Recent developments in dielectric laser acceleration
-- toward the accelerator on a chip

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2) SLAC National Accelerator Laboratory, Menlo Park, CA, USA
3) Stanford University, Stanford, CA, USA
Particle accelerators for science

Size given by final energy & acceleration gradient
ILC design gradient: 31.5 MeV/m

European XFEL, Hamburg

International Linear Collider, ILC
Medical linacs (linear accelerators)
### Particle accelerators: from RF to optical/photonic drive?

<table>
<thead>
<tr>
<th></th>
<th>Conventional linear accelerator (RF)</th>
<th>Laser-based dielectric accelerator (optical)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Based on</strong></td>
<td>(Supercond.) RF cavities</td>
<td>Quartz grating structures</td>
</tr>
<tr>
<td><strong>Peak field limited by</strong></td>
<td>Surface breakdown: 200 MV/m</td>
<td>Damage threshold: 30 GV/m</td>
</tr>
<tr>
<td><strong>Max. achievable gradients</strong></td>
<td>100+ MeV/m</td>
<td>10 GeV/m</td>
</tr>
<tr>
<td><strong>Drive period</strong></td>
<td>~300 ps</td>
<td>~5 fs</td>
</tr>
</tbody>
</table>
Widerøe linac

Switch fields *synchronous* with the particle’s position/velocity

taken from J. Breuer’s thesis

Wideroe, 1928
Ising, 1924
Acceleration at a dielectric structure / phase mask

- Phase front
- Half-period later
- Laser beam propagation direction
- Electron

- Laser beam propagation direction

- Phase front
- Half-period later
- Laser beam propagation direction
Acceleration by phase-synchronous propagation

1. Acceleration
2. Deceleration
3. Deflection
4. Deflection

$t = 0$
$t = \frac{\pi}{2}$
$t = \pi$
Proposed dielectric structures

Yoder Rosenzweig, 2005

Cowan, 2008

Naranjo, ... Rosenzweig, 2012

Chang Solgaard, 2014

... and variants

- Goal: generate a mode that allows momentum transfer from laser field to electrons
- Use first order effect (efficient!)
- Second order effects (ponderomotive) too power costly

For a review and an extensive list of references, see:
An old idea ... I

Proposal for an Electron Accelerator Using an Optical Maser

Koichi Shimoda

January 1962 / Vol. 1, No. 1 / APPLIED OPTICS 33

Fig. 1. Schematic diagram of an electron linear accelerator by optical maser.
An old idea ... II

Electron Acceleration by Light Waves

October 3, 1962

A. Lohmann

Department 522
Photo-Optics Technology
GPD Development Laboratory
San Jose

Aug. 16, 1966

A. W. LOHMANN

PARTICLE ACCELERATOR UTILIZING COHERENT LIGHT

Filed May 27, 1963

3,267,383

2 Sheets-Sheet 2
An old idea ... III

NUCLEAR INSTRUMENTS AND METHODS 62 (1968) 306–310; © NORTH-HOLLAND PUBLISHING CO.

LASER LINAC WITH GRATING

Y. TAKEDA and I. MATSUI

Central Research Laboratory, Hitachi Ltd., Kokubunji, Tokyo, Japan

Received 13 February 1968

Exp. demonstration with mm radiation (keV/m): Mizuno et al., Nature 328, 45 (1987).
Proof-of-concept experiments

30 keV electron beam of an electron microscope column

60 MeV electron beam at SLAC’s NLCTA

Single-sided silica structure
3rd spatial harmonic
25 MeV/m

Dual-sided silica structure
1st spatial harmonic
> 250 MeV/m


J. Breuer, P. Hommelhoff, PRL 111, 134803 (2013)
ACHIP: Accelerator on a Chip International Program

Goals: demonstrate (1) a shoebox-sized 1 MeV accelerator & (2) “transverse effects”

Organizational chart

Pls: R. L. Byer, Stanford, P. Hommelhoff, FAU Erlangen

Sub-Relativistic DLA experiments
Stanford: Harris, Solgaard
Erlangen: Hommelhoff

System integration
(Core DLA groups)
Stanford: Byer, Harris, Solgaard
Erlangen: Hommelhoff

Electron source
UCLA: Musumeci
Erlangen: Hommelhoff
Stanford: Harris, Solgaard

Light Coupling
Stanford: Fan, Vučković

Structures
Stanford: Harris, Solgaard, Byer
Erlangen: Hommelhoff

Simulations
Tech-X: Cowan
U Darmstadt: Boine-Frankenheim

Relativistic DLA experiments
SLAC: England, Tantawi
DESY/UnivHH: Aßmann, Kärtner, Hartl
PSI/EPFL: Ischebeck, Rivkin

Associated Scientific Collaborators
Yenchieh Huang (Tsinghua)
Zhirong Huang (SLAC)
Kazu Koyama (Tokyo U)
James Rosenzweig (UCLA)
Evgenya Simakov (Los Alamos)

Industrial affiliate
Hamamatsu Corp. Japan (joined June 2017)

Sept. 2015 – Aug. 2020

ACHIP Scientific Advisory Board:
Chan Joshi, UCLA, Reinhard Brinkmann, DESY, Tor Raubenheimer, SLAC
Accelerator on a chip

From *individual functional elements* to

*control of complex electron beam dynamics* and *integrated photonics structures*

Hughes et al., arXiv 2019
9th ACHIP collaboration meeting in Hamamatsu (Sept. 12-14, 2019)
Functional elements

• High brightness photocathodes
• Acceleration
• Focusing
• Deflection
• Streaking
• (Beam position monitoring)
• On-chip power distribution
High brightness photocathodes – ongoing

- Nanoblade source (Rosenzweig, PH) also promising
- Compact electron lenses running/under test: immersion, Einzel

<table>
<thead>
<tr>
<th>R (nm)</th>
<th>max $e^-$/pulse</th>
<th>$\epsilon_n$ (nm)</th>
<th>$B_{5D,n}$ (A/cm$^2$)</th>
<th>stability</th>
<th>integrated</th>
</tr>
</thead>
</table>

EAAC, Elba, Italy, Sept. 2019
Dual pillar structure: *function by phase*

- Easy to manufacture, in particular from silicon
- Large gradient: 370 MeV/m (with 100 keV electrons) demonstrated

Dual pillar structures:

Skew modes:
- acceleration and deflection etc.

"cosh mode":
- Acceleration
- Focusing
- Microbunching

"sinh mode":
- Beam steering
- Streaking
- Undulator applications
Acceleration and deflection controlled via optical phase

Freeze phase & simplify: add distributed Bragg reflector

Dual pillar acceleration structures joint with Bragg mirror
Freeze phase & simplify: add distributed Bragg reflector

- Acceleration gradient increase of 57%
- 100% in theory
- Difference likely because of slight phase offset and beam expansion
- Double-humped structure!

Optical focusing of an electron beam I

Dual drive: **focusing forces** (cosh mode, no deflection)

With 100 MV/m incident field: 50 µm focal lengths, corresponding to magnetic quadrupole lens with 1.4 MT/m

Focal length of 20 µm ... infty by decreasing the incident laser field strengths

focusing strength corresponds to magnetic quadrupole lens with >1 MT/m
Example device: dielectric 1550nm -1300 nm demultiplexer. Size: 2.8 x 2.8 \( \mu \text{m}^2 \)
On-chip laser power feeding: tree branch structure

On-chip laser power feeding: interferometric power tuning

First demonstration: waveguide-driven DLA structure
Understanding and controlling beam dynamics

- Staging of subsequent interaction regions
- Attosecond pulse train generation
- Alternating phase focusing
- (Wake field effects)
Demonstration of 2-stage acceleration

Energy gain can be doubled or suppressed depending on the relative phase of the 2 spots.

Image of laser intensity profiles on the grating

Relative phase of laser spots is controlled with sub-cycle precision via a delay stage in one arm of an interferometer.
Demonstration of 2-stage acceleration

Count rates of accelerated electrons with energy gain >30 eV

- Energy gain twice as large
- Linear scaling of energy

Demonstration of 2-stage deflection

- Phase-dependent transverse momentum exchange
- Basis for sub-optical cycle streaking (w/ shorter interaction length, uniform fields)

Attosecond bunch train generation

Imprint energy modulation (cosh mode)

Let electrons propagate freely/ballistically

→ Energy modulation translates into density modulation (non-relativistic: no chicane needed)
Measure spectrograms (electron spectra as function of time delay between buncher and analyzer) as function of buncher field strength.

Careful modeling and comparison of experimental and numerical spectrograms:

**Shortest micropulse: (270 ± 80) attoseconds**

N. Schönenberger, A. Mittelbach, P. Yousefi, J. McNeur, U. Niedermayer, P. Hommelhoff, manuscript under review
Attosecond bunch train generation and coherent acceleration
Attosecond bunch train generation and coherent acceleration

Streaking of microbunched pulses in analyzer structure:

- Shortest micropulse: (700 ± 200) attoseconds, averaged over bunch train

D. S. Black, U. Niedermayer, Yu Miao, Zhexin Zhao, O. Solgaard, R. L. Byer, K. J. Leedle
manuscript under review
Attosecond bunch train generation and coherent acceleration

D. S. Black, U. Niedermayer, Yu Miao, Zhixin Zhao, O. Solgaard, R. L. Byer, K. J. Leedle
manuscript under review
Attosecond bunch train generation in a free space scheme: with ponderomotive electron scattering in a co-moving wave

\(\lambda_1 = 1356 \text{ nm} \ (0.91 \text{ eV}), \ \lambda_2 = 1958 \text{ nm} \ (0.63 \text{ eV})\)
\(\alpha = 41^\circ, \ \beta = 107^\circ\)

- Forward (longitudinal) momentum change only
- Gradient up to 2.2 GeV/m
- Strong energy modulation imprinted

Minimum individual “pulse” duration of 260 as

Related work by groups of Baum, Carbone, Garcia de Abajo, Ropers, Talebi, Zewail

Keeping the beam together:
Alternating phase focusing

Alternate between transverse focusing-longitudinal defocusing and transverse defocusing-longitudinal focusing

**net focusing**

83 keV $\rightarrow$ >1 MeV:
56% transmission for 100pm,
93% for 25pm emittance

Phase-reset structure – towards the photonics LINAC?
Alternating phase focusing: transport
Efficient modeling tool: DLATrack6D

Ongoing development: include wake field effects into tracking, allow tune determination (Niedermayer, Egenolf, MS in preparation)

Example: APF structure. Shown here: beam envelope as fct. of position

Design for 50 keV to 1 MeV accelerator

With VSim (B. Cowan): full simulation including space charge
Extend laser-pulse electron interaction: large energy gains at UCLA Pegasus

**Tilt pulse front** of laser pulses while leaving phase fronts parallel to structure

With 6 MeV electrons and 800nm, 45 fs (=14 \(\mu\)m long) laser pulses:
- Interaction length of 0.5 ... 1 mm
- Max. energy gain of 315 keV – record!
- Gradient of 560 MeV/m
- Soon: >1 MeV gain in cm-long structure?

With 8 MeV electrons and 800nm, 45 fs laser pulses:
- Up to 9 GV/m peak incident field (\(\sim 10\text{TW/cm}^2\))
- Accelerating mode \(1.8\ \text{GV/m}\) in
- Max. accel. gradient of \(850\ \text{MeV/m}\) measured
- Non-linear phase effects due to self-phase modulation in fused silica

Dielectric laser acceleration with relativistic beams

- UCLA Pegasus: 6 MeV
  - Maximum energy gain observed: 315 keV over 0.5mm, 560 MeV/m [1]
  - Soon >1 MeV
- DESY SINBAD ARES: 50 – 100 MeV
- PSI SwissFEL ATHOS: 3 GeV

DLA experiments soon at DESY’s ARES

ACHIP-related experiments planned to be conducted at ARES

- **Stage 1**: External injection of relativistic (50-100 MeV) ultra-short (<2 fs, FWHM) single electron bunches with ~0.5 pC of charge into a 2 µm period grating type DLA
- **Stage 2**: External injection of relativistic (50 MeV) phase-synchronous optical scale microbunch trains (~70 microbunches per train with ~10 fC of bunched charge each, spaced at the DLA period of 2 µm)

First beam expected in week 39/40 (right after EAAC’19)

DLA experiments soon at PSI’s ATHOS
Further research topics

• Plasmonically enhanced structures

• See, e.g.:

PHYSICAL REVIEW ACCELERATORS AND BEAMS 22, 021303 (2019)

Design of a plasmonic metasurface laser accelerator with a tapered phase velocity for subrelativistic particles

ACHIP results so far

✓ Proof-of-concept demonstration of DLA

✓ New structures & dynamics
  ✓ phase-based steering
  ✓ two-stage acceleration
  ✓ chirped structures
  ✓ optical focusing
  ✓ optical deflection
  ✓ beam position monitor
  ✓ (sub-) femtosecond bunching
  ✓ stable transport
  ✓ on-chip Bragg mirror
  ✓ power distribution (theory)

- Cowan PR STAB 6, 101301 (2003)
- Plettner, Byer, et al., PRL 95, 134801 (2005)
- Na, Sieman, Byer, PR STAB 8, 031301 (2005)
- Zhang et al., PR STAB 8, 071302 (2005)
- Plettner et al., PR STAB 8, 121301 (2005)
- Plettner, Lu, Byer, PR STAB 9, 111301 (2006)
- Plettner, Byer, PR STAB 11, 030704 (2008)
- Plettner, Byer, NIMA 593, 63 (2008)
- Cowan PR STAB 11, 011301 (2008)
- Peralta et al., Nature 503, 91 (2013)
- Wu et al., PR STAB 17, 081301 (2014)
- Bar-Lev, Scheuer, PR STAB 17, 121302 (2014)
- Aimidula et al., Phys. Plas. 21, 023110 (2014)
- Leadle et al., Optica 2, 158 (2015)
- Wootton et al., Opt Lett. 41, 2696 (2016)
- Niedermaier et al., PR STAB (2017)
- Cesar et al., Comm. Physics 1, 46 (2018)
- Black et al., PRL 122, 104891 (2019)
- Black et al., submitted

✓ 200.4 MeV/m with few-cycle NOPA-DFG
  (with $\beta = 0.3$ electrons!)

✓ 340 MeV/m (with $\beta = 0.7$ electrons!)

✓ 850 MeV/m with 6 MeV electrons

Plettner et al., PR-STAB (2009)
Breuer, Hommelhoff, PRL 111, 134803 (2013)
Breuer et al., PR-STAB (2014)
McNeur et al., NIMA 829, 50 (2016)
England et al., Rev. Mod. Phys. 2015
Kozák et al., Nature Comm. 8, 14342 (2017)
Kozák et al., NIMA 865, 87 (2017)
Prat et al., NIMA 865, 87 (2017)
McNeur et al., Optica 5, 687 (2018)
Schönenberger et al., submitted
DLA research worldwide

DLA research next to ACHIP:
LAL Orsay: J. L. Babigeon
Technion: L. Schächter, I. Kaminer
Wroclaw: A. Szczepkowicz
Liverpool: C. Welsch
Tel Aviv: J. Scheuer

(Apologies if your name and institution are missing – pls. get in touch)
Outlook: Strawman parameters
Technology perspective: *photonics*

- Power and cost efficient laser technology
  - high average power
  - rugged turn-key fiber technology

- Optical field control available

- (Silicon) nanostructuring capabilities

*Photonics technology!*

World market for photonics: $481$ billion in 2012, expected $620$ billion in 2020
(Nat. Phot. 11, 1, 2016)

*Similar story to radar klystrons (invented 1937) driving accelerator technology thereafter?*

Even 3-d structures


(Robotic) hand-held electron beam for clinicians?

Open positions soon! Pls. get in touch.

Partners/collaborations:

FAU Applied Physics: H. Weber
QEM collaboration
ACHIP collaboration
Ph. Russell, MPL
M. Kling, LMU/MPQ
R. L. Byer + coll., Stanford / SLAC
I. Hartl, F. Kärtner, R. Aßmann, DESY
R. Holzwarth, MenloSystems
Chr. Lemell, J. Burgdörfer, TU Vienna
M. Stockman, Georgia State
A. Högele, LMU
E. Riedle, LMU
G. G. Paulus, Jena
J. Rosenzweig, UCLA

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Zhang

Tobias Boolakee
Philip Dienstbier
Timo Eckstein
Christian Heide
Jonas Heimerl
Martin Hundhausen
Johannes Illmer
Stefanie Kraus
Ang Li
Stefan Meier
Anna Mittelbach
Timo Paschen
Jürgen Ristein
Roy Shiloh
Constanze Sturm
Alexander Tafel
Norbert Schünenberger
Michael Seidling
Peyman Yousefi
Robert Zimmermann
Recent DLA highlights (see slides for references)

- 315 keV energy gain with 6 MeV electrons, soon 1 MeV
- 850 MeV/m accel. gradient
- Integrated structure: waveguide-driven DLA
- Alternating phase focusing scheme & experiment: transport & acceleration structures scalable!
- Attosecond microbunch generation
- Coherent acceleration

**Scalable MeV accelerator on a chip soon?**
Research toward a new kind of laser-driven particle accelerator based on photonics technology

*Photonics-based technology is ripe (and cheap)*

*Sources! Brightness! Integration! Dynamics! Photon generation! ...*

*Much to be demonstrated: accelerator research*