Towards a Fully Integrated Accelerator on a Chip: Dielectric Laser Acceleration (DLA)
From the Source to Relativistic Electrons

Kent P. Wootton – SLAC National Accelerator Laboratory
8th International Particle Accelerator Conference
17th May 2017
Copenhagen, Denmark

Work supported by the U.S. Department of Energy under Contract no. DE-AC02-76SF00515, and the Gordon and Betty Moore Foundation under grant GBMF4744.
Accelerator on a Chip International Program (ACHIP)

PIs: R. L. Byer (Stanford) & P. Hommelhoff (FAU Erlangen)

5 year programme (2015-2020)

- Stanford
- FAU Erlangen
- Purdue
- UCLA
- EPFL
- TU Darmstadt
- Hamburg
- Tech-X

In-kind contributions:
- SLAC
- DESY
- PSI

https://sites.stanford.edu/achip/
Motivating compact electron accelerators

• High gradients enable compact linear accelerators

1947

Applications:

• Radiotherapy
• Industrial/security
• Attosecond science

2013

~MeV m⁻¹

~GeV m⁻¹

SLAC Archives, ARC127

SLAC National Accelerator Laboratory
Laser driven accelerators

“Is there any point in considering the far infrared …?

Only if the breakdown conditions there are different, yielding spectacular values of \(E_0\).”


Material damage fluence and accelerating gradient

Material damage fluence and accelerating gradient

**Damage threshold**

- Al₂O₃: 4.90 J/cm²⁻²
- quartz: 1.00 J/cm²⁻²
- ZrO₂: 3.97 J/cm²⁻²
- HfO₂: 3.64 J/cm²⁻²
- SiO₂: 3.45 J/cm²⁻²
- CaF₂: 2.02 J/cm²⁻²
- SiO₂*: 0.86 J/cm²⁻²
- TiO₂*: 0.67 J/cm²⁻²
- ZnO*: 0.65 J/cm²⁻²
- Si₃N₄: 0.57 J/cm²⁻²
- ZnS: 0.52 J/cm²⁻²
- diamond*: 0.44 J/cm²⁻²
- diamond (poly)*: 0.21 J/cm²⁻²
- SiC*: 0.20 J/cm²⁻²
- ZnSe: 0.18 J/cm²⁻²
- Si: 0.09 J/cm²⁻²
- Al₆.₆GaAs: 0.08 J/cm²⁻²
- InP: 0.06 J/cm²⁻²
- GaP: 0.05 J/cm²⁻²
- Cu: 0.05 J/cm²⁻²
- GaAs: 0.05 J/cm²⁻²
- GaN: 0.04 J/cm²⁻²

* measurement done in vacuum

**SiO₂ (fused silica)**

- Damage threshold: $E = 2J/cm^2, \tau = 100 \text{ fs}$
- $E = 12 \text{ GV m}^{-1}$


Lasers for accelerators

- fs-duration lasers commercially available
- Tabletop-scale fibre, regenerative amplifiers
- Pulse energy 0.1–5 mJ

Dielectric laser accelerator structures

- Dielectric-vacuum structures
- UV and electron beam lithography

Plettner, et al., PRSTAB, 9, 111301 (2006)

Noble, et al., PRSTAB, 14, 121303 (2011)

Cowan, PRSTAB, 11, 011301 (2008)


Noble, et al., PRSTAB, 14, 121303 (2011)

Wu, et al., IEEE JSTQE, 22, 4400909 (2016)
DLA – Acceleration

- Plane wave
- No acceleration

SLAC National Accelerator Laboratory [https://youtu.be/V89qvy8whxY](https://youtu.be/V89qvy8whxY)

Wootton – 8th Int. Part. Accel. Conf. – WEYB1 – 17th May 2017
• Plane wave
• No acceleration
DLA – Acceleration

• Plane wave
• No acceleration
• Refractive index modifies phase
• Acceleration

SLAC National Accelerator Laboratory [Link](https://youtu.be/V89qvy8whxY)

Wootton – 8th Int. Part. Accel. Conf. – WEYB1 – 17th May 2017
DLA – Acceleration

- Plane wave
- No acceleration
- Refractive index modifies phase
- Acceleration

SLAC National Accelerator Laboratory [https://youtu.be/V89qvy8whxY](https://youtu.be/V89qvy8whxY)

Wootton – 8th Int. Part. Accel. Conf. – WEYB1 – 17th May 2017
### Recent DLA Acceleration Experiments

<table>
<thead>
<tr>
<th></th>
<th>SiO$_2$ Single grating</th>
<th>SiO$_2$ Dual grating</th>
<th>Si Single Grating</th>
<th>Si Dual Pillars</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electron Energy</td>
<td>30 keV</td>
<td>8 MeV</td>
<td>96.3 keV</td>
<td>86.5 keV</td>
</tr>
<tr>
<td>Relativistic $\beta$</td>
<td>0.33</td>
<td>0.998</td>
<td>0.54</td>
<td>0.52</td>
</tr>
<tr>
<td>Laser Energy</td>
<td>160 nJ</td>
<td>150 $\mu$J</td>
<td>5.2 nJ</td>
<td>3.0 nJ</td>
</tr>
<tr>
<td>Pulse Length</td>
<td>110 fs</td>
<td>40 fs</td>
<td>130 fs</td>
<td>130 fs</td>
</tr>
<tr>
<td>Interaction Length</td>
<td>11 um</td>
<td>~20 um</td>
<td>5.6 um</td>
<td>5.6 um</td>
</tr>
<tr>
<td>Peak Laser Field</td>
<td>2.85 GV/m</td>
<td>3.5 GV/m</td>
<td>1.65 GV/m</td>
<td>~1.1 GV/m</td>
</tr>
<tr>
<td>Max Energy Gain</td>
<td>0.275 keV</td>
<td>20 keV</td>
<td>1.22 keV</td>
<td>2.05 keV</td>
</tr>
<tr>
<td>Max Acc Gradient</td>
<td>25 MeV/m</td>
<td>0.85 GV/m *</td>
<td>220 MeV/m</td>
<td>370 MeV/m</td>
</tr>
<tr>
<td>$G_{\max}/E_p$</td>
<td>~0.01</td>
<td>~0.18</td>
<td>~0.13</td>
<td>~0.4</td>
</tr>
</tbody>
</table>

* Preliminary
Fundamental accelerator properties

• Structure period $\Lambda = h\beta\lambda$, $\beta = \frac{v}{c}$, $h = 1, 2, 3, \ldots$
• $\lambda = 800$ nm, optical cycle $\rightarrow$ 2.7 fs
• $\lambda = 2$ $\mu$m, optical cycle $\rightarrow$ 6.7 fs
• Bunches occupying a few degrees of laser phase would be sub-femtosecond duration
• What is needed for a tabletop source of relativistic (~1 MeV) attosecond bunches?
Accelerator ‘in-a-shoebox’


- Electron source
- Buncher
- Transverse focussing
- Accelerating structures
- Laser delivery
- Diagnostics/control

Wootton – 8th Int. Part. Accel. Conf. – WEYB1 – 17th May 2017
Electron source emittance requirements

- Admittance of structure between two focussing elements
- Assuming $\lambda = 2 \, \mu m$
  - Gap $g \approx \lambda / 2$

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$L$</td>
<td>1 mm</td>
</tr>
<tr>
<td>$g$</td>
<td>1 $\mu$m</td>
</tr>
<tr>
<td>Admittance</td>
<td>1 nm rad</td>
</tr>
</tbody>
</table>
Low emittance electron sources


Flat RF photocathode

Tungsten nanotip

Diamond nanotip

Silicon nanotip

\[ \varepsilon_n = 5 \text{ nm rad} \]

\[ \varepsilon = 0.3 \text{ nm rad} \]

\[ \varepsilon_n = 1 \text{ nm rad} \]

\[ \varepsilon = 0.08 \text{ nm rad} \]
DC photocathode electron gun

- Photo-assisted field-emission source
- Cathode geometry may be flat or nanotip
- UV and IR laser pulses produced from same source
- Few nm rad transverse emittance
- Electron bunch length \( \tau \approx 100 - 300 \) fs
  - Needs microbunching


Wootton – 8th Int. Part. Accel. Conf. – WEYB1 – 17th May 2017
Buncher – Velocity microbunching

Initial bunch → Energy modulation → Velocity bunching → Main accelerating structure

- Laser
- DLA
- e- beam
- ~0.5 mm


Wootton – 8th Int. Part. Accel. Conf. – WEYB1 – 17th May 2017
Buncher – optical phase-controlled acceleration

Accelaration – sub-relativistic structures

- Synchronicity condition between electron and accelerating mode
  \[ \Lambda = h\beta\lambda \]
  \[ \beta \ll 1? \]
- Accelerate low energy electrons using high-order mode \( h = 3, 4, 5, \ldots \)


Sub-relativistic structures

Increasing chirp to velocity match accelerating electrons


\[
\Lambda = \Lambda_0 + \frac{d\Lambda}{dz} z
\]

Velocity buncher

Chirped accelerating structure

U. Niedermayer, WEPVA003 (this afternoon)
Focussing requirements for demonstration

\[ B' = T^2 \frac{\beta \gamma m_e c}{q_e} \]

- PMQs may be viable for low emittance beams without space charge
- Long term, require MT m\(^{-1}\) transverse gradients for transport of high peak charge microbunches
  - Laser driven focussing structures

Focussing structures – magnetic

Micro electromagnetic quads


200 T m^{-1}

Permanent magnet quads (PMQ)


700 T m^{-1}

Wootton – 8th Int. Part. Accel. Conf. – WEYB1 – 17th May 2017
Focussing structures – laser-driven


0.4 MT m\(^{-1}\)

2 MT m\(^{-1}\)
High-gradient structures – previous experiments

SLAC, 2013 ($\beta \approx 1$)
310 $\pm$ 21 MV m$^{-1}$

Stanford ($\beta \approx 0.5$)
376 $\pm$ 40 MV m$^{-1}$

SLAC ($\beta \approx 1$)
690 $\pm$ 100 MV m$^{-1}$

High-gradient structures – Nonlinear effects

At high fields, self-focussing and self-phase modulation distort phase


Laser pulse before structure
Laser pulse after 500 μm SiO₂

Results in saturation of energy gain

D. Cesar, et al., (in preparation)
Diagnostics/control

Beam transverse position


Temporal + spatial


Electron steering


Wootton – 8th Int. Part. Accel. Conf. – WEYB1 – 17th May 2017
Pulse-front tilt

- Dispersive elements produce pulse-front tilt


- High field <100 fs laser pulse

T. Plettner, et al., *PRSTAB, 9, 111301 (2006)*

- Extended interaction distance
On-chip laser management

Inverse design 1→5 coupler  1→3, 0.3 rad phase advance per arm


Future – 3D printed DLAs

- Nanoscribe feature size < 100 nm
- Enable fabrication of exotic structures, waveguides
- Material damage tests underway


Summary

Tabletop demonstration

• DC photocathodes produce few nm emittance required
• Phase-controlled acceleration suggests velocity bunching feasible
• Integrate with chirped structures, demonstrated
• PMQs may provide necessary focussing for tabletop demonstration

Longer-term integrated accelerator

• Laser-driven focussing structures
• Laser delivery and control on-chip
• 3D printing of photonic crystal structures
Acknowledgments

**Stanford Univ.**
Bob Byer
James Harris
Olav Solgaard
Shanhui Fan
Jelena Vuckovic
Ken Leedle
Andrew Ceballos
Huiyang Deng
Stephen Wolf
Si Tan
Yu Miao
Dylan Black
Peyton Broaddus
Logan Su
Alex Piggott
Jiahui Wang
Tyler Hughes

**Stanford (contd.)**
Zhixin Zhao
Neil Sapra
Levi Ofer
Mike Hennessy
Jim Perales

**FAU Erlangen**
Peter Hommelhoff
Josh McNeur
Martin Kozák
Ang Li
Johannes Illmer
Alexander Tafel

**Purdue Univ.**
Minghao Qi
Yun Jo Lee

**TU Darmstadt**
Oliver Boine-Frankenheim
Uwe Niedermayer
Thilo Egenholf

**Tel-Aviv Univ.**
Jacob Scheuer
Doron Bar-Lev
Avi Gover

**Univ. Hamburg**
Franz Kärntner

**UCLA**
Pietro Musumeci
James Rosenzweig
David Cesar
Jared Maxson
Xinglai Shen
Alexander Ody

**Paul Scherrer Inst.**
Rasmus Ischebeck
Franziska Frei
Eduard Prat
Dominique Zehnder
Simona Bettoni
Nicole Hiller
Micha Dehler

**SLAC**
Joel England
Kent Wootton

**DESY**
Ralph Assmann
Ingmar Hartl
Axel Ruehl
Willi Kuropka
Frank Mayet

**LANL**
Evgenya Simakov
Dmitry Shchegolkov

**LLNL**
Paul Pax
Mike Messerly

---

blue = students

Wootton – 8th Int. Part. Accel. Conf. – WEYB1 – 17th May 2017
DLA posters at IPAC’17

Monday, ABISKØ
MOPVA012 U. Dorda, et al., The Dedicated Accelerator R&D Facility “Sinbad” at DESY

Tuesday, ABISKØ
TUPAB040 B. Marchetti, et al., Status Update of the SINBAD-ARES Linac Under Construction at DESY

Wednesday, VALHALL
WEPVA002 T. Egenolf, et al., Simulations of DLA Grating Structures in the Frequency Domain
WEPVA003 U. Niedermayer, et al., Designing a Dielectric Laser Accelerator on a Chip
WEPVA005 W. Kuropka, et al., Simulation of Many Period Grating-Based Dielectric Laser Accelerators for Electrons
WEPVA006 F. Mayet, et al., A Concept for Phase-Synchronous Acceleration of Microbunch Trains in DLA …
WEPVA007 F. Mayet, et al., Simulations and Plans for a Dielectric Laser Acceleration Experiment at SINBAD
WEPVA011 K. Koyama, et al., Development of a Laser Driven Dielectric Accelerator for Radiobiology Research
WEPVA016 J. Oegren, et al., Dielectric Laser Accelerator Investigation, Setup Substrate Manufacturing …
WEPVA020 Y. Wei, et al., Dielectric Accelerators Driven by Pulse-Front-Tilted Lasers

Thursday, ABISKØ
THPAB013 F. Mayet, et al., A Fast Particle Tracking Tool for the Simulation of Dielectric Laser Accelerators
Wootton – 8th Int. Part. Accel. Conf. – WEYB1 – 17th May 2017