Numerical study of dielectric laser acceleration of nonrelativistic electrons with colonnade structure

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Outline

• Background

• Simulations for DLA

• Experiment plan

• Conclusion
DLA: a compact accelerator concept

Conventional RF linac

Metal, Microwave

Gradient: 100 MV/m

Dielectric laser accelerator

Dielectric, laser

Gradient: GV/m
DLA for radiobiology research

Study the effect of low-dose radiation on the damage process of a living cell.

<table>
<thead>
<tr>
<th></th>
<th>Beam energy</th>
<th>Beam size</th>
<th>Charge per bunch</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hela cell</td>
<td>1 MeV</td>
<td>&lt; 0.5 μm</td>
<td>~0.03 fC</td>
</tr>
<tr>
<td>Kr ion radiation</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Yellow: Ion tracks</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Blue: DNA</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>


Proposed DLA structures

T. Plettner, 2006
E. A. Peralta, 2013

X. Lin, 2001
Robert J. Noble, 2011

B. M. Cowan, 2008
Z. Wu, 2016

K. J. Leedle, 2015
C. M. Chang, 2014
A. Ceballos, 2016

A. Mizrahi, 2004
J. McNuer, 2012
Colonnade structure DLA

Silicon material
Easier fabrication
High gradient
Low skew

\[
E_z = C_s \sinh(k_y y) + C_c \cosh(k_y y) \sin(\theta)
\]

\[
\theta = k_z z - \omega_0 t + \varphi
\]

\[
E_{z,d} = C_d e^{y/\Gamma} \sin(k_z z - \omega_0 t + \varphi)
\]

\[
E_{z,u} = C_u e^{-y/\Gamma} \sin(k_z z - \omega_0 t + \varphi)
\]
Field simulation with CST

Longitudinal field $E_z / E_0$

$E_0$: peak electric field of incident laser

- $E_z$ on electron

50 keV Electron

Laser, 1550 nm

Vacuum

Si

Open Boundary

Periodic Boundary

$W_p ightarrow$

$640$ nm

$640$ nm

$0.0$

$1.6$

$310$ nm

$310$ nm

$310$ nm

$310$ nm

$310$ nm

All harmonics

$\pi$

$\pi$

$\pi$

$-1.6$

$50$ keV Electron

$E_z$ on electron

$E_0$: peak electric field of incident laser
Field along beam axis

\[ F = e \begin{bmatrix} E_y(y, z, t) + nB_x(y, z, t) \\ E_z(y, z, t) \end{bmatrix} = \begin{bmatrix} 0 \\ -\frac{1}{\gamma} \left[ C_s \cosh(k_y y) + C_c \sinh(k_y y) \right] \cos(\theta) \\ [C_s \sinh(k_y y) + C_c \cosh(k_y y)] \sin(\theta) \end{bmatrix} \]

\( E_0 \): peak electric field of incident laser
PIC simulation with plane wave & DC e-beam

Laser (1 GV/m)

y = 155 nm
y = −155 nm

snapshot of the energies of electrons at different positions.
**PIC simulation with plane wave & single electron**

Single electron

\[ y = 155 \text{ nm} \]
\[ y = -155 \text{ nm} \]

\[ e^{-1} \]

\[ \text{difference due to dephasing and deflection} \]

Calculated with \[ G_a = 0.42 \]

\[ 53 \]
\[ 52 \]
\[ 51 \]
\[ 50 \]

\[ 0 \]
\[ 10 \]

\[ z / \lambda_p \]

\[ \text{Energy [keV]} \]

\[ \text{Y displacement [nm]} \]

\[ 155 \]

\[ -155 \]
Evaluation of energy gain with Gaussian laser

Gaussian laser

Beam diameter $2w_0$

Dephasing and deflection are neglected.
Damage threshold 0.2 J/cm$^2$.

\[
G_a = \left( \frac{G_a}{E_0} \right) \sqrt{\frac{2F_{in}}{c \varepsilon_0 \tau_p}} = 0.42 \sqrt{\frac{2F_{in}}{c \varepsilon_0 \tau_p}}
\]

\[
\Delta E = G_a \sqrt{\pi w_{int}} = G_a \sqrt{\pi} \left( \frac{1}{w_0^2} + \frac{2\ln(2)}{\tau_p^2} \right)^{-0.5}
\]

Beam axis

FWHM pulse length $\tau_p$

Energy gain $G_a$ [GV/m]

Laser fluence [J/cm$^2$]

$\tau_p = 100$ fs, $w_0 = 4 \mu m$

- $d=31$ nm
- $d=93$ nm
- $d=155$ nm (center)
Comparison with grating structure

Colonnade structure

Grating structure

\[ E_{\text{max}} : \text{max field in the material} \]

\[ y = 0 \]

\[ \tau_p = 100 \text{ fs}, \ w_0 = 4 \mu m \]

\[ G_a / E_{\text{max}} \]

\[ G_a \]
Experiment considerations (single grating)

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Values</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Laser wavelength</td>
<td>1030</td>
<td>nm</td>
</tr>
<tr>
<td>Average power</td>
<td>11.6</td>
<td>W</td>
</tr>
<tr>
<td>Repetition rate</td>
<td>84</td>
<td>MHz</td>
</tr>
<tr>
<td>FWHM pulse length</td>
<td>150</td>
<td>fs</td>
</tr>
<tr>
<td>Peak electric field</td>
<td>4.2</td>
<td>GV/m</td>
</tr>
<tr>
<td>Fluence</td>
<td>0.35</td>
<td>J/cm²</td>
</tr>
</tbody>
</table>
Experiment considerations (single grating)

Initial beam-grating distance $d = 100$ nm

Single electron

Characteristic interaction distance $w_{int} = 4.8 \, \mu m$, peak e-field $E_0 = 4.2 \, GV/m$

1\textsuperscript{st} harmonic
Conclusions & Outlook

Conclusions:

- The colonnade structure was numerically investigated for 50 keV nonrelativistic electrons.

- We are fabricating single grating structure for experimental test.

Outlook:

- We will perform the experiment with the single grating structure.
Acknowledgement

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