Cornell Injector Performance

Adam Bartnik

Cornell Injector Performance

- as an ERL injector

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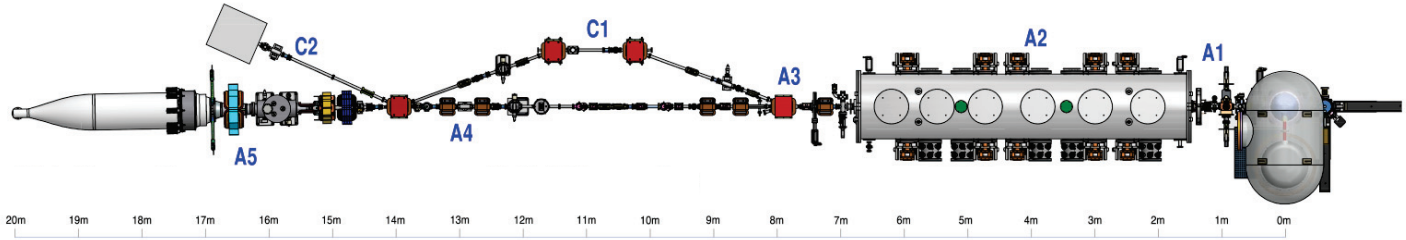
- ~~as an ERL injector~~
- as an FEL injector (e.g. LCLS-II)
- as an injector for EIC applications
- etc…

Cornell Injector Performance

(in new applications)

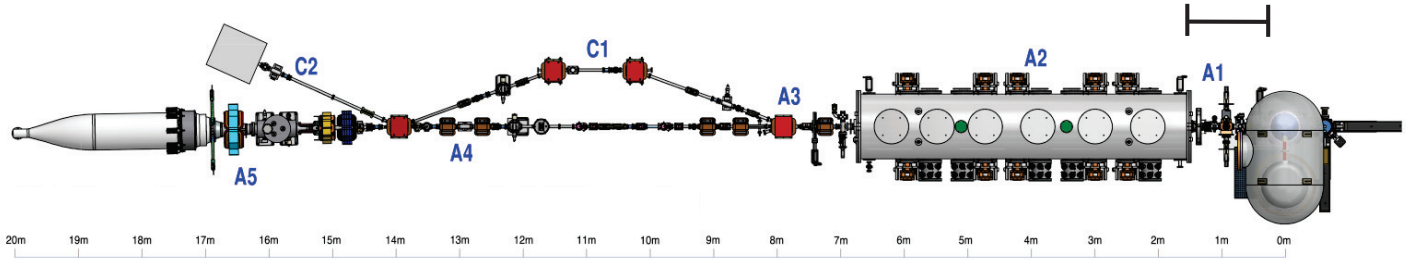
Primary Question: How does the injector perform beyond its original specification?

Injector Layout



Injector Layout

400 kV DC Gun +
Bunching/Focusing



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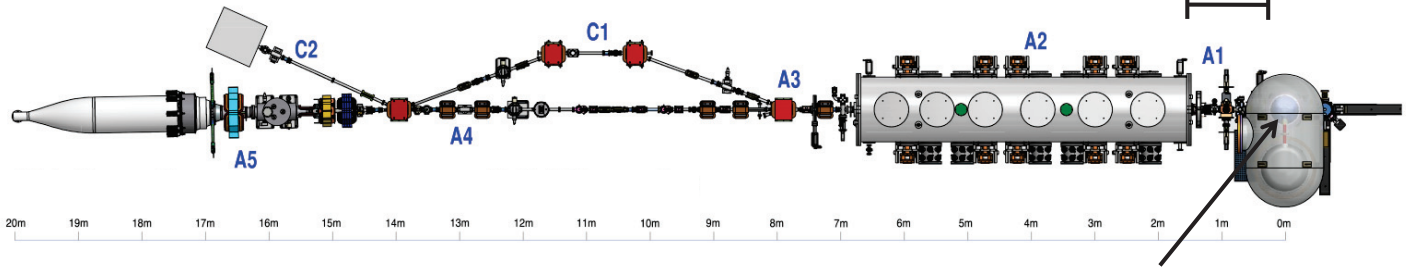

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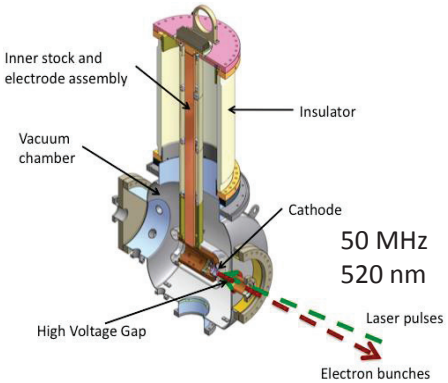

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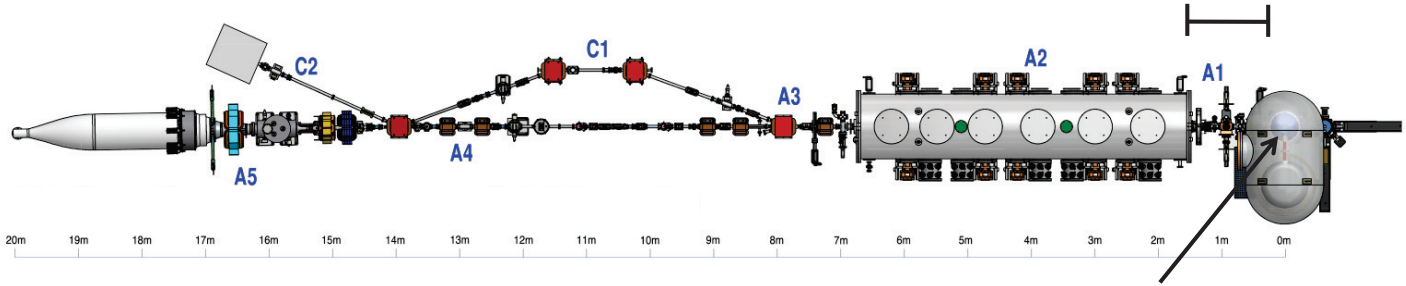
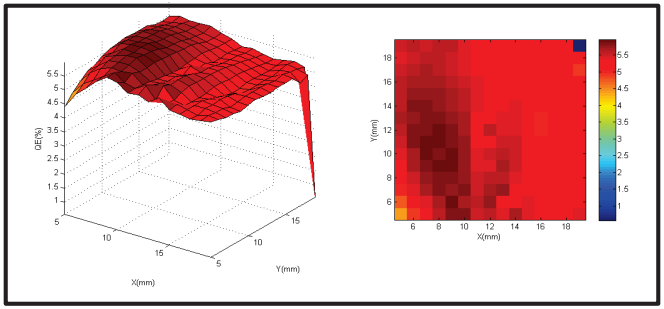
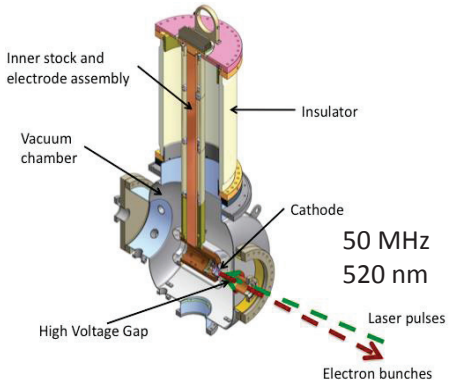


400 kV DC Gun

NaKSb: MTE = 140 meV, QE roughly 5%

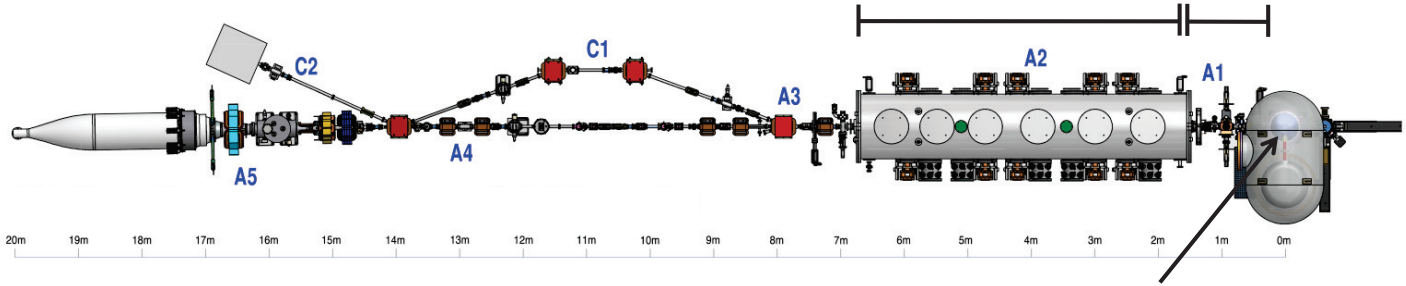




Injector Layout

Short SRF Linac
5 – 15 MeV

400 kV DC Gun +
Bunching/Focusing



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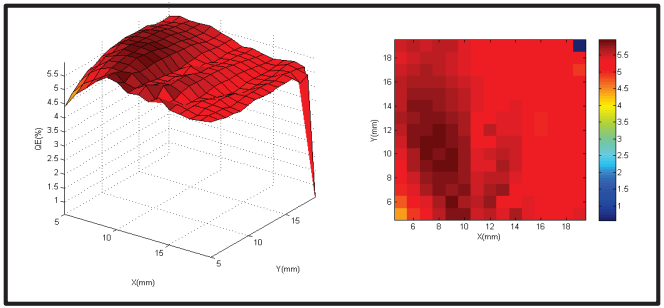

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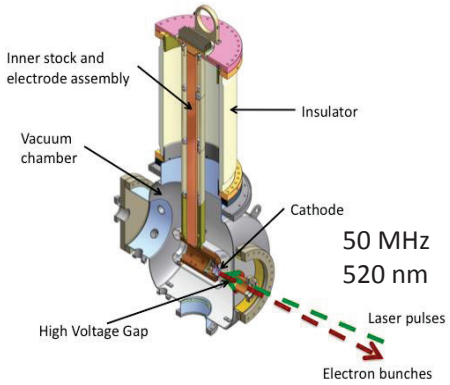

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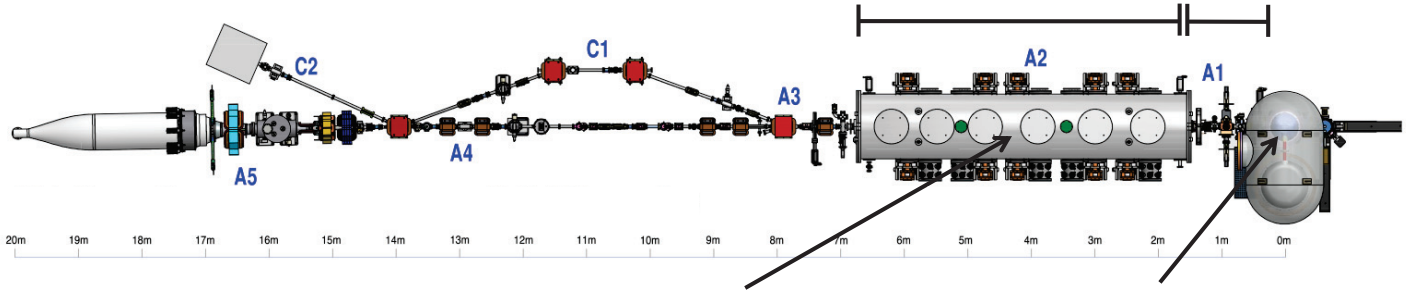

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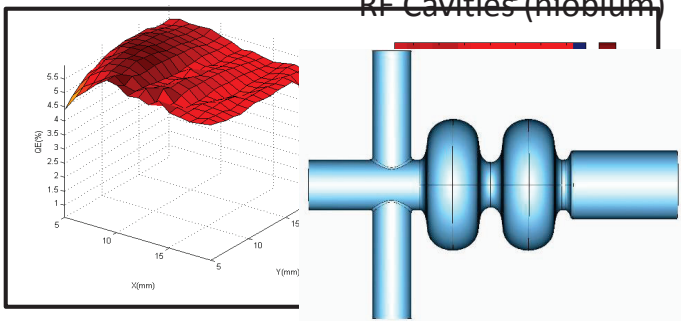
Superconducting
RF Cavities (niobium)



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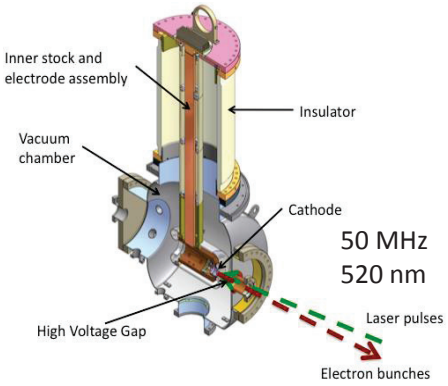

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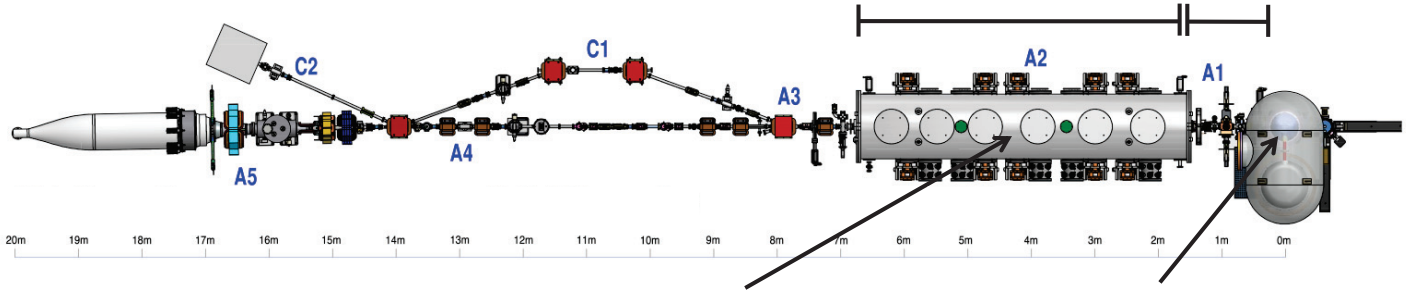

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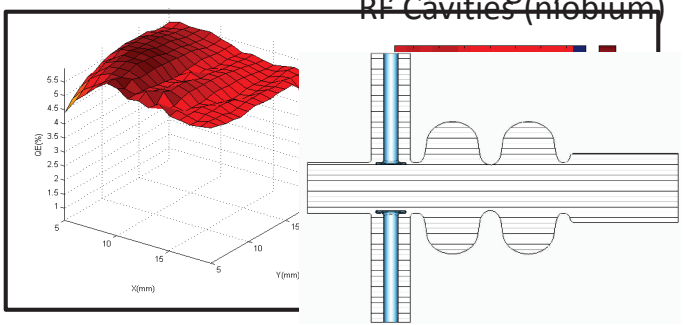

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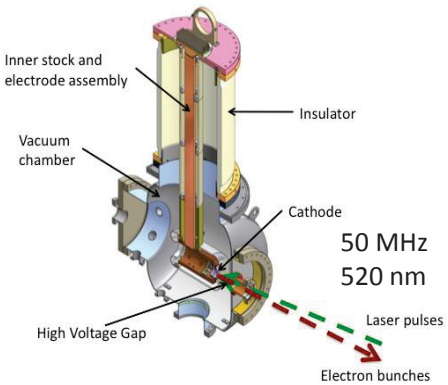
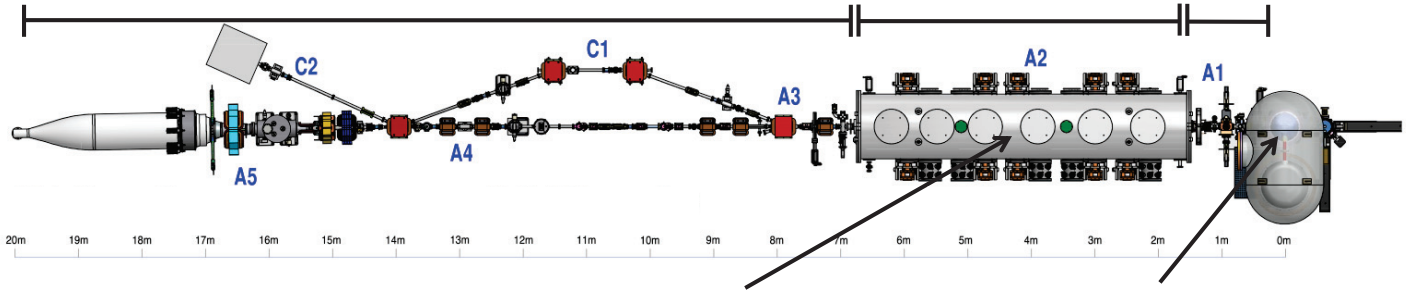


Injector Layout

6 Dimensional Phase Space Diagnostics + High Power Beam Dump + Chicane (Compton Scattering)

Short SRF Linac 5 – 15 MeV

400 kV DC Gun + Bunching/Focusing



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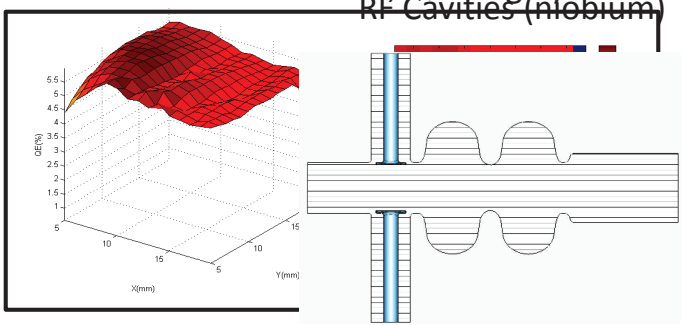

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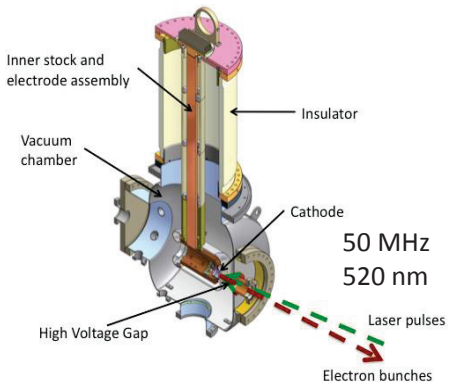

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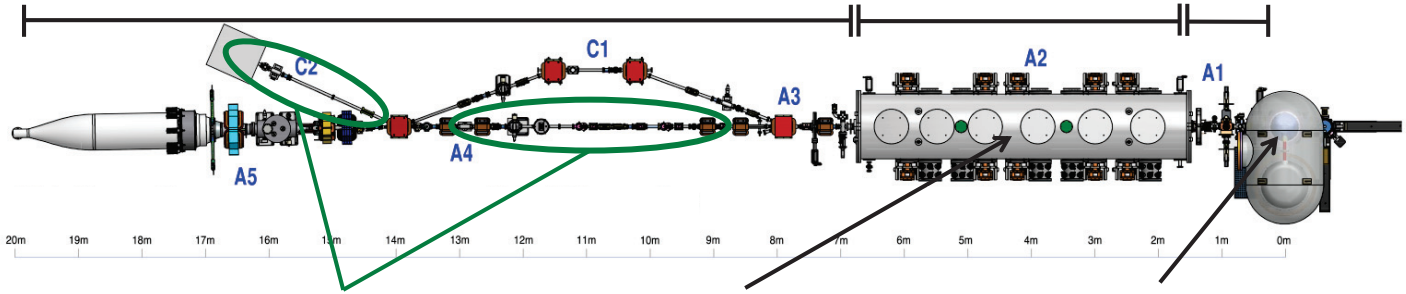

Emittance Measurement System

NaKSb: MTE = 140 meV, QE roughly 5%

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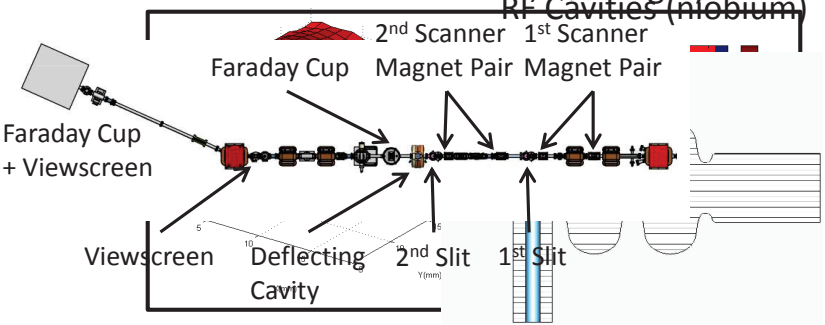

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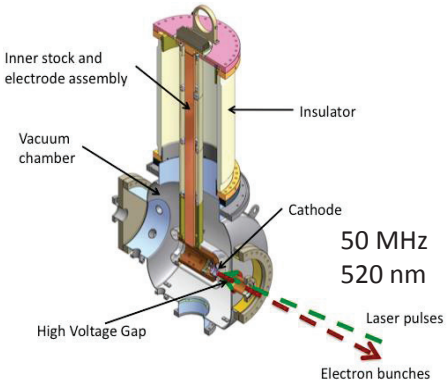
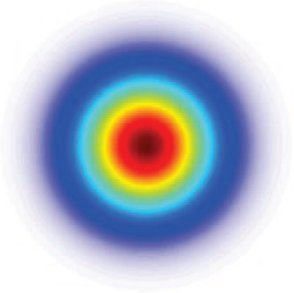
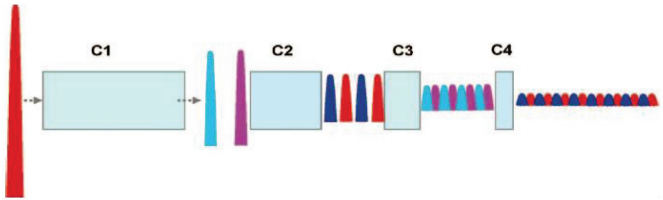


Laser Shaping

Transversely: clip Gaussian laser profile at a given intensity fraction (typically 50%)



Longitudinally: Birefringent Crystals for pulse stacking:



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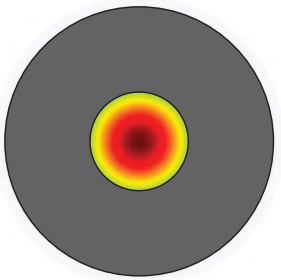

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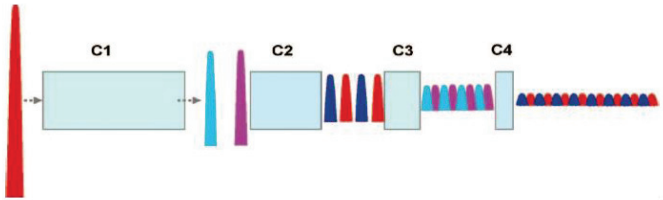

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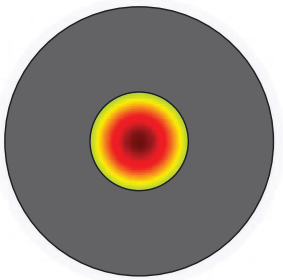

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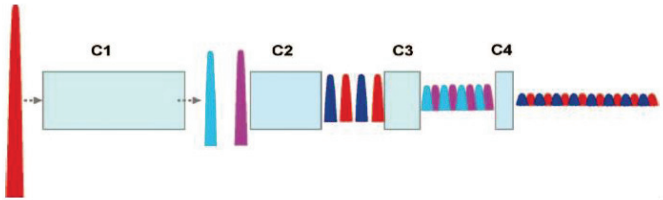

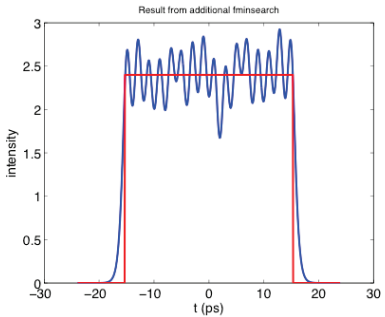

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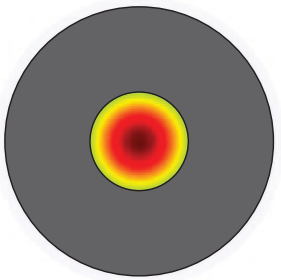

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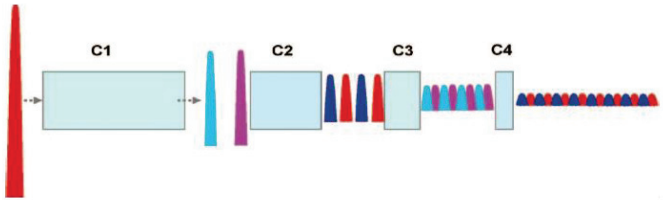

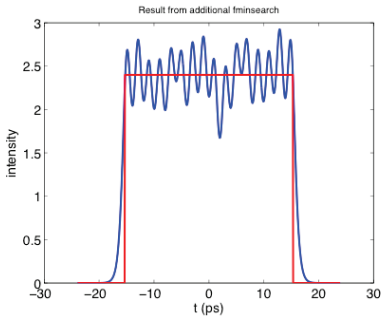

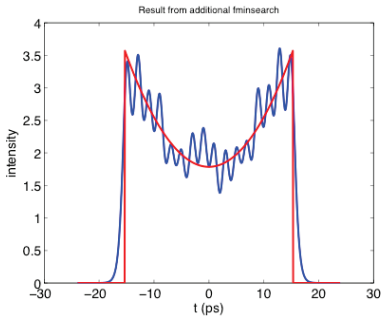

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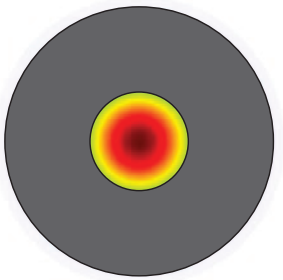

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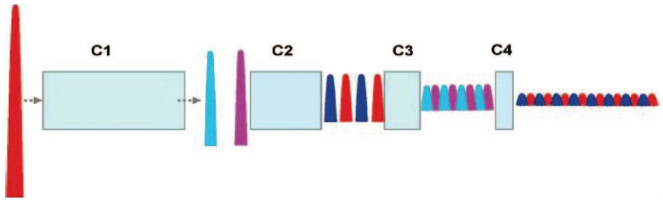
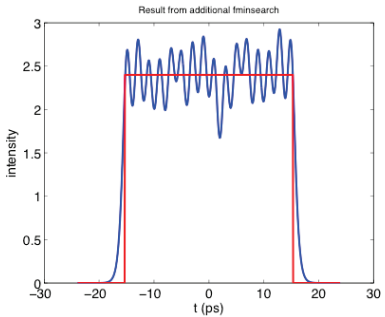
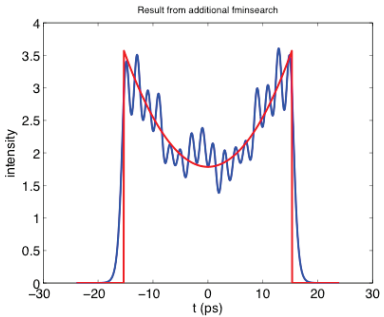
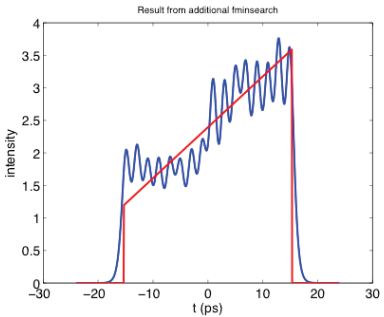








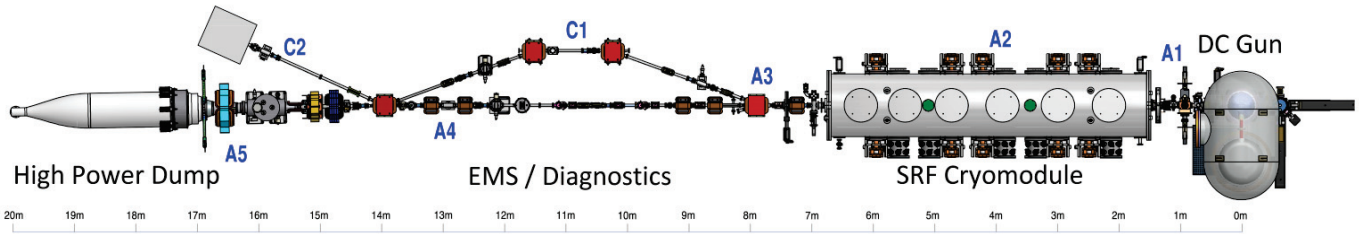
LCLS-II Injector Tests

CU Injector as possible injector for high rep. rate FEL (LCLS-II)

- 9.5 MeV
- Low current (<1 mA)
- Straight linac - No ERL merger section!

- Goal: measure emittance at specified charge / peak current:

Bunch charge	Peak current	Emittance (95%)
20 pC	5 A	0.25 μm
100 pC	10 A	0.4 μm
300 pC	30 A	0.6 μm



Expectations: Simple Scaling

Use previous results to get a rough estimate of what to expect:

- Assume optimal emittance scales like $\varepsilon_{n,x} \propto \sqrt{q_{bunch}}$
- Previously: (in merger)

Bunch charge	$\varepsilon_{n,x}$(100%)	$\varepsilon_{n,y}$(100%)
19 pC	0.33 μm	0.20 μm
77 pC	0.69 μm	0.40 μm

Note prior asymmetry in x , y

- Need around 0.8 μm (100%) emittance to get 0.6 μm (95%)
- Requires removal of asymmetry (Merger? Couplers?)
- Note: emittance may scale worse than $\sqrt{q_{bunch}}$

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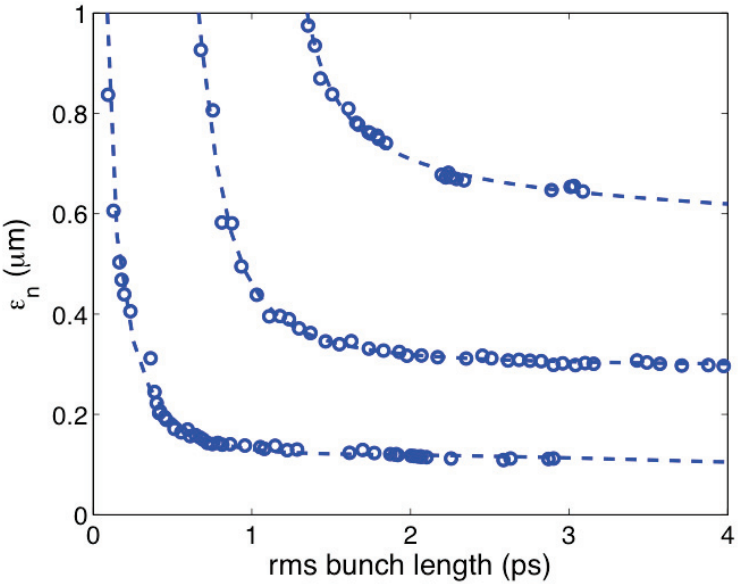
Expectations: MOGA

What does optimization of the injector model predict?

Perform Multi-objective Genetic Algorithm Optimizations:

- Vary all relevant magnet, cavity settings
- Vary laser shaping realistically: truncation fraction, crystal angles



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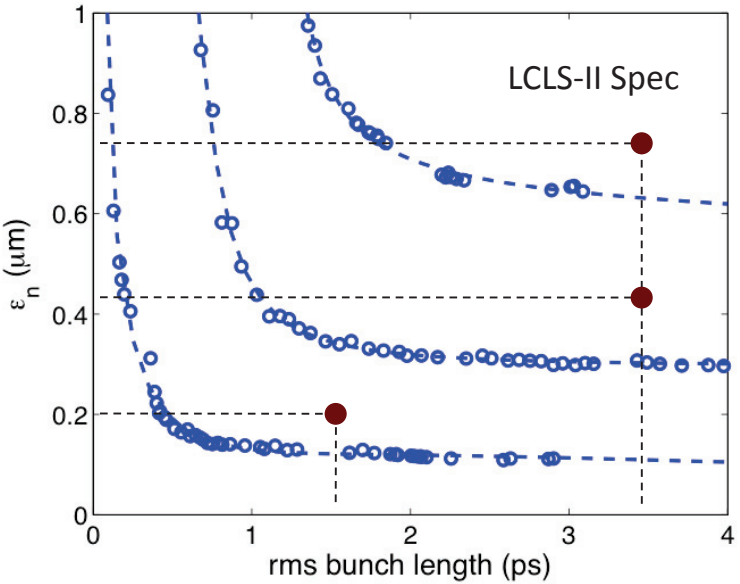

Initial trouble at 20 pC

- Beam Based Alignment
- Loaded optimized settings
- Tuned machine (few weeks)

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20 pC	5 A	0.25 μm
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Bunch charge	Peak current	Emittance (95%)
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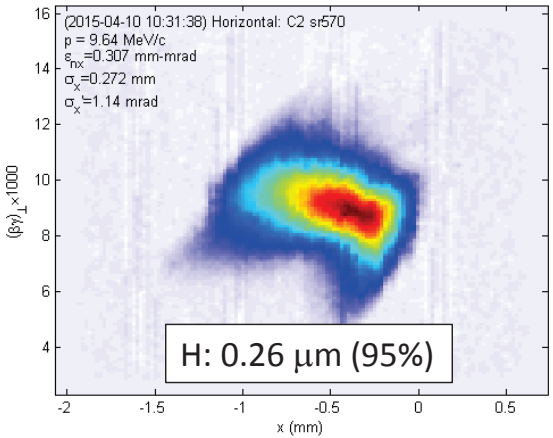
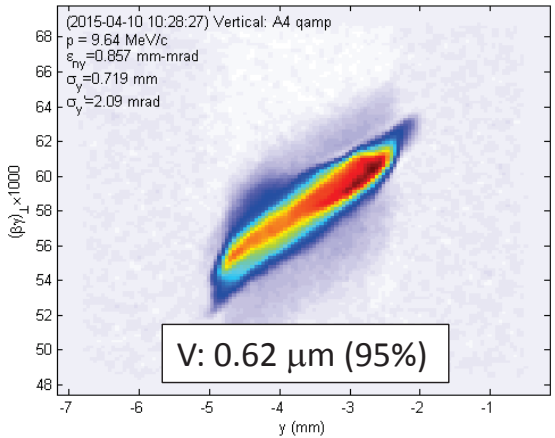
Found emittance X/Y asymmetry that could not be removed!





Can't be from the merger….

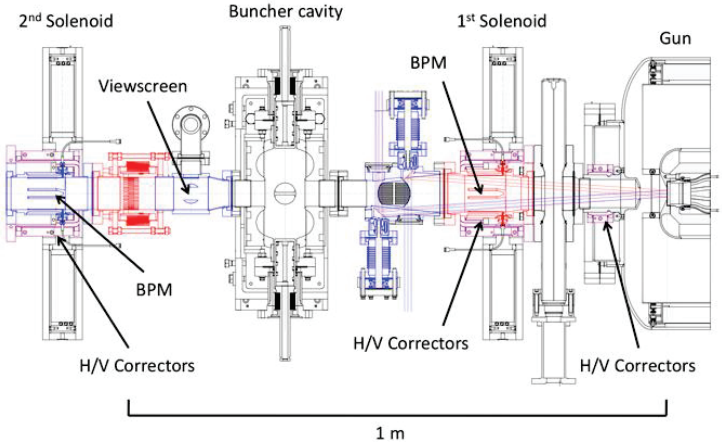
Origin of asymmetry

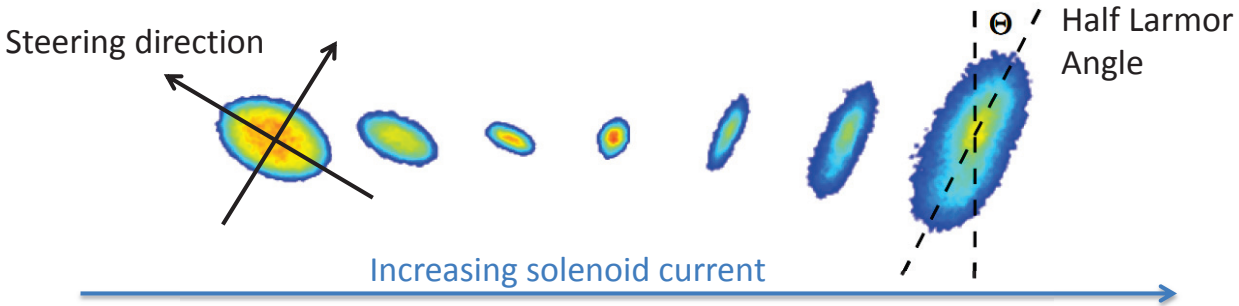
- Found a beam asymmetry after (only) the first solenoid!

With 20 pC and focus near VS:
- Elliptical beam spot
- Ellipse axes aligned with axes of corrector in 1st solenoid…

With 0 pC:
- Beam is round

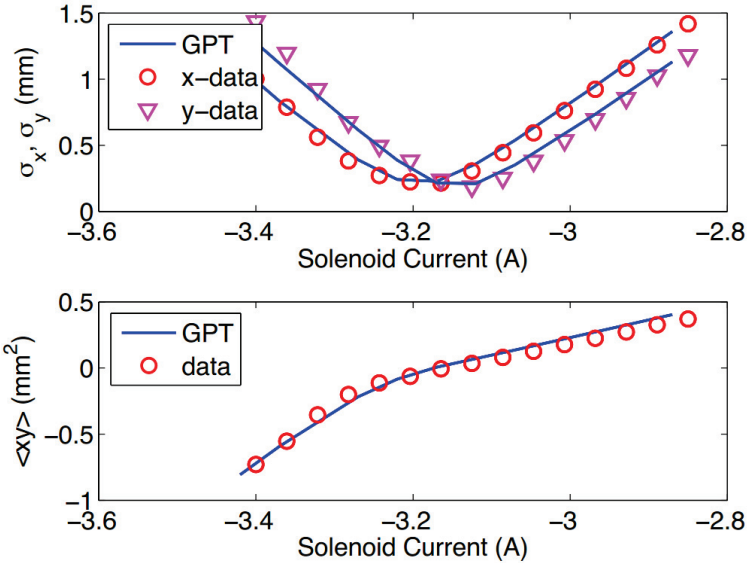
-> Likely culprit: stray quad field





Estimating Quad Strength

- Compared 2nd moments of the beam to simple models of stray quad field **inside** 1st solenoid
  - Best fit: **0.5 G/cm** (at typical solenoid currents)
  - Best fit scales with solenoid current (not shown), flaw in manufacturing?
  - This is a strong enough field to wreck the emittance in simulation

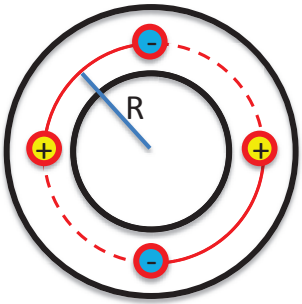


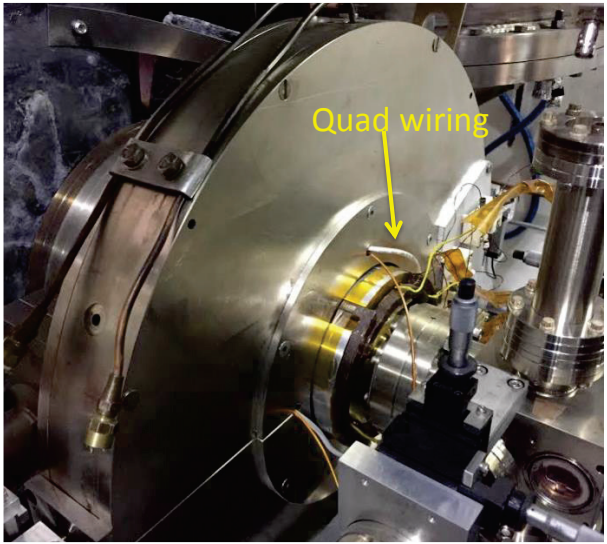
Correcting Quad Coil

BPM cable feed-thrus allow for a 2 coil quad:

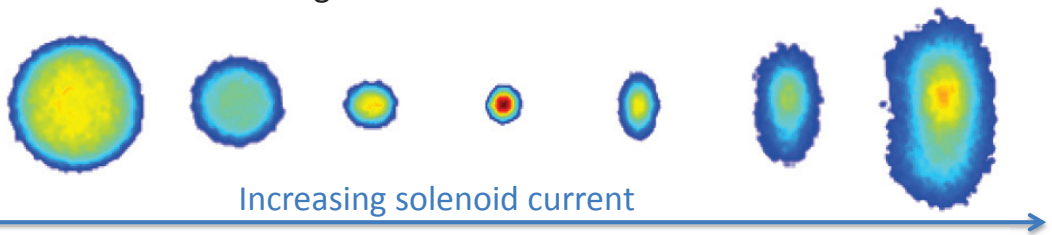
$$B_x \approx \frac{2(NI)\mu_0}{\pi R^2} y$$

$$B_y \approx \frac{2(NI)\mu_0}{\pi R^2} x$$





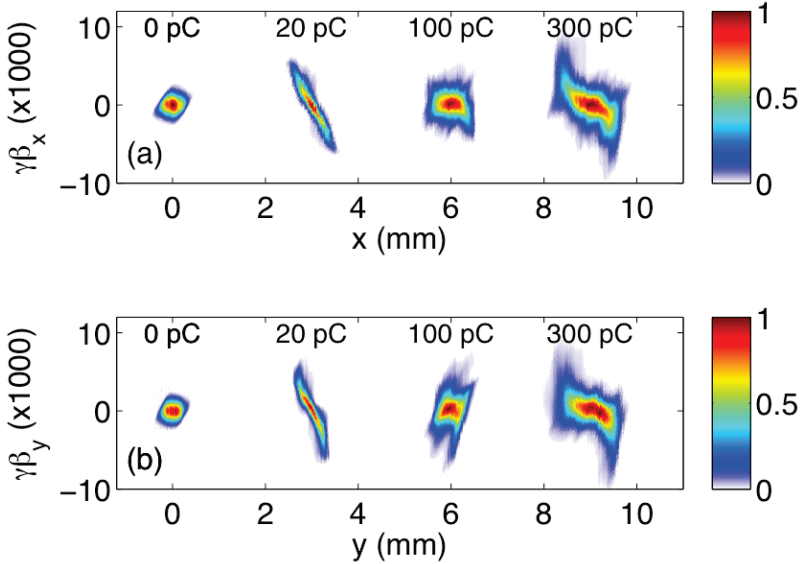
- R = 6”, L = 3”, need **40 amp-turns** of coil
- Removed tilt with 30 amps through coil… still not quite round. Good enough?



Results

After another month of work…

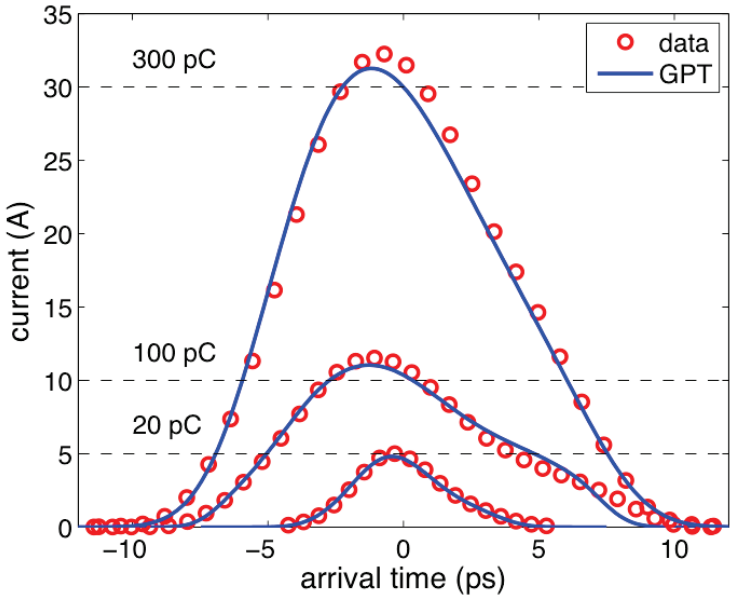
- Emittance asymmetry is gone
- Met spec at all charges
- Same SRF settings for all charges



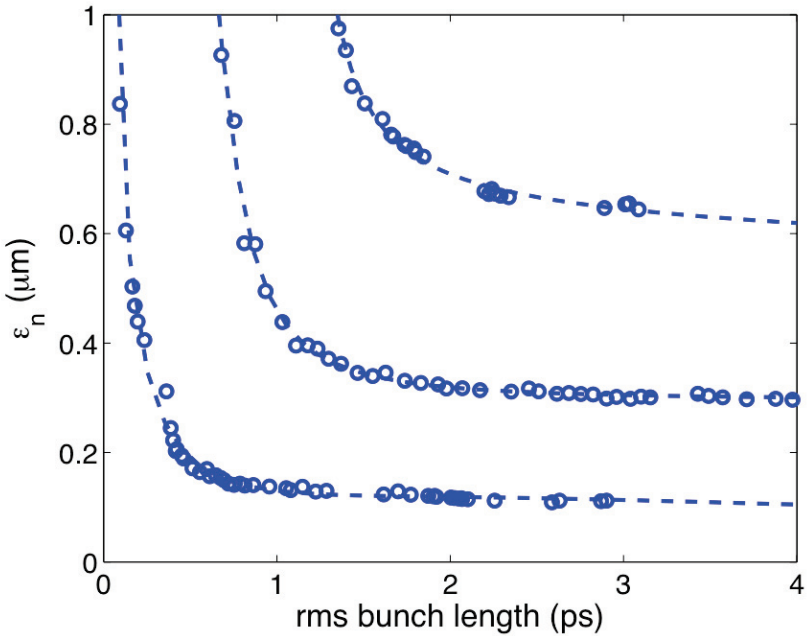
Q (pC)	I_{peak} Target (A)	I_{peak} (A)	ε_n Target (95%, μm)	ε_n (95%, μm)	$\varepsilon_{n,th}/\varepsilon_n$
20	5	**5**	0.25	**H: 0.18, V: 0.19**	**60%**
100	10	**11.5**	0.40	**H: 0.32, V: 0.30**	**80%**
300	30	**32**	0.60	**H: 0.62, V: 0.60**	**70%**

Agreement with Simulation

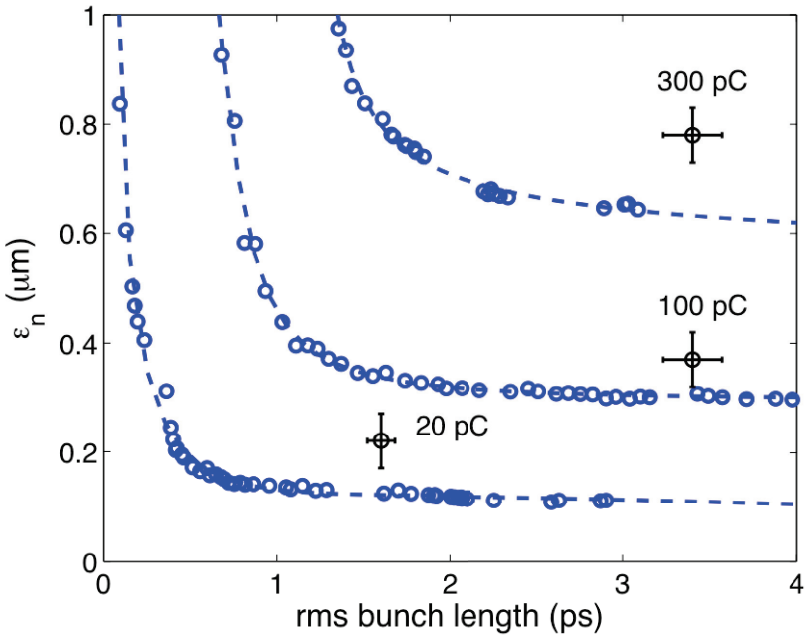
Current profile agrees well at all charges



Effects of the Laser Shape

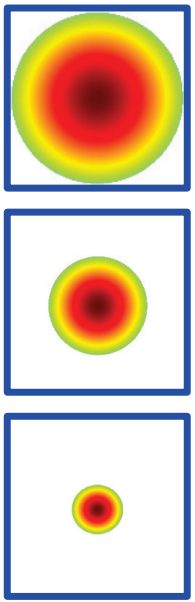


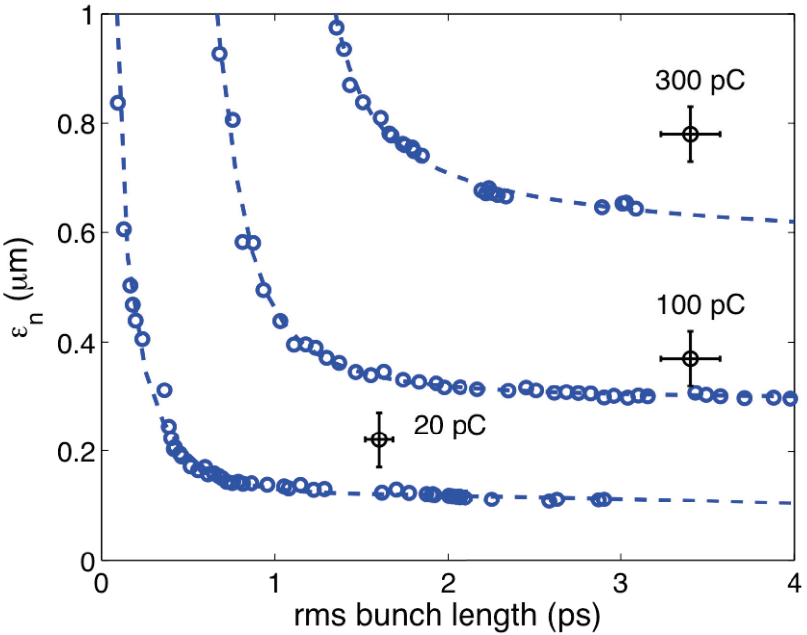
Effects of the Laser Shape



Effects of the Laser Shape

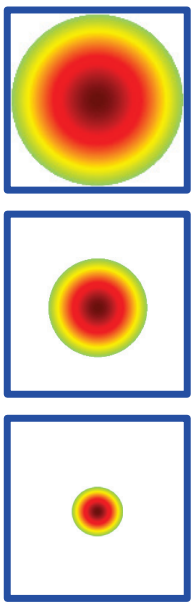
Ideal Shape

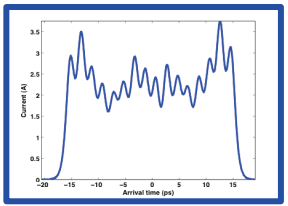


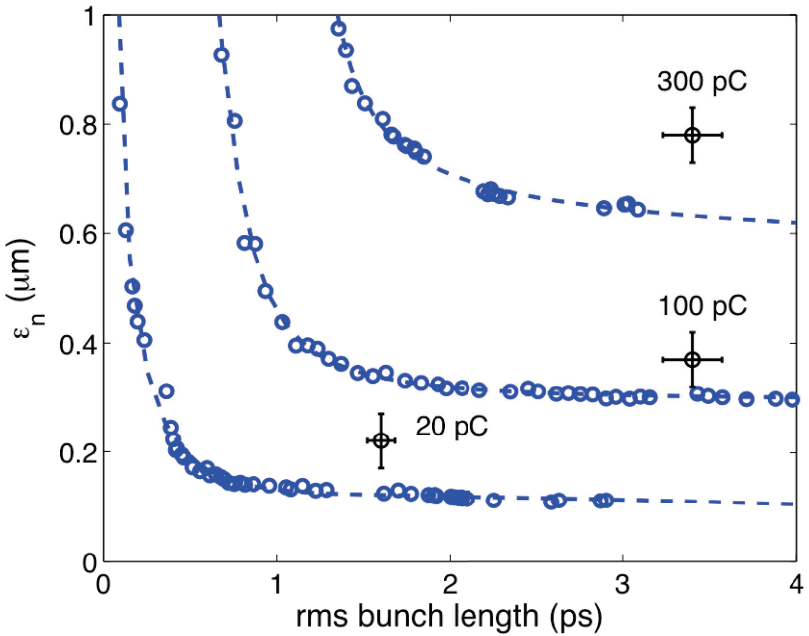


Effects of the Laser Shape

Ideal Shape







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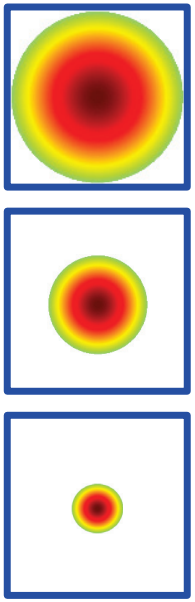

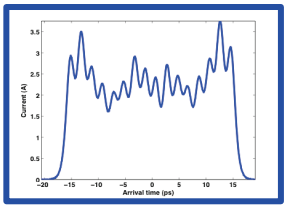

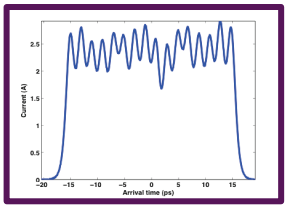

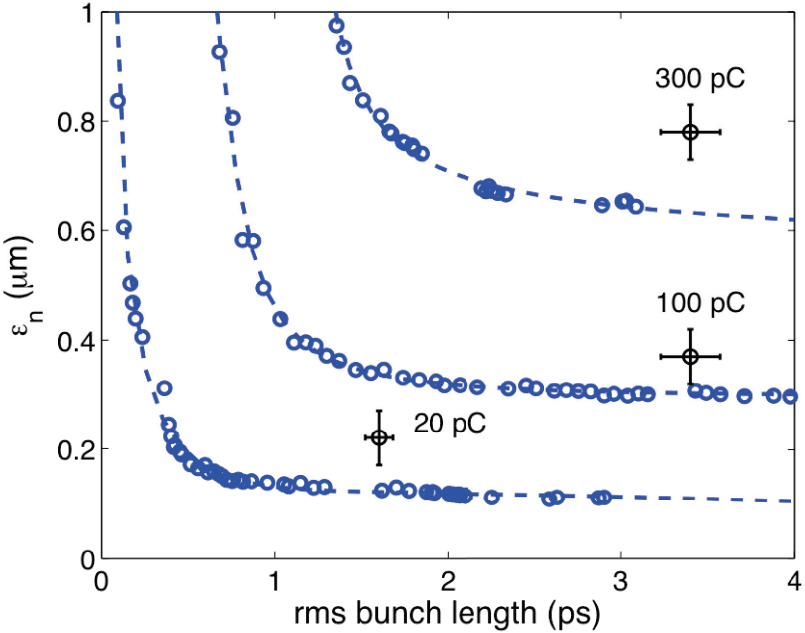

Effects of the Laser Shape

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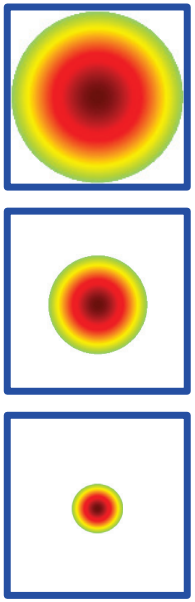

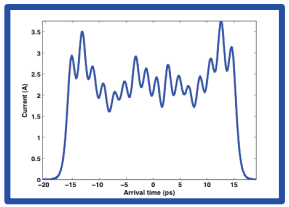

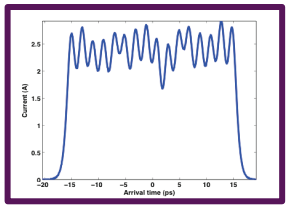

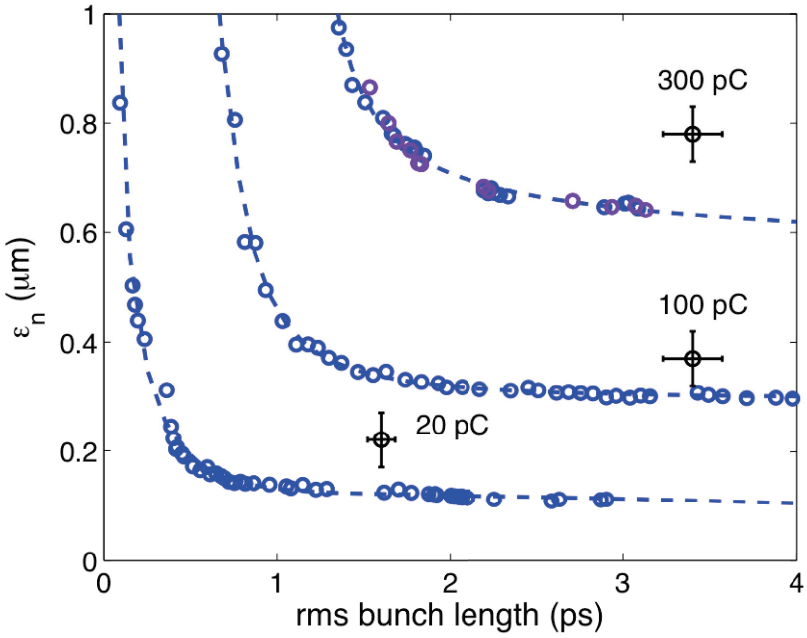

Effects of the Laser Shape

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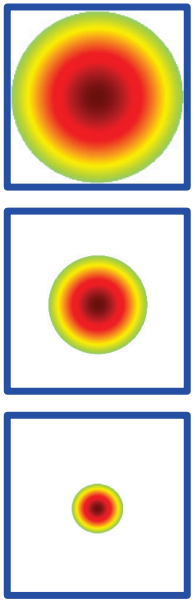
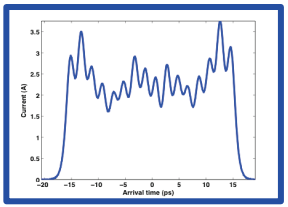
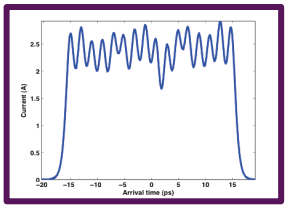
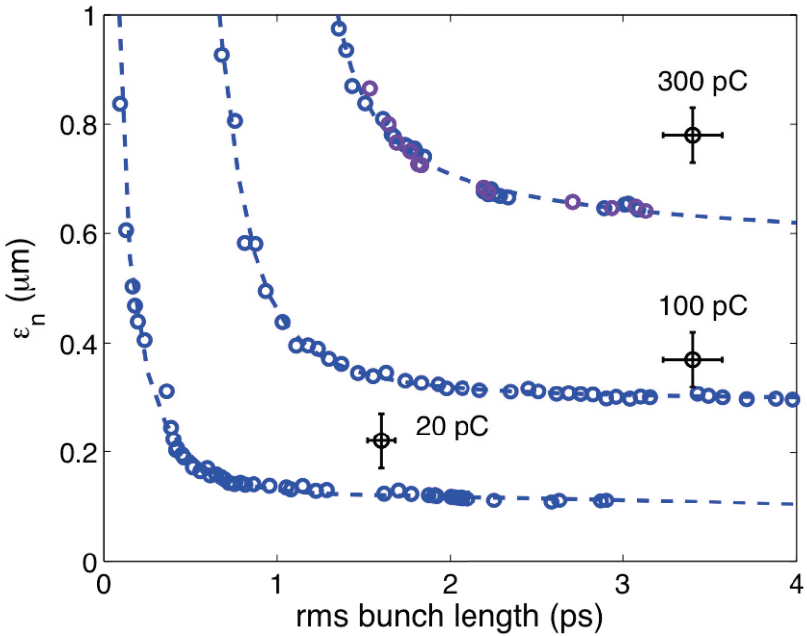
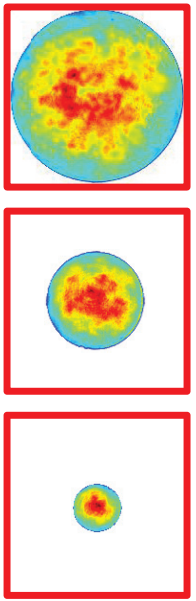








Measured Shape



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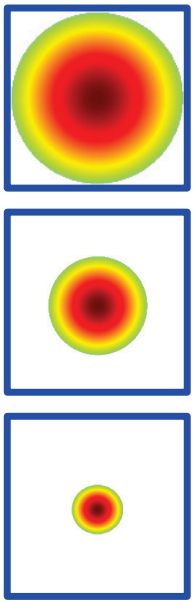
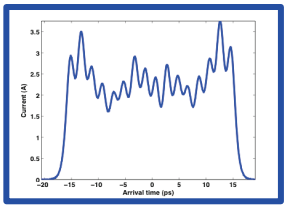
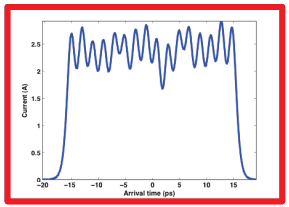
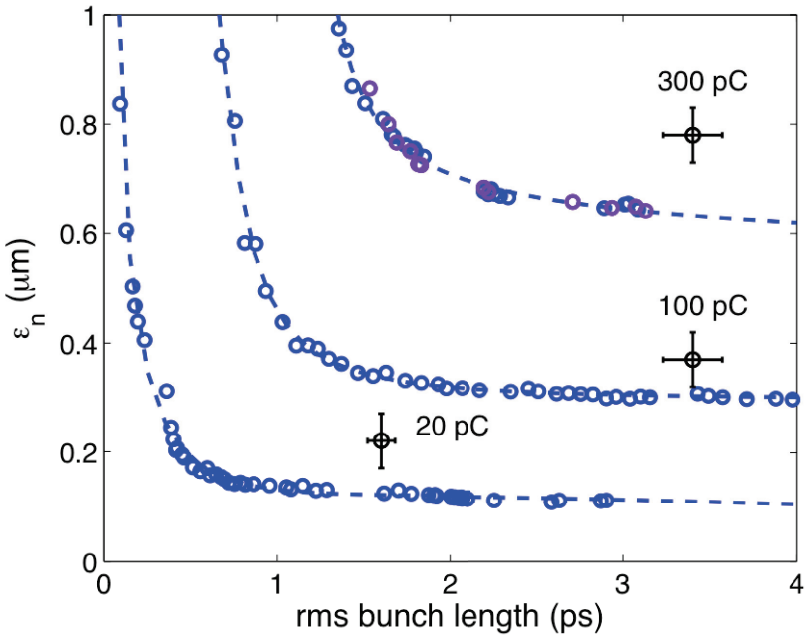
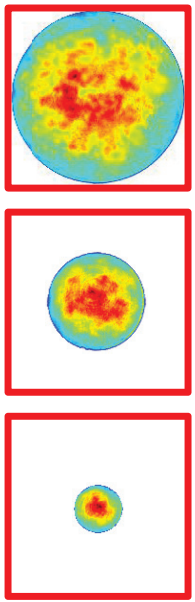








Measured Shape



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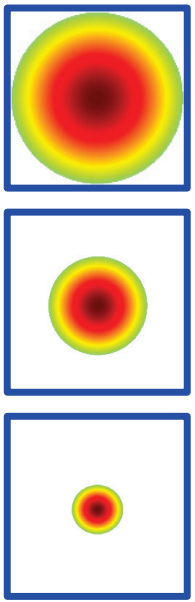
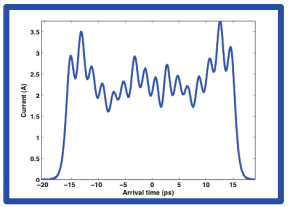
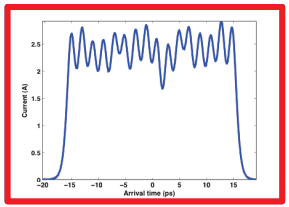
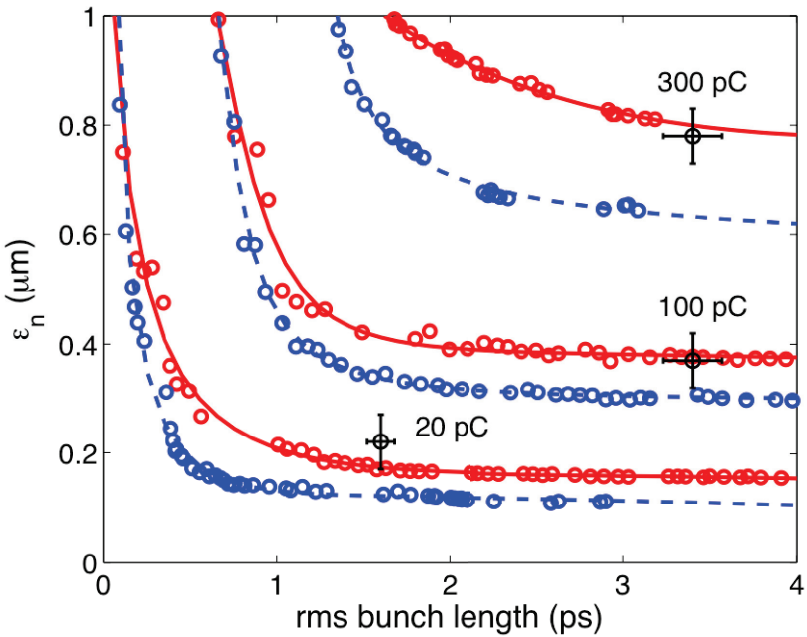
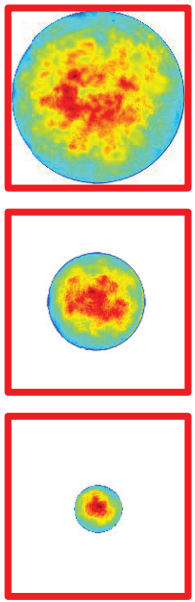








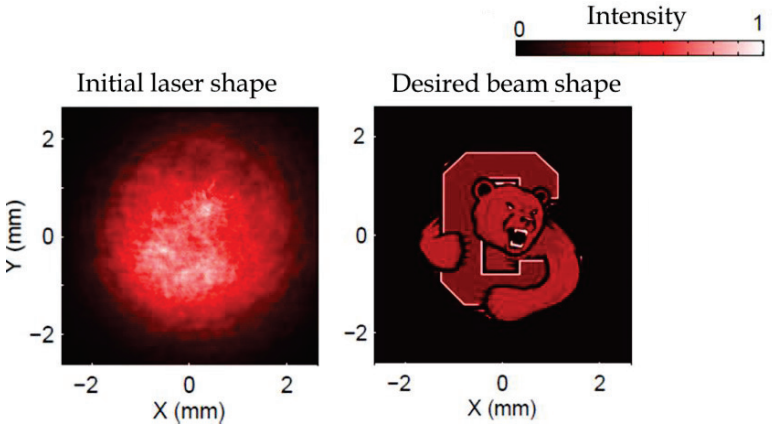
Measured Shape



Arbitrary Laser Shaping

To do better: Need arbitrary (transverse) laser shaping

- See Jared Maxson's talk: WG1, session 2 (Tues 14:00)



J. Maxson et al., Phys. Rev. ST Accel. Beams **18**, 023401 (2015).

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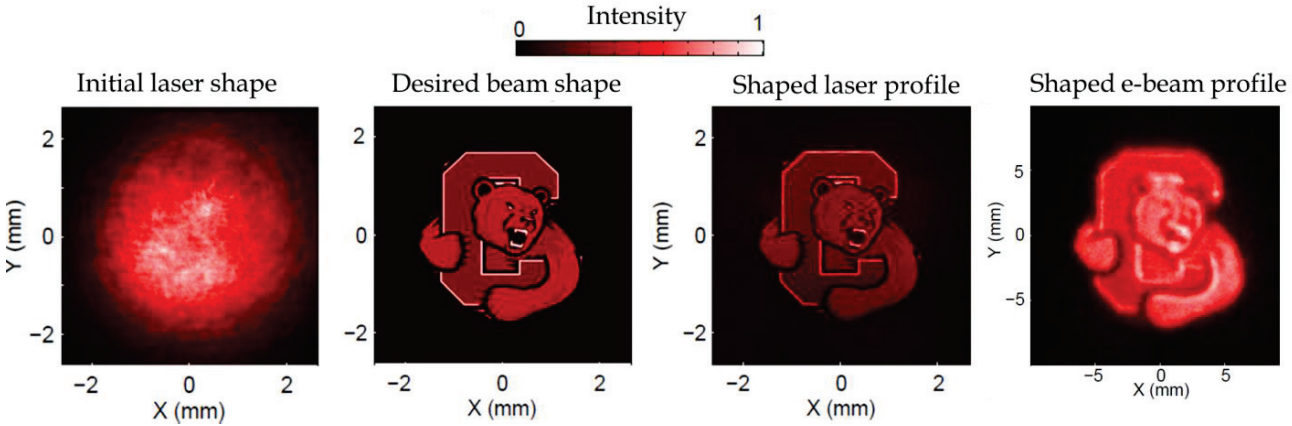
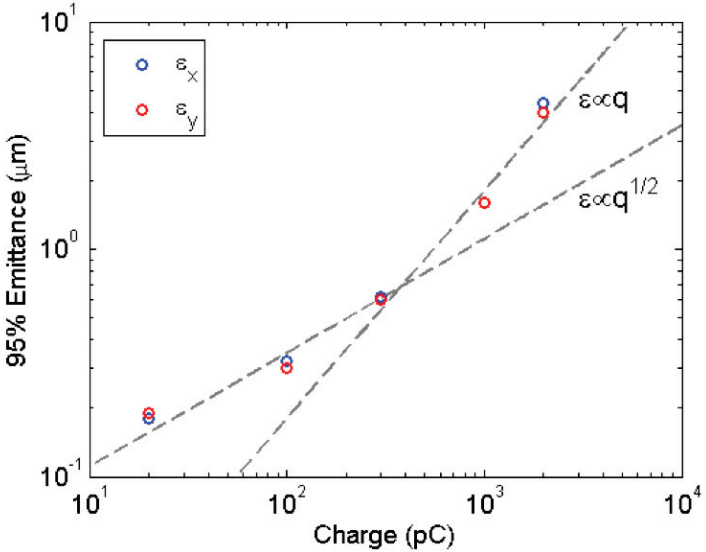


J. Maxson et al., Phys. Rev. ST Accel. Beams **18**, 023401 (2015).

Even larger charge?

- (Omitting analysis of phase spaces, simulations here…)
- Primary result: Emittance trend becomes more linear above 300 pC…

Q (pC)	Peak current (A)	Emittance (95%, μm)
20	5	H: 0.18 V: 0.19
100	11.5	H: 0.32 V: 0.30
300	32	H: 0.62 V: 0.60
1000	50	H: 1.6 V: 1.6
2000	56	H: 4.4 V: 4.0



Summary

- In addition to all ERL specifications, the CU injector meets all LCLS – II requirements
  - Emittance growth well compensated up to 300 pC
  - (at 300 pC) ε_{th} = 0.41 μm, final at 9.5 MeV: ε_n = 0.6 μm
  - Emittance scales roughly as $\sqrt{Q}$
- At higher charge, compensation is worse
  - 1nC: ε_{th} = 0.6 μm, ε_n = 1.6 μm
  - Emittance scales roughly as Q
- Best emittance requires careful control of transverse laser profile
- Need diagnostics to detect unexpected stray fields, and ability to counter them

SLAC

DOE Nuclear Physics awards
DE-SC0012493, DE-AC02-76SF00515

Acknowledgements

Thanks to the Cornell High-brightness Beam Group:

Thanks to ERL15 for the invitation!