Diamond field emitter array cathodes and possibilities for employing additive manufacturing for dielectric laser accelerating structures

Evgenya I. Simakov, Heather L. Andrews, Matthew J. Herman, Kevin M. Hubbard, and Eric Weis

Los Alamos National Laboratory

AAC2016

August 2nd, 2016
Outline

- Motivation: customers for compact accelerators
- LANL’s technologies for laser acceleration
- DFEA cathodes
- Additive manufacturing of micron-size structures
- Conclusions and plans
Motivation
Customers for compact accelerators

National Security: DARPA, DTRA, NA-22

Basic science: ➔

Medicine:
Big problem: accelerators today

Accelerator:

10-30 MV/m

Klystrons:

10 MW each
LANL’s technologies
Cathodes and structures for dielectric laser accelerators
Diamond field emitter array (DFEA) cathodes
Diamond field emitter arrays

- Exquisitely sharp diamond pyramids.
- Current > 1 A/mm².
- Emittance < 1 mm*mrad.
- Photoemission never studied. **Should produce more current with smaller emittance.**

We measured ~20 µA currents emitted by single diamond pyramids.
Limits for achievable currents

<table>
<thead>
<tr>
<th>Field emission cathodes</th>
<th>Field emission in DFEAs</th>
<th>Photoemission (space charge)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10 A/cm²</td>
<td>100 A/cm² = 0.1 mA per 10 µm square</td>
<td>( \varepsilon_0 E/\tau = 10^6 \text{ A/cm}^2 = 1 \text{ A per } 10 \text{ µm square} )</td>
</tr>
</tbody>
</table>

Will quantum efficiency and laser power limit the current?
Example: 193 nm ultraviolet laser
- Wavelength 193 nm (6.4 eV), energy 200 mJ, pulse length 20 ns.
- Focus down to 5 mm x 5 mm.
- 40 W (40 x 6.3 x 10^{18} \text{ eV/s}) in 10µm x 10µm (4 x 10^{19} photons).
- QE is unknown, depends on doping, surface, etc.


- With QE \sim 10^{-3} we get 4 x 10^{16} electrons/emitting surface/s
- 3 mA per 10 µm square

1 A peak current = 10 fC/bunch
**Emittance requirements**

Beam emittance: $0.1 \text{ mm} \cdot \text{mrad} = 100 \text{ nm}$
Transverse size: $10 \, \mu\text{m}$
Angular divergence: $10 \, \text{mrad}$
Travel distance: $1 \, \text{mm}$
Accelerating gradient: $1 \, \text{GV/m}$
Total energy: $1 \, \text{MeV}$
Dedicated cathodes research facility at LANL

- Dedicated DFEA cathodes testing chamber.
- New emittance measurement test stand with $<0.1 \text{ mm}^2\text{mrad}$ resolution built by Nathan Moody (WG5, Tuesday, 10:30 am).
Additive manufacturing of micron-size structures
Nanoscribe Professional GT

Installation occurred October 20th - 23rd 2015.

- 3D laser lithography system
- Resolutions down to 100 nm (highest resolution commercially available)
- Print areas as large as 100 x 100 mm
- 2-photon exposure of common positive-tone photoresists

Print of a LANL designed, greatly scaled down, NIF Cepheus mirror physics package holder. Imaged with CT scan.
Fabrication of woodpile structures

- Nanoscribe system is perfectly suited to print wood-pile structures on a micron scale.
- **Work has already started, supported by LDRD Reserve.**
- MST Division recognizes risks and payoffs associated with this proposal and assigned a mentor (Markus Hehlen) to oversee the project and ensure success.
## Accuracy studies

<table>
<thead>
<tr>
<th>Printing Parameters</th>
<th>Measurement Image</th>
<th>Nominal Dimension</th>
<th>Realized Dimension</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Power: 35%</strong>&lt;br&gt;<strong>Speed: 5000 µm/s</strong></td>
<td>![Image]</td>
<td>9.010 µm 9.021 µm</td>
<td>9.905 µm 9.551 µm</td>
</tr>
<tr>
<td><strong>Power: 40%</strong>&lt;br&gt;<strong>Speed: 5000 µm/s</strong></td>
<td>![Image]</td>
<td>9.010 µm 9.021 µm</td>
<td>9.770 µm 9.271 µm</td>
</tr>
<tr>
<td><strong>Power: 45%</strong>&lt;br&gt;<strong>Speed: 10,000 µm/s</strong></td>
<td>![Image]</td>
<td>9.010 µm 9.021 µm</td>
<td>9.898 µm 9.503 µm</td>
</tr>
</tbody>
</table>
3D printing with composite materials

Use Nanoscribe to print a composite material

10% w/w BaTiO$_3$ in Acrylic Resin
150 µm × 30 µm blocks

Assess the suitability of printable materials for DLA application

<table>
<thead>
<tr>
<th>Material</th>
<th>$\varepsilon'$ (1000 cm$^{-1}$)</th>
<th>$\varepsilon''$ (1000 cm$^{-1}$)</th>
<th>$\varepsilon'$ (2000 cm$^{-1}$)</th>
<th>$\varepsilon''$ (2000 cm$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acrylic</td>
<td>2.2</td>
<td>0.1</td>
<td>2.1</td>
<td>&lt;0.01</td>
</tr>
<tr>
<td>BaTiO$_3$ Crystal</td>
<td>2.79</td>
<td>0.15</td>
<td>4.75</td>
<td>0.05</td>
</tr>
<tr>
<td>Composite</td>
<td>2.3</td>
<td>0.4</td>
<td>3</td>
<td>&lt;0.1</td>
</tr>
</tbody>
</table>
Measuring dielectric properties of new materials

We prepared some test coupons to be taken to CINT-Sandia and analyzed with Mid-IR ellipsometry.

SEM Micrographs of BTO-VeroClear Composite

Photograph of a test coupon with reflected light source
Materials development strategy


Population:
Highly polarizable
Photopolymerizable

Down-Selection → Synthesis → Determine $\varepsilon'$, $\varepsilon''$
Conclusions and plans
Conclusions and future plans

- LANL is funded to do dielectric accelerator research starting in FY17.
- Preliminary studied identified DFEA cathodes as promising sources for DLAs: high beam current and small emittance.
- Additive manufacturing with Nanoscribe Professional GT can produce structures with the right scale features for a DLA operating at micron wavelengths:
  - Fabrication tolerances need to be studied.
  - DLAs require new materials.
- We start in October and welcome collaborations!
  - DLA experiment with a beam produced by the DFEA cathode with field emission.
  - Demonstration of photoemission from DFEAs.
  - New structures to print and test.