Laser Wakefield Acceleration

Pioneering Studies Conducted by the Lasers, Optical Accelerator Systems Integrated Studies (L’OASIS) Program at Lawrence Berkeley National Laboratory

Derek Schaeffer
Advanced Optics, Physics 545
Professor Sergio Mendes
Contents

<table>
<thead>
<tr>
<th>Subsection</th>
<th>Page #</th>
</tr>
</thead>
<tbody>
<tr>
<td>Introduction</td>
<td>3</td>
</tr>
<tr>
<td>Technical Challenges</td>
<td>3</td>
</tr>
<tr>
<td>Plasma Acceleration</td>
<td>4</td>
</tr>
<tr>
<td>Gas-filled Capillary Discharge Waveguide</td>
<td>5</td>
</tr>
<tr>
<td>Future Developments</td>
<td>6</td>
</tr>
<tr>
<td>Applications</td>
<td>6</td>
</tr>
<tr>
<td>Bibliography</td>
<td>6</td>
</tr>
</tbody>
</table>
Introduction

Laser wakefield acceleration is a method of particle acceleration, where a laser pulse is sent through a gas inducing a plasma which then allows free electrons to follow the wake of the plasma wave which was created by the laser pulse. This method is used in contrast to beam-driven wakefield acceleration where an electron beam induces a plasma wake. Current studies in the United States for beam-driven wakefield acceleration are now being carried out at the Stanford Linear Accelerator (SLAC) in California.[1]

Motivation for wakefield acceleration stems from the demand for larger synchrotron accelerators in order to achieve higher energy particle acceleration necessary for the study of particle physics. Currently, the largest synchrotron in the world is the Large Hadron Collider (LHC) located in Switzerland. The LHC is 27 km (17 miles) in circumference and capable of proton acceleration up to 7 TeV.[2-3]

Beam-driven wakefield acceleration has attained 42 GeV over a distance of 85 cm, while laser wakefield acceleration has achieved 1 GeV over 3.3 cm. Current studies in laser wakefield acceleration are being carried out at the Lasers, Optical Accelerator Systems Integrated Studies (L’OASIS) Program at Lawrence Berkeley National Laboratory. The relative compactness of laser wakefield acceleration systems makes them ideal for future particle acceleration systems. This paper discusses the science of laser wakefield acceleration in detail.[1]

Technical Challenges

Particle acceleration in a wakefield is limited to the length by which the laser interacts with a plasma, which is the Rayleigh length of the laser. The Rayleigh length is the distance over which the laser remains focused, and is given by[4]:

$$Z = \frac{\pi w_0^2}{\lambda}$$

where $w_0$ is the beam waist and $\lambda$ is the wavelength of the laser. The total depth of focus for a laser is $2Z$.[5]

Another limiting factor is the dephasing length, given by:

$$L_d = \frac{\lambda_p}{\lambda} \propto n_p$$

where $\lambda_p$ is the plasma wavelength, $\lambda$ is the laser wavelength, and $n_p$ is the plasma density in cm$^3$. The dephasing length is the distance where electrons begin to outrun the plasma wake and start to decelerate.[6]
An estimation of electron energy gain may be given by:

\[ W \propto \frac{0.4I}{\omega_p} \propto 0.9 \left( \frac{\lambda_p}{2\omega_p} \right)^5 P \]

where \( W \) has units of GeV, \( I \) is the laser intensity in Wcm\(^2\), and \( P \) is the peak laser power given in terawatts (TW).[6]

These limitations suggest that GeV energy gains could be obtained by increasing the spot size (2\(\omega_{1,0}\)) using petawatt laser energies. A more efficient approach involves channeling smaller spot sizes over centimeter distances, then limiting acceleration to the dephasing length. Extending the dephasing length is then accomplished using lower plasma densities.[6]

**Plasma Acceleration**

The plasma has the property of being denser at the edges and less dense at the center in the case of the plasma channel. This principle is similar to that of optical fibers, where the center has a higher index of refraction and the surrounding glass has a lower index of refraction. The effect is that the wavefront moves slower through the center than at the edges of the plasma. This flattens the spherical laser wavefront, allowing the laser to maintain its spot size over a longer distance in order to create large plasma waves.[4]

As the laser pulse travels through the plasma, the electric field of the light separates the electrons and nucleons causing charge separation. As the laser pulse leaves the medium, the electrons are pulled back towards the center where the positive charge now remains, causing these electron bunches to accelerate. This action appears to create a “bubble” of positive charge behind the laser pulse moving at nearly the speed of light, which is followed by a region of negative charge where the electrons have converged towards the center. This in turn creates a very strong potential gradient following the laser pulse. A particle introduced to the high-density center of the plasma will then feel acceleration either toward or away from it, which continues until the particle reaches the speed of the plasma wakefield.[7]

An earlier method of wakefield acceleration involved the “igniter-heater” technique using a gas jet. With this method an *igniter* pulse is sent through the gas, to form a “wire” of plasma. A *heater* pulse enters from the side and heats the plasma wire, giving the plasma wire the proper density distributions. Five hundred picoseconds later, time enough for the ions to move out of the way, an intense *driver* pulse is sent through the plasma to induce a plasma wake for particle acceleration.[4, 6]
The “igniter-heater” technique proved to be limited to 100 MeV particle energies because the method of plasma heating was inefficient for the necessary low-density plasmas. To address this problem, a gas-filled capillary discharge waveguide was developed.[6]

Gas-filled Capillary Discharge Waveguide

The capillary is made by laser-machining two halves of sapphire which are fixed together to form a 3.3 cm tube. Hydrogen gas flows into the tube through slots which then fills it. A high voltage discharge across the capillary then turns the hydrogen gas into plasma, and a laser pulse may then be introduced to the capillary to create wakefield acceleration.[6]

The experimental setup at L’OASIS uses a Ti-sapphire laser system with a 10 Hz repetition rate, at λ = 810 nm with 40 fs pulses at full-width half-maximum (FWHM) up to 40 TW of peak power. These pulses have spot sizes of $2\omega_0 = 25 \mu m$ at the capillary entrance.[6]

With pulses of 12 TW, a plasma density of $3.5 \times 10^{18} \text{ cm}^{-3}$ and a capillary 225 $\mu$m in diameter, beams of 0.48 GeV were created with an energy spread of less than 5% rms. For a capillary diameter of 310 $\mu$m and power pulse of 40 TW with plasma density $4.3 \times 10^{18} \text{ cm}^{-3}$, a 1 GeV beam with spread of 2.5% rms is created but with less reliable performance. Future improvements to performance may be accomplished by electron injection into the plasma wake.[6]
Future Developments

Current work is underway to build a new laser wakefield accelerator called the Berkeley Lab Laser Accelerator (BELLA), which may be operational in 2013. The goal of the BELLA program is to develop a 10 GeV module based on the gas-filled capillary waveguide. Multiple 10 GeV modules could then be put together and energies of 1 TeV or greater could be accomplished in only a few hundred meters, compared to 7 TeV in 27 km as in the case of the Large Hadron Collider.[2, 8]

Applications

Creating GeV electron beams from cm-scale devices proves to be ideal as an adjustable pulsed radiation source, with a frequency range from X-ray to THz.[6] This makes it ideal for research in such areas as material science, biology, chemistry, environmental science, or archaeology. The technology could potentially end up in hospitals as well. [1]

Particle accelerators such as BELLA may eventually help investigate cosmological particle acceleration, such as ultra-high-energy cosmic rays with energies on the order of $10^{20}$ eV. BELLA could also help verify the theory of quantum electrodynamics at high energies.[1, 8]

Bibliography

2. Group, C.C., CERN FAQ. 2008, CERN.