DEVELOPMENT OF WATER JET PLASMA MIRROR FOR STAGING OF LASER PLASMA ACCELERATORS*

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Abstract

Staging Laser Plasma Accelerators (LPAs) is desirable in order to maintain a high overall accelerating gradient while reaching beam energies of 100 GeV and above. This requires incoupling of additional laser beams into accelerating stages. It is imperative to minimize the distance that is needed for laser incoupling in order to achieve this high overall accelerating gradient. A plasma mirror is investigated as the final coupling optic reducing the coupling distance from tens of meters, using a conventional optic, to as small as a few cm. Both a planar water jet and a nitrocellulose foil are used as reflecting surfaces and characterized. A maximum reflectivity of 70% was obtained using both surfaces.

INTRODUCTION

Laser Plasma Accelerators (LPAs) have now achieved electron beams with percent level energy spread, small divergence [1] and energies up to 1.1 GeV [2]. With PW class lasers becoming more available, scaling this energy up to 10 GeV is expected. However, in order to reach the 100 GeV range and beyond, multiple accelerator stages become preferable due to laser pulse depletion and electron-wake dephasing in a single stage.

The energy gain of a single stage, W, scales inversely with the plasma density, n^{-1}. Using normalized laser intensities of $a_0 > 1$, as is typical with LPAs, the laser depletion length scales as $n^{-3/2}$ [3]. This means that for each stage, a high energy gain requires a low density which in turn lengthens the accelerator. To get a 1 TeV energy gain from a single accelerating stage, the accelerator must be on the order of 1 km long [4]. Thus multiple stages of LPAs could achieve 1 TeV energy gain over a shorter distance. Furthermore, a staged LPA can potentially run at higher repitition rates due to the lower laser energy requirements.

In a multi-stage LPA, reducing the coupling distance is important in reducing the total length of the accelerator. The generic way to couple multiple accelerators is shown in Fig. 1. The size of the laser beam on the final coupling optic should be large enough to keep the fluence below the damage threshold of the optic. For a sub-ps pulse, the damage threshold for the dielectric optical coating is on the order of 0.05 J/cm^2. This limits the minimum coupling distance between LPA stages. In order to focus a 10 J pulse of 800 nm light into a 50 μm spot, the distance between the final coupling optic and the accelerating stage should be on the order of 10 m in order to prevent damage of the optic. Looking at Fig. 2 this means the total linac length for a 5 TeV LPA is $\approx$ 1.8 km. Furthermore complicated transport systems may be necessary to couple the electrons across such a distance [4]. To minimize the coupling distance, a plasma mirror concept is investigated.

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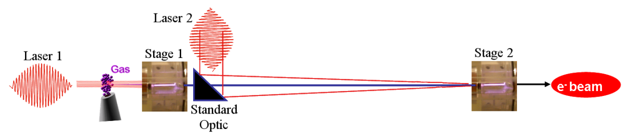

Figure 1: Schematic of generic approach to LPA staging.

LPA STAGING USING PLASMA MIRROR

Plasma Mirrors (PMs) were developed alongside high power ultrafast lasers. A laser pulse with peak intensity of the order $10^{15} - 10^{17}$ W/cm^2 will ionize most targets creating a supercritical plasma during the rise of the main pulse of the laser. At such densities, a sheet of plasma will act as a reflecting surface to the rest of the pulse and has been used to improve the pulse contrast in multi-TW class lasers. Prepulses and background light not intense enough to “trigger” the mirror will not be reflected [5]. Since PMs operate at much higher intensities than conventional optics,

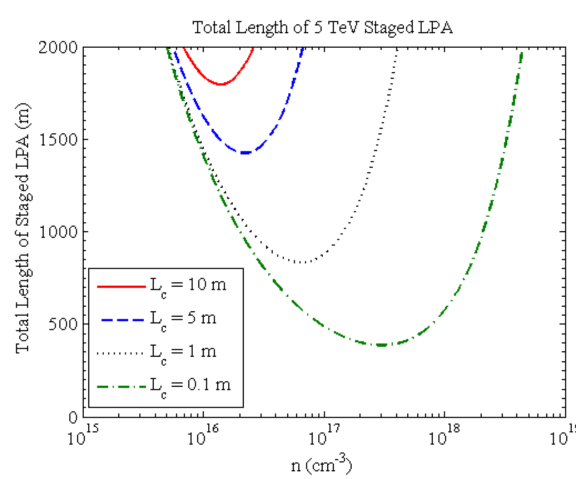

Figure 2: Main single-linac length versus plasma density n_0 for several laser in-coupling distances L_c, $E_b = 5$ TeV and $a_0 = 1.5$ [6]

they might be used as a final coupling optic in staging LPAs and reduce the coupling distance. For a 1 PW peak power laser and focal spot of 50 μm, the coupling distance reduces to ≈10 cm. This effectively reduced the distance of a 5 TeV linac to ≈ 500 m, a reduction of ≈ 1.3 km from using conventional optics (see Fig. 2).

Due to the nonlinearity of PMs, they are harder to operate than conventional optics. The PM should have high reflectivity, maintain the quality of the laser profile, operate at high repetition rates, and not produce enough debris to damage other optics in the accelerator system. Using a solid target allows better vacuum and a more easily controllable surface profile. However, it needs to be mechanically scanned due to the local destruction of the surface on every shot and can produce debris. With 1-10 Hz laser systems, the scanning should not prove a problem; however, with a kHz system, this becomes a challenge. A planar liquid jet target solves the repetition rate problem as the surface is renewed automatically. Such a system was demonstrated using a 1 kHz laser and an ethylene glycol jet [7]. Ethylene glycol's high viscosity and low vapor pressure make it favorable in maintaining a flat surface. It still has the potential to damage optics due to the carbon-containing compounds. On the other hand, water does not contain carbon, and as such, will not eject any damaging debris. The low viscosity of water poses a challenge in creating a planar liquid jet, though the use of guiding structures and low flow speeds can mitigate this problem [8].

CHARACTERIZATION OF PLANAR WATER JET PM

The water jet system proposed here is made in-house using a 0.7 mm diameter glass capillary glued in a copper tube bent to an angle of ≈ 60^o. The water is flowed onto a guiding structure consisting of a 100 μm thick metal shim with a 4 mm diameter hole cut into it. A 0.35 mm diameter mesh with 150 μm thickness was glued to the opposite side of the water flow to stabilize the film at low pressure. This resulted in a 150 μm thick water film within the 4 mm hole on the shim. The film is accessible through the holes in the mesh (see Fig. 3).

Using a 50 fs pulse in one of the probe lines of the 100 TW Ti:Sapphire TREX laser system, reflectivity of the water jet PM at 50 torr backing pressure was measured by collecting the reflected beam on a CCD camera and calibrating the CCD with respect to input laser power. The reflectivity of a 5 μm thick nitrocellulose foil was also measured using the same technique at various pressures. An XPW system was used to enhance the pulse contrast of the input pulse (10^{-5} with respect to highest non-main pulse intensity). The beam was focused to a spot of ≈ 20 μm using an achromat lens with a 140 mm focus.

As seen in fig. 4, maximum achieved reflectivity of the foil and the water jet is about 70%. The reflectivity curves are similar at similar pressures suggesting that reflectivity is not limited by the target used as the PM. The triggering

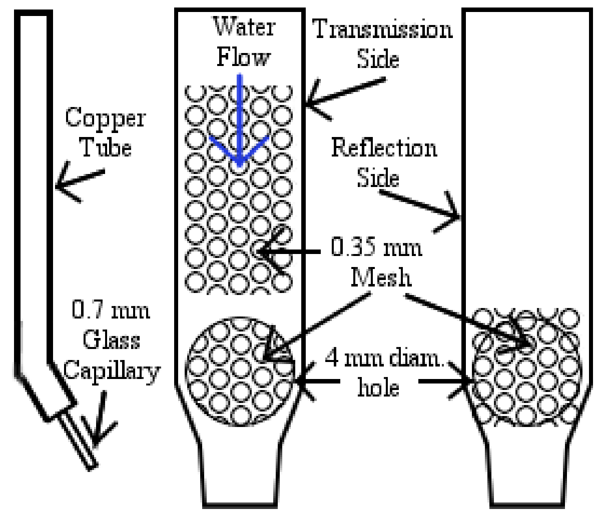

Figure 3: Schematic of water jet and guiding structure.

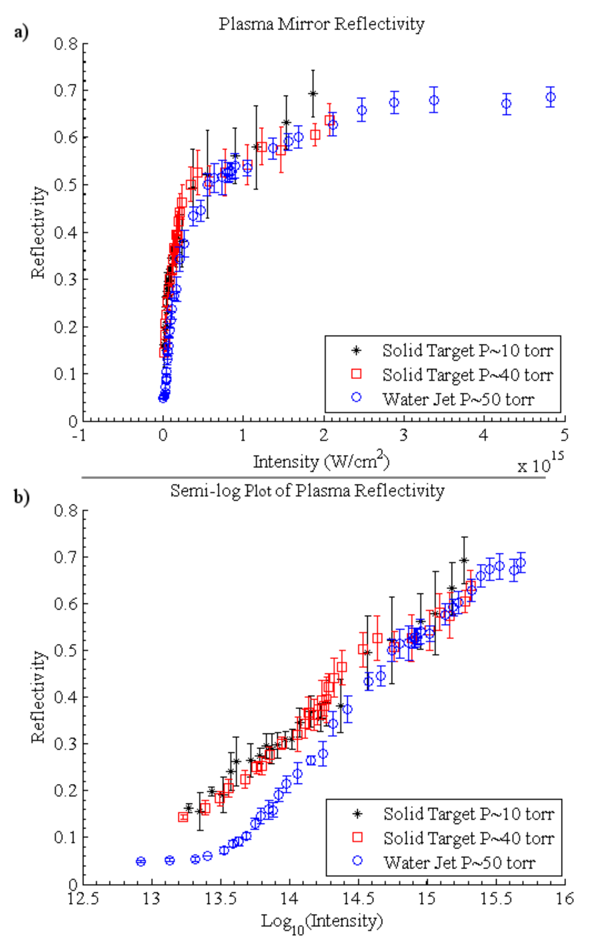

Figure 4: a) Reflectivity of plasma mirror. b) Semi-log plot of reflectivity.

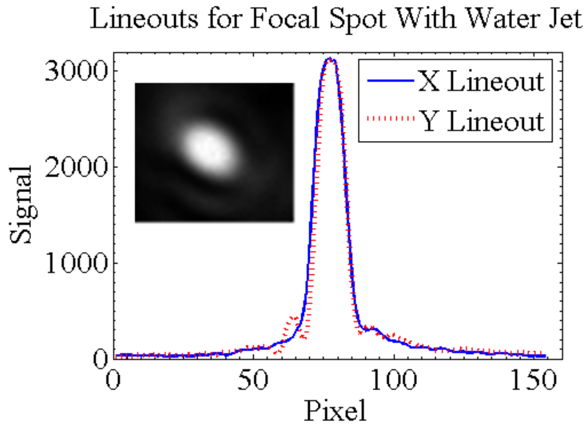

Figure 5: Near field image of the mode of TREX laser reflected from water jet at $\approx$ 50 torr pressure.

occurs on the order of 10^{13} W/cm^2, similar to results seen in Ref. [9]. A leveling off of the reflectivity occurs near 1.5×10^{15} W/cm^2. This may be caused by the remaining air inside the chamber being ionized by the main pulse creating small plasma mirrors that scatter the pulse. This is suggested by higher reflectivities of the solid target at ≈ 10 torr and the reflected spectrum of the laser pulse. The reflected beam is seen to be blue shifted at the highest intensity, which is characteristic of the ionization of air. This blue shifting is not observed below the leveling off of the reflectivity. Further tests using the foil in millitorr backing pressure should help to illuminate this problem. The reflected spot is stable down to pressures of $\approx$ 50 torr. Below this pressure, bubbles begin to form near the outlet of the water jet and flow accross the film. A re-focused image, using an f=150 mm lens, of the reflected laser pulse is seen in Fig. 5. A white 3×14.5 cm ceramic plate was placed at a 45^o angle $\approx$ 3.5 cm from the point of reflection on the foil to collect the ejected debris. After $\approx$ 3000 shots, no visible debris can be seen on the plate. More tests will be conducted to determine whether or not the debris is an issue.

SUMMARY

Staging technology will define the total length of future LPA systems. Reducing the coupling distance of an LPA is critical in maintaining the high accelerating gradients which make LPAs attractive. a concept was explored that uses PMs as the final coupling optic for the laser. Both planar water jet and solid target PMs were investigated. A solid target makes operation at a high-vacuum easier and potentially better reflectivities, but planar water jets allow high repetion rate systems with minimal effort. The maximum reflectivity achieved using both types of PMs was 70%. It is possible that this reflectivity can be increased by reducing the backing pressure in the chamber. A differential pumping stage is being designed to reduce the amount of air that the laser must pass through before reaching the water jet. Tests with a solid target in millitorr backing pressure will be done to further test this idea. Using the water jet, re-focused images show that the reflected beam is similar to the input beam. Future tests should determine whether solid targets eject enough contaminants to damage optics in the LPA system preventing their use, though initial tests are promising.

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