $a_0>1$ (which are typically used for LWFAs), accelerating length in plasma is limited by laser energy depletion which scales as $n^{-3/2}$. In order to increase the energy gain at a given laser energy, we are forced to use lower density plasma which in turn will increase the required propagation length. These considerations are illustrated in Fig.1 which shows energy gain and single stage length for a laser plasma accelerator (calculated using a fluid code [6]). We can see from Fig.1 that in order to reach an energy of 1 TeV in a single stage plasma density of ~10^{15}cm^{-3} is required, while the accelerating length in this case has to be of the order of 1km. Staging allows

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one to use higher plasma densities that produce higher peak accelerating gradients. It results, as we show below, in significant reduction of the total length of the LWFA for

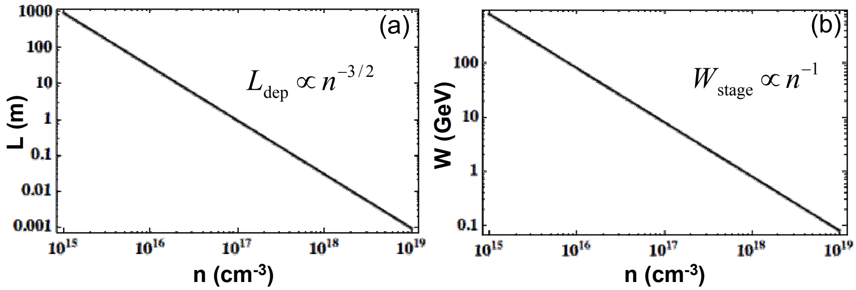

FIGURE 1. (a) Single stage length (a) and (b) energy gain in a laser plasma accelerator as a function of plasma density, with normalized laser intensity a_0=1.

TeV level energies. Additionally, staged LWFAs will use multiple laser systems (one for each stage) that can potentially run at high repetition rate since the energy requirement is much reduced from a single stage device.

A generic approach to staging laser wakefield accelerators is schematically illustrated in Fig.2. The accelerating modules (either gas jets or capillaries) are arranged in series, with a separate laser beam coupled into each one of them. Thus the length of a single stage is a sum of the accelerating length L_{dep} and the distance L_c required for coupling an additional laser beam. The number of stages as a function of plasma density is shown in Fig.3a. The total accelerator length for a final energy of 1TeV is shown in Fig.3b for several different coupling lengths L_c. We can see that the total acceleration length exhibits a minimum that determines the optimal plasma density. Operating at this optimal density with L_c on cm-scale will allow TeV level energy gain in a total distance of about 100 m. Minimizing L_c will therefore be one of the most important challenges involved in staging.

The most direct approach to in-coupling a laser beam would involve placing a final focusing optic in the path of the electron beam while making an opening for the electrons to pass through as shown in Fig.2. The laser beam size on the optic should be large enough so that the power density is below the damage threshold of the dielectric optical coating, which for sub-ps pulses is of the order of 0.05 J/cm^2. This condition puts a lower limit on the distance between the accelerating stages. For example, for a 10 J laser pulse focused into a 50 μm spot, in order to keep the power density below the damage threshold, the distance between the focusing optics and the accelerating stage (and hence the coupling distance L_c) should be of the order of 10m. This reduces

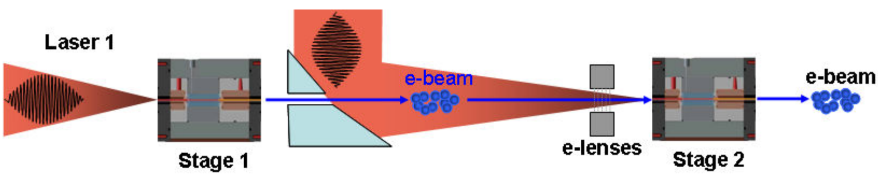

FIGURE 2. Schematic illustration of LWFA staging.

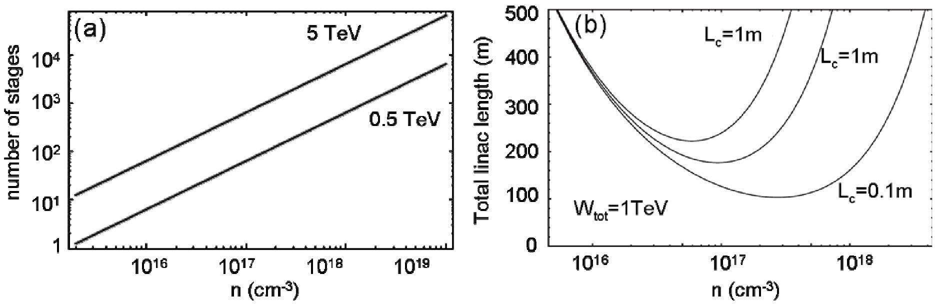

FIGURE 3. (a) Number of stages and (b) total length of staged LWFA as a function of plasma density

the average accelerating gradient to ~1 GV/m and results in the total length of the accelerator of ~10km. Additionally, at these long L_c, complicated electron beam transport lines can be required for coupling electrons from one stage to the other. Alternative solutions will therefore be needed in order to preserve the advantages of laser plasma accelerators over conventional technology. In the next section we will discuss one of such alternative approaches that is based on using reflection of a supercritical plasma surface, i.e., a plasma mirror

ACCELERATOR STAGING USING PLASMA MIRRORS

The concept of plasma mirrors has developed together with advances in high power ultrafast lasers [7-9]. Laser pulses with peak intensities of the order of 10^{15}-10^{17}W/cm^2 will ionize a solid target and produce supercritical plasma during the rise of the pulse. The rest of the pulse will thus 'see' a plasma surface acting as a high reflector. This concept proved useful for enhancing the pulse contrast in multi-TW class lasers since low intensity background and prepulses do not produce plasma and therefore are not reflected.

Plasma mirrors operate at intensities of the order of 10^{16}W/cm^2 – orders of magnitude higher than any conventional optics. From the perspective of laser accelerator staging, it should therefore be possible to significantly reduce the distance between the accelerating stages by employing a plasma mirror as the final in-coupling optic. Assuming a drive laser beam with 0.5PW peak power and focal spot of 50 μm, the coupling distance reduces to ~10cm. As fig 2b shows, this significantly reduces the overall laser-plasma accelerator length.

At the same time, being a highly nonlinear system, plasma mirror are harder to operate than conventional optics. Several considerations should be taken into account. First, the plasma mirror should provide high reflectivity while preserving the quality of the laser beam. Second, since the surface of the target is locally destroyed on every laser shot, a fresh target surface must be supplied. Lastly, producing large amount of debris can result in decreased performance and even damage of conventional optics and diffraction gratings. In the following we examine these requirements in detail.

Several research groups have reported detailed studies of the reflectivity of the solid target plasma mirrors [7-10]. Typical 'triggering' intensities (laser power at which reflection starts to increase compared to Fresnel reflection) are of the order of 10^{13} to

10^{14} W/cm^2, with peak specular reflectivity reaching 70-80% at intensities around few 10^{16} W/cm^2. A sharp drop in specular reflectivity has been observed around 10^{17} W/cm^2 and has been attributed to nonlinear expansion of the plasma [8, 9]. The reflected mode quality was found to be similar to that of the input beam since near the maximum the reflectivity of the plasma scales approximately as $I^{1/2}$, where I is the input intensity [9]. It should be noted that the quality of the reflection depends strongly upon the intensity contrast of the laser pulse. In cases where ps to ns pre-pulses are strong enough to ionize the target before the arrival of the main pulse, nonlinear expansion of the plasma will strongly degrade the mirror performance.

Most plasma mirror systems demonstrated previously employed mechanical scanning of solid state targets in order to provide a fresh surface for every new shot of the laser [7-10]. While this is acceptable for lasers with repetition rates in the range of 1 to 10Hz, future laser plasma accelerators are expected to operate at kHz repetition rate, which will make the implementation of mechanical scanning extremely challenging. An alternative solution that was first described in Ref.[11] employs using a continuously flowing planar liquid jet. In this case the renewal of the surface is achieved automatically. The authors of Ref. [11] demonstrated their approach with 1kHz repetition rate laser using a jet of ethylene glycol. While using ethylene glycol is attractive due to its high viscosity and low vapor pressure, it does not relieve the danger of potential contamination of the optics by carbon-containing compounds.

Substituting water for ethylene glycol in the liquid jet can solve the contamination problem. The development of a planar water jet, however, represents a significant challenge due to the low viscosity of water (about 20 times smaller than that of ethylene glycol). Several solutions have been proposed including reflecting a jet from a flat solid surface [12], razor blades to form the flow [13] and guiding structures [14]. The guiding structure, which is usually a "u"-shaped wire inserted in the nozzle, prevents surface tension collapse of the water jet for the low flow speeds that are needed to create a laminar flow. Using a guiding structure as shown below, allows achieving stable planar water jet suitable for use as a plasma mirror

CHARACTERIZATION OF THE WATER JET PLASMA MIRROR

For development of the water jet plasma mirror we have utilized a commercial sapphire nozzle designed for use in dye lasers. The cross section of the nozzle is 3.9 x 0.3mm. A u-shaped guiding structure has been cut from a piece of metal shim and inserted into the nozzle. The flow in the jet was gravity driven providing speeds of ~2cm/sec. Under these conditions a stable flow is established providing a flat reflection surface. The thickness of the jet was measured by femtosecond interferometry to be around 200μm.

Initial plasma mirror tests have been conducted at atmospheric pressure using 300 fs pulses in one of the probe lines of the 100 TW Ti:Sapphire TREX laser system. An XPW system has been implemented to ensure the high intensity contrast of the input pulse (10^{-5} with respect to ps pre-pulse, 10^{-8} with respect to ASE pedestal) [15]. The laser beam was focused by an achromatic lens to approximately a 30 μm spot. The

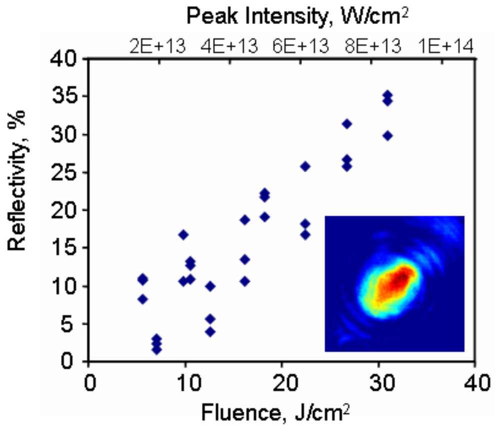

FIGURE 4. Reflectivity of water jet plasma mirror. The inset shows near field image of reflected mode

reflected beam has been observed by a CCD camera, and reflectivity has been calculated by calibrating the CCD with respect to the input laser power.

Plasma mirror reflectivity as a function of input fluence and intensity is shown in Fig.4. Due to the limitations in the probe line power, we were unable to test the plasma mirror above 10^{14} W/cm^2. However, the reflectivity curve follows closely the results observed by the other groups [8, 9], so we believe that similar reflectivity of 70-80% can be achieved by increasing the intensity to ~10^{16} W/cm^2. In order to characterize the plasma mirror at this power, however, a vacuum environment is necessary, otherwise the interaction of the intense laser with air at atmospheric pressure can produce significant reshaping of temporal and spatial structure of the pulse. In order to analyze the stability of the water jet at low pressures, initial tests have been conducted. The results are illustrated in Fig.5, which shows the reflected near field spots of a HeNe laser focused on the water jet in a vacuum chamber. The jet remains stable providing good quality reflection down to about 20 Torr. Below this pressure, bubbles start forming on the jet, manifesting the onset of boiling. Differential pumping will be necessary in order to integrate the water jet plasma mirror into the high vacuum environment used in laser plasma accelerators. The design of such a differential pumping system is currently in progress.

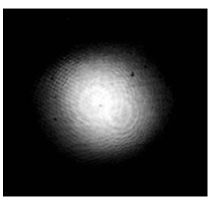

FIGURE 5. Near field image of the mode of HeNe laser reflected from the water jet at the pressure of 25.6 torr

SUMMARY

In summary, staging of laser plasma accelerators allows one to overcome laser depletion limitations. The total length of a staged accelerator can be optimized by proper selection of plasma density and by minimizing the coupling distance. The latter can be achieved by using a plasma mirror as final optic for laser in-coupling. Use of a planar water jet as a renewable non-contaminating plasma mirror has been proposed and an initial experimental characterization has been performed. We believe that staging together with further progress in LWFAs will enable compact laser-plasma accelerators to generate particle energies suitable for high-energy physics research.

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