Laser-plasma wakefield acceleration in tapered capillary discharge waveguides

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Abstract— Enhancing the electron bunch properties in a laser wakefield accelerator by tapering the longitudinal plasma density has been experimentally demonstrated. Comparison has been made between density (i) increasing with distance (positive taper), (ii) constant (no taper) and (iii) decreasing with distance (negative taper). All three produce narrow energy spread, low divergence electron bunches but a mean enhancement of 22% (from 205 MeV to 250 MeV) for the central energy is obtained with a positive taper. A negative taper exhibits improved pointing angle (0.4 mrad) and stability (1.7 mrad r.m.s.).

Keywords- Hot Particles, Radiation Dosimetry, EGSnrc, Monte Carlo, Imaging Photon Detector, Extrapolation Chamber, RadioChromatic Dye Film, Non-uniform Dose Distribution, Skin Dosimetry. Radiological Protection.

INTRODUCTION

The basis of the laser-plasma wakefield accelerator (LWFA) is the creation of a very large accelerating gradient (~1 GeV/cm) by a terawatt- or petawatt-scale laser pulse focused into underdense plasma and a wide variety of recent experiments have illustrated its potential for serving as ultra-compact next-generation sources of high energy particle and radiation beams [1,2]. Benchmark demonstrations include the first monoenergetic electron beams [3,4,5] generated in the 100-200 MeV range, 1 GeV monoenergetic electron beams [6] produced with a 40 TW laser, LWFA- driven undulator synchrotron radiation in the visible [7] and soft X-ray [8] spectral regions and LWFA-driven gamma-ray betatron radiation [9]. Two of these experiments [6,9] utilised as the accelerating medium a gas-filled capillary discharge waveguide (CDW) which supports operation at lower plasma density (n ~10^18 cm^-3), as compared with gas jets [3,4,5,7,11], thus leading to higher electron energies (n) [10]. Lower plasma densities are also supported in gas cells [8,12], that can simply be a CDW without the discharge, and plastic ablative CDWs [13,14], that are not as robust as sapphire or alumina gas-filled CDWs.

Future LWFA-based light source and collider user facilities will have less stringent laser requirements if the electron energy can be increased for a given laser power, for example, generating GeV energies suitable for driving an X-ray free-electron laser with a more compact, almost turn-key10 TW laser system. Energy gain in a homogeneous plasma is limited by dephasing (electrons out-running the accelerating phase of the wake and eventually losing energy) and the idea of introducing a longitudinal plasma density gradient (tapering) to offset dephasing has been around since the 1980s [15]. Theoretical studies have predicted significant energy increase [16,17] and, in this letter, we report on the first experimental confirmation of energy enhancement in a LWFA. Protection applications the International Commission on Radiological Protection ICRP recommends the use of a depth of 70 µm and the dose is averaged over an area of 1cm^2 [9-10] with a tapered plasma density (increasing with
distance. Implementing the taper has been achieved in gas-filled CDWs by applying a femtosecond laser micromachining production technique [18] and efficient laser pulse guiding has been confirmed at low intensity [19]. Previous ablative CDWs with a linear taper have been produced [20] but no acceleration studies have been reported. In addition to energy enhancement, significant reduction of beam pointing angle and stability is obtained for oppositely tapered density (decreasing with distance).

A Ti:sapphire laser pulse (energy = 800 mJ, full-width at half-maximum duration = 40 fs and wavelength \( \lambda_0 = 800 \text{ nm} \)) is focused to a (radius at 1/e\(^2\)) waist \( w_{0L} = 20 \text{ m} \) at the entrance plane of the capillary under investigation such that, initially, the power = 20 TW, intensity = 1.6 \( \times 10^{18} \text{ W/cm}^2 \) and normalized vector potential \( a_0 = eE/m_0c \) \( \alpha = 0.9 \) where \( E \) is the electric field strength, \( c \) is the speed of light in vacuum, \( e/m_0 \) and \( e \) and \( m_0 \) are the electron charge and rest mass respectively. Before the laser pulse enters the capillary, hydrogen gas is injected at a backing pressure of 140-200 mbar and an underdense plasma is formed by applying a22 kV, 900 ns voltage pulse between two electrodes located at either end of the capillary [22]. Measurement of a transient current pulse, peaking at ~300 A (in our case), is evidence of a high degree of ionization [23]. Thermal conduction to the capillary walls sets up a parabolic radial profile in the electron density distribution and laser diffraction can be exactly compensated by plasma lensing enabling efficient transport over several centimetres with little energy loss and excellent mode structure [24]. However, relativistic self-focussing and photon acceleration can still occur, thus helping to produce a trailing evacuated bubble into which electrons are injected from the background plasma.

Table 1 summarizes the properties of the pertinent CDWs that are labeled TP, S and TN respectively. In each capillary, an estimate of the on-axis density has been obtained with Raman spectroscopy of the transmitted laser pulse [25], as shown in Fig. 1(a) for capillary TP. In the case of tapered channels, this diagnostic provides the average (or midpoint) density, with the estimated start-to-end density change determined by the corresponding cross-section change [19]. The density values are consistent with Raman [25], interferometer [26,27], Stark-broadened spectroscopy [19,27] and betatron radiation [9] measurements obtained in similar CDW experiments.

Table 1. Diameter \( D \), taper rate \( = D/2L \), where \( D \) is the diameter change over length \( L (= 40 \) mm in each case) and measured on-axis plasma density \( n \) for each capillary type. The density tapers for types TP and TN are estimated from the respective taper rates.

<table>
<thead>
<tr>
<th>Name</th>
<th>TP</th>
<th>S</th>
<th>TN</th>
</tr>
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<tbody>
<tr>
<td>Taper</td>
<td>Positive</td>
<td>Zero</td>
<td>Negative</td>
</tr>
<tr>
<td>( D ) (( \text{m} ))</td>
<td>282</td>
<td>230</td>
<td>230</td>
</tr>
<tr>
<td>( = 10^{-4} )</td>
<td>6.25</td>
<td>0</td>
<td>8.0</td>
</tr>
<tr>
<td>( n ) (( 10^{18} \text{ cm}^{-3} ))</td>
<td>3.1 (2.5, 3.8)</td>
<td>3.5 - 5.7</td>
<td>3.6 (4.7, 2.8)</td>
</tr>
</tbody>
</table>
Guiding of high-power laser pulses in each capillary is comparable in terms of transmitted laser energy and mode structure. For our laser conditions, the entrance laser beam waist is less than the matched waist, \( w_{0m} \) \([\text{m}]\) \( \approx 1.48 \times 10^5 \frac{R_{we}^{1/2}}{[\text{m}]} / n^{1/4} [\text{cm}^3] \) where \( R_{we} \) is the entrance radius, that introduces a periodic oscillation in the transverse beam profile (scalloping) as it propagates along the waveguide [23]. In our case, \( w_{0m} \) \( 32-44 \text{ m} \) compared to \( w_{0l} = 20 \text{ m} \). Despite being far from the matched condition, however, reasonable energy transmission of \((67 - 10)\%\) is obtained for all three capillary types at the laser-discharge synchronization timing for best guiding [Fig. 1(b)], confirming that guiding is equally efficient in the presence of a density taper [19]. In each case, later timing results in reduced transmission of \((30 - 10)\%\) due to plasma wake formation and subsequent electron beam production [25].

At relativistic intensities, after initial waveguiding, electron beam propagation in a CDW is dominated by self-focusing, i.e., the waveguide influences the propagation only at the beginning of the interaction. This is evident in our observations that virtually no electron beam production was achieved in a larger diameter \((300 \text{ m})\) straight capillary, in agreement with other experiments in this laser intensity range [6, 24], nor in positively tapered capillaries with a similarly wide entrance diameter \((320 \text{ m} \text{ or } 305 \text{ m} \text{ or } 183 \text{ m})\). When the channel entrance is too wide, the initial beam diffraction is too great for subsequent self-focusing, strong wake generation and self-trapping of electrons. Furthermore, even the capillary type \( S \) with diameter \( 230 \text{ m} \) struggled to self-inject at lower plasma densities, hence, the density was typically increased (Table 1) to facilitate injection in this capillary.

The beam profile of electron beams exiting each capillary have been captured on a Lanex screen located \(0.6\text{ m}\) downstream and imaged by a charged-coupled device (CCD) camera. Table 2 summarizes the beam relative charge, divergence and pointing behavior collected in large data sets. The relative charge data collected on this uncalibrated screen, that also contain the low energy tail, are consistent with absolute charge measurements for the high energy bunches (see later). Most charge was injected into the bunch, on average, in the capillary TP. Perhaps the positive density gradient favors greater laser self-focusing.
Table 2. Beam profile data giving the mean (minimum) electron beam relative charges
Q_{rel}, r.m.s. divergences \( \theta \) and pointing angles \( \phi \) in the vertical Y and horizontal X planes respectively for each capillary type where each uncertainty is the r.m.s. standard deviation.

<table>
<thead>
<tr>
<th>Name</th>
<th>TP</th>
<th>S</th>
<th>TN</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of shots</td>
<td>88</td>
<td>68</td>
<td>100</td>
</tr>
<tr>
<td>Mean ( Q_{rel} ) [a.u.]</td>
<td>2.6 ± 4.8</td>
<td>0.5 ± 0.4</td>
<td>1.5 ± 2.1</td>
</tr>
<tr>
<td>Mean (Min.) ( \theta_Y ) [mrad]</td>
<td>3.3 ± 2.0 (0.8)</td>
<td>1.6 ± 0.9 (0.7)</td>
<td>2.1 ± 1.7 (0.6)</td>
</tr>
<tr>
<td>Mean (Min.) ( \theta_X ) [mrad]</td>
<td>3.5 ± 2.5 (0.9)</td>
<td>1.8 ± 1.2 (0.7)</td>
<td>1.5 ± 1.1 (0.5)</td>
</tr>
<tr>
<td>Mean ( \phi_Y ) [mrad]</td>
<td>-2.3 ± 6.6</td>
<td>-19 ± 10</td>
<td>-0.4 ± 2.1</td>
</tr>
<tr>
<td>Mean ( \phi_X ) [mrad]</td>
<td>2.0 ± 7.6</td>
<td>9.0 ± 13</td>
<td>0.3 ± 1.3</td>
</tr>
</tbody>
</table>

As shown in Fig. 2(a), the mean beam r.m.s. divergence for each is in the range 1.3-3.3 mrad with the best shots less than 1 mrad, down to just 0.5-0.6 mrad for capillary TN. The divergence scales proportionately with the charge [21] which accounts for the larger divergence for capillary TP while the similar mean divergences for lower charge S and TN data indicate a lower intrinsic limit for the divergence and, thus, the transverse emittance, has been reached. Assuming a source size of 2-3 \( \mu \)m, the minimum normalized transverse emittance is estimated to be \( \sim 0.5 \mu \)m mrad, consistent with pepper-pot emittance measurements in a gas jet accelerator that showed detection resolution-limited values of 1.1 \( \pi \) mm mrad [21].

Figure 2(b) illustrates the large differences in pointing angle and stability between the capillary types. Capillary S suffered from both a large angle and poor stability which may be a product of this accelerator operating extremely close to the injection threshold (one third of shots producing no electrons, all other shots with little charge). The highest quality capillary in terms of close-to-axis pointing angle (0.3-0.4 mrad in both axes) and smallest pointing fluctuations (just 1.3 mrad in the horizontal axis) was type TN. This may be related to the negative longitudinal plasma density gradient driving an increase in the accelerating bubble size as the interaction evolves.
FIG. 2 (color online). (a) Example images of the beam profile and (b) pointing distribution for each capillary type (TP: red closed circle, S: blue triangle, TN: black open circle). The beam line axis is indicated by a white cross and the origin respectively.

Electron energy spectra have been obtained by transporting the electrons through a triplet of electromagnetic quadrupole magnets (each of field strength 120 mT) and an imaging magnetic dipole spectrometer (field strength $B_{ES} = 0.91-1.25$ T) [12]. A Ce:YAG crystal located at focal plane of the spectrometer is imaged with a CCD camera. The acceptance angle for the quadrupoles aperture is 8 mrad therefore the beam pointing (Table 2) impacts on the number of shots that are successfully captured in the electron spectrometer. The energy spectrum measurements are summarized in Table 3 for shots showing a discernable electron bunch of finite energy spread, with type TN (best pointing angle and Monoenergetic electron bunches with narrow energy spread are obtained in all three capillary types [Fig. 3(a)]

The bunches. In agreement with theory [15,16,17], positive tapering TP produces an energy enhancement (22% in the mean central energy of the electron bunch) with respect to capillary S. This behavior is reflected in the smaller converse energy reduction (~10% with respect to type S) obtained with negative tapering TN. Note that most of the type S data was acquired at the higher end of its applied density range ($\sim 5.7 \times 10^{18}$ cm$^{-3}$) where injection was relatively easier while in the density range directly comparable to the other capillary types ($\sim 3.5 \times 10^{18}$ cm$^{-3}$) no significant electron energy increase was observed. Comparing types TP and TN, the energy difference is apparent despite the respective densities being very closely matched.

The highest central energy for type TP was 290 MeV with upper electron energy of 320 MeV (Fig. 3(a)]. The energy enhancement obtained (20-40%) for a positive taper compares well with an analytical model [17] predicting ~100-300% gain for a linearly tapered accelerator when one compares the respective taper rates ($0.33 \times 10^{18}$ cm$^{-3}$/cm in our experiment, $3.5 \times 10^{18}$ cm$^{-3}$/cm in the model). This is despite that model being solely for single particle acceleration, neglecting effects like laser pump depletion and self-focusing. Experimentally, therefore, type TP also represents a gentle taper rate and further optimisation of the micromachining manufacturing process [18] should increase the taper rate while still facilitating self-injection. Nevertheless, these results demonstrate
the success of applying a positive longitudinal plasma density gradient to boost the final electron energy.

**Table 3.** Energy spectrum data giving the mean (maximum) electron bunch charge \( Q \), central energy \( E \) and measured absolute energy spread \( \sigma_{\text{MEAS}} \) and the minimum measured relative energy spread \( \sigma_{\text{MEAS}}/\gamma \) of the electron bunch for each capillary type where each uncertainty is the r.m.s. standard deviation.

<table>
<thead>
<tr>
<th>Name</th>
<th>Number of shots</th>
<th>TP</th>
<th>S</th>
<th>TN</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean (Max.) ( Q ) [pC]</td>
<td></td>
<td>2.6 ± 2.3 (6.6)</td>
<td>0.2 ± 0.1 (0.3)</td>
<td>1.3 ± 1.1 (5.1)</td>
</tr>
<tr>
<td>Mean (Max.) ( E ) [MeV]</td>
<td></td>
<td>250 ± 25 (290)</td>
<td>205 ± 5 (211)</td>
<td>184 ± 17 (229)</td>
</tr>
<tr>
<td>Mean (Min.) ( \sigma_{\text{MEAS}} ) [MeV]</td>
<td></td>
<td>14 ± 8 (3.3)</td>
<td>4 ± 1 (2.0)</td>
<td>13 ± 5 (4.8)</td>
</tr>
<tr>
<td>Min. ( \sigma_{\text{MEAS}}/\gamma ) [%]</td>
<td></td>
<td>1.6</td>
<td>1.0</td>
<td>2.6</td>
</tr>
</tbody>
</table>

**FIG. 3** (color online). (a) Example images of the energy spectrum and (b) absolute energy spread dependence on charge for each capillary type (TP: red closed circle, S: blue triangle, TN: black open circle). Electron spectrometer \( B_{\text{ES}} = 1.25 \) T except for type TN where \( B_{\text{ES}} = 0.91 \) T. Inset is the corresponding simulated r.m.s. spectrometer resolution \( R \) for each capillary calculated as a function of divergence \( \theta \) at the respective mean central energy values.

The dependence of the measured absolute energy spread on the charge is shown in Fig. 3(b) with all three capillary types conforming to the same overall dependence. Very low charge bunches arising from very low injection volumes lead to the smallest energy spreads [28] while, at higher charge, beam loading effects [29] may also act to broaden the energy spectrum.
The narrowest measured bunch r.m.s. relative energy spreads are in the range 1-2% (determined solely for that bunch and ignoring lower energy bunches or pedestals). Beam line simulations using the General Particle Tracer code [30] indicate that the electron spectrometer resolution is also in the 0.5-2.5% range for the typical bunch properties observed in experiment [inset of Fig. 3(b)]. Therefore, the narrowest spread bunches for types TP and S have been strongly convoluted by the detection system response and the true minimum energy spread is less than 1%, as has been observed for gas jet accelerators driven either by single [12] or colliding [28] laser pulses.

REFERENCES