High Accuracy Adaptive (transverse) Laser and Electron Beam Shaping

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

Jared Maxson
Cornell University

ERL 2015, BNL

Outline

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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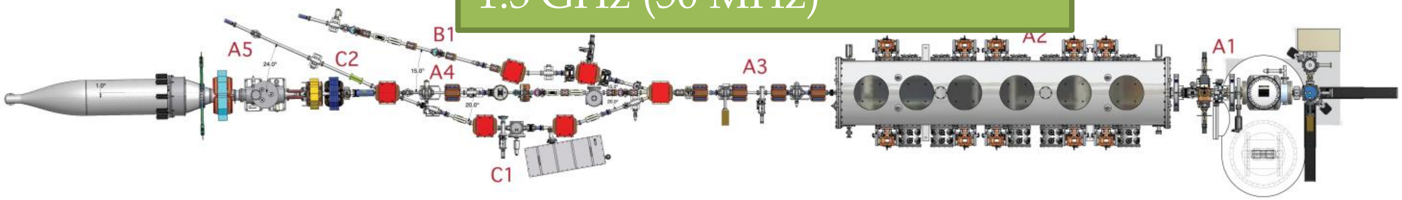
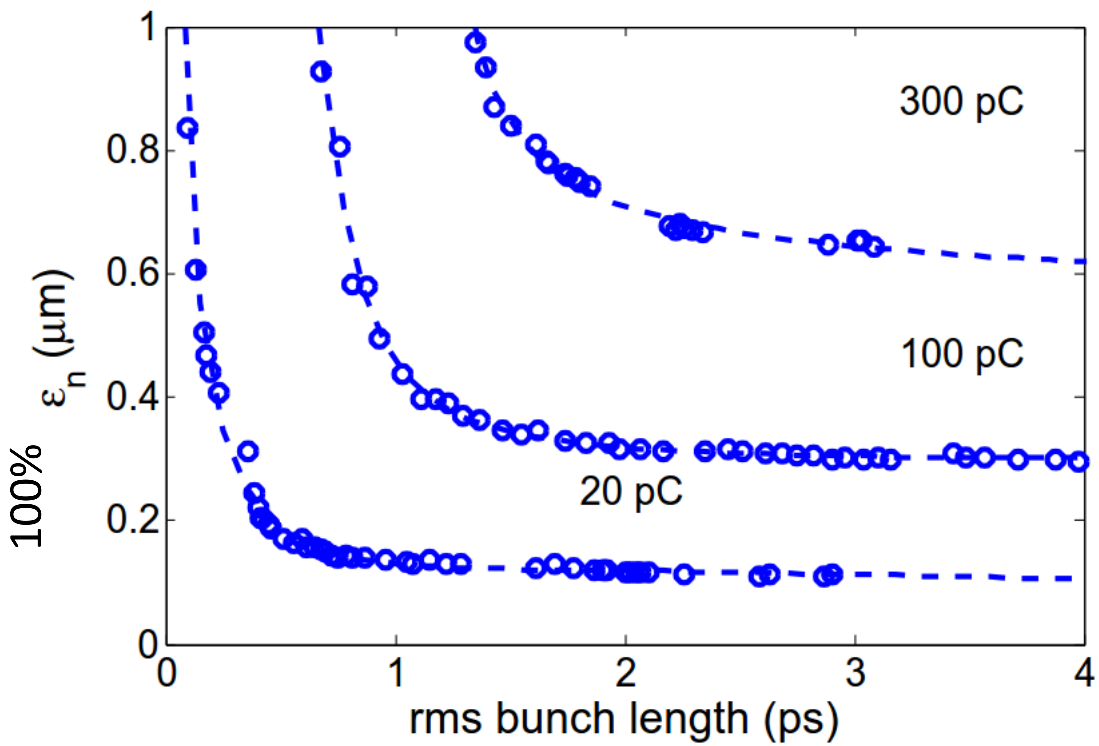
Motivation: simulation vs. expt.

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



Use MOGA to determine optimum laser distribution +beamline settings:



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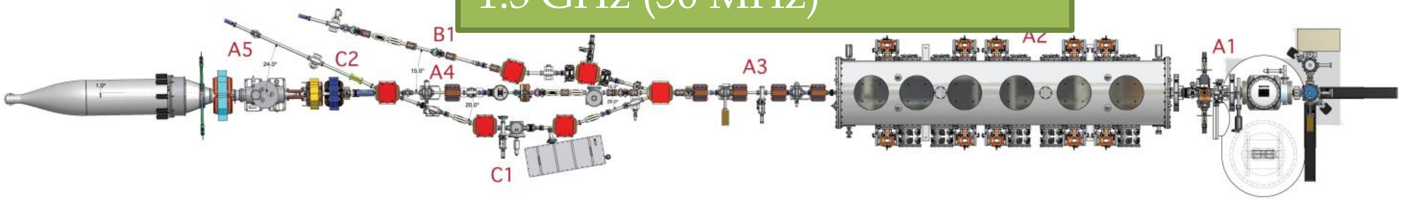

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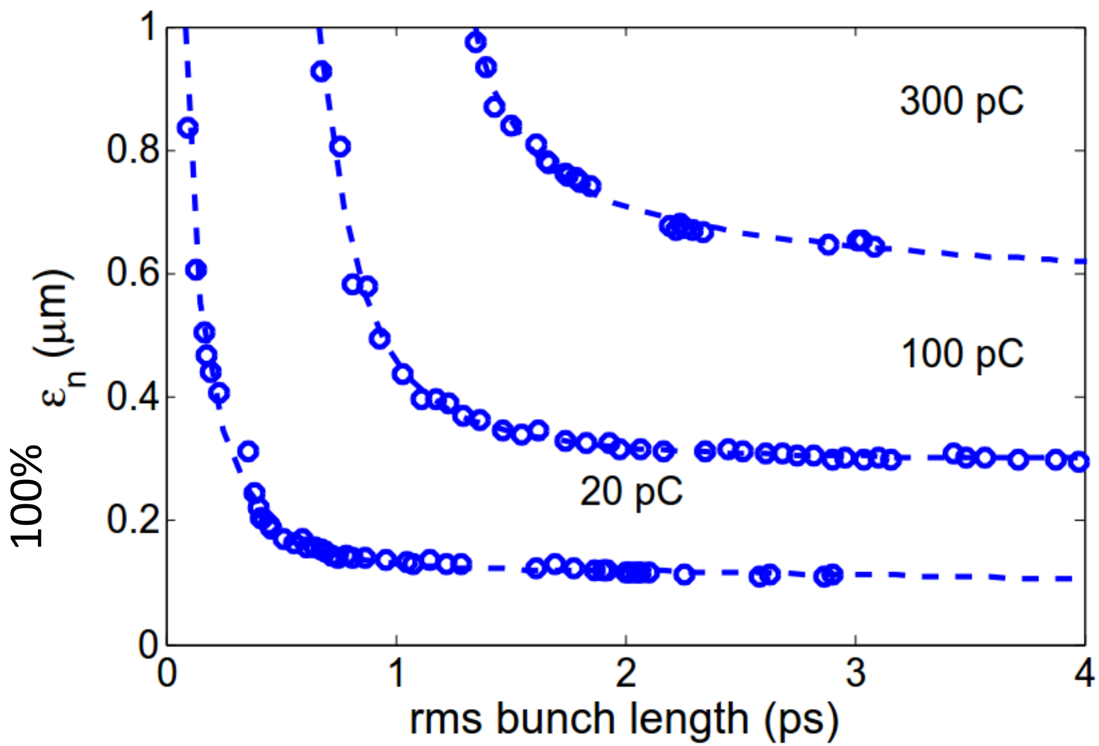

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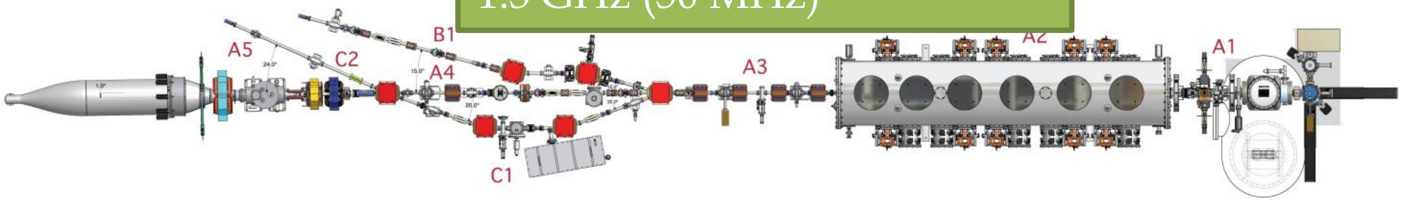

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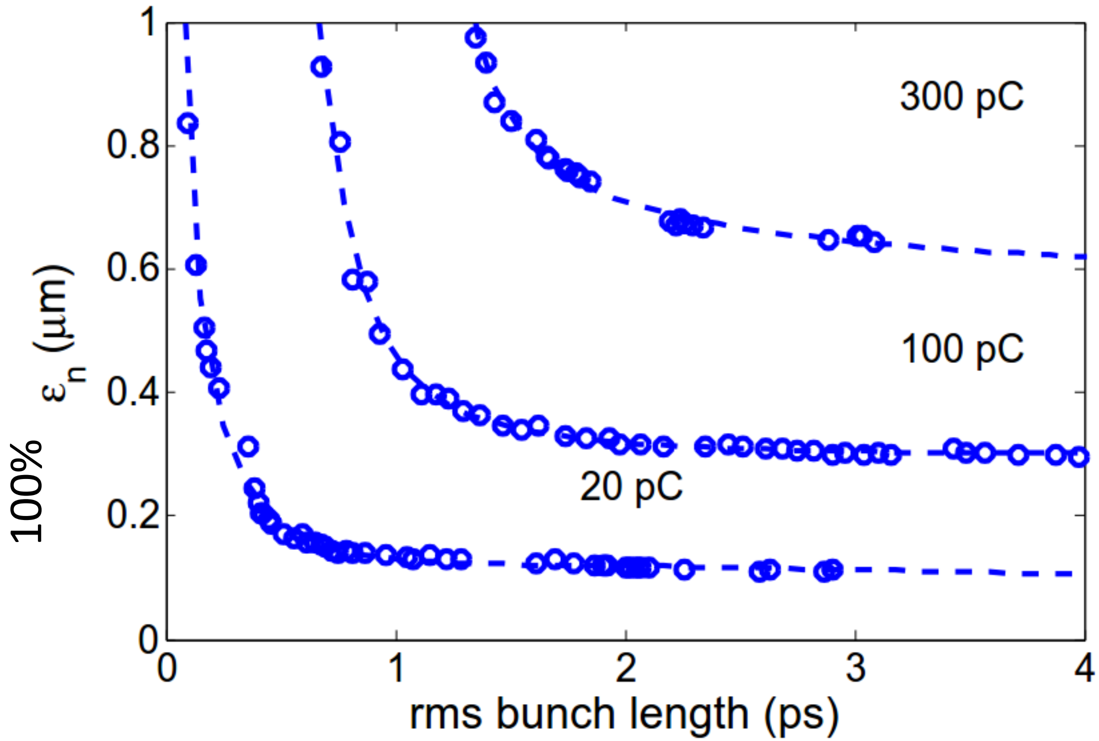

Most of the optimal front dominated by thermal emittance!

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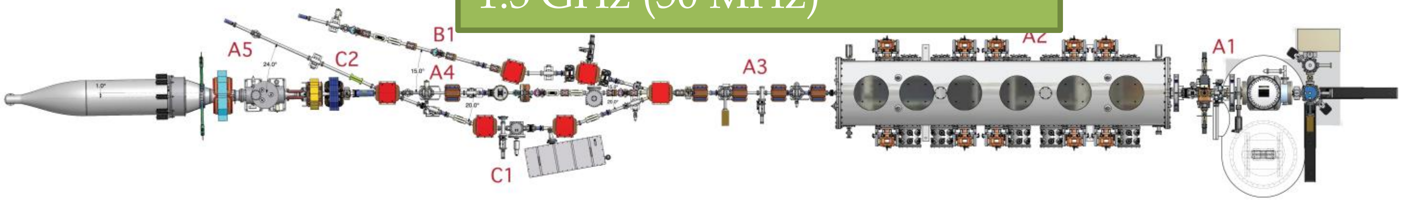

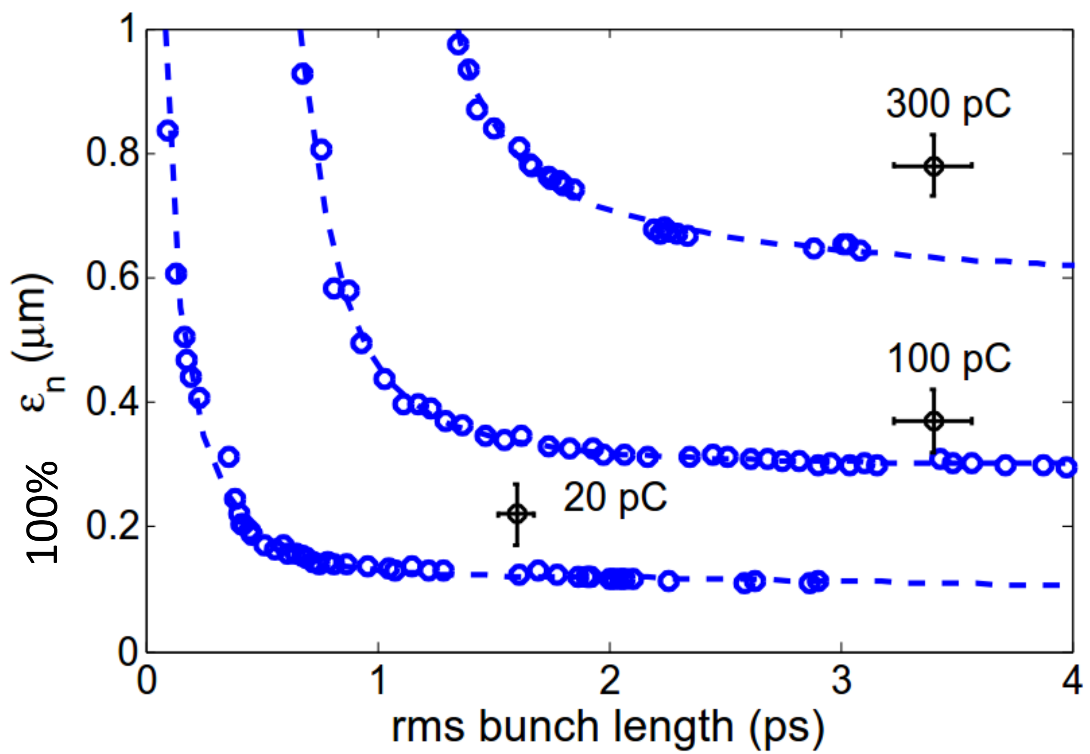

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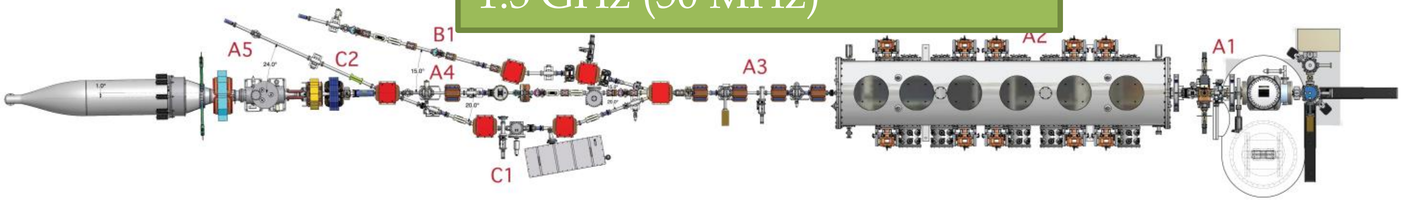

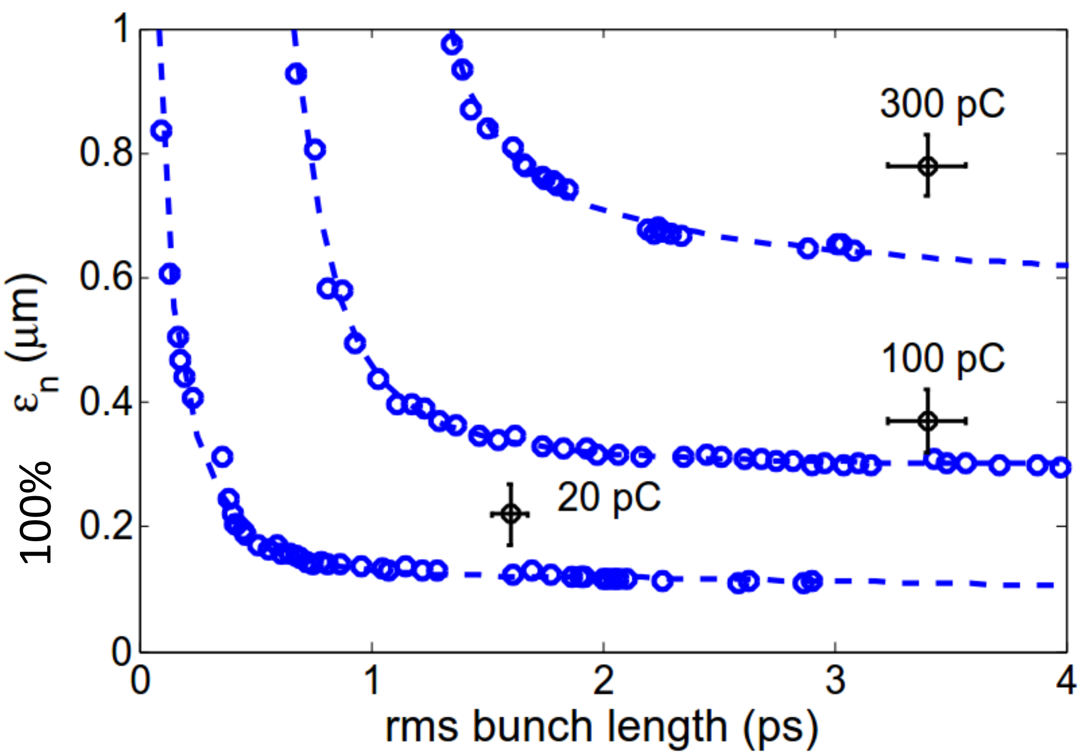

What have we missed?

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

(longitudinal shape well modeled)

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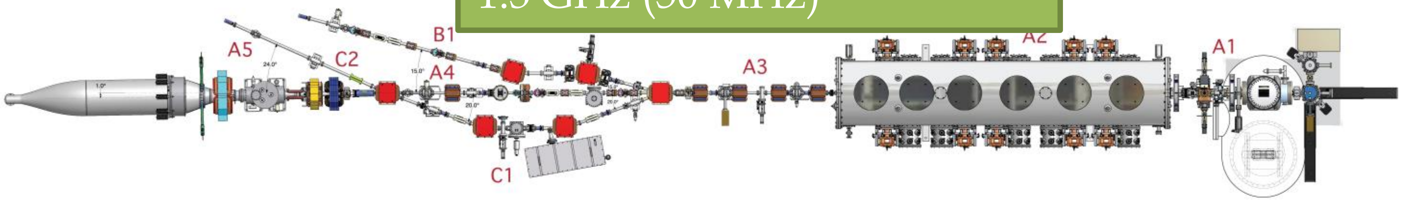

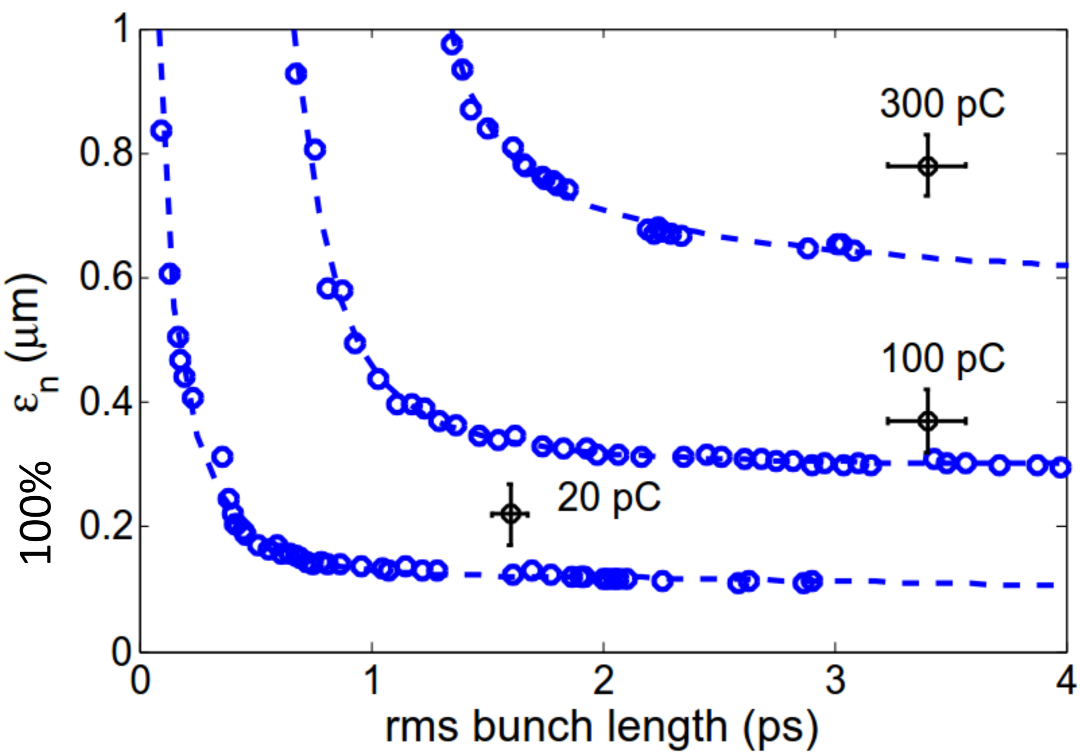

By and large, yes!

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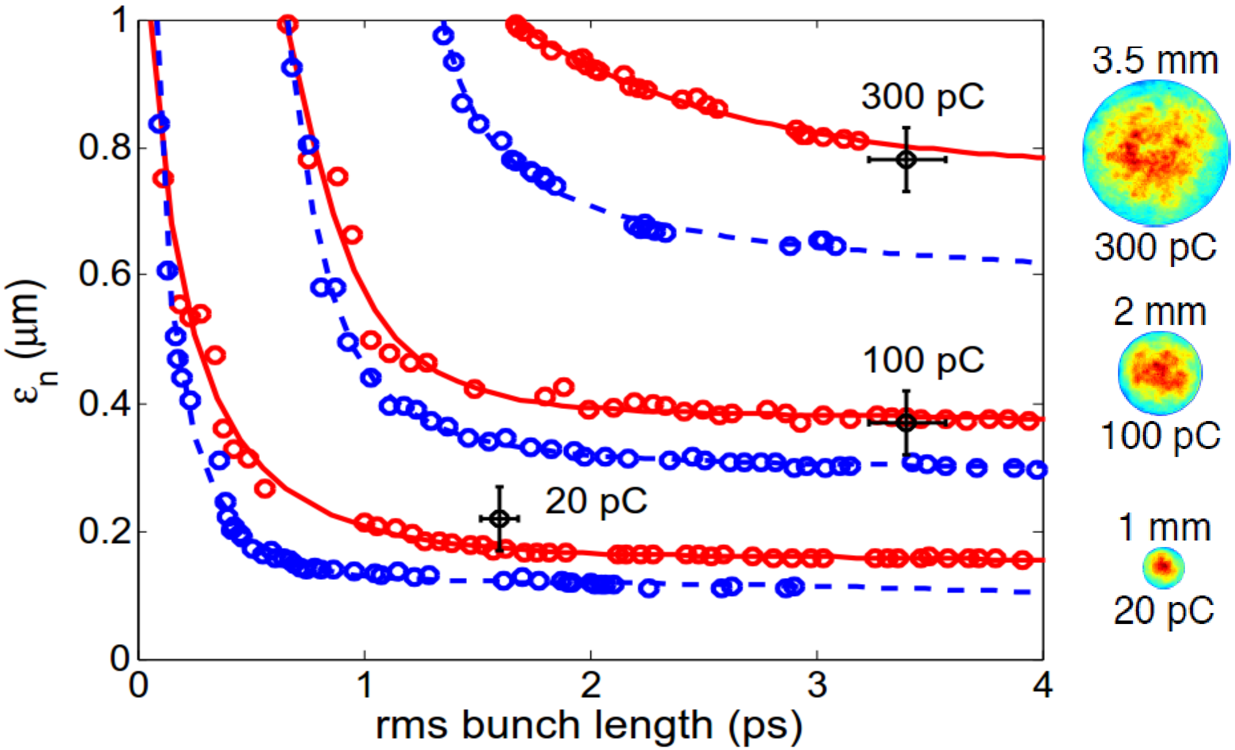
Optimization vs. Reality

- Now, force the optimizer to use the actual measured beam transverse profile!

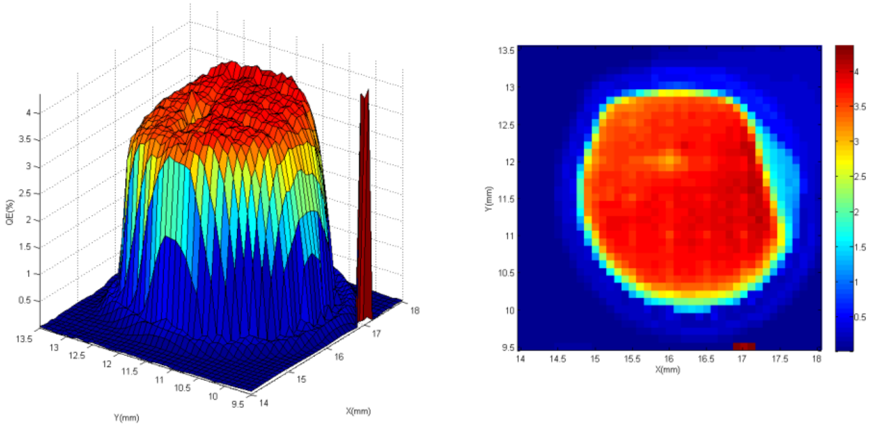


Need high accuracy transverse laser shaping to obtain optimal emittance!

Data courtesy of Colwyn Gulliford.
C. Gulliford et al., Appl. Phys. Lett. **106**, 094101 (2015)

What do you want out of your laser shaper?

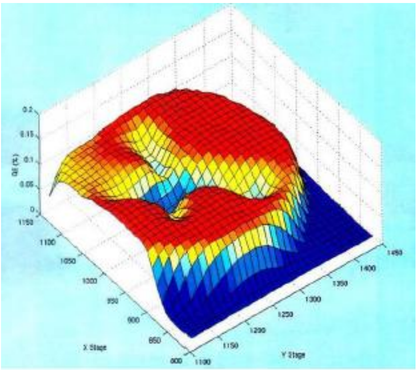
- **Previous optimizations: want something accurate!**
- **Practical aspects of laser shaping: Want something adaptive.**
- Quantum Efficiency of cathodes has spatial variation (from growth)



Cornell grown NaKSb

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

CEBAF GaAs cathode:
3 offset laser spots used.



J. Grames, AIP Conf. Proc. 980 (Vol. 110), 2007

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

I. Methods for transverse laser shaping

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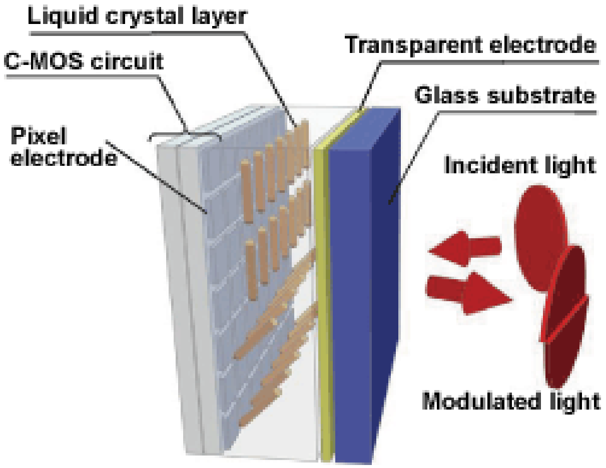
- We have tried lots of things:
  - Commercial, cheap shapers exist, not generally adaptive
  - Deformable mirror ? (H Tomizawa, Quantum Electronics, 2007) → not accurate enough.

I. Adaptive electron beam shaping with a spatial light modulator.

Liquid Crystal SLMs

- *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 $1\ \mathrm{W/cm^2}$
- Can function as a:



HPK Photonics

Generalized lens (refractive shaper):

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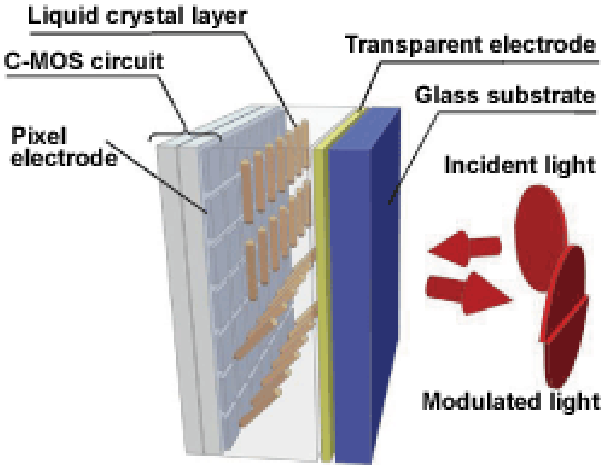

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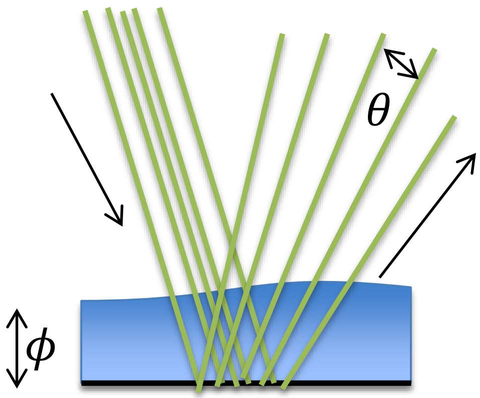

Not terribly accurate… Not lossy.

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

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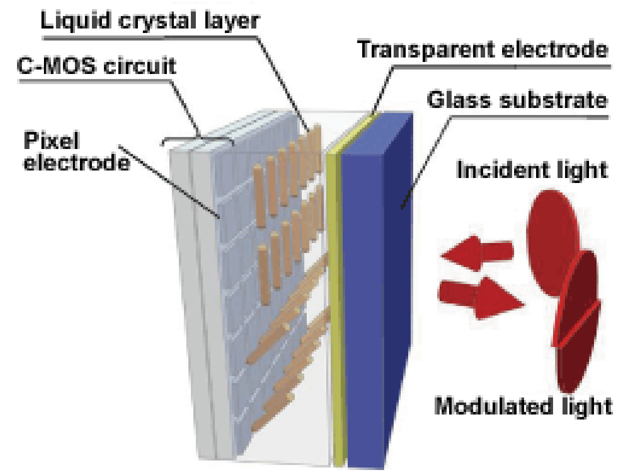

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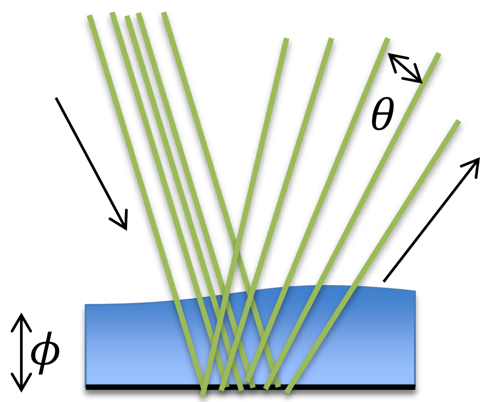

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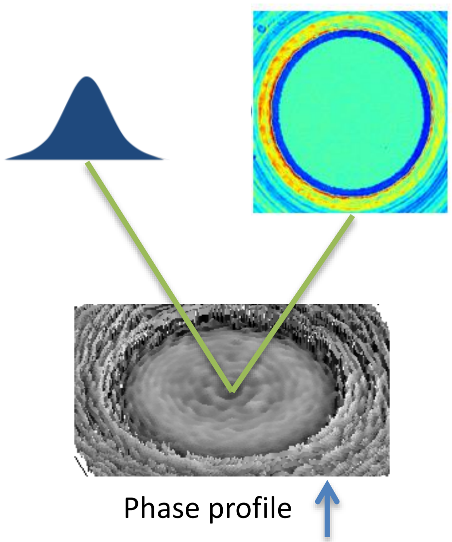
Phase grating (diffractive shaper):



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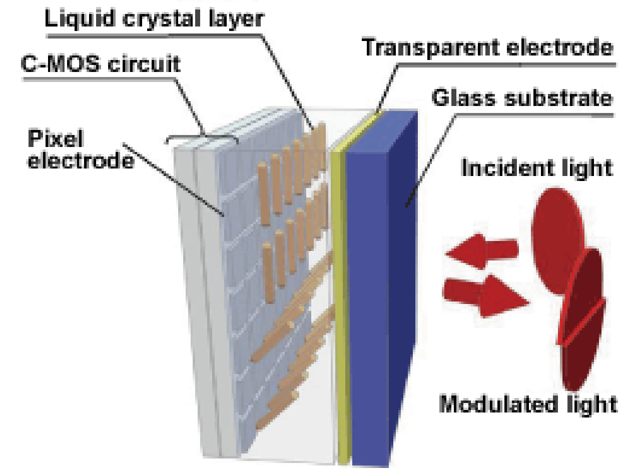

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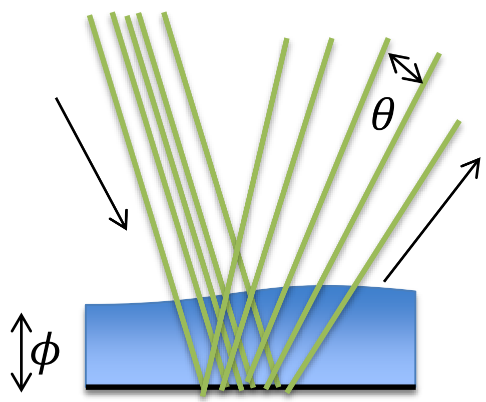

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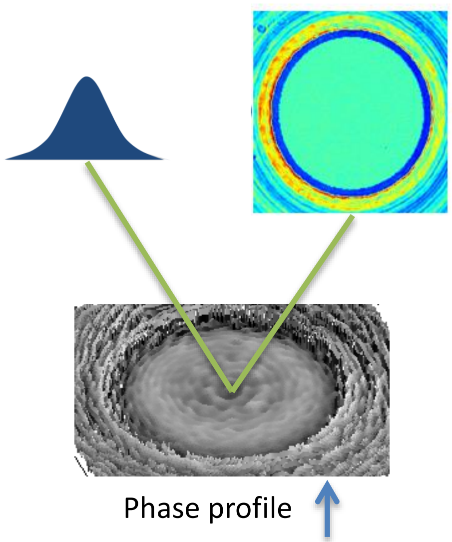
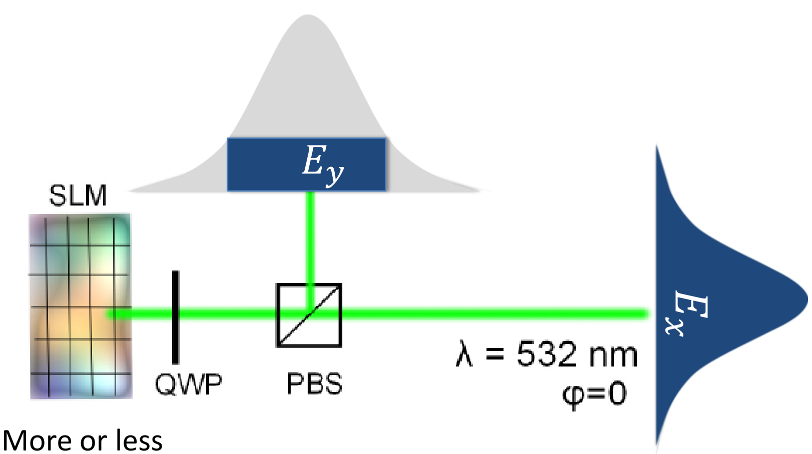


Very accurate! Lossy.

Polarization rotator (shaping via tunable masking):

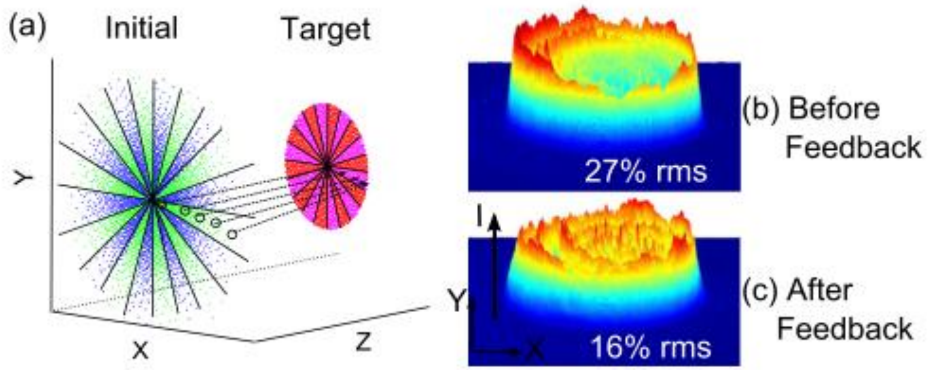


More or less accurate? More or less lossy?

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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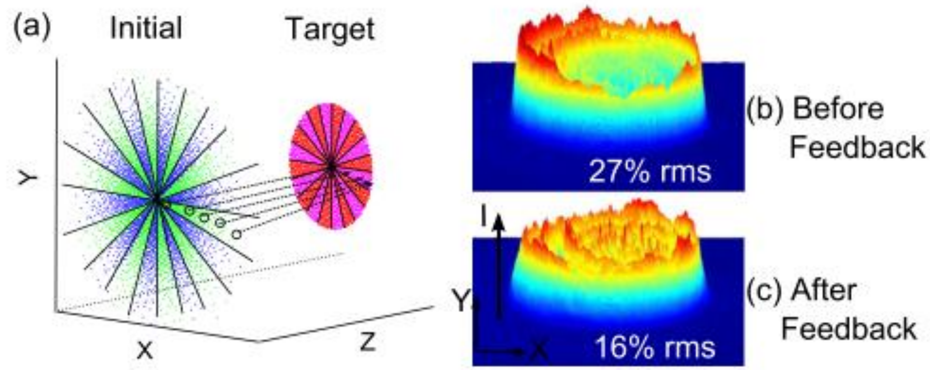
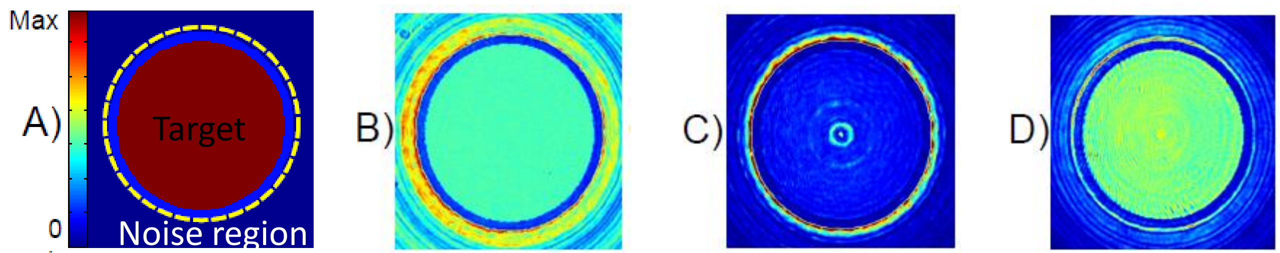


Changing input and output beam size →

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.



B) Error = 3.6%
Efficiency = 15%

C) Error = 33%
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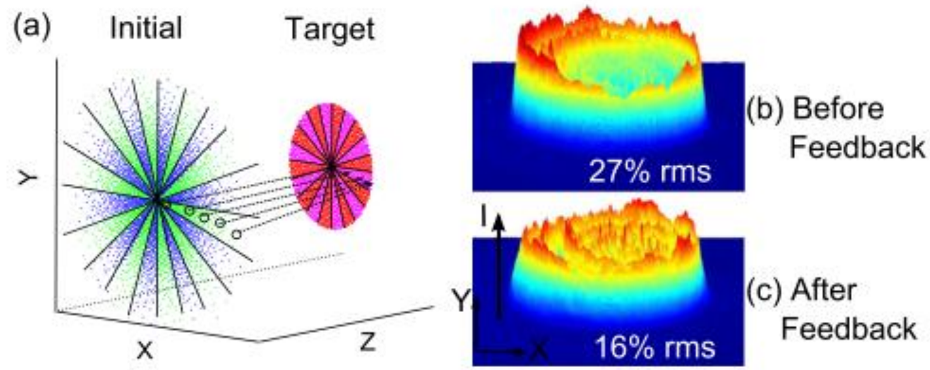

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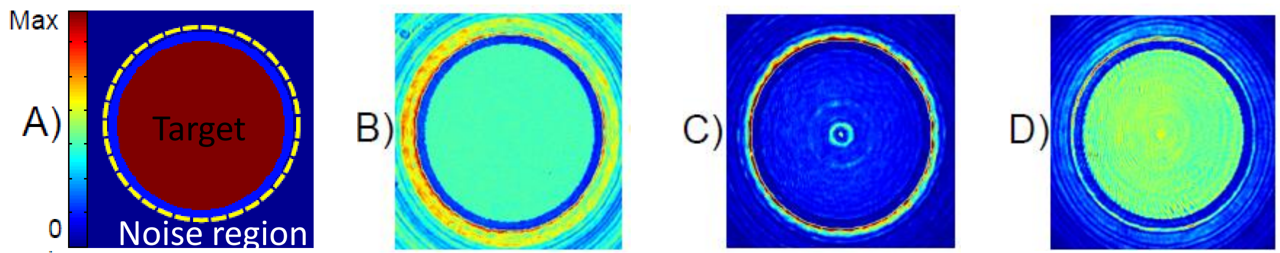

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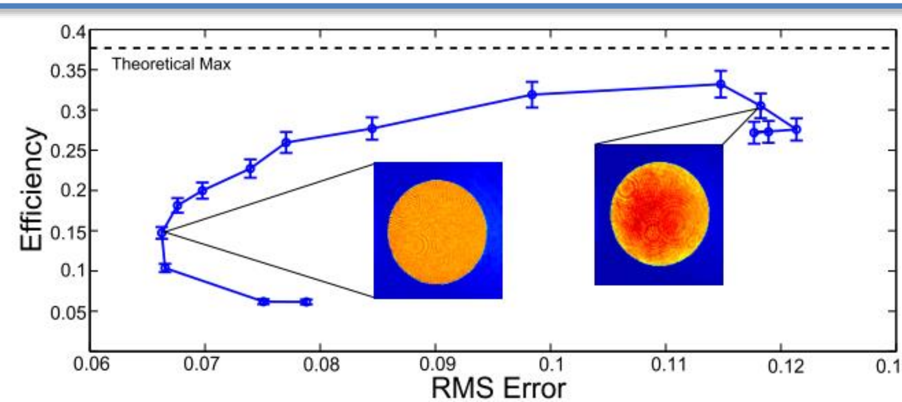
Polarization Subtractive Shaping
- Simple to setup, compute phase
- Efficiency matches simple estimates
- Nearly as accurate as the diffractive method!



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Cornell Laboratory for Accelerator-based Sciences and Education (CLASSE)

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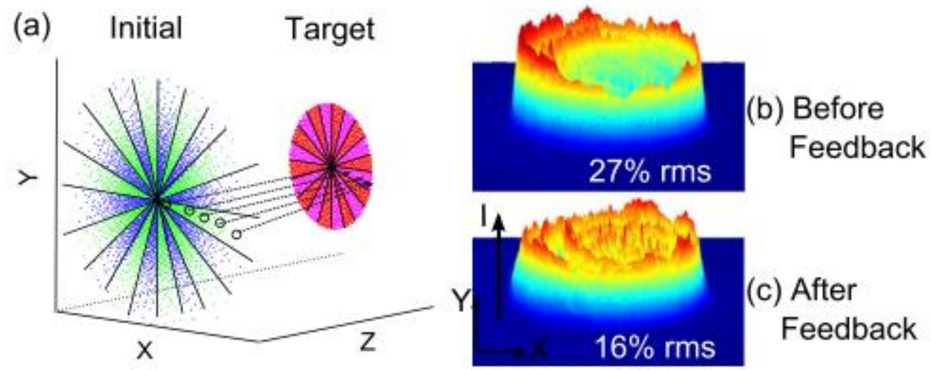

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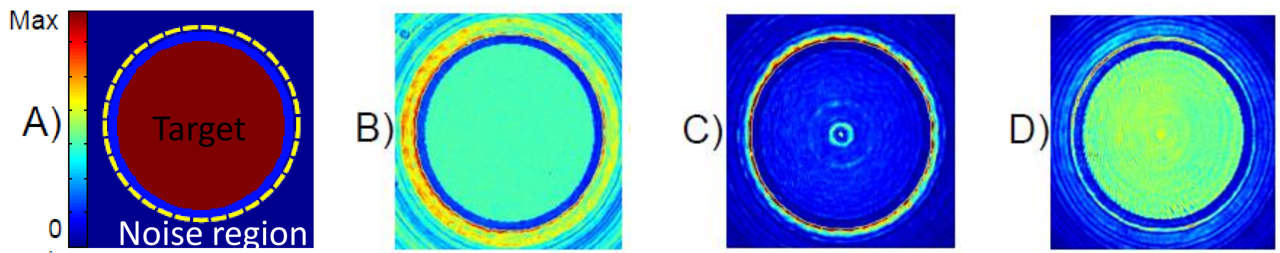

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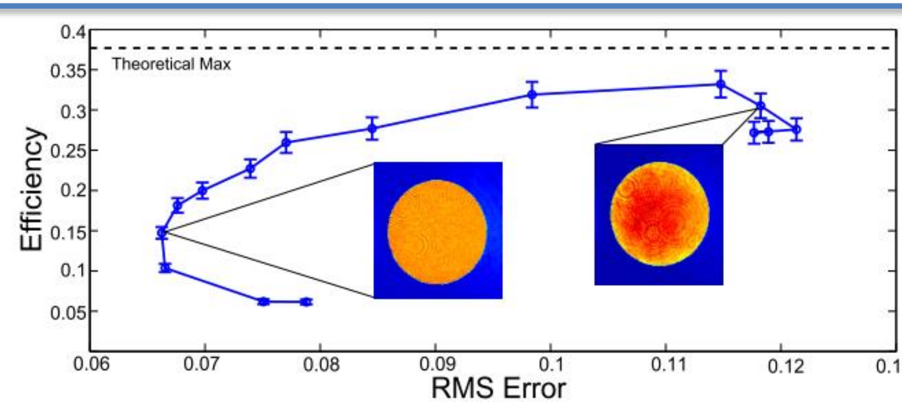

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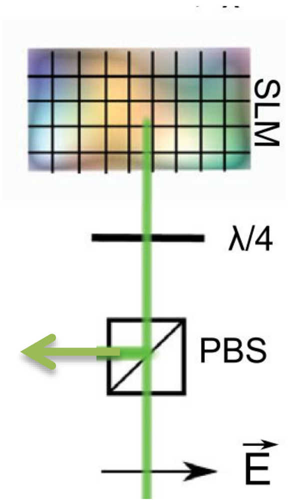
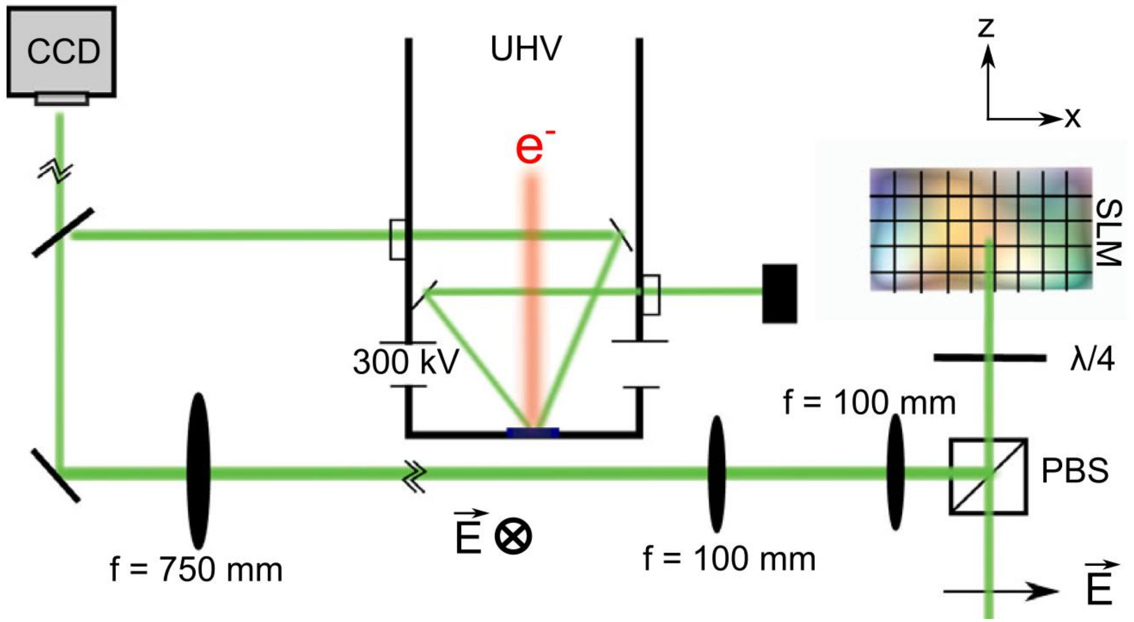
Shaped lasers->Shaped e-beams



DC 532 nm laser input (no space charge)

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

Shaped lasers->Shaped e-beams



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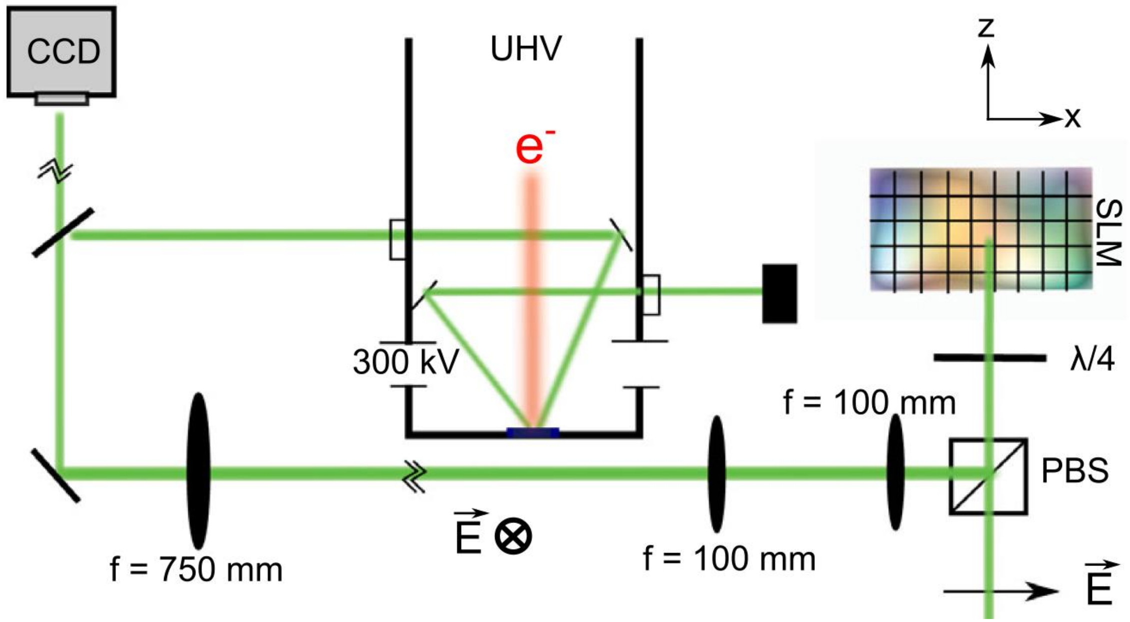
(Cartoon of) Cornell Segmented 400 kV Gun



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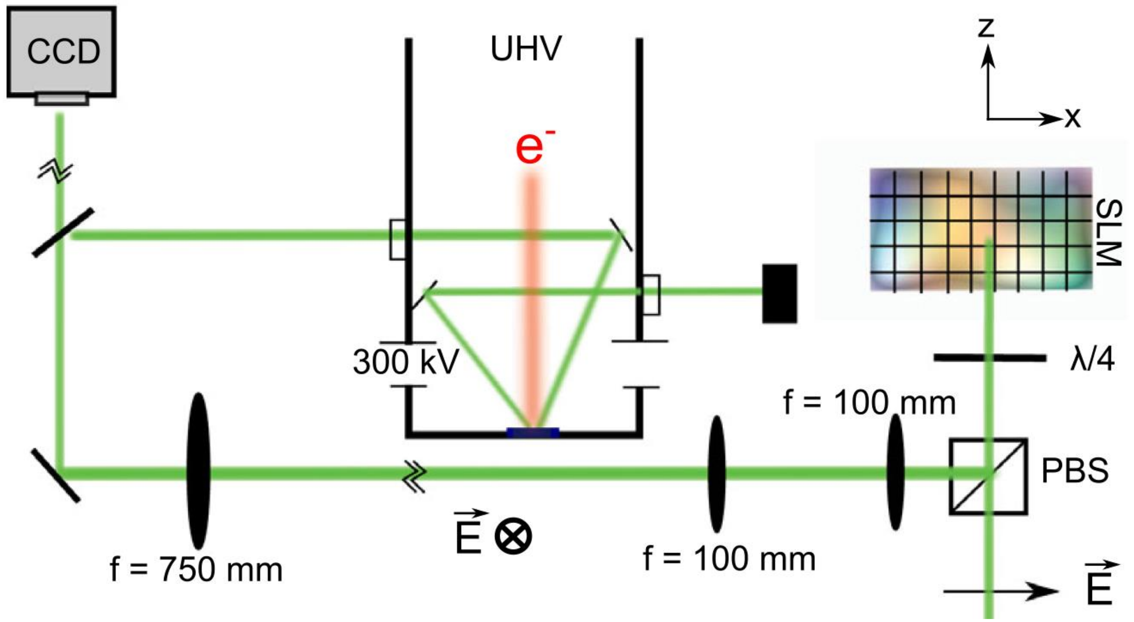

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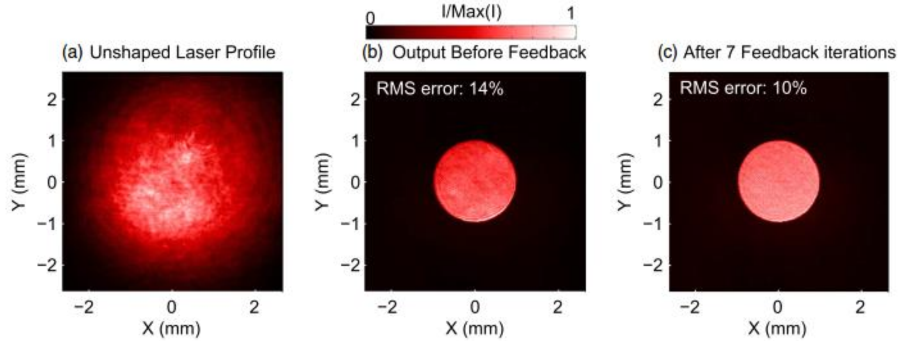
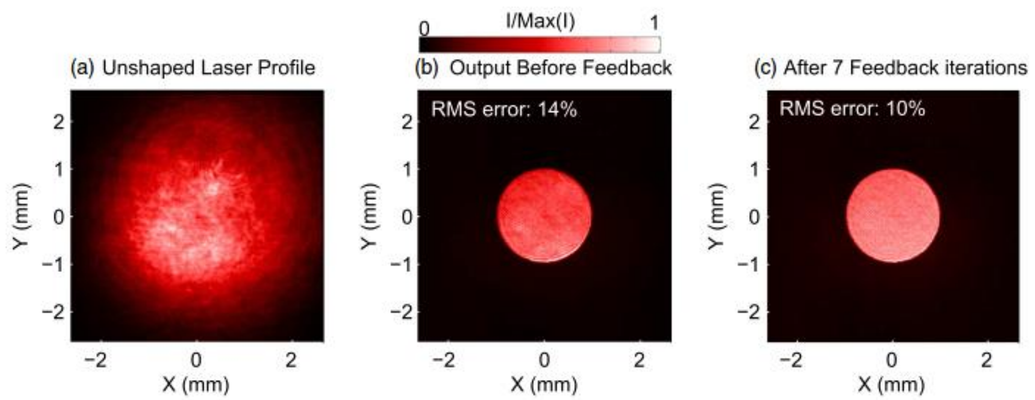
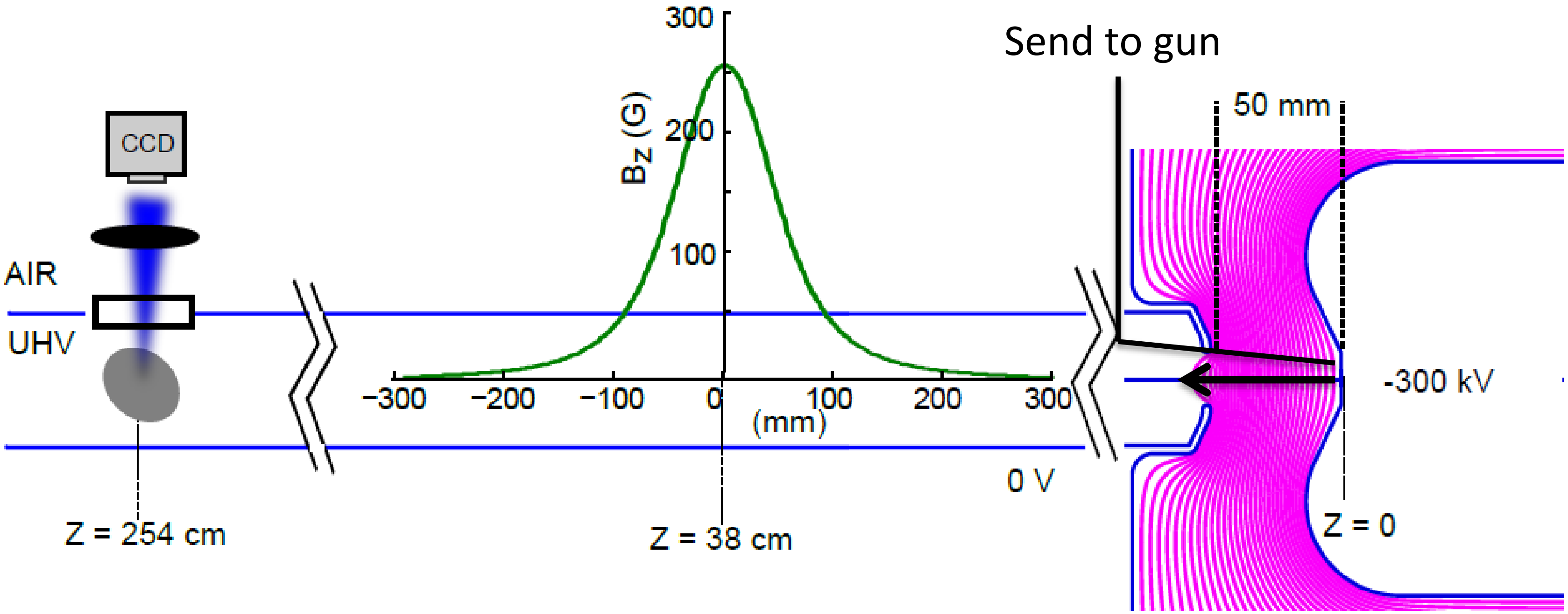
DC 532 nm laser input (no space charge)

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



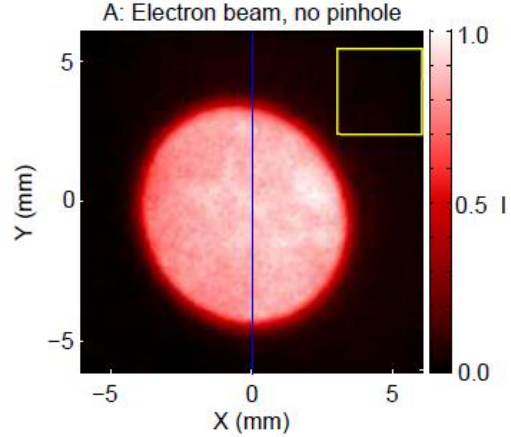
Imaging the Electrons

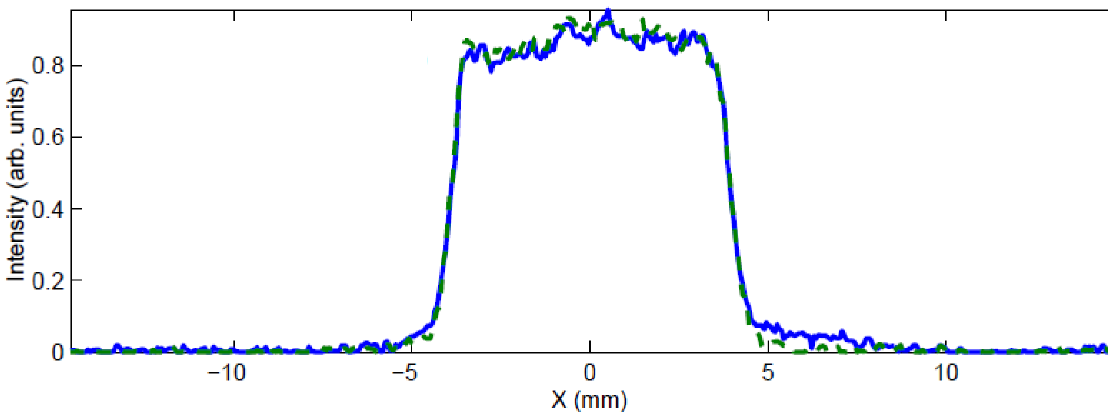




Imaging the Electrons

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





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

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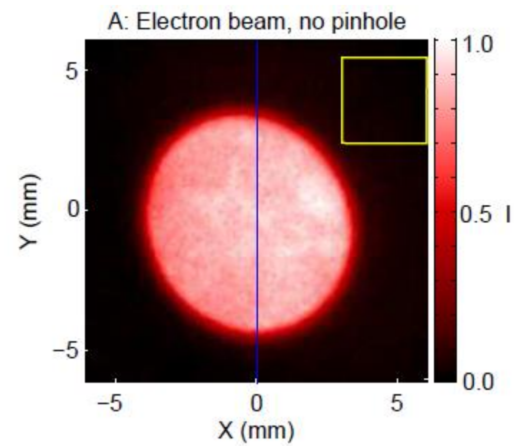
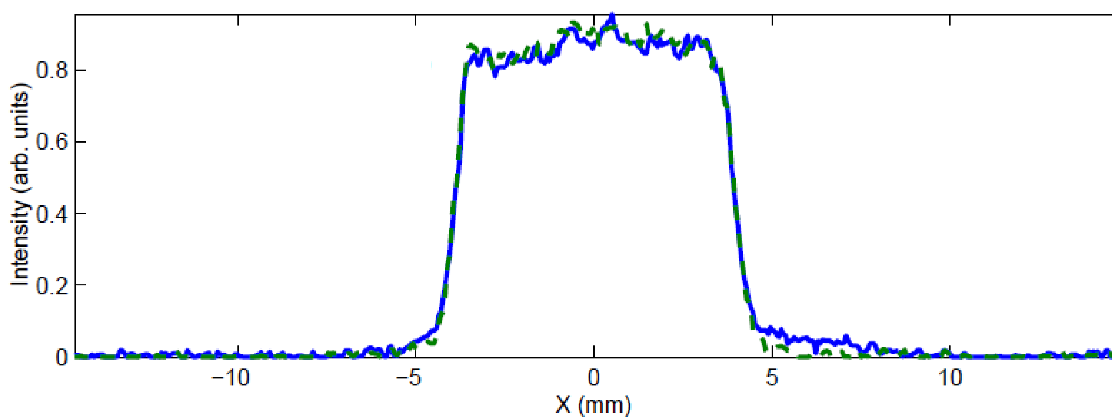


But our circle isn't circular anymore.

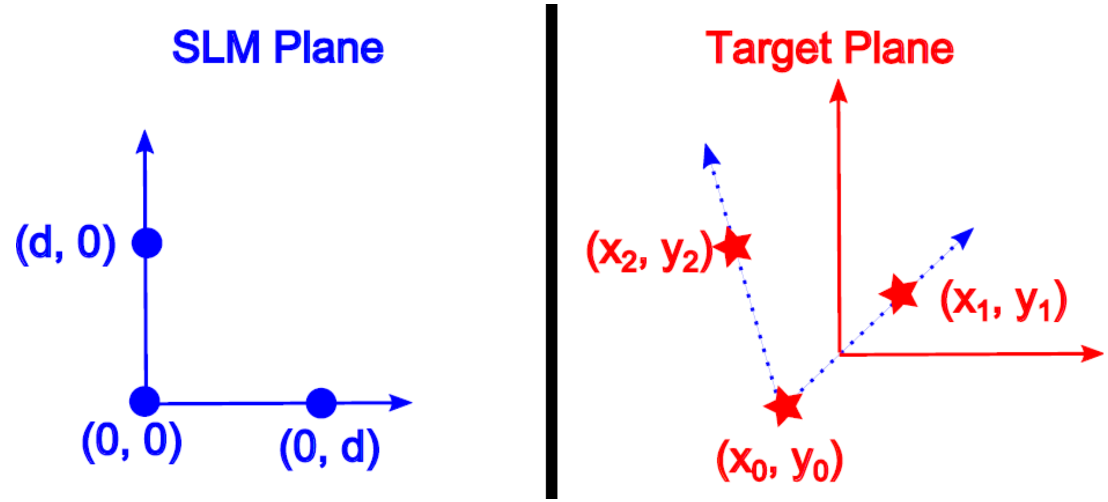
Stray quadrupole field (not solenoid).



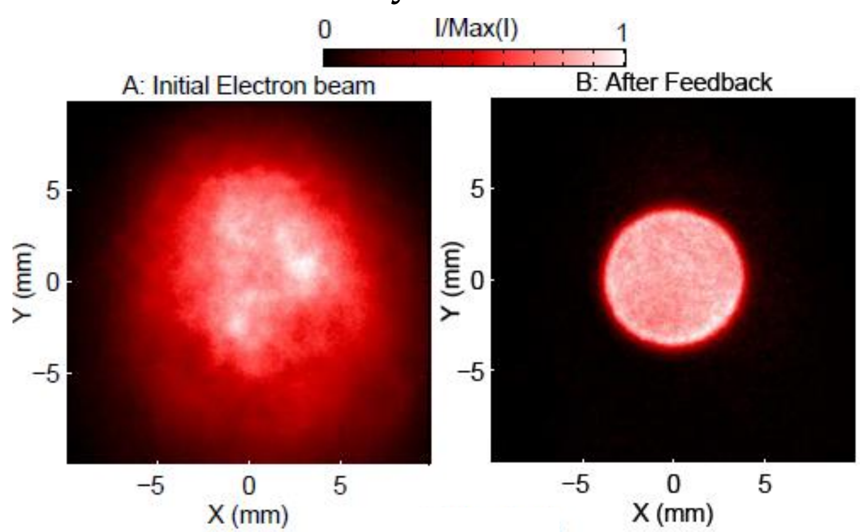
J.Maxson et al., PRSTAB **18**, 023401 (2015)

Electron beam feedback

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



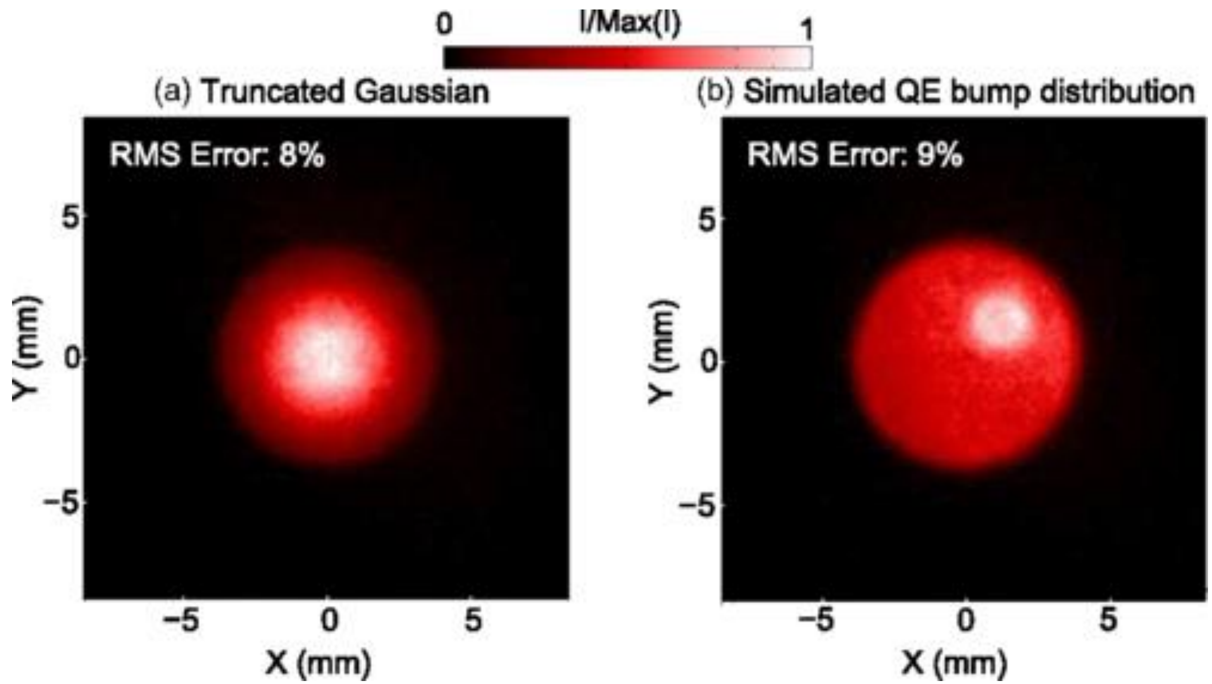
Knowing this, we can feedback directly on the e-beam. Never image the photons!



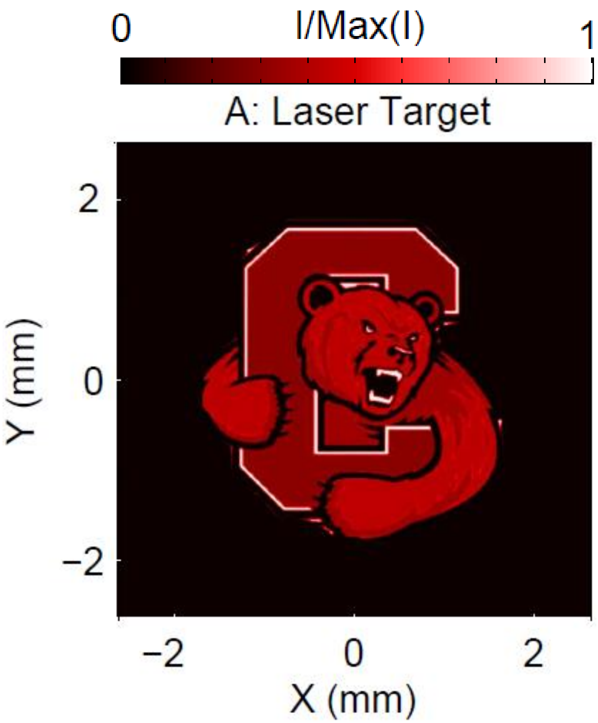
Never directly images the laser
Accounts for any QE variation!

Beam feedback: Additional shapes

- A few additional demonstrative shapes:

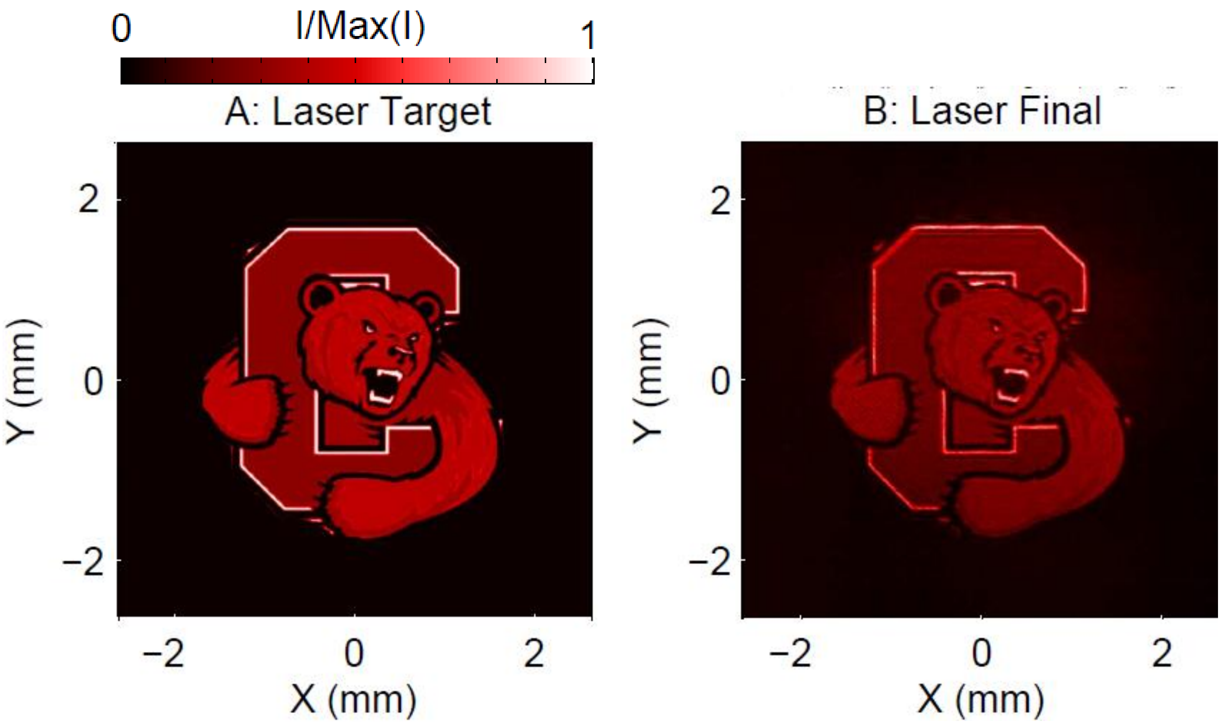


Detailed Shapes



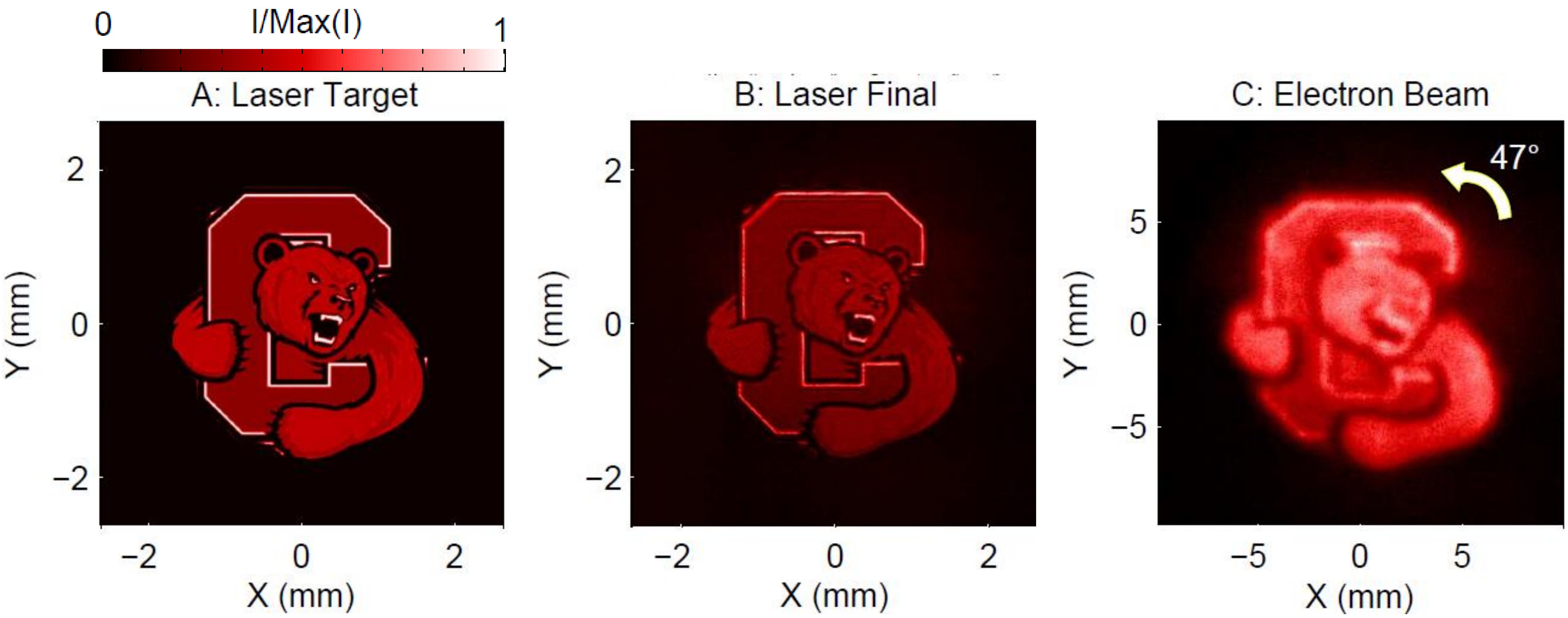
J.Maxson et al., PRSTAB **18**, 023401 (2015)

Detailed Shapes



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

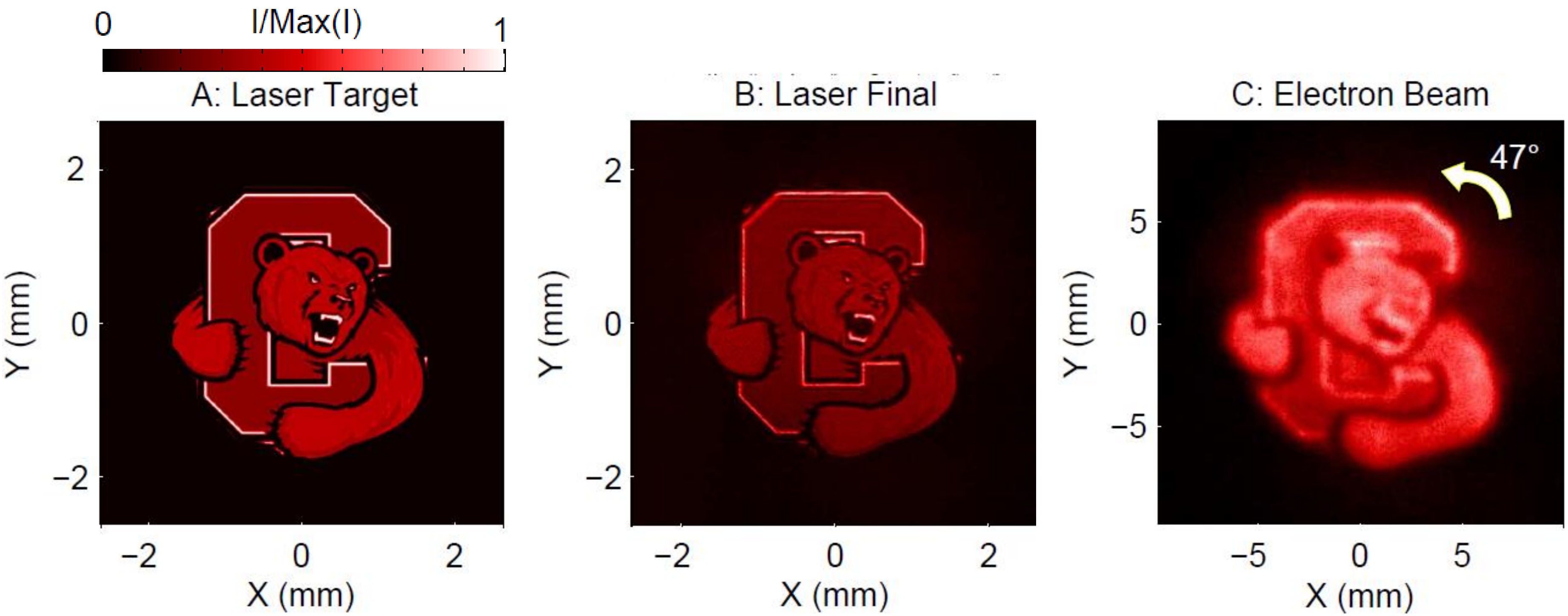
Detailed Shapes



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

Detailed Shapes

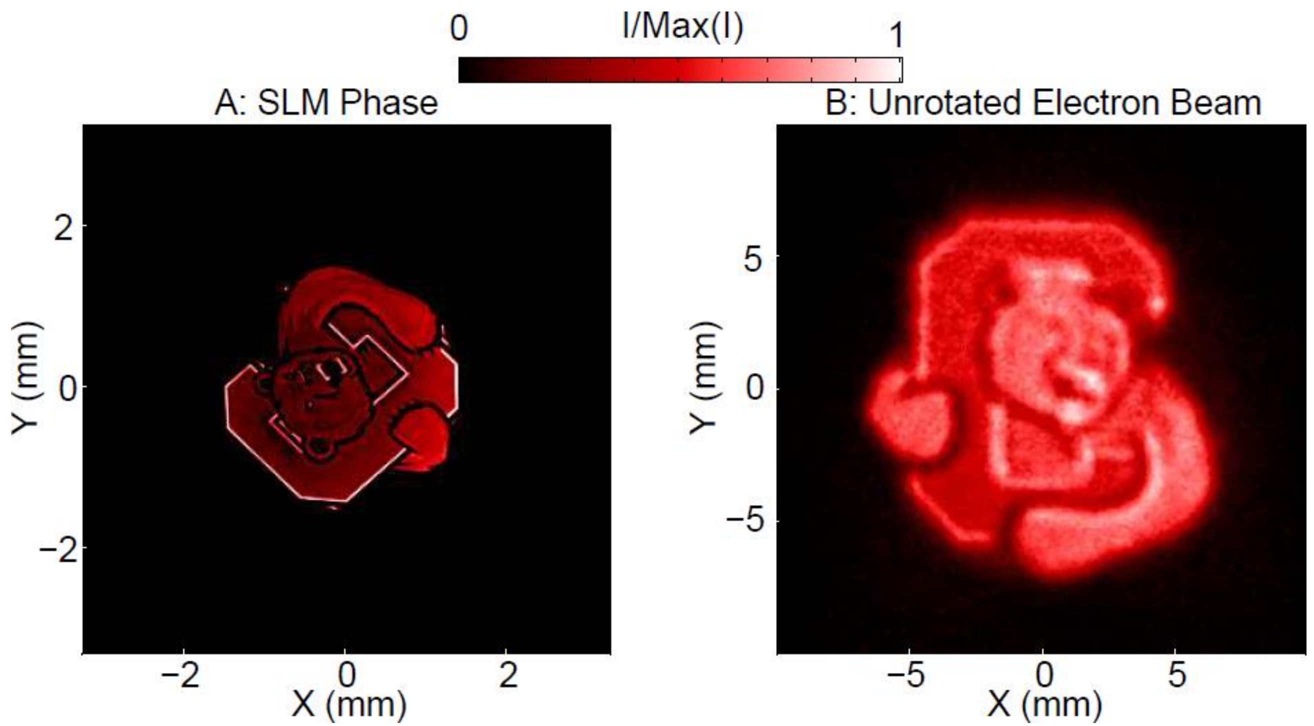
- Back to preshaping the laser: try something harder!



- Sharp features are well preserved!

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

Detailed Shapes: e-beam feedback



- 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.

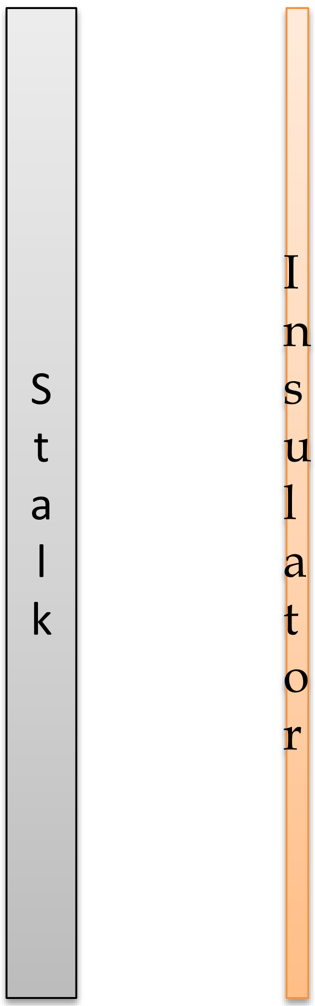
- **Accurate, adaptive electron transverse electron beam distributions are a reality.**

Acknowledgements

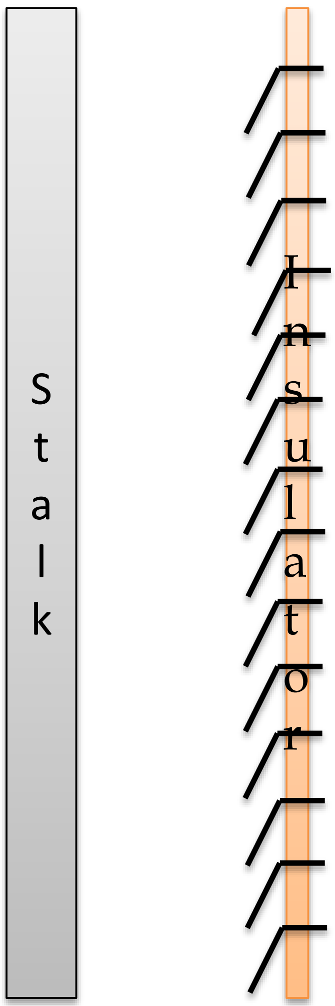
- Many acknowledgements required!
  - Advisors (formal or otherwise): Ivan Bazarov, Bruce Dunham, Karl Smolenski
  - All things mechanical: Tobey Moore, Jeff Mangus, Mitch Bush, Ed Foster, John Stilwell, Jim Sexton, Mike Palmer
  - Cathodes: Luca Cultrera
  - Technical support: John Dobbins, Adam Bartnik, John Barley
  - 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

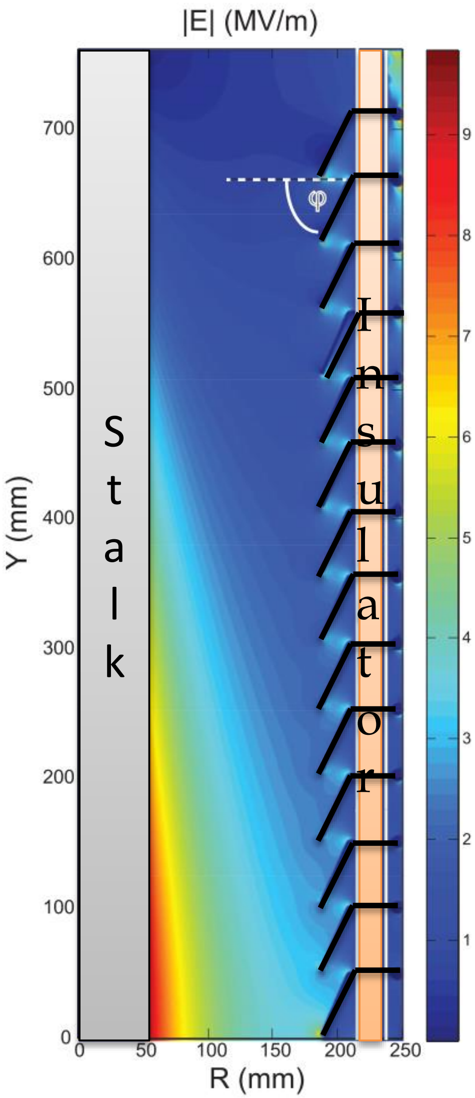
Cornell MKII Gun: Segmented



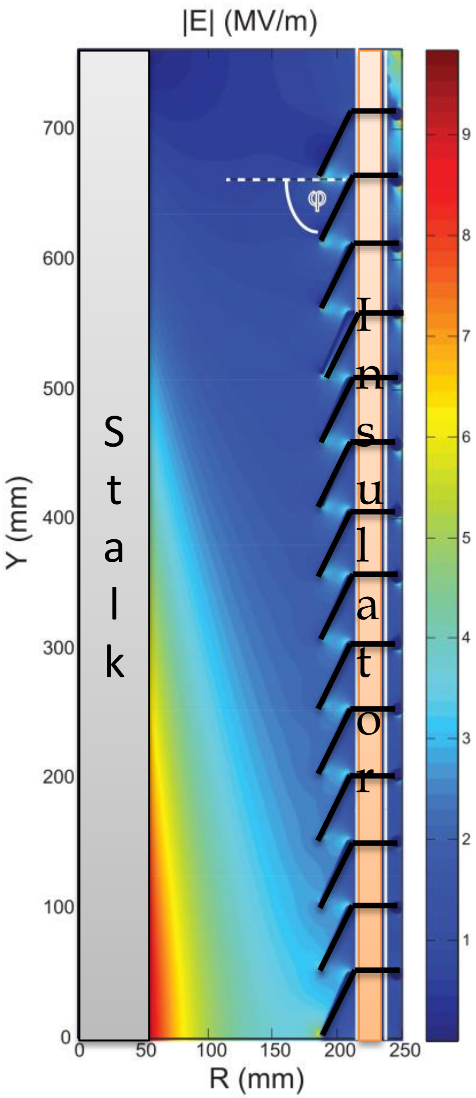
Cornell MKII Gun: Segmented



Cornell MKII Gun: Segmented

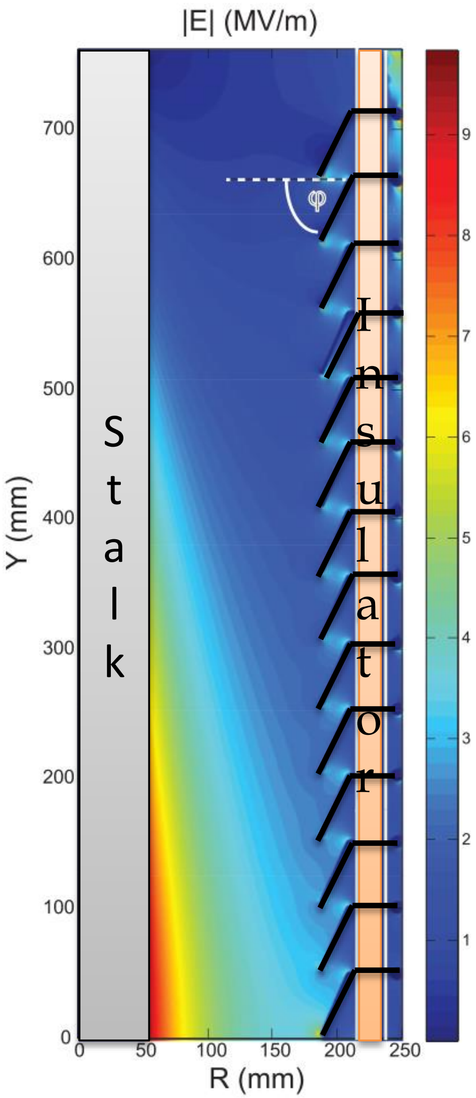


Cornell MKII Gun: Segmented

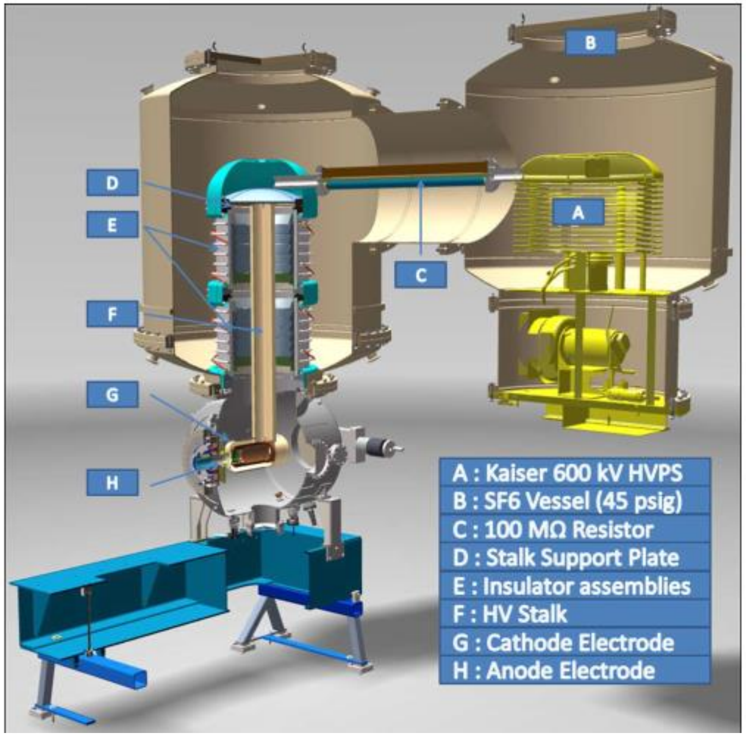


Fields at 750 kV

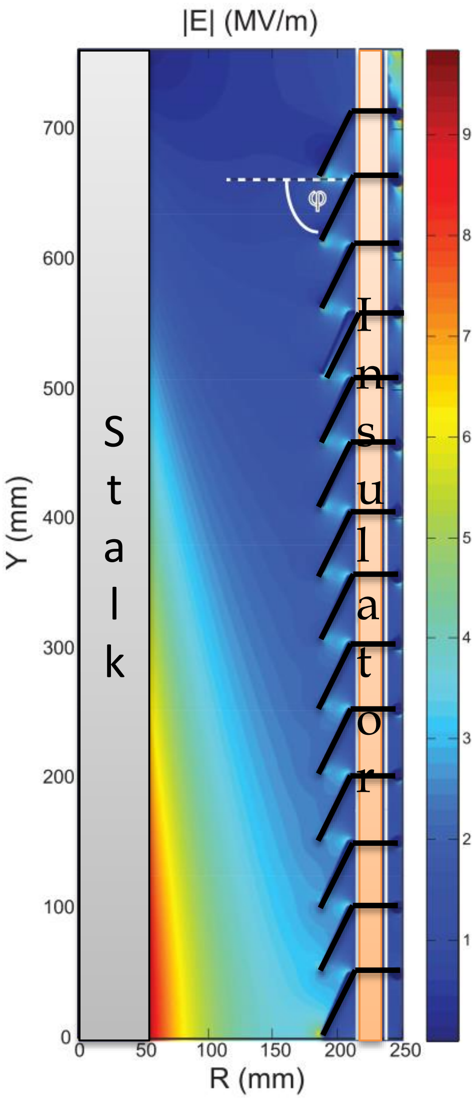
Cornell MKII Gun: Segmented



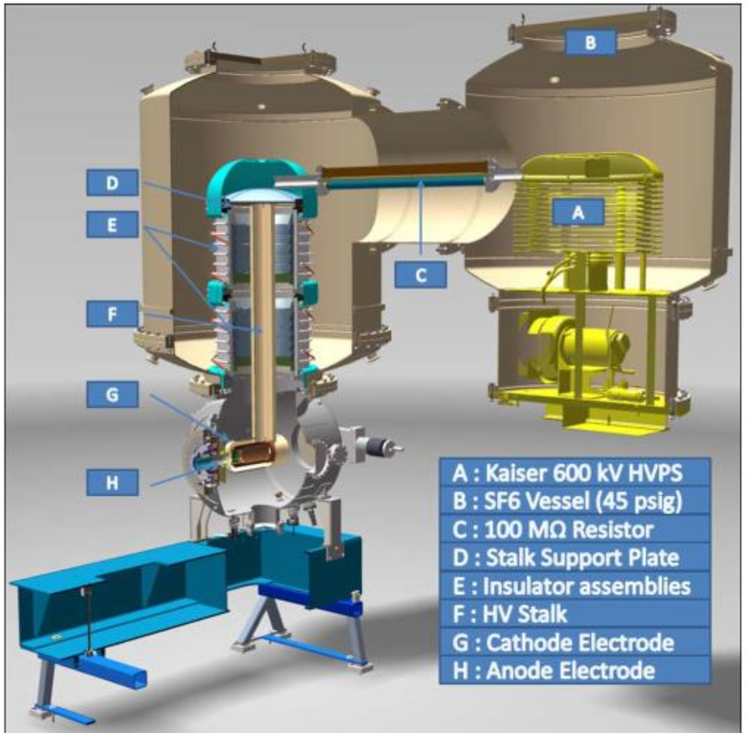
Fields at 750 kV



Cornell MKII Gun: Segmented

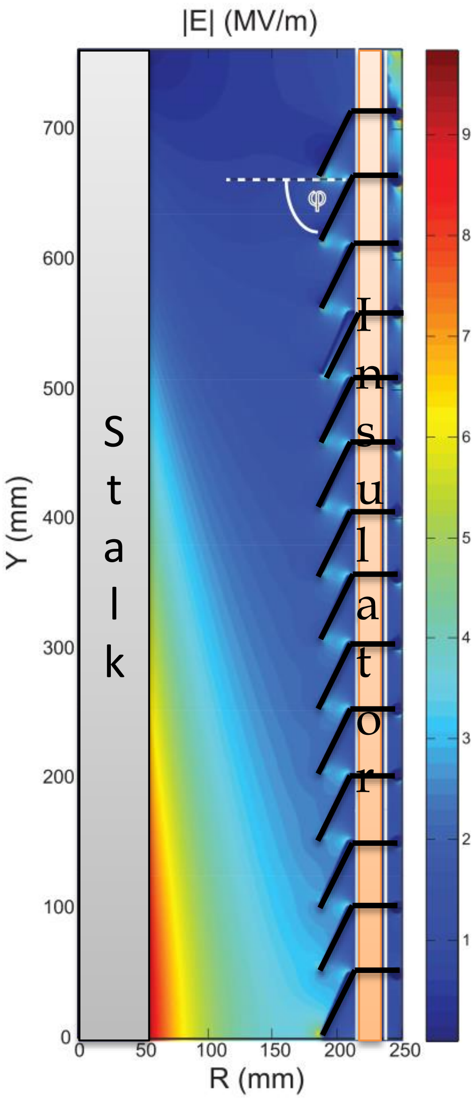


Fields at 750 kV

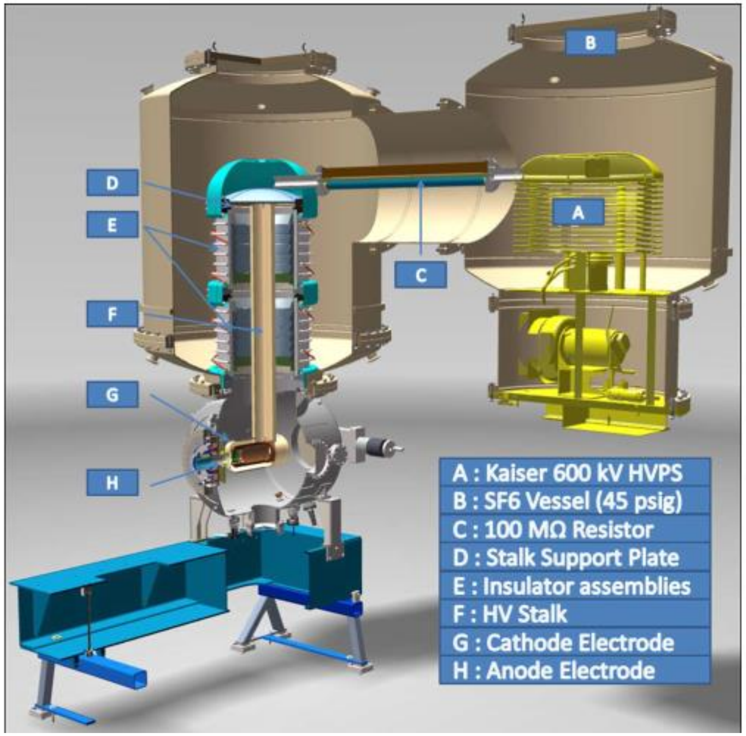


Mechanical Design: Karl Smolenski, Bruce Dunham

Cornell MKII Gun: Segmented



Fields at 750 kV

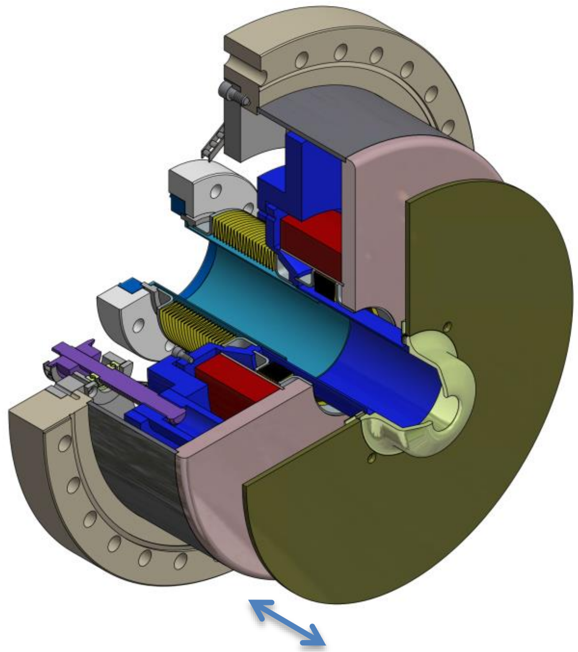


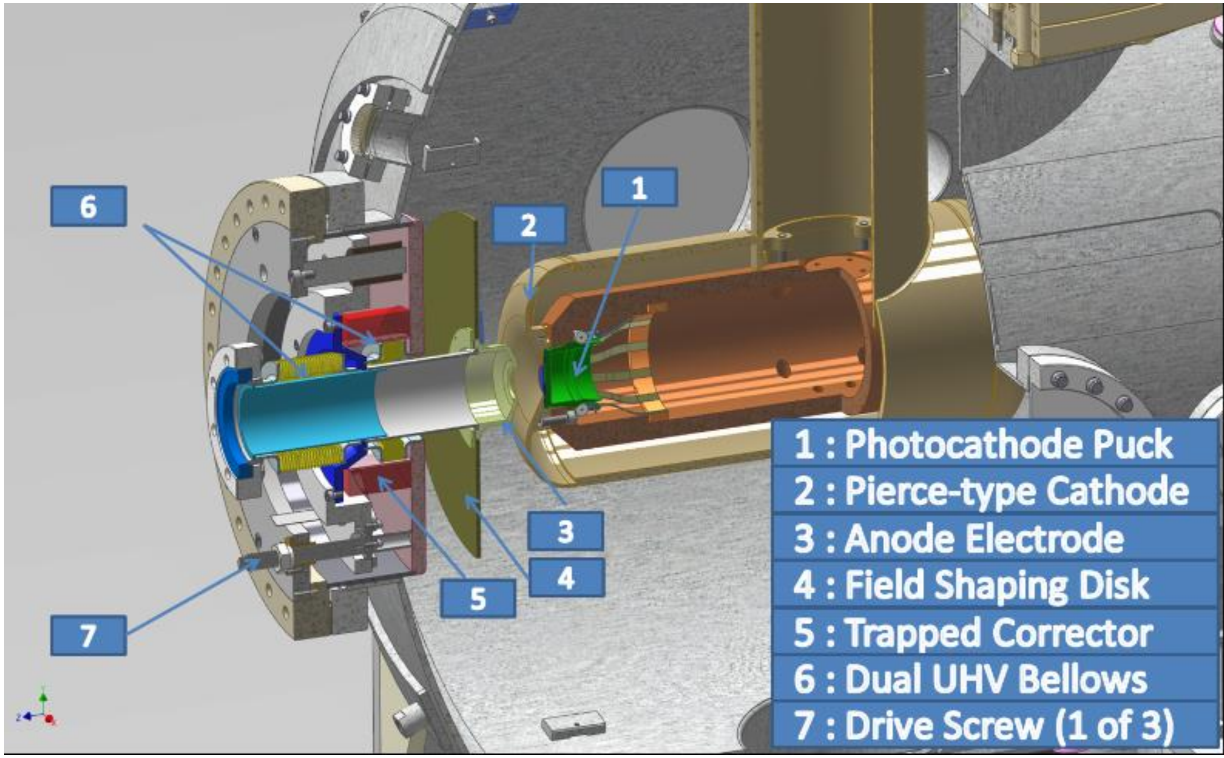
Mechanical Design: Karl Smolenski, Bruce Dunham

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

A movable anode

- A moveable anode provides an adjustable photocathode field.

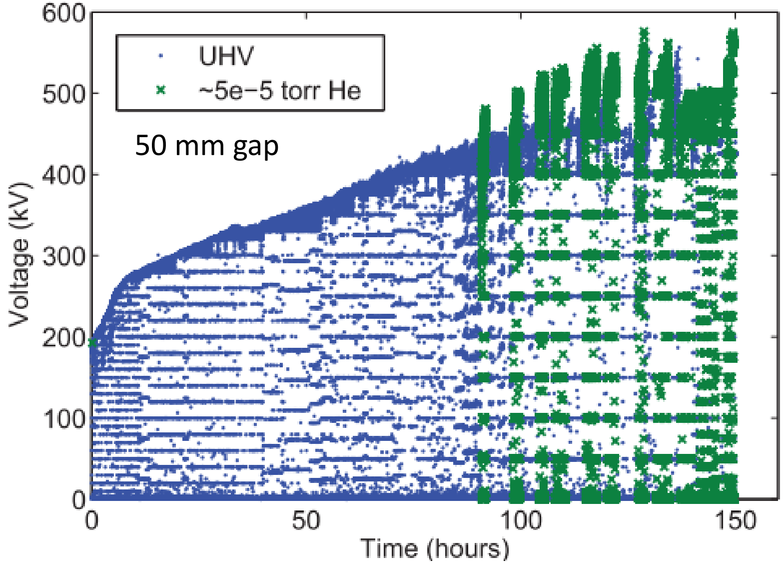




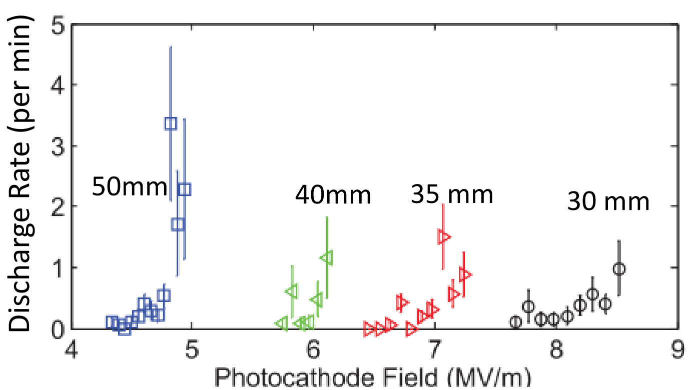
Mechanical Design: Xianghong Liu

HV Performance

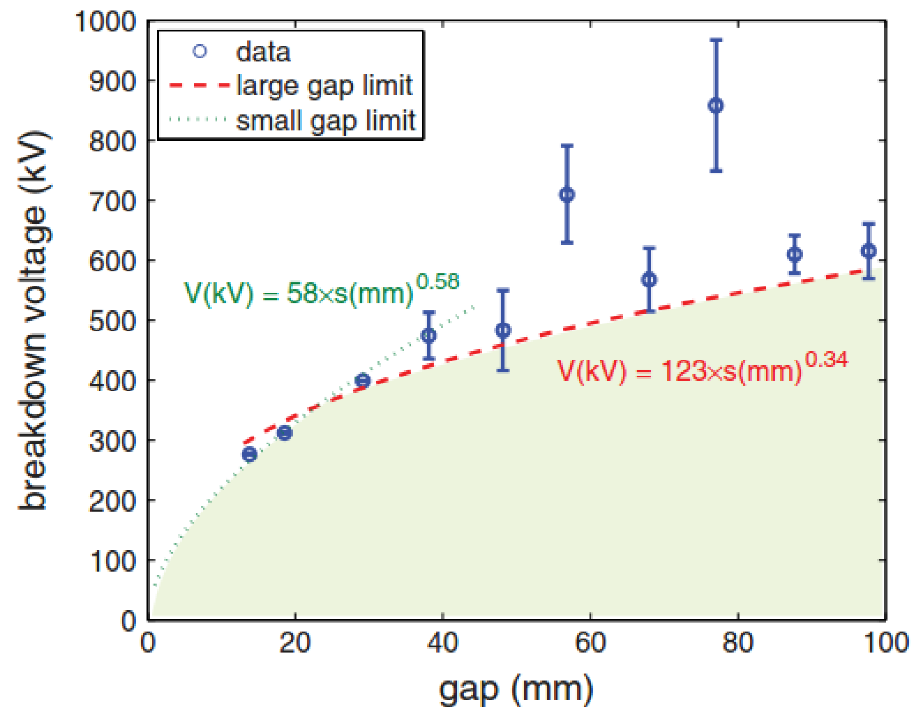
J. Maxson et al., RSI **85**, 093306 (2014)



Stability test with various gaps:

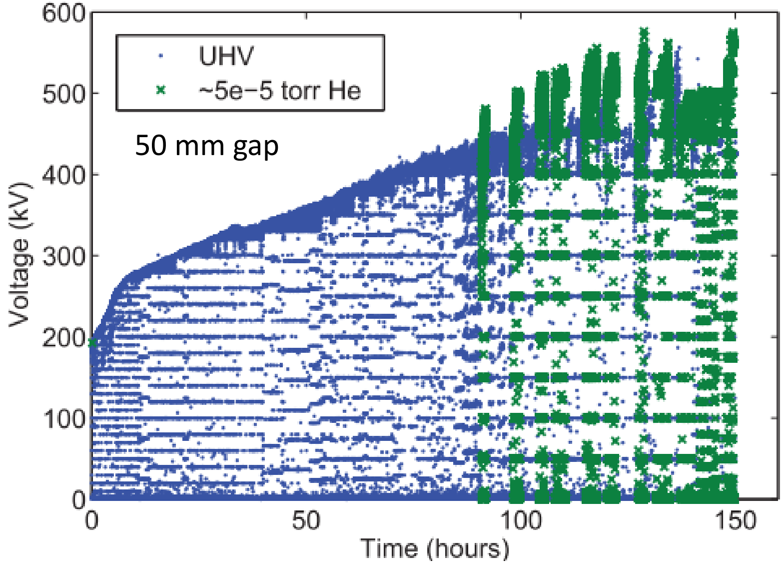


P. Slade, *The Vacuum Interrupter*, CRC Press, 2008

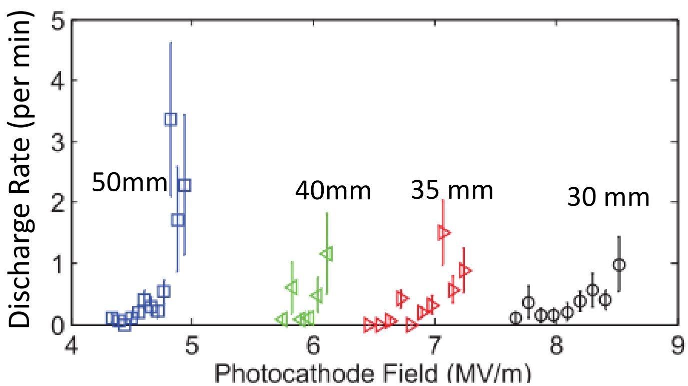


HV Performance

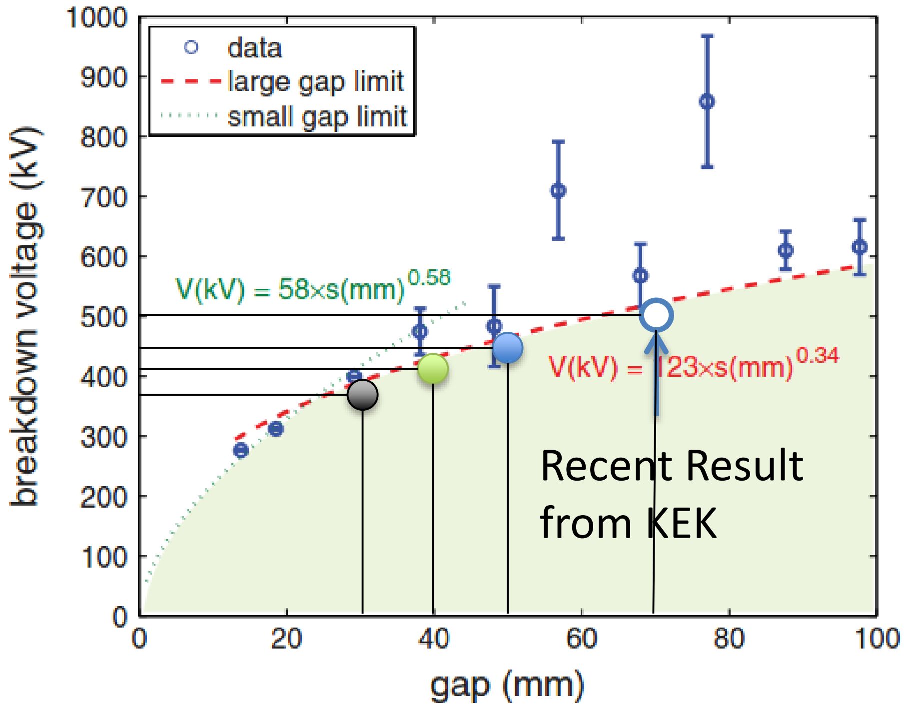
J. Maxson et al., RSI **85**, 093306 (2014)



Stability test with various gaps:

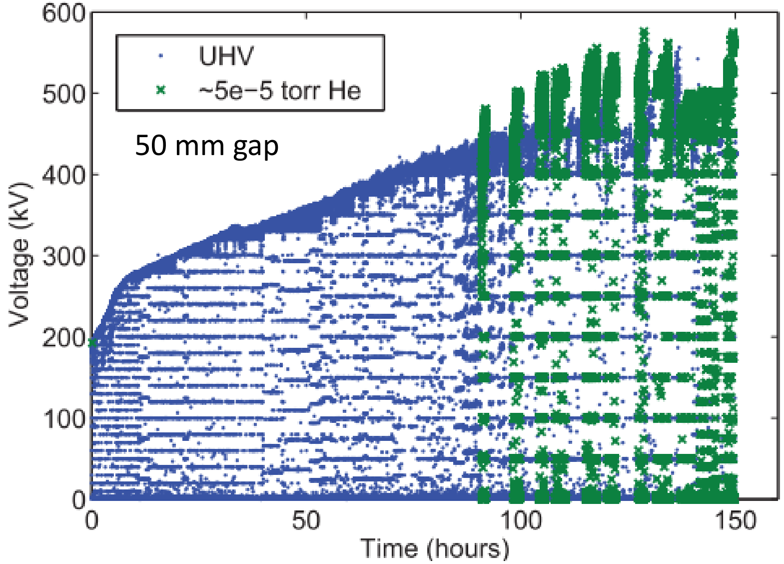


P. Slade, *The Vacuum Interrupter*, CRC Press, 2008

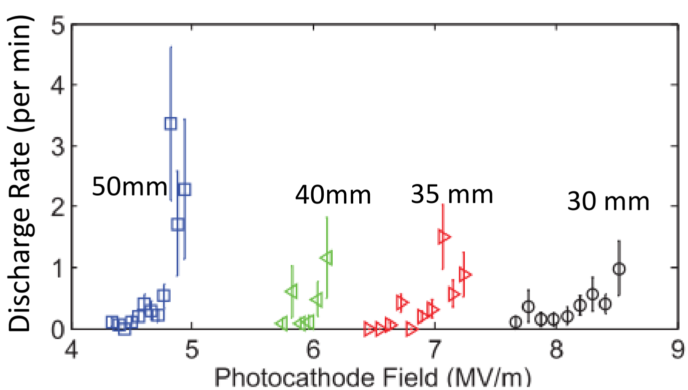


HV Performance

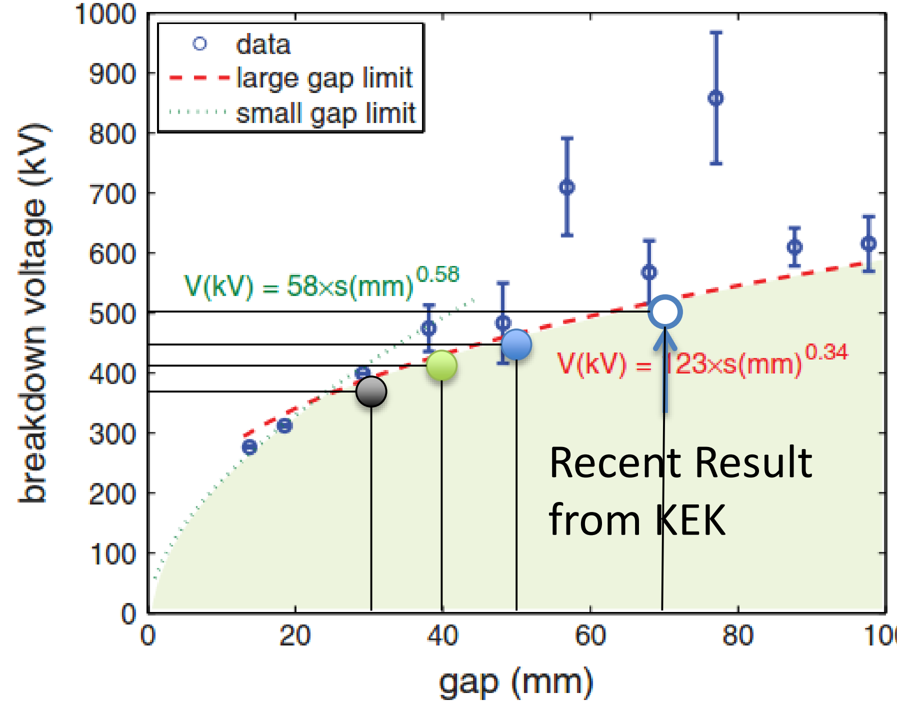
J. Maxson et al., RSI **85**, 093306 (2014)



Stability test with various gaps:



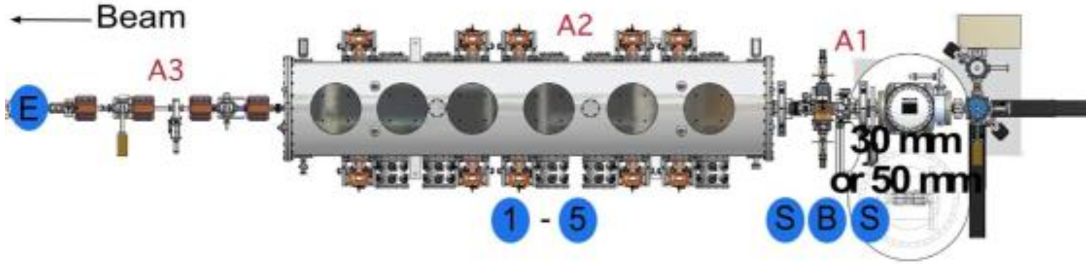
P. Slade, *The Vacuum Interrupter*, CRC Press, 2008

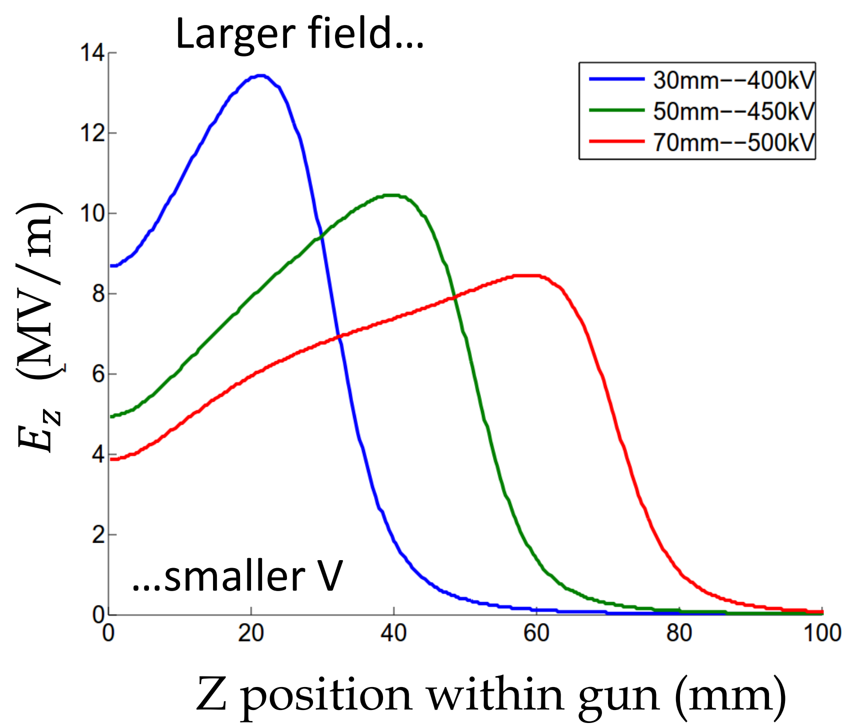


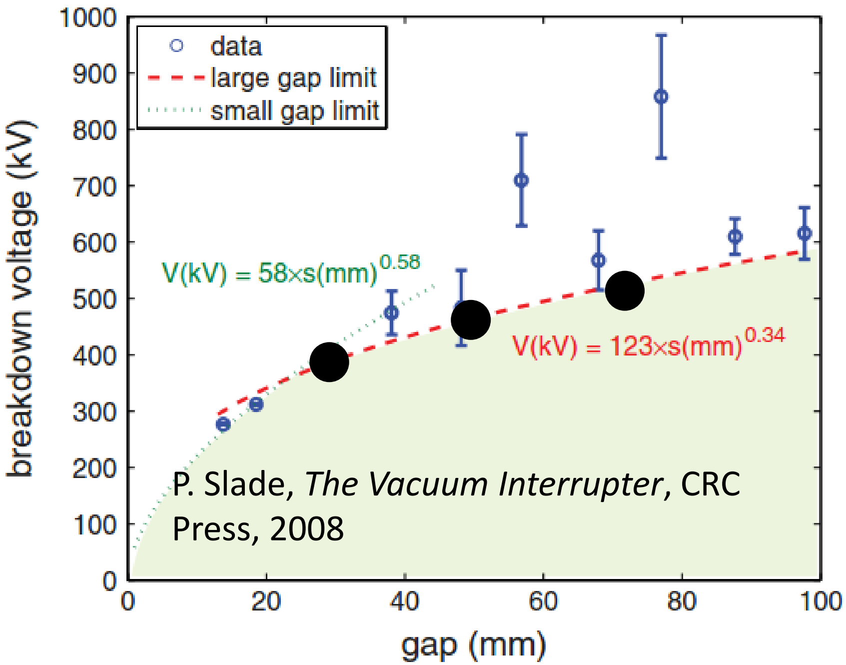
- Surprisingly good agreement between different HV systems.
- But what configuration is best for the beam emittance? –Turn to simulations.

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

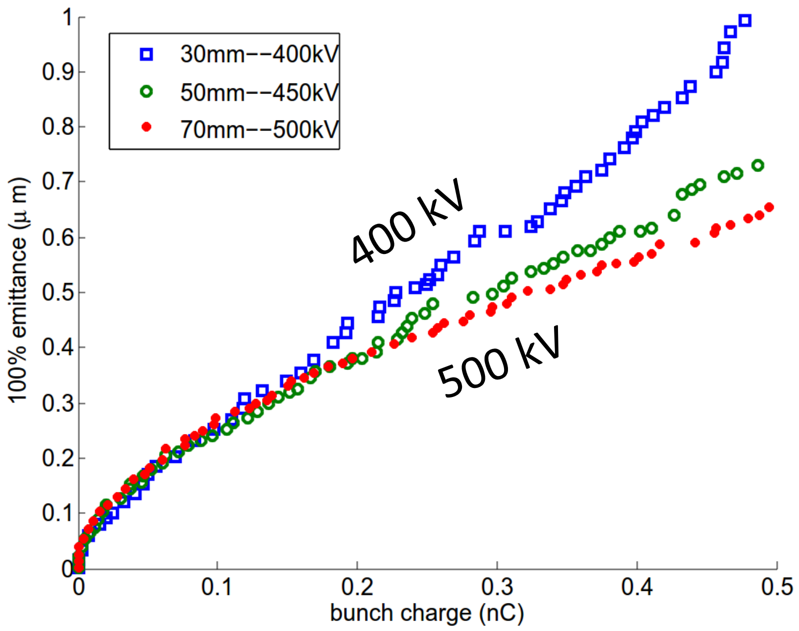
- 500 kV: 70mm
- 450 kV: 50 mm
- 400 kV: 30 mm

- Optimize these 3 w.r.t. emittance, fix only the gun voltage and $MTE = 120\ meV$. Vary *everything else.*
- Scan the charge up to 500 pC

DC gun, various gaps

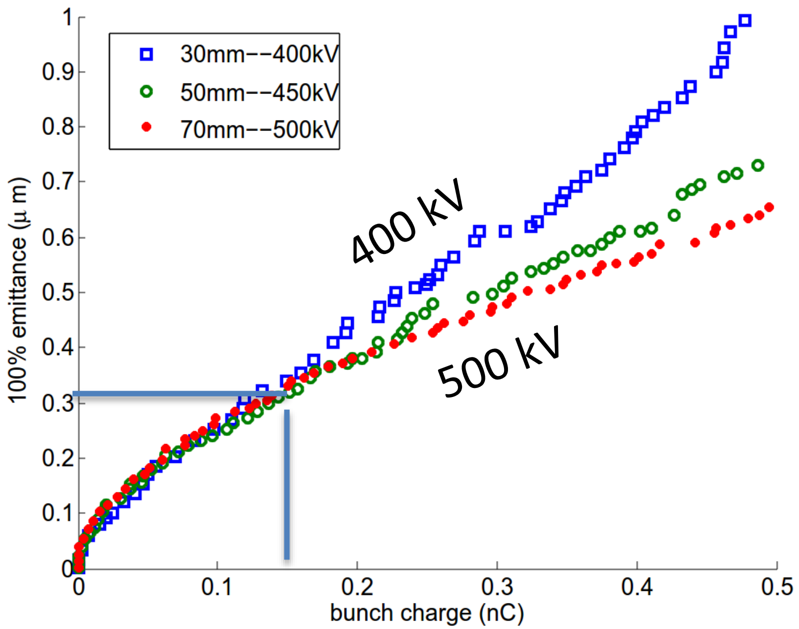
- 500 kV: 70mm
- 450 kV: 50 mm
- 400 kV: 30 mm

- Optimize these 3 w.r.t. emittance, fix only the gun voltage and $MTE = 120\ meV$. Vary *everything else.*
- Scan the charge up to 500 pC



DC gun, various gaps

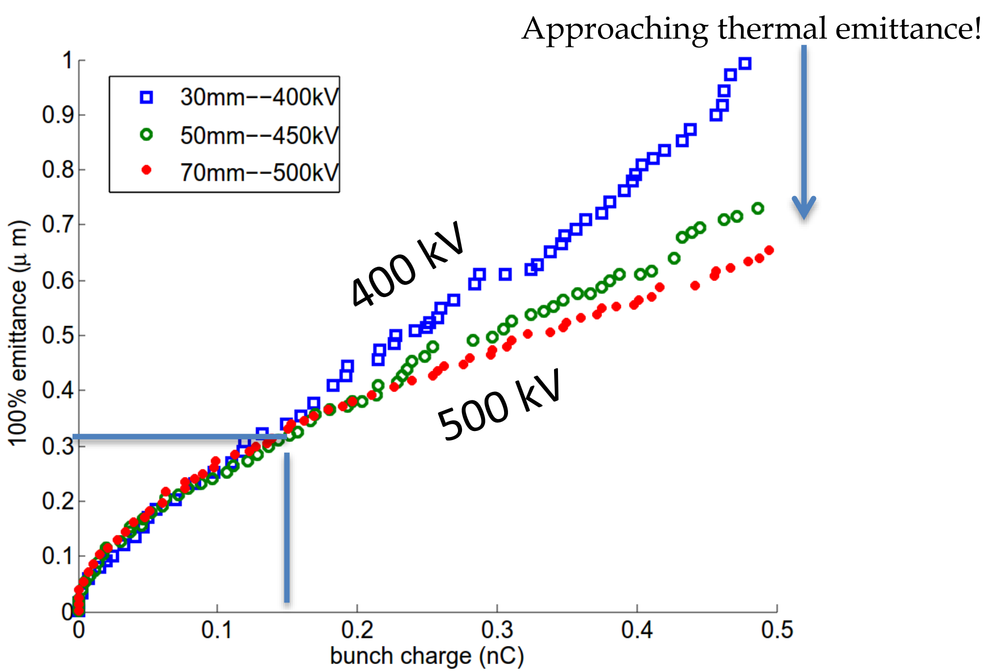
  - 500 kV: 70mm
  - 450 kV: 50 mm
  - 400 kV: 30 mm
- Optimize these 3 w.r.t. emittance, fix only the gun voltage and $MTE = 120\ meV$. Vary *everything else.*
- Scan the charge up to 500 pC



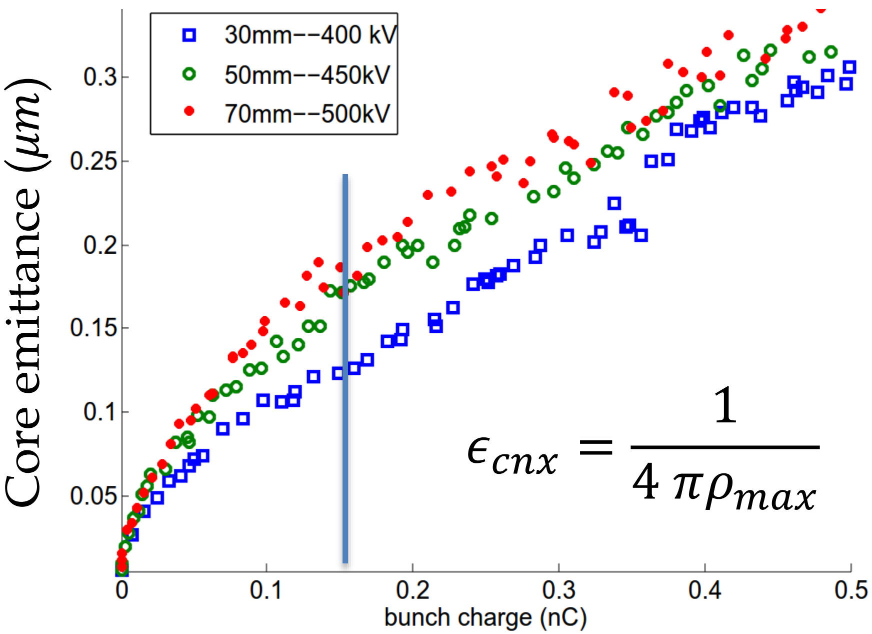
DC gun, various gaps

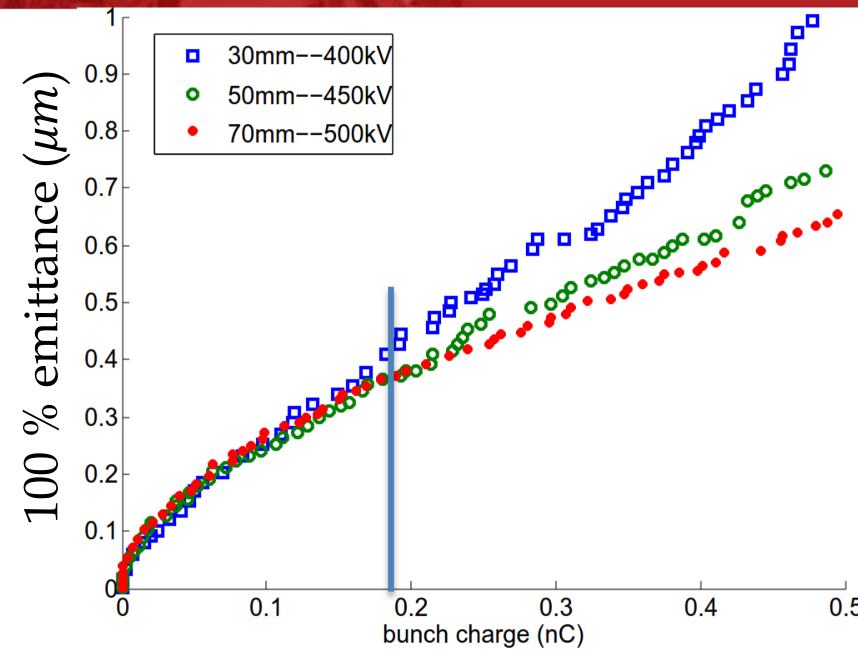
- 500 kV: 70mm
- 450 kV: 50 mm
- 400 kV: 30 mm

- Optimize these 3 w.r.t. emittance, fix only the gun voltage and $MTE = 120\ meV$. Vary *everything else.*
- Scan the charge up to 500 pC

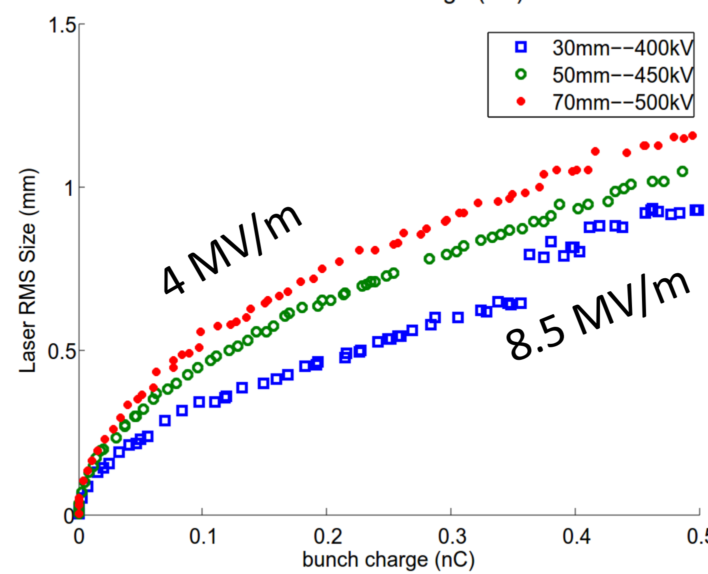


How about the core emittance?



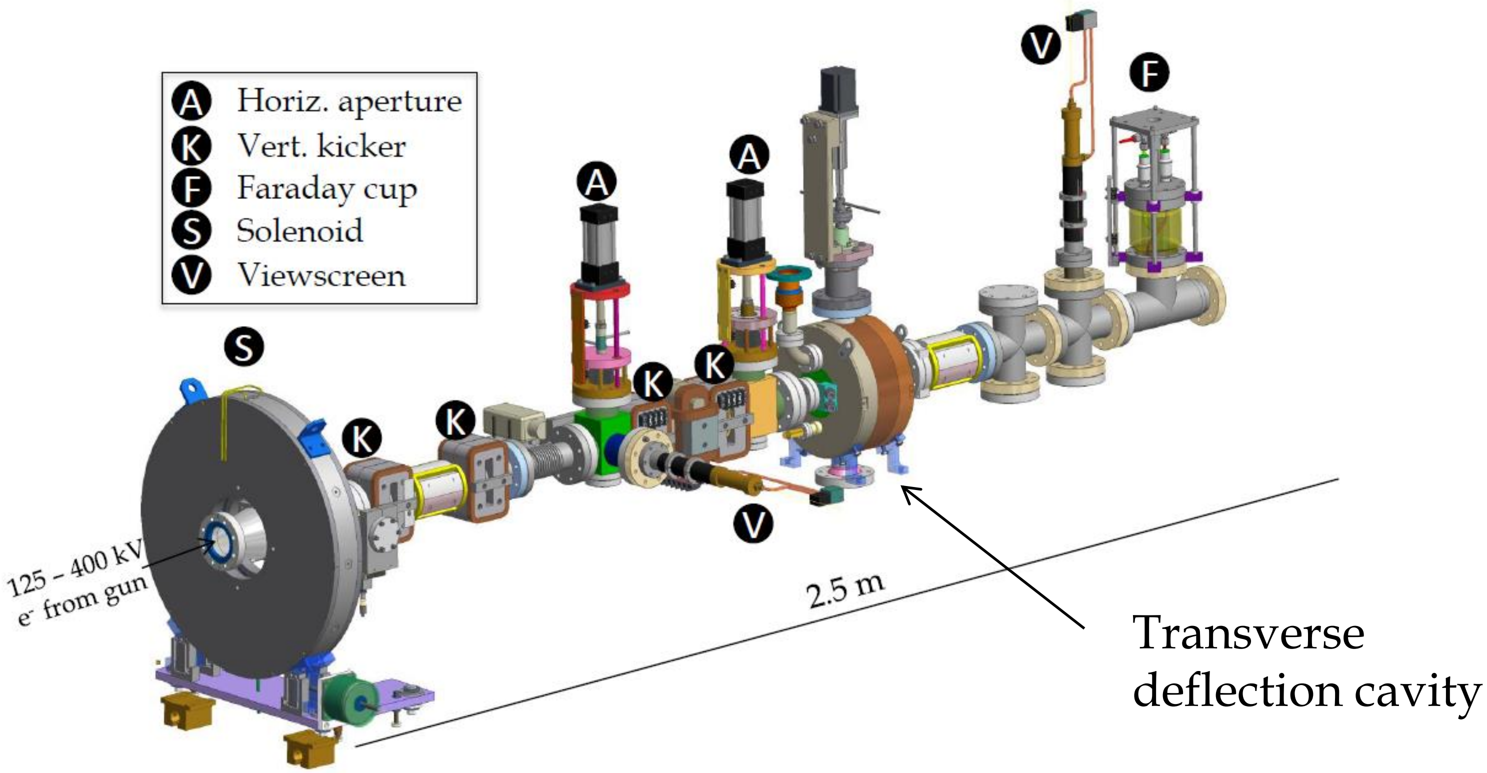


- Higher Field→ Smaller laser spot size
- 30 mm gap has superior emittance performance up to ~150 pC in Cornell Injector.
- (Smaller core emittance, equal 100% emittance)
- Core emittance is a **strong invariant.** (RMS emittance is not.)



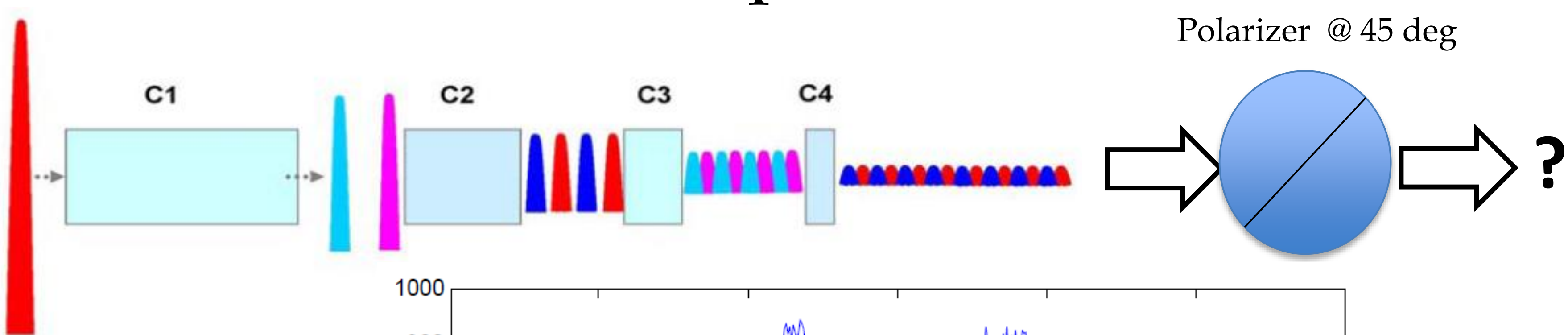
J. Maxson et al., RSI **85**, 093306 (2014)

- DC gun experimental beamline:



Temporal Shaping with SLM

- 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.