DESIGNING OF THE LASER DRIVEN DIELECTRIC ACCELERATOR

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Requirements

Electron / X-ray is much easier to make the compact source.

Energy deposition; LET (linear energy transfer) \( e/x < \) ion
\[ \text{LET(keV/µm)} < 1 ; > 100 \]

The beam size (irradiation area) is smaller than 1 µm.

The charge is 0.01 fC to 0.1 fC. \( \approx 10^2 - 10^3 \) electrons/µm²

The beam energy is several tens keV to 1 MeV.

The pulse width is sub fs. \( (\mu^3\text{-bunch}) \)

The exit of the accelerator and specimen are observed through the transparent window.

A laser-driven dielectric accelerator, i.e. photonic crystal accelerators, makes it possible to realize a tabletop/mobile system.
Structures of PCA

Phase Modulation Masked Structure

Silica, $\lambda=800\text{nm}$, $E_z=830\text{ MV/m}$


Wave Guiding Structures

Silica, $\lambda=1890\text{ nm}$, $E =400\text{ MV/m}$


Silicon, $\lambda=2200\text{nm}$, $E_z=400\text{ MV/m}$

Alternate Direction of the Field is Produced by the Optical Path-difference

Polarization

Laser pulse

Electric field of the laser

E-field on the axis

Fave front

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If the initial electron is non-relativistic, the grating constant must be gradually changed from small value to the laser wavelength.

\[
L_G = 2L_P
\]

\[
\frac{H_P}{\lambda_L} = \frac{1}{2(n-1)}
\]

\[
D \leq \frac{2L_P^2}{N\lambda_L}
\]

\[
L_G \leq \lambda_L
\]

\[
\frac{\nu_0}{c} = \frac{L_G}{\lambda_L}
\]
\[ L_G = 2L_P \]
\[ \frac{H_P}{\lambda_L} = \frac{1}{2(n-1)} \]
\[ D \leq \frac{2L_P^2}{N\lambda_L} \]
\[ L_G \leq \lambda_L \]
\[ \nu_0/c = L_G/\lambda_L \]

If the initial electron is non-relativistic, the grating constant must be gradually changed from small value to the laser wavelength.

In a real situation, the refractive and interference effects deform the field structure. The asymmetry of the field, higher harmonics of the field relaxes the matching condition.

Numerical simulation

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FDTD-simulation

FDTD (Finite-Difference Time-Domain method) simulation software package developed at MIT to model electromagnetic systems.

http://ab-initio.mit.edu/wiki/index.php/Meep

Intensity of the laser pulse; \( I_L = 10^{13} \text{W/cm}^2 \) (8.7GV/m) on entrance surfaces of dielectric.
Laser wavelength; \( \lambda_L = 1.55 \text{μm} \).
Channel width; \( D = \lambda/4 = 0.39\text{μm} \).
Pillar height; \( (H_p = 0.9\lambda = 1.5\text{μm}) \) varied.

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Field strengths in $xt$-space for different grating constants

\[ E_{\text{acc}} = \frac{1}{L} \int_0^L E_x(x, t) \, dx \]
\[ x = vt + x_0 \]
Acceleration field along the axis

Field strengths in $xt$-space for different grating constants

\[ E_{acc} = \frac{1}{L} \int_0^L E_x(x, t) \, dx \]

\[ x = vt + x_0 \]

very sensitive to the initial phase of the injection

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Optimum Pillar Height

$I_{th}=10^{13}$ W/cm$^2$ (1 J/cm @ 100fs) ; $E_{th}= 8.7$ GV/m is assumed.

$\lambda_L = 1.55 \mu$m
$L_G = 1.55 \mu$m

$L_p/L_G = 0.6$
$L_p/L_G = 0.5$
$L_p/L_G = 0.4$

$I_{th} = 10^{13}$ W/cm$^2$ (1 J/cm @ 100fs) ; $E_{th} = 8.7$ GV/m is assumed.

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Optimum Pillar Height

$I_{th} = 10^{13} \, \text{W/cm}^2 \, (1 \, \text{J/cm} @ 100\text{fs}) \, ; \, E_{th} = 8.7 \, \text{GV/m} \, \text{is assumed.}$

$Optimum \, parameters \, of \, the \, structure \, are \, L_p/L_G \approx 0.5 \, \text{and} \, H_p/\lambda_L \approx 0.9.$

$\lambda_L = 1.55 \, \mu m \, \text{and} \, L_G = 1.55 \, \mu m$
Acceleration from the low energy in the constant grating period

\[ \frac{L_G}{\lambda_L} = 1.0 \]

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Acceleration from the low energy in the constant grating period

Slow electron can be accelerated even if the period is constant.

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Acceleration from the low energy in the constant grating period

Slow electron can be accelerated even if the period is constant.

Acceleration field is very sensitive to the injection phase.

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Laser intensity = $10^{13}$ W/cm² ($E = 8.7$ GV/m)
Laser intensity = $10^{13}$ W/cm$^2$ (E = 8.7 GV/m)

Accel. length to get 1 MeV,
3 mm for $E_0 = 10$ keV
2.2 mm 70 keV
<table>
<thead>
<tr>
<th>Parameters</th>
<th>Expression</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Accelerator Length</td>
<td>$L_A$</td>
<td>3 mm</td>
</tr>
<tr>
<td>Channel width</td>
<td>$W$</td>
<td>0.1 mm</td>
</tr>
<tr>
<td>Irradiation Area (per side)</td>
<td>$A = W L_A$</td>
<td>$3 \times 10^{-3} \text{cm}^2$</td>
</tr>
<tr>
<td>Laser Intensity (damage threshold)</td>
<td>$I_{th}$</td>
<td>$10^{13} \text{ W/cm}^2$</td>
</tr>
<tr>
<td>Two sides irradiation</td>
<td>Laser Power (total)</td>
<td>$P_L = 2P_{th}A$</td>
</tr>
<tr>
<td></td>
<td>Pulse width</td>
<td>$\tau_L = L_A/v_{eff}$</td>
</tr>
<tr>
<td></td>
<td>Energy (total energy)</td>
<td>$E_L = P_L\tau_L$</td>
</tr>
</tbody>
</table>

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In order to decrease the laser energy, the laser pulse must locally irradiate around the electron bunch.
### Accelerator and Laser Parameters

<table>
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<td>Accelerator Length</td>
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<td>$W$</td>
</tr>
<tr>
<td>Irradiation Area (per side)</td>
<td>$A = W \cdot L_A$</td>
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<td>Energy (total energy)</td>
<td>$E_L = P_L\tau_L$</td>
</tr>
<tr>
<td>Number of Pulses (one side)</td>
<td>$N$</td>
</tr>
<tr>
<td>Laser Power per Pulse</td>
<td>$P_{L,N} = P_L/N$</td>
</tr>
<tr>
<td>Pulse Width</td>
<td>$\tau_{L,N} = \tau_L/N$</td>
</tr>
<tr>
<td>Energy (total) (per pulse)</td>
<td>$E_{L,N} = E_L/N$</td>
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<tr>
<td>Pulse Width</td>
<td>$\tau_{L,N} = \tau_L/N$</td>
</tr>
<tr>
<td>Energy (total) (per pulse)</td>
<td>$E_{p,N} = E_L/2N^2$</td>
</tr>
</tbody>
</table>

- **1 MeV**
  - Accelerator Length: 3 mm
  - Channel width: 0.1 mm
  - Irradiation Area (per side): $3 \times 10^{-3} \text{cm}^2$
  - Laser Intensity (damage threshold): $10^{13}$ W/cm$^2$
  - Laser Power (total): 60 GW
  - Energy (total): 3 J
  - Number of Pulses (one side): 10
  - Laser Power per Pulse: 3 GW
  - Pulse Width: 50 ps
  - Energy (total) (per pulse): 1.5 mJ
Sketch of a fiber-laser-pumped accelerator

Optical microscope

Oscillator
Phase shifters
Amplifiers

Fiber laser

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Sketch of a fiber-laser-pumped accelerator

- Oscillator
- Phase shifters
- Amplifiers
- Fiber laser

Thin window
SiN; 10 - 100 nm thick
Capacity of the dish; < 1 ml

atmospheric pressure
vacuum

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1. The deformation of the wavefront in the phase-modulation-masked-type accelerator relaxed the matching condition. The slow electron to be accelerated even under the geometry of $L_G=\lambda_L$.

2. The electron initially at the low energy of 20 keV felt the acceleration field strength of 20 MV/m and gradually felt higher field as the speed was increased. The ultra relativistic electron felt the field strength of 600 MV/m.

3. Restrictions on the laser is relaxed by adopting sequential laser pulses. The required laser power is estimated to be 3 GW/pulse when ten pairs of sequential laser pulse is irradiated.