Do optical-scale structures make suitable accelerators for colliders?

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on behalf of the MAP Team
Particle Beam Physics Laboratory

This talk is like an act of Congress:
it steals from everyone, gives back to few, and
may have unintended consequences.
NO.
The naysayers lined up to explain why our DLA accelerator could never work

- won’t work
- won’t work at low energies
- can’t build it
- can’t align it
- can’t power it
- can’t get beam into it

A few believers kept the DLA flame going...
"Worth its weight in dielectrics"

GETTING
PAST NO

ACCELERATING IN
DIFFICULT SITUATIONS

Opti Cal
A DLA-based collider requires a new operating regime
High gradient acceleration only does a little to change the demands
Collider costing models favor high gradients but demand high efficiency and low capital costs.

Facility costs scale roughly with power consumption and facility size.

Largest cost driver for a linear collider is the acceleration.
- ILC geometric gradient is \( \approx 20 \text{ MV/m} \rightarrow 50 \text{ km} \) for 1 TeV.

Size of facility is costly
- Higher gradients

ILC Breakdown (2007)

T. Raubenheimer
Conventional facilities designs may not transfer over and we have little experience with km optical scale structures.

NIF & LIGO may be useful guides.
On the other hand, “conventional” collider beam emittances and sizes match well with DLA.
Beamstrahlung and beam disruption favors low charge per bunch...

For flat beams

\[ D \approx 2r_e \frac{\sigma_z}{\gamma\sigma_x\sigma_y} N \]

For \( D << 1 \), we can have luminosity enhancement

Reference beamstrahlung parameter:

\[ \gamma_0 = \frac{r_e \lambda_c}{\sqrt{2\pi} \sigma_r \sigma_z} \frac{\Gamma}{N} \]

complicated interplay... but low \( N \) is generally favored
Efficiency is a concern in any collider.

- Modulators (83%)
- Klystrons (65%)
- Distribution (93%)
- RF Feedback (85%)

Wall-plug 230 MW

Cryo 34 MW

125 MW for acceleration → 18% AC → beam efficiency

51 MW RF Power

RF to beam (62%)

22 MW
Efficiency and beam loading have been considered in optical structures.

Much more work needed
The DLA solves some critical problems. New problems are introduced.

<table>
<thead>
<tr>
<th>Generic Collider</th>
<th>High Gradient (CLIC)</th>
<th>DLA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Need high beam-energy</td>
<td>Higher Gradients</td>
<td>Very High Gradient</td>
</tr>
<tr>
<td>Need ultra-low emittance</td>
<td>-</td>
<td>Ultra low charge and short beams</td>
</tr>
<tr>
<td>Need nm beams &amp; stability</td>
<td>-</td>
<td>Inherently nm scale</td>
</tr>
<tr>
<td>Beamstrahlung</td>
<td>-</td>
<td>Ultra low charge beams</td>
</tr>
<tr>
<td>Efficiency</td>
<td>Two Beam Accelerator</td>
<td>(smoke and) mirrors</td>
</tr>
</tbody>
</table>
Potential DLA-based collider parameters match well to general collider goals

<table>
<thead>
<tr>
<th></th>
<th>ILC Nom.</th>
<th>DLA</th>
</tr>
</thead>
<tbody>
<tr>
<td>E(_{\text{cms}})</td>
<td>1000</td>
<td>1000</td>
</tr>
<tr>
<td>Bunch Charge</td>
<td>2.00E+10</td>
<td>1.00E+04</td>
</tr>
<tr>
<td># bunches/train</td>
<td>2820</td>
<td>375</td>
</tr>
<tr>
<td>train repetition rate</td>
<td>5.00E-06</td>
<td>20</td>
</tr>
<tr>
<td>final bunch length</td>
<td>1.00</td>
<td>1</td>
</tr>
<tr>
<td>design wavelength</td>
<td>230609.58</td>
<td>0.8</td>
</tr>
<tr>
<td>Invariant Emittances</td>
<td>10/0.04</td>
<td>1e-04/1e-04</td>
</tr>
<tr>
<td>I. P. Spot Size</td>
<td>554/3.5</td>
<td>0.5/0.5</td>
</tr>
<tr>
<td>Enh Lumi/ top1%</td>
<td>4.34E+34</td>
<td>4.58E+34</td>
</tr>
<tr>
<td>Beam Power</td>
<td>22.6</td>
<td>6.0</td>
</tr>
<tr>
<td>Wall-Plug Power</td>
<td>104.0</td>
<td>120.1</td>
</tr>
<tr>
<td>Gradient</td>
<td>30</td>
<td>830</td>
</tr>
<tr>
<td>Total Linac Length</td>
<td>33.3</td>
<td>1.2</td>
</tr>
</tbody>
</table>

E. Colby
The choice of accelerator technology impacts the size and nature of the beam produced...

Breakdown limits metal:

\[ E_s = 220(f[\text{GHz}])^{1/3} \text{ MV/m} \]

<table>
<thead>
<tr>
<th></th>
<th>RF</th>
<th>Optical</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gradient</td>
<td>10-100 MeV/m</td>
<td>1-10 GeV/m</td>
</tr>
<tr>
<td>Energy gain per period</td>
<td>1 MeV</td>
<td>1 keV</td>
</tr>
<tr>
<td>Repetition Rate</td>
<td>100 Hz</td>
<td>10-100 MHz</td>
</tr>
<tr>
<td>Charge per Bunch</td>
<td>0.1 - 1+ nC</td>
<td>10 - 100 fC</td>
</tr>
<tr>
<td>Bunch Length</td>
<td>1-100 ps</td>
<td>&lt;1-10 fs</td>
</tr>
</tbody>
</table>

\[ E_{\text{acc}} \sim \frac{P_{\text{rf}}}{\lambda} \]

key: charge and time scale; not gradient
A Livingston-like plot of the number of cavities shows exponential growth over design iterations.
Optical structures naturally have sub-fs time structures and favor high rep. rate operation.

- Optical structures have sub-femtosecond (fs) time structures.
- They favor high repetition rate operation.

**Fill Time**
- Micropulse: 1 ps
- Macropulse: 1-5 ps

**Laser Cycle**
- 3.3 fs
- Charge capture: < 1 fs

**Emission Time**
- 100-1000 ns (1-10 MHz)

**Pulse Duration**
- Micropulse: femtosec
- Laser Pulse: picosec
- Emitter Pulse: nanosec
Of available power sources at wavelengths shorter than microwaves, lasers are the most capable. The lack of sources, materials and fabrication technology force us to make a leap from Microwave to Optical.
A variety of optical-scale dielectric structures are under consideration.

PBG-fiber-based structures afford large apertures and length-scalability.

~2.5 GV/m

Planar structures offer beam dynamics advantages as well as ease of coupling power.
The MAP structure consists of a diffractive optic coupling structure and a resonant cavity.

For gap $a$ and dielectric $b-a$ idealized resonance:

$$\cot \left( k_z \sqrt{\varepsilon - 1} (b - a) \right) = k_z a \sqrt{\varepsilon - 1} / \varepsilon$$

Tuning: control “matching” layer $(b-a)$.

$$E_z = E_0 \cos(\omega z / c)$$
The MAP is a moderate-to-low Q structure which matches well with existing laser technology.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Laser wavelength</td>
<td>800nm</td>
</tr>
<tr>
<td>Cell length</td>
<td>800nm</td>
</tr>
<tr>
<td>Effective gradient</td>
<td>1.5 GeV/m</td>
</tr>
<tr>
<td><strong>Quality factor Q</strong></td>
<td><strong>800</strong></td>
</tr>
<tr>
<td>Effective shunt impedance R</td>
<td>2000 ohms</td>
</tr>
<tr>
<td>Effective shunt impedance per unit</td>
<td>2.0833 ohms</td>
</tr>
<tr>
<td>R/Q</td>
<td>2.5 ohms</td>
</tr>
<tr>
<td>R/Q per unit</td>
<td>0.0026 ohms</td>
</tr>
<tr>
<td>Transit factor</td>
<td>0.86</td>
</tr>
<tr>
<td>Stored energy</td>
<td>0.9 mJ</td>
</tr>
<tr>
<td>Power dissipation</td>
<td>&lt;1% (0.75 MW)</td>
</tr>
<tr>
<td><strong>Fill time</strong></td>
<td><strong>0.5 ps</strong></td>
</tr>
<tr>
<td>Laser intensity</td>
<td>100 MW</td>
</tr>
<tr>
<td>Laser pulse length</td>
<td>1.8ps</td>
</tr>
<tr>
<td>Energy gain per unit cell</td>
<td>~2.5keV</td>
</tr>
</tbody>
</table>
The laser-powered MAP can provide relativistic electron beams in an optical-scale device.

- Easy power coupling
- "Easy" to scale & stage
- Flat beams
- Low wakefields

>50µm
MAP simulations are now including acceleration, beam dynamics and material properties.

**Resonant Fields (@ t = 7 ps)**
- Incident laser

**Input laser source**
- can correspond to actual Ti:Al₂O₃ laser

**Energy Distributions**

**Energy Gain**
Thousand period structures—mm long and ~1 MeV gain—are now being produced.
Beam testing has begun at SLAC’s E163 facility which hosts a suite of micro accelerator tools.
An energy spectrometer is capable of separating transmitted from scattered electrons. Structure causes energy loss (dE/dx) to misaligned particles. No structure at IP. E-163 PMQs.
A “Dummy Structure” and mount was designed for beam transmission studies.

Glass dummy structure

Slot in dummy structure (not to scale)

Aluminum holder for glass structure
For the first time, beam was transmitted through the optical-scale structure!

**Bunches from NLCTA Beamline**

Spot size = 96 x 83 µm²  
$\varepsilon_x = 43$ µm-rad  
$\varepsilon_y = 24$ µm-rad

- Electrons that lost energy while traveling through glass
- Electrons that made it through slot

- Theoretically, we expect peaks to be separated by 0.5 MeV
- With calibration of 1.776 KeV/pixel, we find separation of 0.337 MeV

Data analysis is ongoing
Just one more thing...
(three, really)
1. an all optical $\gamma\gamma$ collider?
A MAP-based **undulator** structure has been designed. For \( E = 3 \text{ GV/m} \), \( B_{\text{eqv}} = 10 \text{ Tesla} \).
A hard x-ray light source powered entirely by lasers and on a laptop scale will be a **Quantum FEL**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Optical Und.</th>
<th>Conventional</th>
</tr>
</thead>
<tbody>
<tr>
<td>FEL Wavelength</td>
<td>~0.1 Å (10 keV)</td>
<td></td>
</tr>
<tr>
<td>Beam energy</td>
<td>10s MeV</td>
<td>100s MeV</td>
</tr>
<tr>
<td>Emittance (norm.)</td>
<td>0.06 µm</td>
<td></td>
</tr>
<tr>
<td>Current</td>
<td>2000 A</td>
<td></td>
</tr>
<tr>
<td>Charge</td>
<td>1 fC (whew! ~10⁴ e⁻)</td>
<td></td>
</tr>
<tr>
<td>FEL Parameter (ρ)</td>
<td>10⁻⁵</td>
<td>10⁻³</td>
</tr>
<tr>
<td>Undulator parameter</td>
<td>10⁻³</td>
<td>~1</td>
</tr>
<tr>
<td>Undulator period</td>
<td>1-20 µm</td>
<td>1 cm</td>
</tr>
<tr>
<td>Saturation length</td>
<td>~10 cm</td>
<td>~1 m</td>
</tr>
</tbody>
</table>

because \( \frac{\hbar \omega}{E} \approx 6 \times 10^{-4} \)

one photon emitted recoils > FEL bandwidth, \( \rho \)
2. a High-Q MAP
It may be possible to create a fully integrated optical accelerator and laser.

Vacuum slots cut into a monolithic structure allow for very low losses.

High Q = ns fill times & kw peak power needs

A diode laser naturally provides long pulses of moderate power.
3. an ultra-low beta MAP
Using slow-light techniques, we may accelerate heavier particles such as protons and muons.

Coupled cavity WGs are a periodic chain of microcavities in which light propagation is realized by tunneling from one cavity to another. Group velocities of $c/100$ are possible.

A MAP based on these concepts is being designed for the acceleration of heavy charged particles.
We have the opportunity to develop a suite of on-chip particle beam tools

- guns
- sub-relativistic structures
- undulators
- monolithic structures
- muons, protons, ions
- coherent THz/x-ray sources
- IFEL accelerator
- deflecting cavities
- focusing
- ultra-fast sources
- ICS Gamma-Ray Source

all using laser-driven dielectric structure
Do optical-scale structures make suitable accelerators for colliders?

YES
The road to a viable DLA-based accelerator for colliders is still long. Drivers (and funders) wanted.

- reliable many-period acceleration
- tolerances & alignment
- beam manipulation
- injection
- positrons
- polarized beams
- radiation damage
- thermal management
Acknowledgments

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      Josh McNeur (Grad - Simulations)
      Esperanza Arab (Staff - Engineering)
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