Dielectric Laser Acceleration

R. J. England (SLAC, Stanford)

ATF Science Planning Workshop
Brookhaven National Laboratory
October 15-17, 2019
Dielectric Laser Accelerator (DLA) Concept: Towards an “Accelerator on a Chip”

Modelocked Thulium Fiber Laser ($\lambda = 2\mu m$, $10\mu J$, $300k$)

- Required lasers are MHz rep rate, low pulse energy, wallplug efficiency $\sim 30\%$

- 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.
Fiber lasers suitable for driving future integrated DLA systems are compact and low-peak power.

**Menlo Systems 2um Fiber Laser**

All polarization maintaining TmHo fiber with free space stretcher/compressor

2050nm, 1 MHz, 10 uJ, 10W average, 400-500fs, $300k

**Demonstrated Fiber MOPA**

**Large Mode Area Fiber Amp**

---

**Opt. monitor**

0.1 nJ

~ 0.4 nJ (4 mW)

~ 10 MHz

20 nJ

0.5 nJ

~ 1 MHz

400 nJ (400 mW)

10 μJ (10 W)

< 800 fs

(~ 400-500 fs typical)
Research lasers employed in university settings provide greater versatility for initial demonstrations.

Stanford ACHIP Laser: Light Conversion Yb:KGW Regen + OPA

- 1W, 1030 nm, 76MHz, 80fs CEP locked oscillator
- 20W, 50-200kHz, 100-400uJ, 290fs Regen
- 2.3W, 100kHz, 23uJ, 250fs 2um Signal from OPA
Global DLA Effort & Funding

Accelerator on a Chip International Program (ACHIP) 2015 to 2020
• 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 - $13.5M / 5 years = $2.7M/year (Moore Foundation, low overhead ~ 12%)
LANL - $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.

Large international effort in this area largely funded by Moore Foundation. Since that program will end in 2020, other funding sources are being explored.
Highlighted Recent Results: Proof of Concept Experiments

**Laser-driven focusing**


**High gradient (0.3 → 0.85 GV/m)**


**Increased energy gains**

Hommelhoff Group, FAU Erlangen, Germany

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

POC experiments use non-ideal test beams from conventional sources. With microbunching, focusing, and nanotip sources, MeV net acceleration is possible.
The components for an integrated 1 MeV shoebox sized accelerator are coming together.

**Stanford “glassbox” test system**

*Stanford “glassbox” test system*

**Compact electron gun w/electrostatic lens**


N. Sapra, et al., in review Science (2019)

**Optimized DLA components via inverse design**

- Splitters
- Couplers

T. Hirano (Hamamatsu, visiting scientist at Stanford University)

- 3000 e-/pulse, 100 kHz rep
- 0.2 nm emittance
- A. Ceballos, Stanford

S. Sapra, et al., in review Science (2019)
Concept for Injector + Multistage Accelerator (2-5 Year)

Thulium Fiber Laser (2μm)

Master Clock

Master Oscillator

CEP phase locked network

Oscillator 0

Oscillator 1

Oscillator 2

Oscillator 3

Oscillator N

Injector/Buncher

50 keV

β ≈ 1

1 MeV

fused silica

MZI Controlled DLA Linac with APF Focus

5-10 MeV
Relativistic vs. Subrelativistic Experiments

Future integrated DLA systems are envisioned to combine sub-relativistic nanotip injector with a relativistic (≥ 1 MeV) energy linac. Conventional DC and RF electron sources provide interim solutions for parallel studies in both regimes.

**Subrelativistic Energy Experiments (e.g. Stanford, Erlangen):**
- Compatible with university optics labs, DC electron sources (30-100 keV)
- Integration with compatible nanotip field emission sources (Si, Diamond, LaB6)
- Low-charge, low-emittance bunches (1 to 1000 e/pulse, < 1 nm emittance)
- Targeting low-current applications e.g. electron diffraction, compact medical

**Relativistic Energy Experiments (e.g. SLAC, UCLA, DESY, PSI):**
- Utilize available high-brightness RF photoinjector electron beams (pC, 1-10 Hz)
- POC demonstrations of fundamental beam dynamics in DLA structures
- Compatibility with SiO₂ and other high damage threshold materials
- Highest gradients and energy gains demonstrated in this energy regime

Relativistic test facilities enable crucial advances in gradient, energy gain, and understanding of beam dynamics with fC bunches.
A 5-Year initiative in DLA has been approved by the Gordon and Betty Moore Foundation (2016 – 2021)

**ACHIP: Accelerator on a Chip International Program**

$13.5M / 5 years

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

**Systems Integration**
(Core DLA Groups)
Stanford: Byer, Harris, Solgaard
Erlangen: Hommelhoff

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

**Light Coupling**
Stanford: Fan, Vuckovic
Purdue: Qi

**Structure Design & Fabrication**
Stanford: Byer, Harris, Solgaard
Erlangen: Hommelhoff

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

**Scientific Advisors**
SLAC: Burt Richter
Stanford: Persis Drell

**Relativistic DLA experiments**
SLAC: England
DESY/UnivHH: Assmann, Kaertner, Hartl
PSI/EPFL: Ischebeck, Frei
Planned Relativistic DLA Experiments: DESY/Hamburg

Main goal at SINBAD: Demonstration of net-energy gain in grating DLAs

Stage 1: Short-bunch beam demonstration

First experiment with ultra-short bunches leveraging the compression techniques available @ ARES

Stage 2: Microbunching + net acceleration

Drive both the energy modulation of a long bunch and the DLA interaction with the same laser to achieve sub-fs microbunches and phase-lock

- Detailed experimental plan developed with simulational support
- Commissioning of DLA test area proceeding with first experiments starting now
- New DLA drive laser for 2um operation being installed with Hartl and Kaertner groups
Planned Relativistic DLA Experiments: PSI/EPFL

Infrastructure for ACHIP experiments at SwissFEL:

- DLA test facility for 3 GeV beam injection
- Electron optics, instrumentation & alignment system
- Laser system to be donated from FAU Erlangen
- Wake effects, FEL seeding, radiation studies

Wake effects

Simulation of e-beam modulation experiment

Asymmetric beta function

Modulation after 1 mm
Planned Relativistic DLA Experiments: UCLA

Experiments at UCLA Pegasus Facility

- High gradient & energy gain (0.85 GV/m, 300 keV) results from FY17 published
- Experiment with 2cm DLA acceleration and > 1 MeV energy gain anticipated to begin Fall FY20
- New laser purchased/installed with ACHIP support
- Flat beam transform optics implemented
- Electron transmission test completed in July 2019

40 mJ, 60fs Ti:Sapphire

Fast oscillation for focusing

Grating
Imaging lens
Programmable Liquid Crystal phase mask (LC-SLM)

Pulse front tilt + phase shaped beam

2cm x 80um DLA

λ/4
Recent UCLA laser upgrade informs the requirements for future relativistic energy DLA experiments

UCLA Pegasus: Continuum Trident X-40-100

- New transport line to bunker installed
- Partially funded by Moore (~ 50 %)
- Specs: 800 nm, 40 mJ – 80 fs, 10 Hz
- Transport in Pegasus bunker in August
- Chirped pulse to avoid non linearities
- Synchronization to RF

Factory Tests

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Measured</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pulse Energy</td>
<td>45 mJ</td>
</tr>
<tr>
<td>Pulse Duration</td>
<td>61 fs</td>
</tr>
<tr>
<td>Central Wavelength</td>
<td>783 nm</td>
</tr>
<tr>
<td>Angle Jitter</td>
<td>1.65 µrad</td>
</tr>
<tr>
<td>$M_x^2$</td>
<td>1.34</td>
</tr>
<tr>
<td>$M_y^2$</td>
<td>1.38</td>
</tr>
</tbody>
</table>

Laser layout schematic
Relativistic Energy DLA Science Thrusts

**Electron beam only:**
- Electron irradiation tests (radiation hardness, charging of dielectrics)
- Transmission testing and “drifting current” wakefield measurements

**Laser only:**
- Materials characterization (laser induced damage threshold, LIDT)

**Electron + Laser:**
- Net acceleration of compressed and/or optically microbunched beams
- High energy gain using a single pulse front tilted laser pulse
- Ponderomotive Focusing and Energy-Gain via phase control of the laser
  - Higher current studies (wakefields, beam loading efficiency, transport, halo)
  - Demonstration of a DLA-based (laser-driven dielectric) undulator

ATF experiments could contribute in multiple areas. Although some efforts (green arrows) are planned at other facilities, ATF’s capabilities would enable unique studies with higher beam currents and relaxed tolerances.
### Desired Beam and Laser Parameters for DLA Experiments at Relativistic Injection Energies

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Demonstration</th>
<th>Ideal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bunch Charge</td>
<td>≤ 1 pC</td>
<td>1-5 fC</td>
</tr>
<tr>
<td>Beam Energy</td>
<td>1 to 100 MeV</td>
<td>-</td>
</tr>
<tr>
<td>Normalized Emittance</td>
<td>≤ 1 µm</td>
<td>1-5 nm</td>
</tr>
<tr>
<td>RMS Spot Size</td>
<td>1 to 10 µm</td>
<td>10 to 100 nm</td>
</tr>
<tr>
<td>Laser Wavelength</td>
<td>1 to 10 µm</td>
<td>1 to 2 µm</td>
</tr>
<tr>
<td>Laser Pulse Length</td>
<td>0.25 to 3 ps</td>
<td>0.1 to 1 ps</td>
</tr>
<tr>
<td>Laser Pulse Energy</td>
<td>0.2 to 30 mJ</td>
<td>1 to 10 µJ</td>
</tr>
<tr>
<td>Rep Rate</td>
<td>1-10 Hz</td>
<td>10-100 MHz</td>
</tr>
<tr>
<td>Energy Spread</td>
<td>2.6e-4</td>
<td>2.6e-4</td>
</tr>
</tbody>
</table>

ATF appears equipped to meet most requirements for demonstration experiments at 10 micron wavelength.
CO$_2$-Laser-Driven Dielectric Laser Accelerator
W. D. Kimura, I. V. Pogorelsky, and L. Schächter

- 10 µm wavelength has many advantages for driving DLAs
  - 10X larger grating dimensions → higher charge, easing of e-beam requirements, reduced fabrication tolerances, easier staging, less wakefield losses

- Can use same CO$_2$ laser to drive IFEL prebuncher to send microbunches into DLA → increases amount of accelerated charge

- Over 10 MeV energy gain in 1-cm DLA possible using ATF 9-GW CO$_2$ laser

- Fe:ZnSe-laser-pumped CO$_2$ laser being developed by ATF
  - Enables considering strawman collider design (10,000 x 1 cm DLA stages)
  - 63 CO$_2$ laser amplifiers operating at 20 kHz delivering 100 pulses resulting in 2 MHz pumping of DLAs

\[
\mathcal{L} = \frac{fN_e^2}{4\pi\sigma^2_\perp} = 10^{34} \text{ s}^{-1}\text{cm}^{-2}
\]

provided $\sigma^2_\perp = 2.5 \text{ nm}^2$

W. Kimura (STI Optronics)– AAC 2018 presentation
Benefits of 10 um DLA Experiments at ATF

10x aperture and 10x angular acceptance → 100x more charge
More effective ponderomotive focusing / smaller resonant defocusing
10 times easier to fabricate structure (but which material?)
Optically pumped CO$_2$ laser for compactness and efficiency
Unique experimental opportunity at ATF. Only facility in the world with high power CO$_2$ laser and relativistic electron beam.
Reliable bunching schemes in place. (Cascaded buncher, N. Sudar PRL 2018)

<table>
<thead>
<tr>
<th>Input energy</th>
<th>50 MeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max output energy</td>
<td>90 MeV</td>
</tr>
<tr>
<td>Charge accelerated</td>
<td>1 pC</td>
</tr>
<tr>
<td>Effective Gradient</td>
<td>1.7 GV/m</td>
</tr>
<tr>
<td>Laser energy</td>
<td>20 mJ</td>
</tr>
<tr>
<td>Laser pulse length</td>
<td>2 ps</td>
</tr>
<tr>
<td>DLA Length</td>
<td>2 cm</td>
</tr>
<tr>
<td>Spot size</td>
<td>5 um</td>
</tr>
<tr>
<td>Emittance</td>
<td>20 nm</td>
</tr>
</tbody>
</table>

Simulation for 5cm structure (75 MeV gain)

Energy distribution

Long. Phase space

W. Kimura and P. Musumeci
### Experiment Timetable for 10 Micron Structure Development and Testing at ATF

**Primary Tasks:**
1. Exploration of MIR-compatible materials (Si, Ge, BaF$_3$, CaF$_2$, GaAs, GaN, etc)
2. Structure fabrication and damage testing (laser only) at ATF
3. POC experiment with a pulse front tilted CO$_2$ laser on a 2cm DLA

<table>
<thead>
<tr>
<th>Work performed at SNF</th>
<th>Year 1</th>
<th>Year 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Procure material samples</td>
<td>Perform preliminary microfabrication test on materials</td>
<td>Fine-tune DLA structure design and fabricate new structures as needed</td>
</tr>
<tr>
<td>Work performed at ATF</td>
<td>Microfabricate DLA structures for DLA experiment</td>
<td>Perform POP DLA experiment</td>
</tr>
<tr>
<td>Test materials using ATF CO$_2$ laser</td>
<td>Test materials using ATF e-beam</td>
<td>Setup POP DLA experiment at ATF</td>
</tr>
</tbody>
</table>

- **Work performed at Technion**: Provide theoretical analysis and modeling support (see Sec. 5.4)

---

Conclusions

Significant progress in DLA over the last 4 years:
- Ongoing 5-year international collaboration funded by Moore Foundation
- Gradients ~ 1 GV/m, energy gain > 0.3 MeV demonstrated
- Prototype “shoebox” demonstration system online at Stanford
- Dedicated ACHIP working group for relativistic energy experiments

Parameters for DLA experiments using RF injectors
- low-charge low-emittance operation (≤ 1 pC, e_N ~ 3 to 100 nm)
- moderate peak-power (20-40 milliJoule)
- laser pulse front tilt and optically microbunched electrons desired

Desirable Features for Experiments at ATF
- 10 µm operation allows relaxed tolerances on structure size, alignment
- high pulse energies would enable extended (10-MeV scale) interactions
- studies of high (pC) charge throughput, beam loading, wake effects
- requires material studies, new structures designed for 10 µm*

*Primary cost hurdle is structure development. Other funding avenues being explored.