Laser-Plasma Accelerator Developments in Japan

Kazuhisa Nakajima*
High Energy Accelerator Research Organization Ibaraki, Japan

In a state of the art of ultra-intense lasers, the highest laser intensities reach a TeV range in terms of the ponderomotive energy exerted on matter. This implies that a forefront of high energy particle physics phenomena may be revealed with super-strong laser-matter interactions. The recent status of laser wakefield accelerator (LWFA) experiments proceeded at JAERI-APR are presented to accomplish high energy gains of the order of GeV with the high quality electron beam injector. A new concept of super high energy particle acceleration mechanism based on super-strong laser-plasma interactions is presented, named as “Dirac accelerator.”

1. GeV Laser Accelerator Developments at JAERI-APR

As an intense laser pulse propagates through an underdense plasma, the ponderomotive force expels electrons from the region of the laser pulse. This effect excites a large amplitude plasma wakefield with phase velocity approximately equal to the group velocity of laser pulse, given by

\[ v_g = c \left(1 - \frac{\omega_p^2}{\omega^2}\right)^{1/2}, \]

where \( \omega_p \) is the electron plasma frequency, \( n_e \) is the ambient electron plasma density and \( \omega \) is the laser frequency. The maximum axial wakefield occurs at the plasma wavelength, \( \lambda_p \approx 0.57 \tau \) in a plasma with the resonant electron density, \( n_e \approx 3.5 \times 10^{21}/\tau^2 \) in terms of a FWHM pulse duration \( \tau \) [fs]. When a Gaussian driving laser pulse with the peak power \( P \) [TW] is focused on the spot size \( r_0 \) [\um], the maximum axial wakefield yields

\[ (eE_z)_{\text{max}} [\text{GeV/m}] \approx 8.6 \times 10^4 P \lambda^2 / (\tau r_0^2 y_L), \]

where \( y_L = (1 + a_0^2/2)^{1/2} \) takes account of nonlinear relativistic effects, and \( a_0 = 6.8 \lambda P^{1/2}/r_0 \) is the laser strength parameter for the linear polarization [1].

Several effects limit the energy gain in a single-stage of laser-plasma accelerators; laser diffraction, electron dephasing, pump depletion and laser-plasma instabilities. In order to achieve the acceleration energy gains of higher than 1 GeV in a single stage with a cm-scale length, it is necessary to extend the acceleration length limited by diffraction effects of laser beams. We develop the channel-guided LWFA in which both the driving laser pulses and particle beams can be guided

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value 1</th>
<th>Value 2</th>
<th>Value 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy gain [GeV]</td>
<td>0.5</td>
<td>1</td>
<td>10</td>
</tr>
<tr>
<td>Pulse duration ( \tau ) [fs]</td>
<td>20</td>
<td>50</td>
<td>100</td>
</tr>
<tr>
<td>Peak power [TW]</td>
<td>100</td>
<td>40</td>
<td>20</td>
</tr>
<tr>
<td>Spot radius [\um]</td>
<td>30</td>
<td>20</td>
<td>10</td>
</tr>
<tr>
<td>Laser strength parameter</td>
<td>1.8</td>
<td>1.7</td>
<td>2.4</td>
</tr>
<tr>
<td>Plasma density ( [10^{18} \text{ cm}^{-3}] )</td>
<td>8.8</td>
<td>1.4</td>
<td>0.35</td>
</tr>
<tr>
<td>Accelerating gradient [GeV/cm]</td>
<td>1.9</td>
<td>0.7</td>
<td>0.55</td>
</tr>
<tr>
<td>Diffraction length [cm]</td>
<td>1.1</td>
<td>0.5</td>
<td>0.12</td>
</tr>
<tr>
<td>Dephasing length [cm]</td>
<td>0.4</td>
<td>5.5</td>
<td>56</td>
</tr>
<tr>
<td>Channel length [cm]</td>
<td>no</td>
<td>1.5</td>
<td>20</td>
</tr>
</tbody>
</table>

*Electronic address: nakajima@post.kek.jp
through Z-pinch capillary discharge plasmas with a cm-scale length. The parameters to test electron acceleration of GeV energies are shown in Table I. The designs of the LWFA are based on availability of the 10 Hz table-top ultrashort, ultrahigh peak power Ti:Sapphire laser pulses with duration of 20 fs and energy of 2 J developed at JAERI-APR [2].

In order to produce a high quality electron beam with low momentum spread and small pulse-to-pulse energy stability, it is required that femtosecond electron bunches should be injected with the energy higher than trapping threshold and femtosecond synchronization with respect to an accelerating phase space of the wakefield, which is typically less than 100 fs in a longitudinal scale and 10 µm in a transverse size. For this purpose, we have developed the laser acceleration test facility at JAERI-APR, which can deliver a high quality electron beam consisting of a photocathode RF gun and a compact race-track microtron [3], and a femtosecond bunch generation system. The microtron accelerates a low emittance beam injected from photocathode RF gun at 4 MeV to 150 MeV after 25 turns. The beam injector generates a 150 MeV single electron bunch at 10 Hz with a charge of 95 pC, that is the transmission efficiency of 80% after 25 turns. The normalized beam emittance is as low as < 5π mm · mrad and the bunch width is as short as < 10 ps in FWHM.

We have conceived a method capable of generating a femtosecond electron pulse injected into a correct wakefield phase within a few femtoseconds. Generation of femtosecond electron pulses with femtosecond synchronization is based on slicing a bunch through a process of energy modulation created in the interaction of electrons with a femtosecond laser pulse split from a main pump pulse. A scheme of femtosecond bunch-slicing is shown in Figure 1.

The optical guiding of a laser pulse can be made through the plasma density channel with a parabolic electron-density profile. We have developed a stable cm-scale plasma channel produced by an imploding phase of fast Z-pinch discharge in a gas-filled capillary without wall ablation [4]. The Z-pinch capillary discharge system has been assembled from the Marx generator and the water capacitor with four laser trigger spark gaps. This system can generate a 10 cm long capillary discharge in a diameter of 1 mm driven by 100 kA current without time jitter.

2. New Ultrahigh Energy Acceleration Concept

The ponderomotive potential scattering results in acceleration of electrons via a point-like interaction with the strong laser fields. This acceleration length will be at most a half of the laser pulse length when the reflection condition is satisfied:

$$ y' = y^* y_0 (1 - \beta_0 \beta^*) \leq y_L = (1 + a_0^2 / 2)^{1/2}, $$

where $y^* = (1 - \beta^{*2})^{-1/2}$, $\beta^* = v_g / c$, and $y_0$ and $\beta_0$ are the initial energy and velocity of the particle, respectively. The scattering occurs at the point where $y' = y_L$. In this regime the ponderomotive scattering off the laser pulse works as particle acceleration mechanism which we
Figure 2: (a) The required laser field $a_0$ and intensity $I$, and (b) the Lorentz factor $\gamma^*$ corresponding to the required group velocity and the corresponding plasma density for the electron acceleration from the injection energy $E_{inj} = 150$ MeV to the GeV range of the final energy.

call as “Dirac Accelerator.” Let us consider the acceleration of the electron from the injection energy $y_0$ to the accelerated final energy $\gamma$ via the ponderomotive interaction with the laser field in a plasma with the density $n_e$. The required group velocity, the corresponding Lorentz factor of the laser pulse and the ponderomotive energy of the laser field are

$$\beta^* = \frac{y_0 \beta_0 + y \beta}{y_0 + y}, \quad \gamma^* = \frac{y_0 + y}{\sqrt{2[1 + y y_0(1 - \beta \beta_0)]^{1/2}}}, \quad \gamma_L = \left[\frac{1 + y y_0(1 - \beta \beta_0)}{2}\right]^{1/2}. \quad (3)$$

Figure 2 shows (a) the required laser field and intensity, and (b) the Lorentz factor corresponding to the required group velocity and the corresponding plasma density for the electron acceleration from the injection energy $E_{inj} = 150$ MeV to the GeV range of the final energy. The laser pulse with the ponderomotive energy $\gamma_L$ can accelerate an electron with the initial energy $y_0$ up to the maximum final energy $\gamma_{max}$ given by

$$\gamma_{max} = 2 \gamma_L^2 y_0 (1 + \beta_0 \beta_L) - y_0 \quad (4)$$

For super high energy acceleration, these parameters are approximately given as

$$\gamma_L \approx (y/4 y_0)^{1/2}, \quad \gamma^* \approx (y y_0)^{1/2} \approx y/2 y_L, \quad y_0 \approx y/4 y_L^2 \approx \gamma^{*2}/y. \quad (5)$$

The Dirac accelerator makes it possible to accelerate electrons up to 1 PeV ($\gamma \approx 2 \times 10^9$) energy provided with the injection energy 250 MeV ($y_0 \approx 500$), the plasma density $n_e \approx 1.1 \times 10^9$ cm$^{-3}$ ($\gamma^* \approx 10^9$), and the laser intensity $2.7 \times 10^{24}$ W/cm$^2$ ($\gamma_L \approx 1000, a_0 \approx 1414$) for the wavelength $\lambda_L = 1$μm. This laser intensity can be produced by focusing $\sim 400$ PW on the spot radius $r_0 = 3$μm.

3. Conclusions

We have made developments of the high quality beam injector consisting of the photocathode RF gun and the 150 MeV microtron and the 2 cm plasma waveguide using the fast Z-pinch capillary discharge to achieve GeV range electron acceleration by LWFA using the 100 TW, 20fs, 10 Hz laser at JAER-APR. In addition to these experimental achievements, we will construct the femtosecond bunch slicing stage as a part of the laser acceleration test facility to generate a femtosecond electron pulse injected into laser wakefields with femtosecond accuracy.

In the ultra-relativistic regime of the laser intensity, the ponderomotive scattering results in particle acceleration in plasmas, which is called as Dirac accelerator based on the strong field-particle point-like interaction different from classical acceleration mechanism such as RF accelerators and LWFA. The Dirac accelerators can accelerate electrons up to PeV range energies with the laser intensity $> 10^{24}$ W/cm$^2$ in a point-like interaction.
References