High Accuracy Adaptive (transverse) Laser and Electron Beam Shaping

...and a bit about DC gun emittance vs. gun gap

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ERL 2015, BNL
I. Motivation: Why do you want from your laser shaper?

II. Methods for transverse laser shaping

III. Adaptive electron beam shaping with a spatial light modulator.
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Motivation: simulation vs. expt.

Cornell Photoinjector, 9 MeV, 1.3 GHz (50 MHz)

Use MOGA to determine optimum laser distribution + beamline settings:

Motivation: simulation vs. expt.

Can it be demonstrated experimentally?

Data courtesy of Colwyn Gulliford.
Motivation: simulation vs. expt.

Can it be demonstrated experimentally?

Most of the optimal front dominated by thermal emittance!

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What have we missed?

Model captures everything but the **transverse laser shape**!

(longitudinal shape well modeled)

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What have we missed?

Model captures everything but the transverse laser shape!

By and large, yes!

Data courtesy of Colwyn Gulliford.
• Now, force the optimizer to use the actual measured beam transverse profile!

Need high accuracy transverse laser shaping to obtain optimal emittance!

Data courtesy of Colwyn Gulliford.
• Previous optimizations: want something accurate!
• Practical aspects of laser shaping: Want something adaptive.
• Quantum Efficiency of cathodes has spatial variation (from growth)

Cornell grown NaKSB

• QE damaged during high current operation. Laser shaping could “fill” in the holes!

CEBAF GaAs cathode: 3 offset laser spots used.

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   • Want something accurate and adaptive.
   • Would be nice if it were efficient, too!

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I. Methods for transverse laser shaping
   - We have tried lots of things:
     - Commercial, cheap shapers exist, not generally adaptive
     - Deformable mirror? (H Tomizawa, Quantum Electronics, 2007) \(\rightarrow\) not accurate enough.

I. Adaptive electron beam shaping with a spatial light modulator.
• **SMALL** array of electronically controlled LCs
  – 20 um pixel pitch!
  – 95% fill factor
• Each pixel is capable of applying a different phase delay $\phi_{ij} \sim \phi(x, y) \in [0, 2\pi]$ to linearly polarized light
• **Thermal** damage threshold roughly 1 W/cm$^2$
• Can function as a:

  Generalized lens (refractive shaper):
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\theta = \frac{1}{k_0} \nabla \phi(x, y)
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Liquid Crystal SLMs

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  \[
  \theta = \frac{1}{k_0} \nabla \phi(x, y)
  \]
  Not terribly accurate... Not lossy.

  **Phase grating** (diffractive shaper):
  Very accurate! Lossy.

HPK Photonics
**Liquid Crystal SLMs**

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- Can function as a:
  - Liquid Crystal SLMs
  - HPK Photonics
  - Generalized lens (refractive shaper)
  - Phase grating (diffractive shaper)
  - Polarization rotator (shaping via tunable masking)

\[
\theta = \frac{1}{k_0} \nabla \phi(x, y)
\]

Phase profile

More or less accurate? More or less lossy?

\( \lambda = 532 \text{ nm} \)

\( \varphi = 0 \)
Examples from the 3 methods

**Refractive Shaping**
- Constructed a new algorithm to compute adaptive refractive phases for non-ideal profiles.
- Even still, not accurate enough (but very efficient! ~ 90%)

J Maxson et al., Applied Physics Letters 105, 171109 (2014);
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Diffractive Shaping
- Iterative FT transform to calculate phases
- Throws out light
- Current technology limits the discontinuity of phase
- Hard (not impossible) to predict efficiency beforehand.

Changing input and output beam size

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**Polarization Subtractive Shaping**
- Simple to setup, compute phase
- Efficiency matches simple estimates
- Nearly as accurate as the diffractive method!

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Shaped lasers -> Shaped e-beams

DC 532 nm laser input (no space charge)

J. Maxson et al., PRSTAB 18, 023401 (2015)
Shaped lasers $\rightarrow$ Shaped e-beams

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(Cartoon of) Cornell Segmented 400 kV Gun

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Shaped lasers->Shaped e-beams

Start by pre-shaping the laser, and performing error correction

J. Maxson et al., PRSTAB 18, 023401 (2015)

DC 532 nm laser input (no space charge)
Imaging the Electrons

(a) Unshaped Laser Profile
(b) Output Before Feedback
(c) After 7 Feedback iterations

Send to gun

Z = 254 cm

Z = 38 cm

Z = 0

-300 kV

50 mm
Imaging the Electrons

- Transmit previous flattop to the photocathode.
- Electron beam output: Both QE and the laser are flat.

J. Maxson et al., PRSTAB 18, 023401 (2015)
Imaging the Electrons

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But our circle isn’t circular anymore.

Stray quadrupole field (not solenoid).

J. Maxson et al., PRSTAB 18, 023401 (2015)
Electron beam feedback

- We can account for stray field (and solenoid rotation) by measuring the coordinate transformation between the SLM and the viewscreen.

Knowing this, we can feedback directly on the e-beam. Never image the photons!

Never directly images the laser
Accounts for any QE variation!
• A few additional demonstrative shapes:
Detailed Shapes

A: Laser Target

J. Maxson et al., PRSTAB 18, 023401 (2015)
Detailed Shapes

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Detailed Shapes

A: Laser Target

B: Laser Final

C: Electron Beam

J. Maxson et al., PRSTAB 18, 023401 (2015)
Detailed Shapes

- Back to preshaping the laser: try something harder!

- Sharp features are well preserved!

J. Maxson et al., PRSTAB 18, 023401 (2015)
- e-beam establishes an extremely precise relationship between the SLM → photocathode → viewscreen
- We can both account for (measure!) electron aberrations and QE variations.
Conclusions

• High accuracy, adaptive laser transverse profiles boost brightness and operational stability for high current accelerators.

• SLMs operating in the polarization subtraction mode well-suited for photoinjector shaping.

• Accurate, adaptive electron transverse electron beam distributions are a reality.
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  – Vacuum: Yulin Li, Xianghong Liu, Brian Kemp, Tobey Moore
  – Fellows grads: Colwyn Gulliford, Siddharth Karkare, Hyeri Lee
  – Many, many more among CESR and CHESS!
...a bit about DC gun emittance vs. gap
Cornell MKII Gun: Segmented

Fields at 750 kV
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Fields at 750 kV
Fields at 750 kV

Mechanical Design: Karl Smolenski, Bruce Dunham
Cornell MKII Gun: Segmented

Fields at 750 kV

Clean room assembly: treat the gun like an SRF cavity!

Mechanical Design: Karl Smolenski, Bruce Dunham
A movable anode

- A moveable anode provides an adjustable photocathode field.

Mechanical Design: Xianghong Liu
HV Performance

J. Maxson et al., RSI 85, 093306 (2014)

Stability test with various gaps:

P. Slade, The Vacuum Interrupter, CRC Press, 2008

\[ V(kV) = 58 \times s(mm)^{0.58} \]

\[ V(kV) = 123 \times s(mm)^{0.34} \]
HV Performance

J. Maxson et al., RSI 85, 093306 (2014)

Stability test with various gaps:

- Discharge Rate (per min)
  - 50 mm gap
  - 30 mm gap
  - 35 mm gap
  - 40 mm gap


Recent Result from KEK

\[
V(kV) = 58s(mm)^{0.58}
\]

\[
V(kV) = 123s(mm)^{0.34}
\]
HV Performance

J. Maxson et al., RSI 85, 093306 (2014)

Stability test with various gaps:

- Surprisingly good agreement between different HV systems.
- But what configuration is best for the beam emittance? –Turn to simulations.

P. Slade, The Vacuum Interrupter, CRC Press, 2008
DC gun, various gaps

- Choose 3 Cornell style guns as the injector source → use MOGA
  - 500 kV: 70mm
  - 450 kV: 50 mm
  - 400 kV: 30 mm

DC gun, various gaps

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• Optimize these 3 w.r.t. emittance, fix only the gun voltage and $MTE = 120 \text{ meV}$. Vary everything else.

• Scan the charge up to 500 pC
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Approaching thermal emittance!
How about the core emittance?

- Higher Field $\rightarrow$ Smaller laser spot size
- 30 mm gap has superior emittance performance up to $\sim 150$ pC in Cornell Injector.
- (Smaller core emittance, equal 100% emittance)
- Core emittance is a strong invariant. (RMS emittance is not.)

\[
\epsilon_{cnx} = \frac{1}{4 \pi \rho_{max}}
\]

J. Maxson et al., RSI 85, 093306 (2014)
- DC gun experimental beamline:
• Birefringent temporal shaping crystals + downstream linear polarizer?

Temporal profile with polarizer (SLM), measured with deflection cavity.

Requires tweaking of crystal angles, but a reasonable flattop is possible.

50 Mhz, q = 0
25 ps rms (5 crystals)

Linear polarizer ok!