Dielectric Laser Accelerators

Snowmass AF6 Meeting Sept 23, 2020

R. J. England


Global DLA Effort & Funding

CURRENT ACTIVE PROGRAMS: ACHIP (multiple PIs), Euclid Tech Labs, U. Tokyo (Uesaka), LANL (Simakov), U. Liverpool (Welsch)

Accelerator on a Chip International Program (ACHIP) 2015 to 2022
• Major international effort (8 universities, 2 US + 2 EU labs, 2 companies)
• Countries involved: US, Germany, Taiwan, Japan, Switzerland, Israel
• Funded by Moore Foundation plus in-kind DOE support
• Most DLA effort worldwide falls under this program; additional work in UK, China

Existing programs provide guidance on future R&D Costs
ACHIP - $19.5M / 7 years = $2.7M/year (Moore Foundation, low overhead ~ 12%)
LANL (2018-2020) - $3M over 3 years = $1M/year
SLAC, DESY, PSI: International Lab (DOE & internal) in-kind support (~$1.8M/year)

Future program(s) should be at similar effort levels to maintain critical mass
May be subdivided into parallel programs under multiple funding sources.
Assumes funding from government funding agencies (50 to 60% overhead).
Due to low overhead of Moore Foundation gift grant, continuation under other funding sources would need ~ 2x current funding for equivalent effort level.
Current State of the Art

DLA included under ANAR and ALEGRO 2017-2019 workshops. HEP roadmaps developed on 30 year time scale with core working group established.

**Supporting Technologies are Well-Established:**

- **Laser Requirements:** 1-10 µJ, <1 ps, 10-50 MHz rep rate (low cost, form factor, off-the-shelf)
- **Integrated Photonics:** facilitated by microchip industry; low-cost, nanometric precision

**Gradient and Energy Scalability:**

- **High-gradient operation with** 850 MeV/m average electron gradient and **0.3 MeV** energy gain and **phase/dispersion control**. Higher gradients possible -- 1.8 GV/m axial fields experimentally demonstrated in fused silica DLA. (UCLA, D. Cesar 2018)
- **POCs have demonstrated key concepts needed for energy scaling:** transverse and longitudinal **focusing**, optical **pre-bunching** and injection, **net acceleration**, integrated waveguide **coupling**, extended transport, **staging** of laser pulses.
- **ACHIP aims to develop a cm-scale 1 MeV tabletop accelerator by FY21**

**Particle Source Technology:**

- **DLA approach works equally well with electrons and positrons.**
- **HEP luminosity** (2e34 for ILC) in DLA scenario is feasible with 2e6 particles per bunch train (100-500 fC, divided into 100-200 microbunches) at 20-40 MHz train rep rate of modern lasers.
- **Proposed source for HEP** is low-charge high-rep SRF gun + positron target & damping rings
- **Nanotip sources** (fA - pA average current) used in recent POCs are attractive for intermediate applications (e.g. UED, medical); but **not** indicative of ultimate beam current limits
Intermediate Applications

- Technical group established under ACHIP to evaluate a range of applications.
- Three DLA Applications workshops with external experts (most recent June 23, 2020).
- R&D developments needed for intermediate applications (e.g. beam transport, staging, higher beam current) are also relevant for HEP.

Promising near-term (< 5 year) applications include medical, radiobiology, attosecond pump-probe and UED/UEM: leverages nanotip source technology, with moderate energies (1 to 10 MeV) and beam currents (< 1 nA).

<table>
<thead>
<tr>
<th>Application</th>
<th>Field</th>
<th>Time-Scale</th>
<th>Kinetic Energy</th>
<th>Species</th>
<th>Beam Power</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radiobiology</td>
<td>Science</td>
<td>5 yrs</td>
<td>100 keV to 5 MeV</td>
<td>e-</td>
<td>5 mW</td>
</tr>
<tr>
<td>UED/UEM Source</td>
<td>Science</td>
<td>5 yrs</td>
<td>1-5 MeV</td>
<td>e-</td>
<td>10 to 50 μW</td>
</tr>
<tr>
<td>Catheterized Electron Source</td>
<td>Medical</td>
<td>5 yrs</td>
<td>1 to 10 MeV</td>
<td>e-</td>
<td>1-3 mW</td>
</tr>
<tr>
<td>Compton X-ray Source</td>
<td>Medical</td>
<td>5-10 yrs</td>
<td>10 to 60 MeV</td>
<td>e-</td>
<td>20 to 60 mW</td>
</tr>
<tr>
<td>Low-power EUV</td>
<td>Industry</td>
<td>5-10 yrs</td>
<td>10 to 100 MeV</td>
<td>e-</td>
<td>0.5 W</td>
</tr>
<tr>
<td>Proton/Hadron Therapy</td>
<td>Medical</td>
<td>10-20 yrs</td>
<td>70 to 250 MeV</td>
<td>p+</td>
<td>3-400 mW</td>
</tr>
<tr>
<td>Compact XFEL</td>
<td>Science</td>
<td>10-20 yrs</td>
<td>1 GeV</td>
<td>e-</td>
<td>1.5 kW</td>
</tr>
<tr>
<td>Multi-Axis Tomography</td>
<td>Science</td>
<td>10-20 yrs</td>
<td>1 GeV</td>
<td>e-</td>
<td>1.5 kW</td>
</tr>
<tr>
<td>Colliding Beam Fusion</td>
<td>Industry</td>
<td>20+ yrs</td>
<td>15 keV to 1 MeV</td>
<td>p+</td>
<td>1 MW</td>
</tr>
<tr>
<td>Linear Collider</td>
<td>HEP</td>
<td>20+ yrs</td>
<td>1 to 10 TeV</td>
<td>e/-e+</td>
<td>10 to 200 MW</td>
</tr>
</tbody>
</table>

New “on a chip devices” are coming forward presently and may offer significant improvement in delivery of radiation, from collimation to brachytherapy compatibility, to array use, and finally to cost.
Current and Future Test Facilities

**Current Test Facilities:**

**UCLA Pegasus:** 1-8 MeV photoinjector+linac; Ti:Sapphire laser; low-charge, norm. emittance ~ 30nm-rad

- High gradient and high energy gain demonstration experiments

**Stanford:** 30 to 100 keV nanotip emission sources for low-energy structure evaluation

**FAU Erlangen:** 30 kV SEM and supertip field emission source test stands; 2μm laser testing

**Future Planned (Funded) Test Facilities (1 to 5 year timeline):**

**PSI SwissFEL** 3 GeV beam line - dedicated DLA diagnostic and vacuum chamber

- Laser driven undulator, wakefield studies, radiation damage testing

**DESY SINBAD** 100 MeV beamline -- short bunches (few fs); optically microbunched beams anticipated

- Net acceleration experiments; particle deflection/streaking

**FAU and Stanford:** 1 MeV university test bench: demonstrate basic staging and integrated component capabilities; proposed outcome of ACHIP

**Other Potential Test Facilities (1 to 5 year timeline):**

**NLCTA (SLAC)** – currently in minimal operation mode; used in earlier (2013-2015) experiments

**ATF (BNL)** – high power CO₂ laser; capabilities for hosting advanced accelerator experiments
Summary

Key Advantages of Dielectric Laser Accelerators (DLA) for e+e- linear collider (LC):
Linear acceleration mechanism in a static structure with vacuum channel.
Critical technologies (laser development, nanofab) already near LC requirements.
Unique bunch format (fC charge at 10 to 50 MHz rep rate) with beamstrahlung loss ~ 1%
High fiber laser efficiencies (30 to 50% wallplug) facilitate modest power consumption.

Primary Challenges for a DLA Collider:
Small beam apertures → challenge with regard to wakes, halo, and long-distance transport.
Need high-rep (10 – 50 MHz) low charge (fC) normalized emittance (< 1 nm) e- and e+ sources.
Funding for this area of research is not directly focused on HEP applications.

Takeaway Points:
DLA has compelling advantages that position it as a competitive LC technology
Requirements of a LC impose major technical challenges for all advanced concepts
DLA’s challenges are distinct from other concepts but not necessarily less surmountable
# Strawman Collider Parameters

## Table of Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Units</th>
<th>CLIC 3 TeV</th>
<th>DLA 3 TeV</th>
<th>DLA 250 GeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bunch Charge</td>
<td>e</td>
<td>3.7e9</td>
<td>3.0e5</td>
<td>3.8e5</td>
</tr>
<tr>
<td>Rep Rate</td>
<td>MHz</td>
<td>5e-5</td>
<td>20</td>
<td>60</td>
</tr>
<tr>
<td>Beamstrahlung E-loss</td>
<td>%</td>
<td>28.1</td>
<td>1.0</td>
<td>0.6</td>
</tr>
<tr>
<td>Enhanced Luminosity / top 1%</td>
<td>cm-2/s</td>
<td>2.0e34</td>
<td>3.2e34</td>
<td>1.3e34</td>
</tr>
<tr>
<td>Wallplug Power</td>
<td>MW</td>
<td>582</td>
<td>374</td>
<td>152</td>
</tr>
</tbody>
</table>

## Diagram Description

- **High-rep (50 MHz) electron source**
- **E-damping ring**
- **E-linac (1 TeV/km)**
- **Final Focus**
- **E+ target**
- **E+ linac (1 TeV/km)**
- **E+ damping ring**
- **Auxiliary electron source**
- **E+ preaccelerator**
- **Fiber laser feeds**
- **CEP phase locked network**
- **6 fiber lasers per 6" wafer module 1 kW per laser**
- **Local Oscillator**
- **Thulium fiber laser λ=2 µm**
- **DLA single stage of acceleration**

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**CLIC**

- **Parameter**: Bunch Charge
- **Units**: e
- **Value**: 3.7e9

**DLA**

- **Parameter**: Beamstrahlung E-loss
- **Units**: %
- **Value**: 28.1

**DLA 250 GeV**

- **Parameter**: Enhanced Luminosity / top 1%
- **Units**: cm-2/s
- **Value**: 2.0e34
Exploratory R&D is projected to continue over the next ten years, with the goal of developing few-MeV demonstration prototypes for industrial or medical applications by 2025. A dedicated working group is proposed to proceed in parallel to address challenges specific to a linear collider.

Dielectric Laser Accelerator (DLA) Concept: Towards an “Accelerator on a Chip”

Modelocked Thulium Fiber Laser (λ = 2µm, 10µJ, $300k)

Required lasers are MHz rep rate, low pulse energy, wallplug efficiency ~ 30%

Dielectric materials can withstand GV/m fields and kilowatts of average power

Can be mass produced using techniques of the integrated circuit industry.

SEM images of DLA prototypes tested at SLAC

DLA research aims to produce ultracompact nanofabricated devices for particle acceleration, powered by efficient solid-state lasers.
Highlighted Recent Results: Proof of Concept Experiments

**laser-driven focusing**

Laser


**high gradient (0.3 → 0.85 GV/m)**

Laser


8 MeV electrons


**increased energy gains**

S4800 2.0kV x1.50k SE(M)

Hommelhoff Group, FAU Erlangen, Germany

D. Cesar, et al., Optics Express 26 (22), 29216 (2018)

POC experiments use non-ideal test beams. With microbunching, focusing, and nanotip sources, net acceleration to MeV scale is possible.
Highlighted Recent Results: Towards an MeV-Scale Tabletop Device

**Stanford “shoebox” test system**

- Dual Drive Lasers
- Optimal DLA components via inverse design

- Compact electron gun w/electrostatic lens
  - -32 to -33kV
  - -30kV
  - Ceramic spacer
  - Si tip emitter
  - 3000 e-/pulse, 100 kHz rep rate
  - 0.2 nm emittance

- Prototype e-gun
  - Courtesy T. Hirano (Hamamatsu, visiting scientist at Stanford University)

- Optimized DLA components via inverse design

- Nature Photonics (2019)
Projected ACHIP Parameters (1 vs. 5 Year Time Scale)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Units</th>
<th>Near Term</th>
<th>Longer Term</th>
<th>R&amp;D Improvement Path</th>
</tr>
</thead>
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<tr>
<td></td>
<td></td>
<td>1 Year*</td>
<td>2-3 Years</td>
<td></td>
</tr>
<tr>
<td>Final Electron Kinetic</td>
<td>MeV</td>
<td>1</td>
<td>5</td>
<td>Multi-stage high-gradient relativistic linac</td>
</tr>
<tr>
<td>Energy</td>
<td>MeV/m</td>
<td>73</td>
<td>357</td>
<td>AVM optimization of structure field enhancement</td>
</tr>
<tr>
<td>Peak Unloaded Gradient</td>
<td>MeV/m</td>
<td>73</td>
<td>357</td>
<td>Improved coupling of emitter to DLA</td>
</tr>
<tr>
<td>Trapped MacroBunch Charge</td>
<td>e</td>
<td>9</td>
<td>1511</td>
<td>Upgrade to high-rep rate fiber laser systems</td>
</tr>
<tr>
<td>Bunch repetition rate</td>
<td>MHz</td>
<td>0.1</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td>Laser Pulse Duration</td>
<td>fsec</td>
<td>250</td>
<td>250</td>
<td></td>
</tr>
<tr>
<td>Microbunch Charge</td>
<td>e</td>
<td>0.05</td>
<td>8.3</td>
<td></td>
</tr>
<tr>
<td>Microbunch duration</td>
<td>attosec</td>
<td>260</td>
<td>260</td>
<td></td>
</tr>
<tr>
<td>Microbunches per Train</td>
<td>#</td>
<td>181</td>
<td>181</td>
<td></td>
</tr>
<tr>
<td>Design wavelength</td>
<td>micron</td>
<td>2</td>
<td>2</td>
<td>Confinement in orthogonal (invariant) direction</td>
</tr>
<tr>
<td>Invariant Emittance</td>
<td>nm</td>
<td>0.05</td>
<td>0.10</td>
<td>Improved pre-bunching and injection</td>
</tr>
<tr>
<td>RMS Beam Size X</td>
<td>micron</td>
<td>0.05</td>
<td>0.05</td>
<td></td>
</tr>
<tr>
<td>RMS Beam Size Y</td>
<td>micron</td>
<td>1.00</td>
<td>1.00</td>
<td>Improved efficiency, e.g. laser recirculation</td>
</tr>
<tr>
<td>Electron Capture Efficiency</td>
<td>#</td>
<td>0.21</td>
<td>0.56</td>
<td>(Assumes 1 cm delivery area with dE/dz of Water)</td>
</tr>
<tr>
<td>Electron Channel Width</td>
<td>nm</td>
<td>420</td>
<td>420</td>
<td></td>
</tr>
<tr>
<td>Beam Power</td>
<td>µW</td>
<td>0.2</td>
<td>3657</td>
<td>Upgrade to phase locked fiber lasers</td>
</tr>
<tr>
<td>Delivered Dose</td>
<td>Gy/s</td>
<td>5e-4</td>
<td>1.6</td>
<td></td>
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<tr>
<td>Total Laser Power</td>
<td>W</td>
<td>0.4</td>
<td>478</td>
<td></td>
</tr>
<tr>
<td>Laser Pulse Energy</td>
<td>µJ</td>
<td>3.9</td>
<td>7.5</td>
<td></td>
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<tr>
<td>Geographical Gradient</td>
<td>MeV/m</td>
<td>73</td>
<td>203</td>
<td></td>
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<tr>
<td>Total Linac Length</td>
<td>mm</td>
<td>13</td>
<td>24</td>
<td></td>
</tr>
</tbody>
</table>

*Includes several month setup of new test chambers (“glass” box and Erlangen shoebox).