Cornell Injector – DC Gun Design and Operation

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Outline

Gun Design
- Global optimization
- New design choice
- Construction and Processing

Cathodes
- Primary remaining challenges

Laser
- Laser shaping
- Considerations for high current

Goals for Gun Operation
- Emittance
- High current

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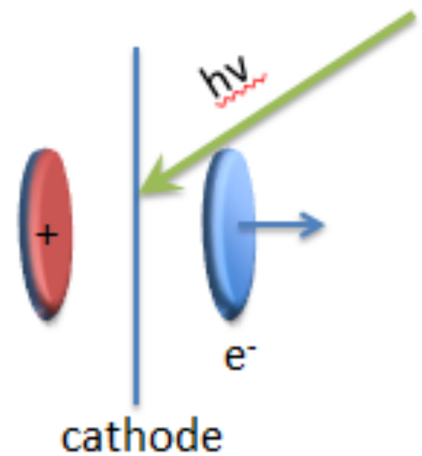
Gun Design

- Max beam brightness limited by cathode field



$$B_{max} = \frac{\epsilon_0 mc^2}{2\pi}\frac{E_{cath}}{MTE}$$

$$\epsilon_{nxy,\mathrm{th}} = \sigma_{xy}\sqrt{\frac{\mathrm{MTE}}{mc^2}}$$

- Need high gun voltage to preserve brightness
- How high is high enough?
  - Do we need SRF?
- Need full simulation and optimization

Gun Design

Consider two injector designs

1. CU Injector
   - DC gun, 2 solenoids, buncher, ICM
   - Laser with arbitrary shaping

2. SRF
   - SRF gun, 1 solenoid, ICM
   - Laser with arbitrary shaping

Vary all parameters of the system

- Design of the gun(s)
- Laser shape
- All optics

Perform global optimization

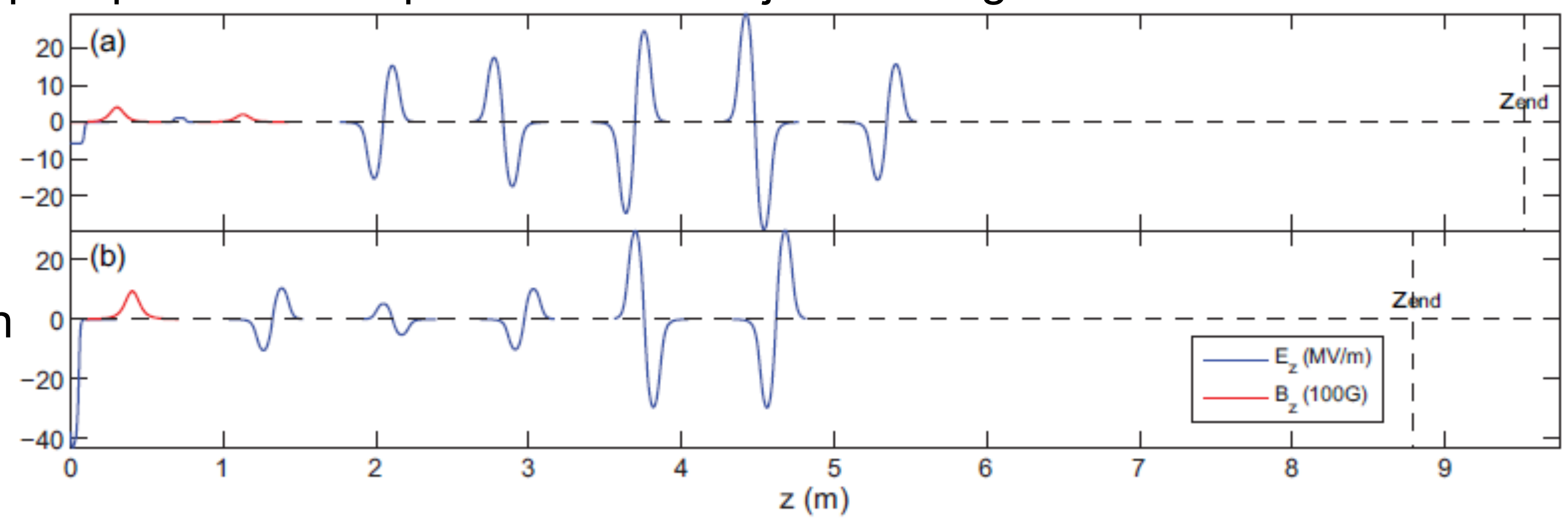
- How well do each perform at a variety of bunch charges?

Gun Design

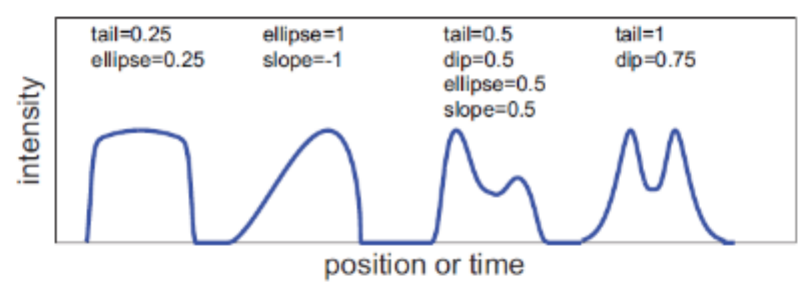
Example optimized field profiles in both injector designs

DC Gun

SRF Gun



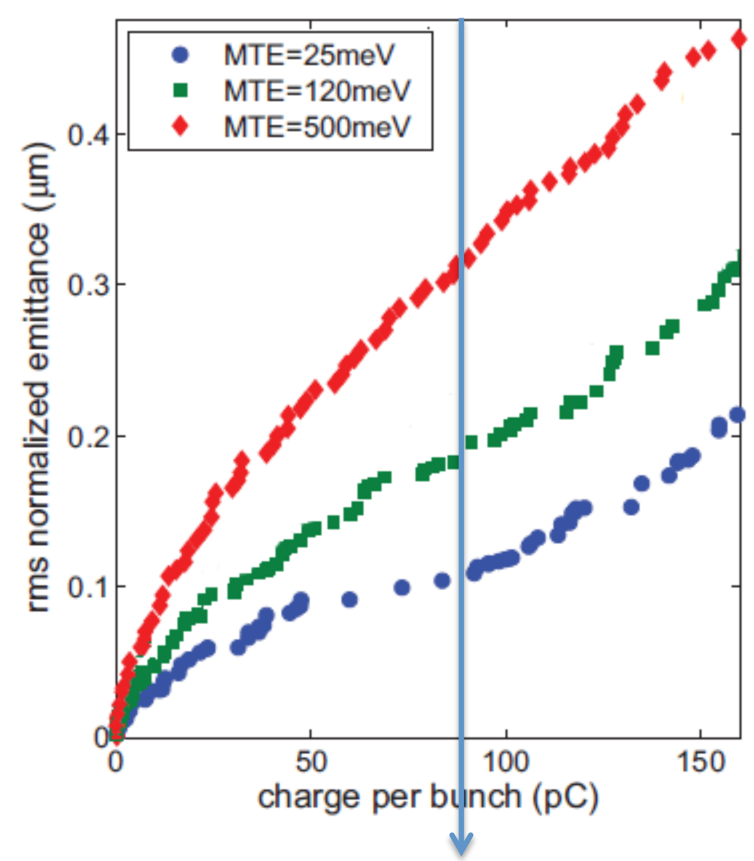
Temporal Laser Distribution: Parameterize shape as superposition of a few basic types



Transverse Laser distribution*:* *Gaussian with variable σ and cutoff radius.*

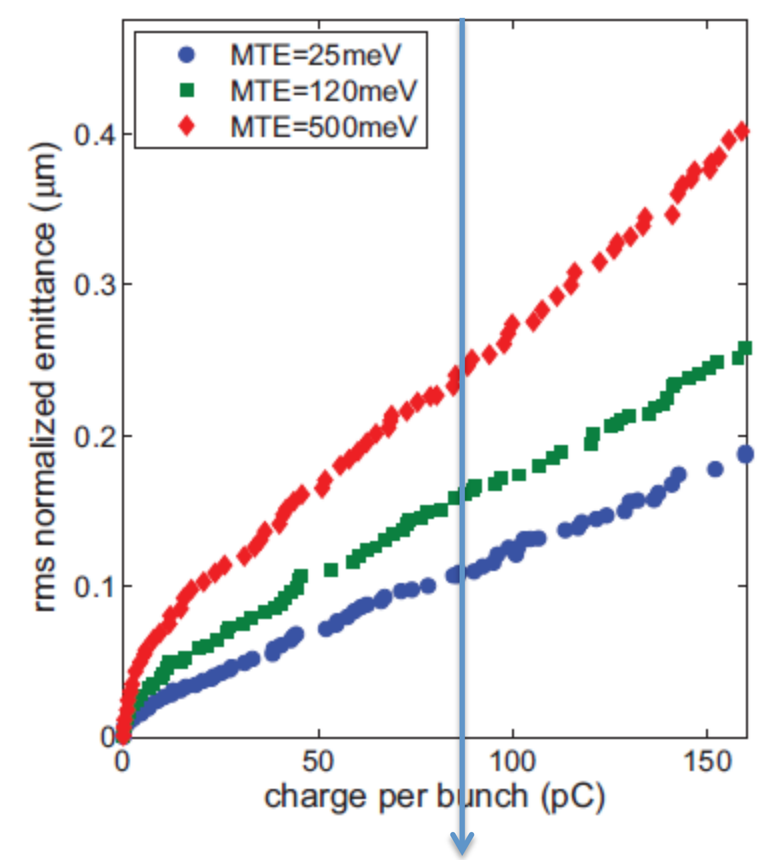
Gun Design

DC Gun



V=470 kV , E_{cath}=5.1 MV/m

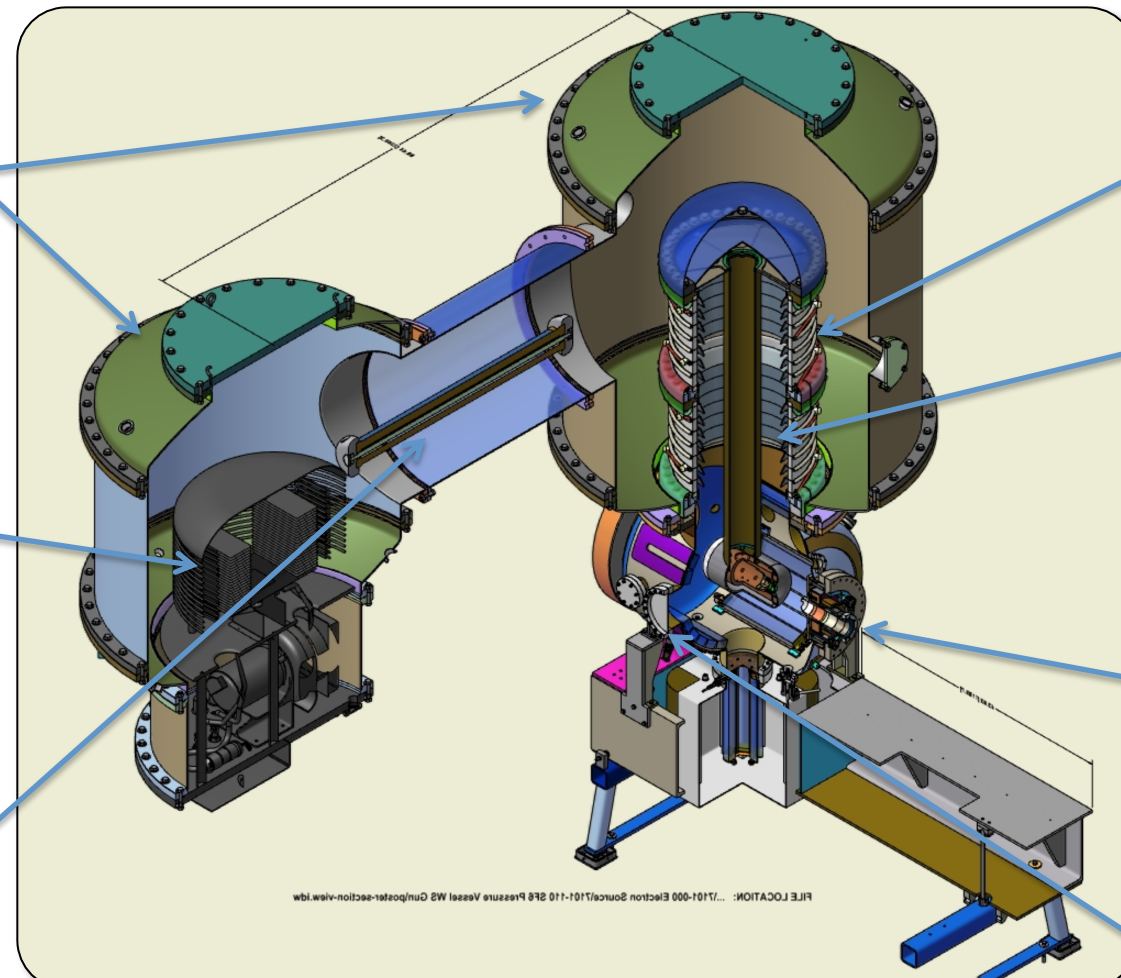
SRF Gun



V=1.6 MV

- SRF wins, but not by much
- Emittances within *20%, with voltages 3x different!*
- Moderate voltage (470 kV) and *high photocathode field*

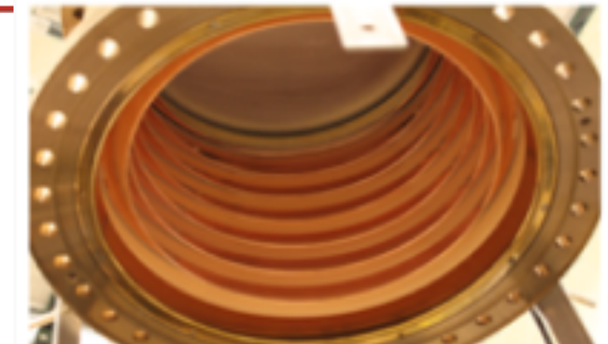
Gun Design

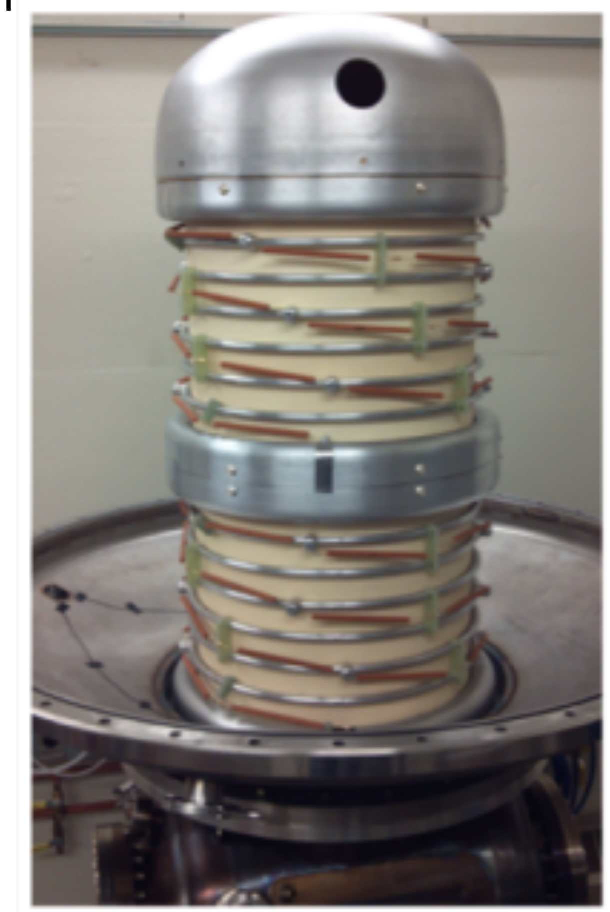


SF6 @ 4 atm
Kaiser 600kV PS
100-300 MΩ
Segmented, shielded insulator (KEK)
50'' 316LN stalk
5 cm gap, 25º focusing
Ion pump *behind* 3500l/s Capacitorr NEG pump (x2)

Gun Design

- Mitigate punch-through: shield the ceramic!
- Brazed Alumina segments with kovar ring in each joint.
- Inside: Cu protection rings entirely shield ceramic from field emitted electrons
- Outside: Mount 500MΩ resistors between each segment (1GΩ / 2 in parallel)
  - Allows differentiation between field emission going to ground or going to the rings!
  - If anode floats, can distinguish between emission from stalk, cathode, and direct to ground.





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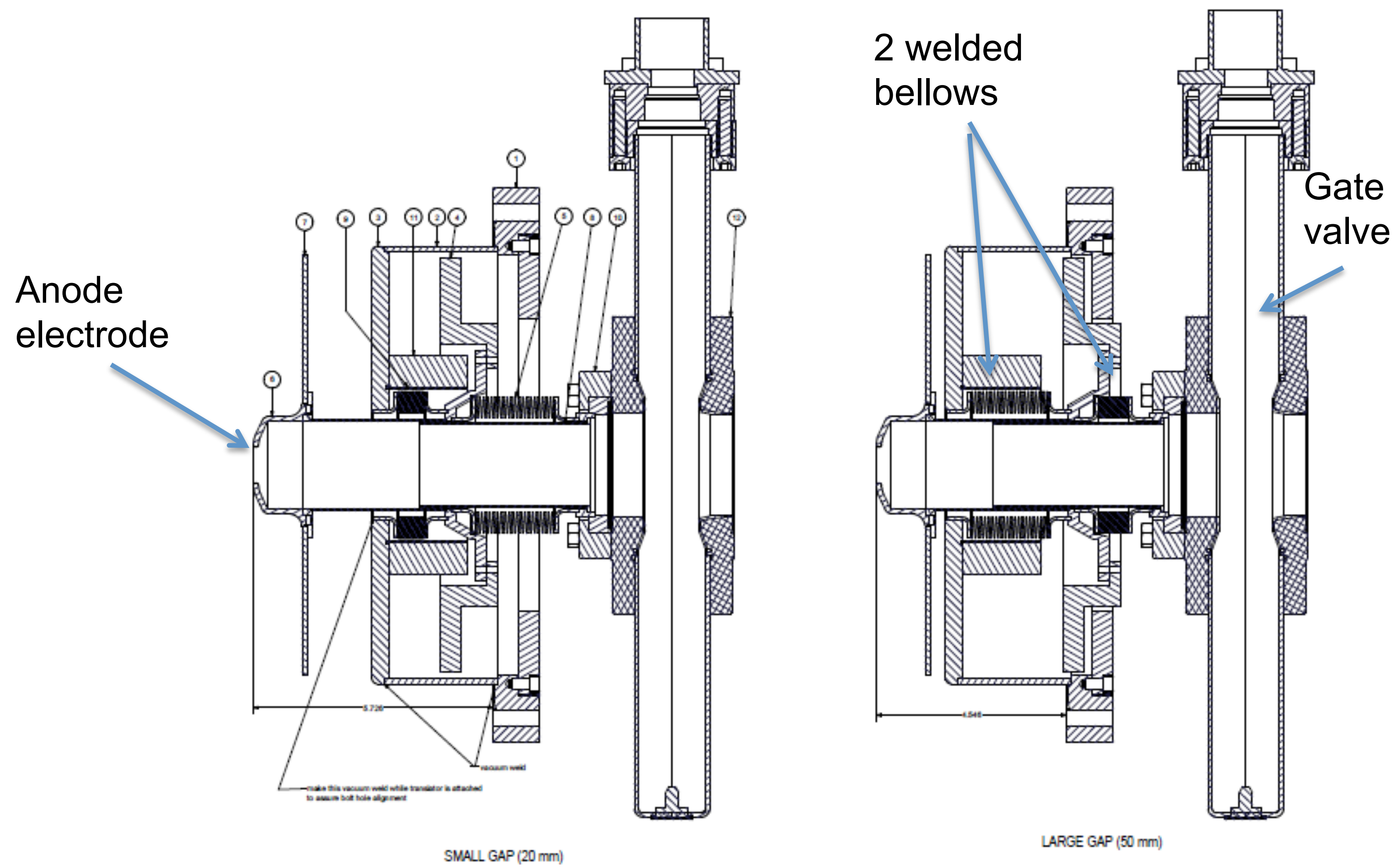
Gun Design

- *Cathode field* is crucial
- Translatable anode to tailor the field
- **2-5 cm adjustable gap**



Gun Design

- Followed SRF cleaning procedure
  - Chemistry on all electrodes
  - HPR all surfaces
  - Clean roc
- During NEG ed.
  - **Large b mination while hc**
- Reached 39
- Decided to c

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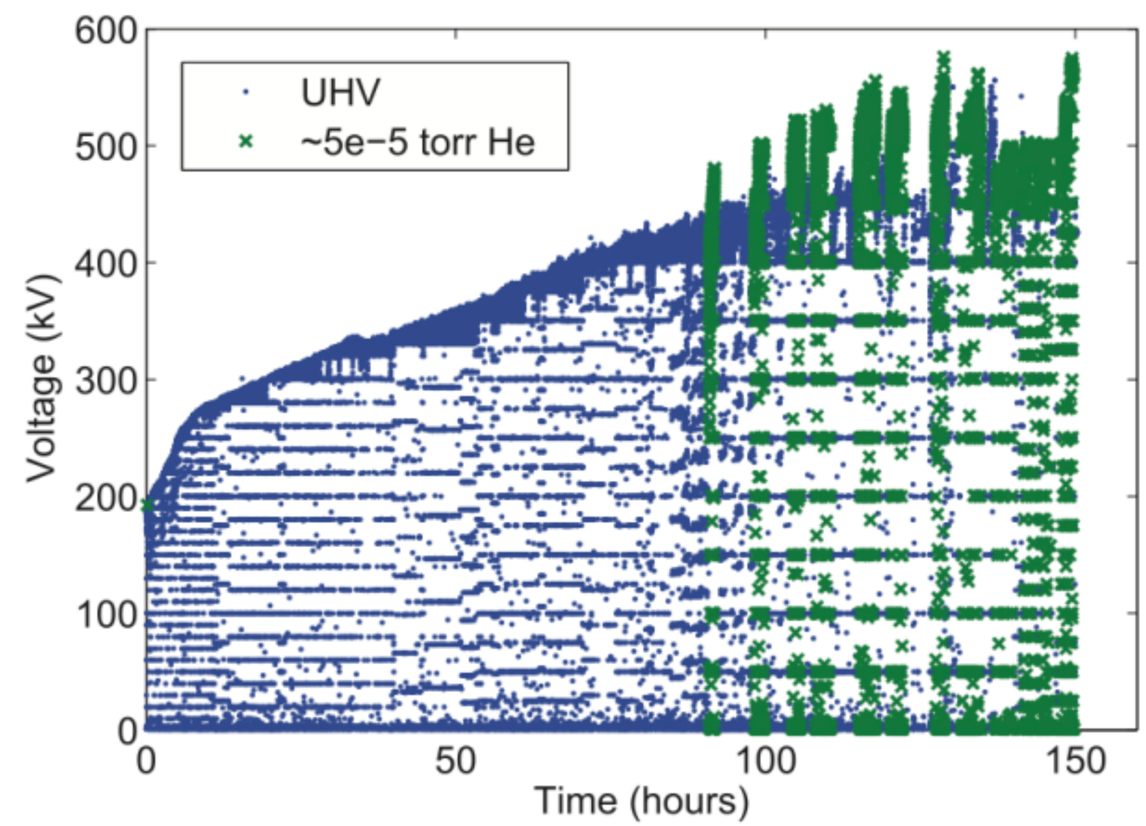
Gun Rebuild

- Used SRF cleanroom facility (class 10).
- Processed up to 485 kV in vacuum
    - 575 kV with gas processing
    - 425 kV stable operation for beam



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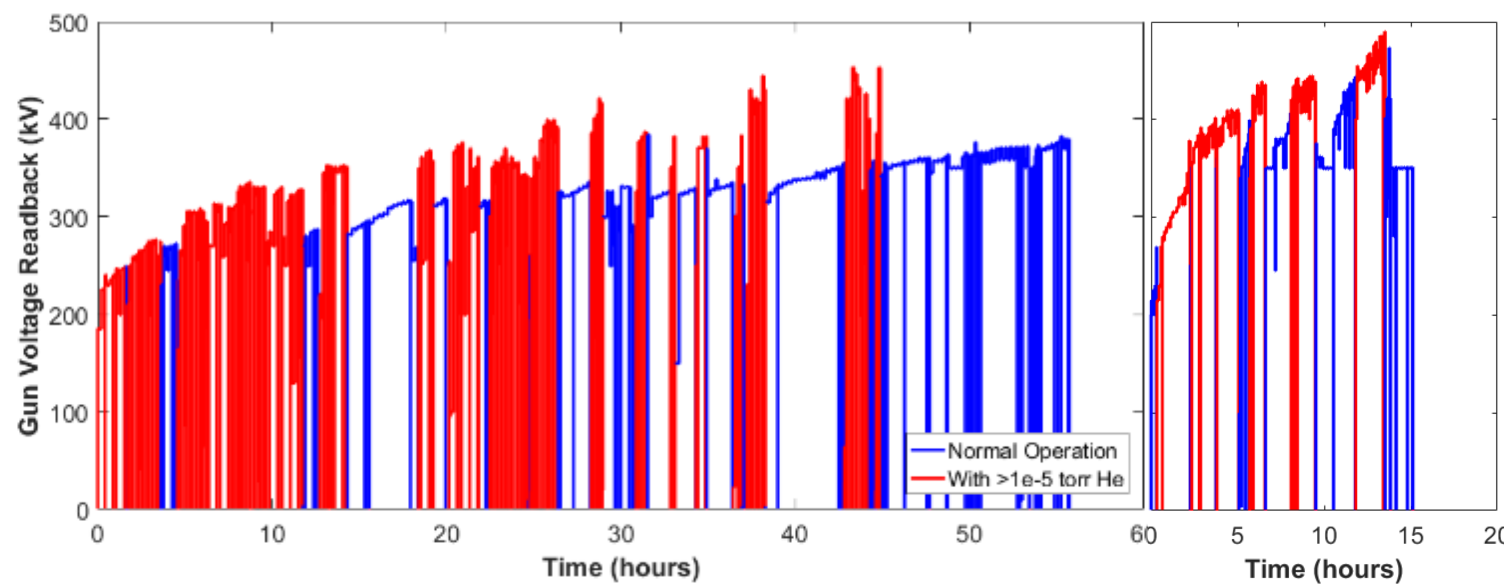
Gun Processing – CU Gun

- After moving to final location for CBETA, needed new processing
- After 70 hours, stable running at ~350 kV, high enough for CBETA (comparable to previous plot after the same time)



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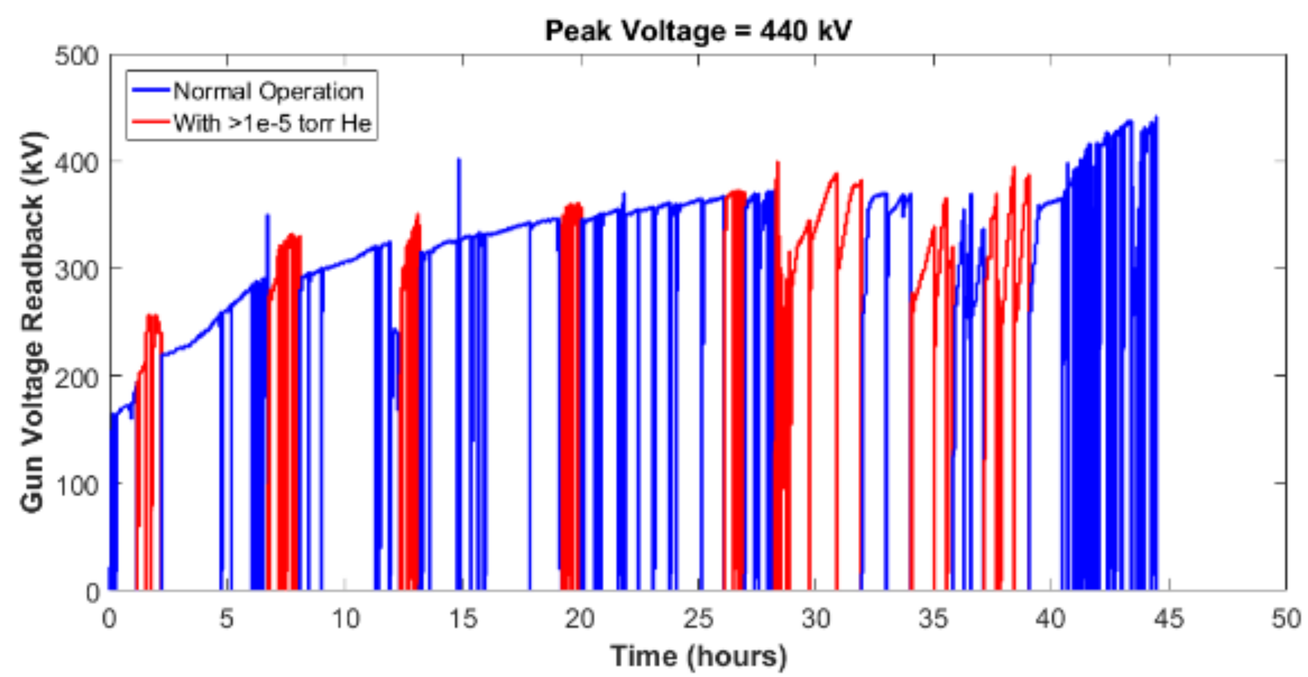
Gun Processing – BNL Gun

- We built an "identical" gun for BNL's LeRHIC project
- After 45 hours, stable running at 440 kV (more was achieved later at BNL)
- Something was done better in the second gun build (!!)



Cathode

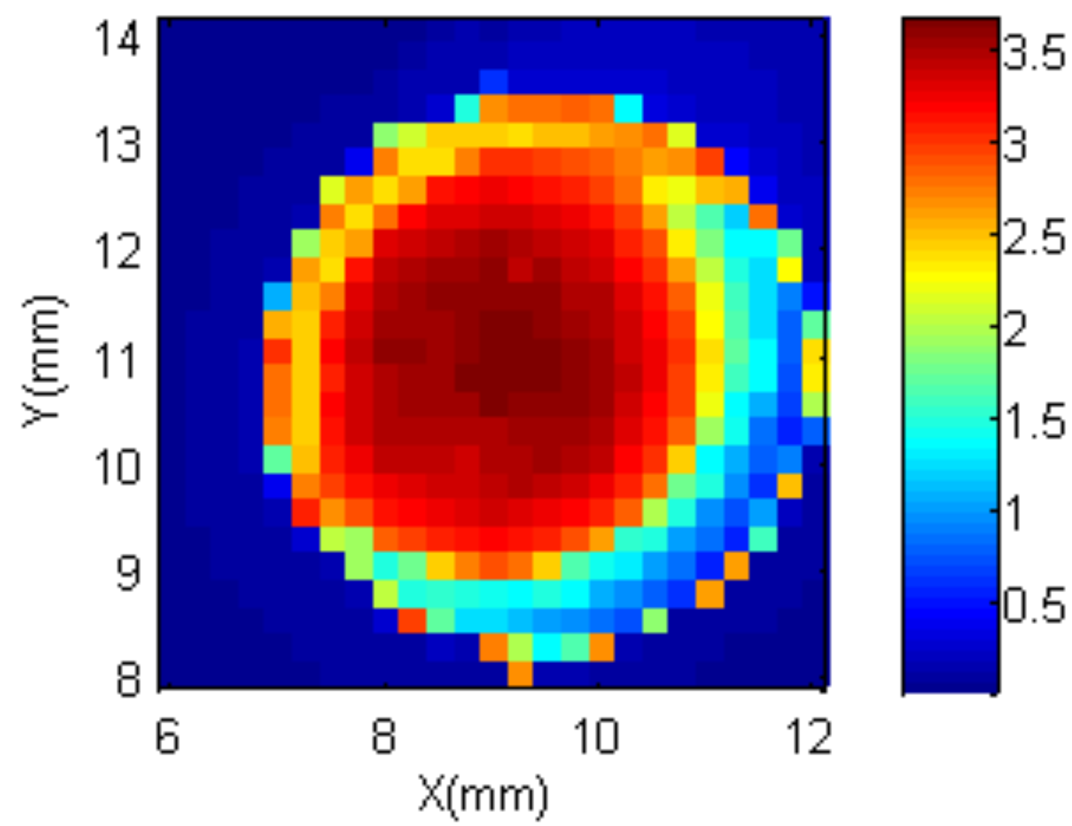
What requirements do cathodes have in CBETA?

Challenge	Comment	Status
Lifetime > 10,000 C	40 mA for 3 days	**Done**
QE > 1%	40 mA @ 1% QE = 10 W of laser power	**Done**
Cathode emit. < 0.5 μm/mm	MTE < 150 meV, ε_{cath} @ 125 pC < 0.25 μm	**Done**
Localized, offset active area	Roughly = laser size, reduces halo	**Done**
QE spatially flat	(or compensated with laser shaping)	**Done**
Response time < 1 ps	Long tails will be lost in RF	**Done**

- No new cathode research is required for current operation needs
- The remaining work is in **preserving them** during usage, because it is *easy* to ruin a cathode…

Cathode

New cathode, QE at low voltage = 3%



3 mm active area

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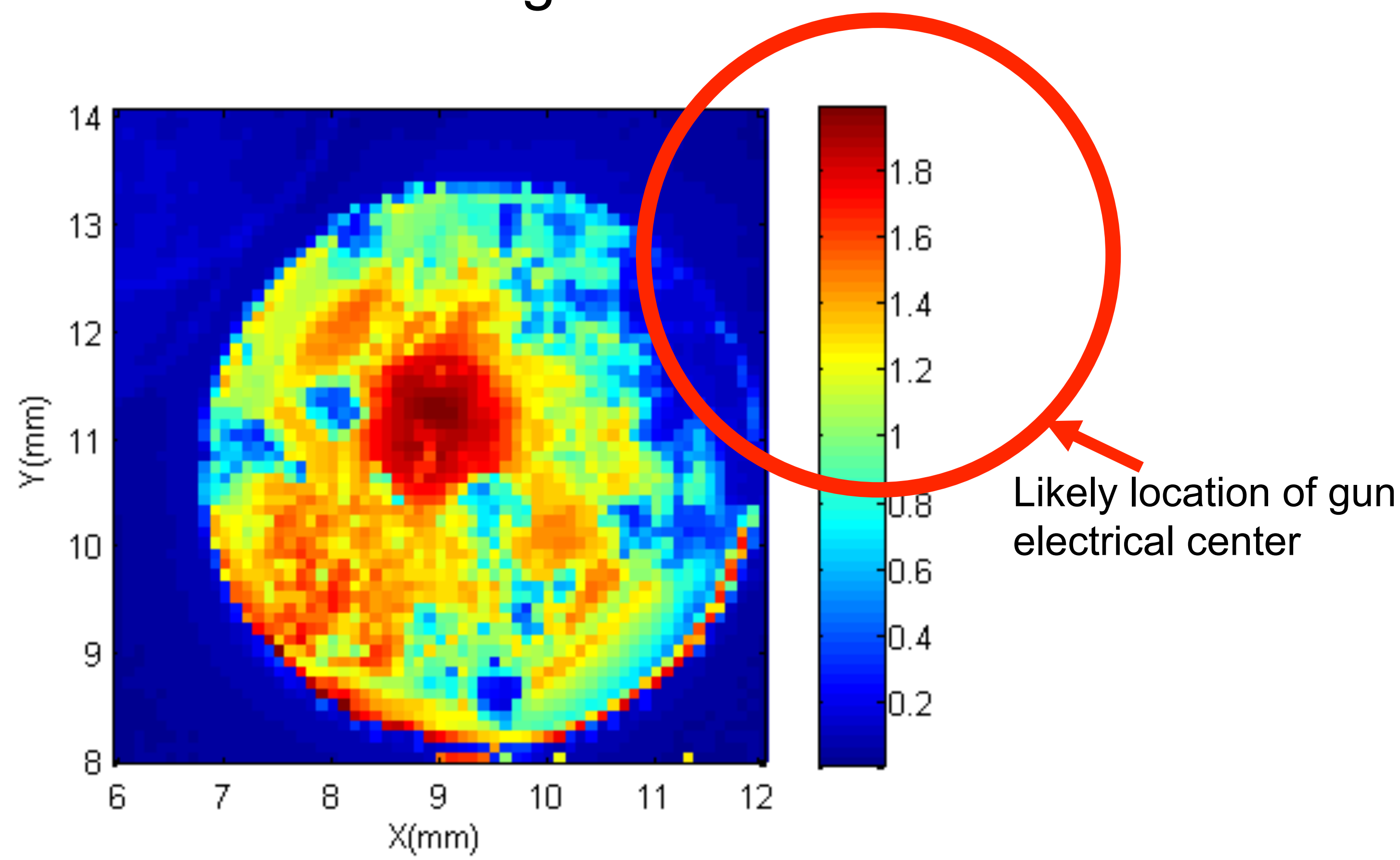
Cathode

After extracting 4500 C…

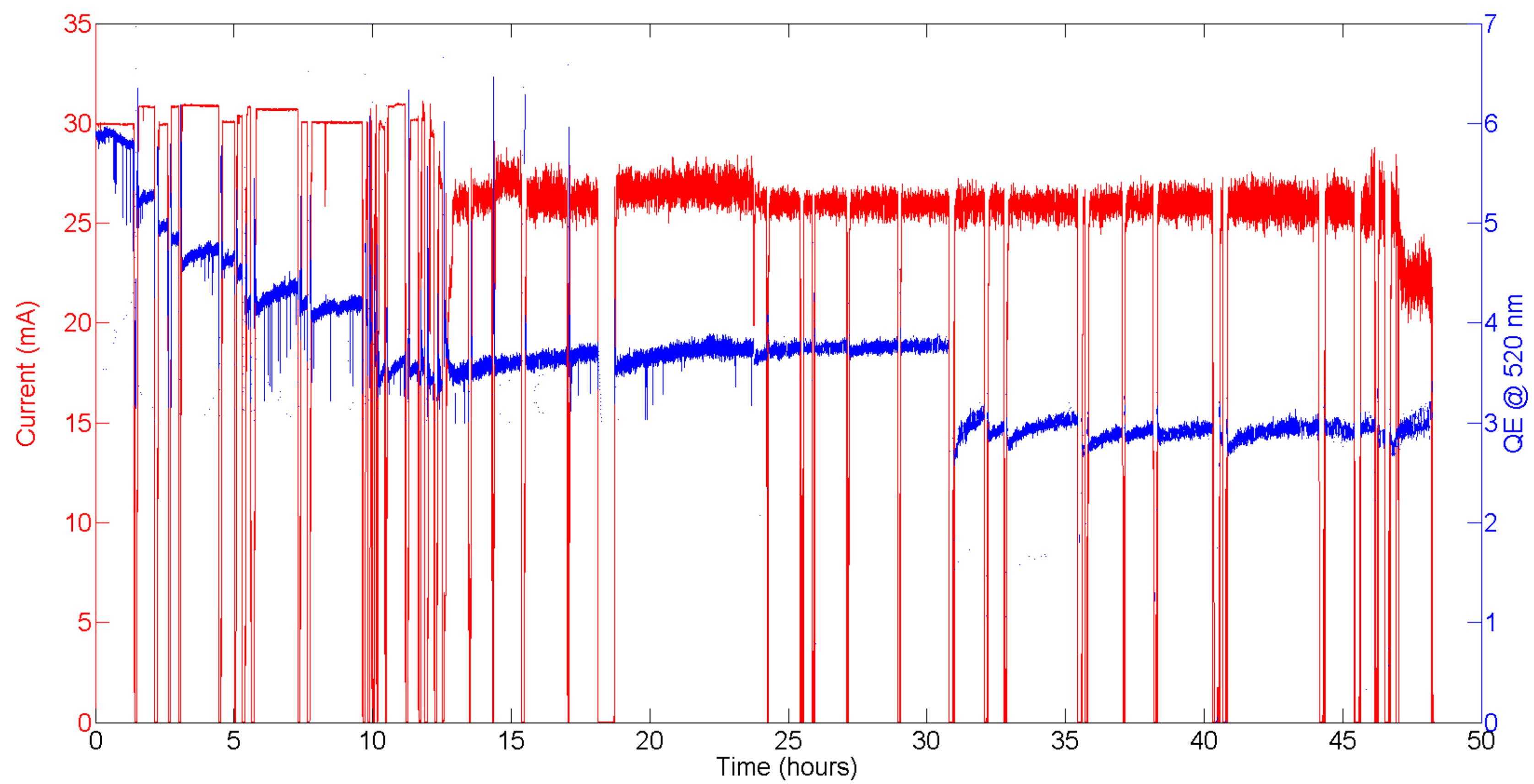


But this wasn’t ideal operation…

Cathode

The cathode experienced many machine trips (note: full injector, not just gun)

- Machine trips (often) cause massive ion back-bombardment of cathode
- Even without trips, center of cathode experiences slower degradation
- We typically extract charge from sides of cathode to avoid this
  - This sets a limit on bunch charge!



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Laser Transverse Shaping

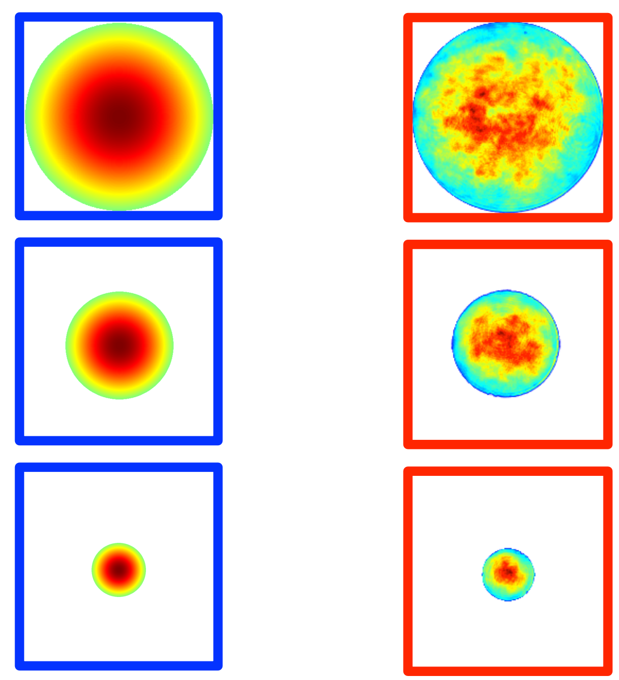
- Laser size scales as ~$Q^{1/2}$
  - Central 6 mm of cathode is utterly destroyed by ion back-bombardment
  - Laser is clipped at R > 9 mm
  - Maximum laser size ~ 6 mm
    - Is 900 pC the largest we can extract in high current?

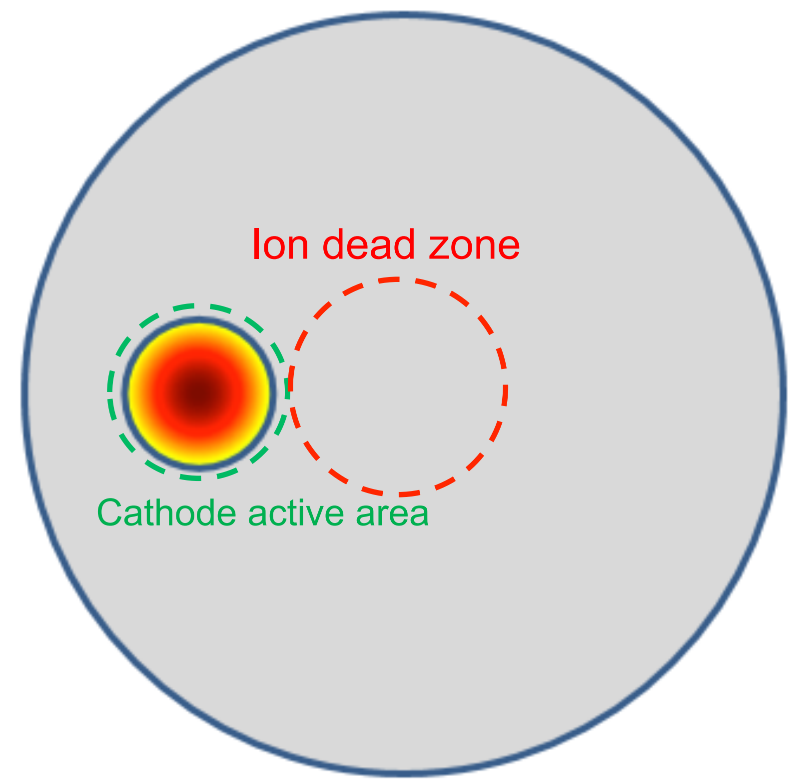
Ideal Shape   Measured Shape

Q = 300 pC
D = 3.5 mm

Q = 100 pC
D = 2 mm

Q = 20 pC
D = 1.0 mm



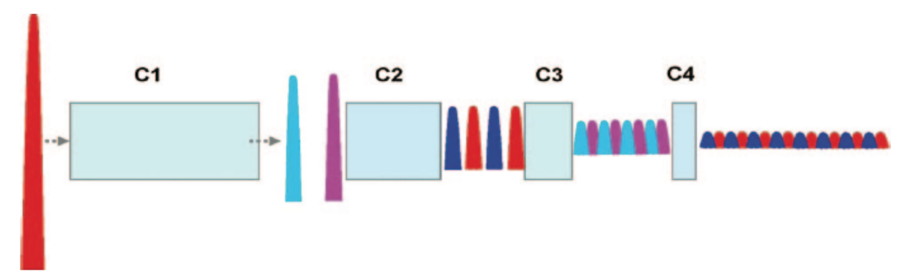


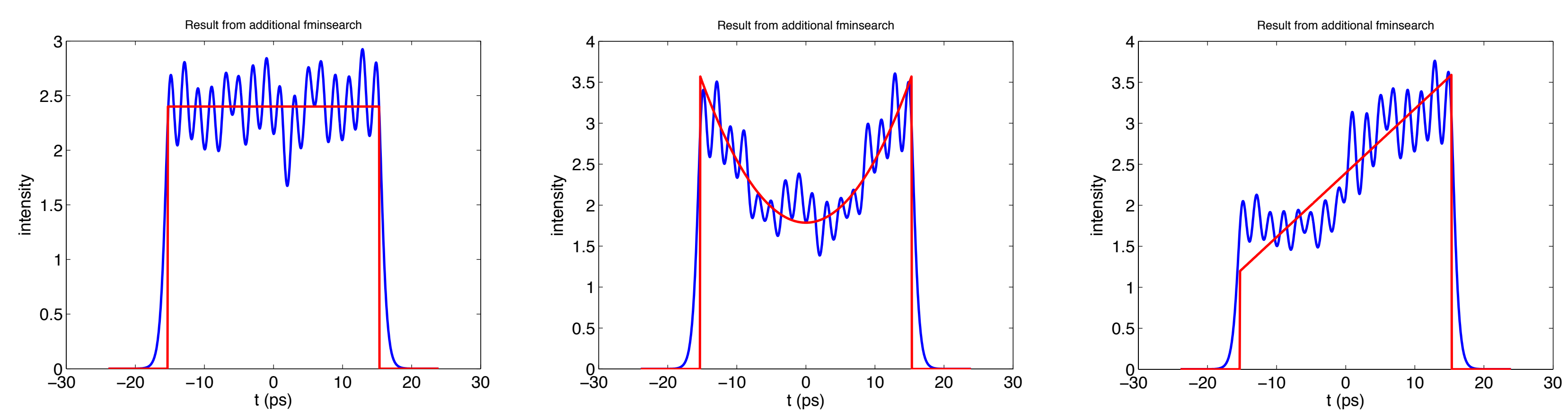
Position of laser on cathode

Laser Longitudinal Shaping

Longitudinally: Birefringent Crystals for pulse stacking

- Could be used to shape laser, roughly
- Typically, just use "flat-top" longitudinal profile, fixed length ~ 8 ps





Charges above ~1 nC

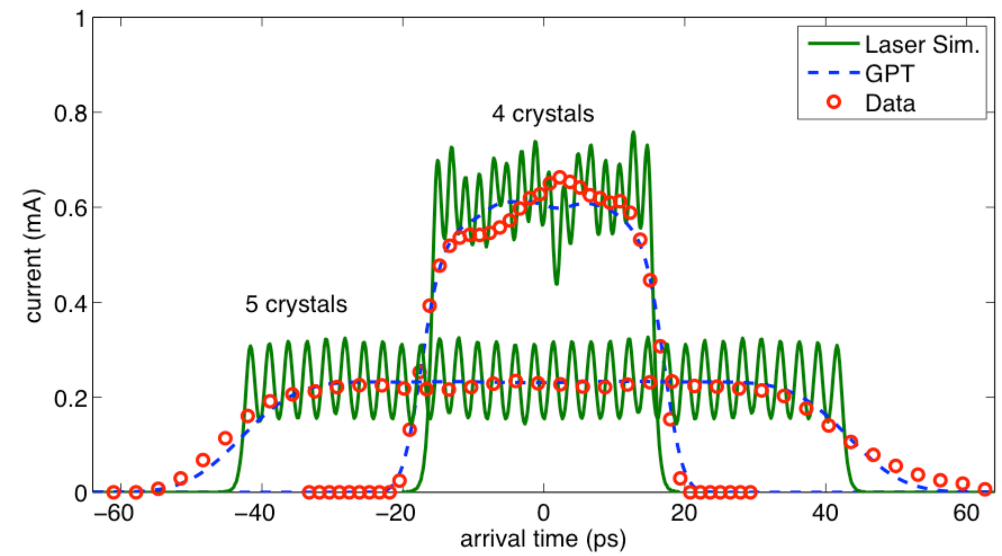
Problem:

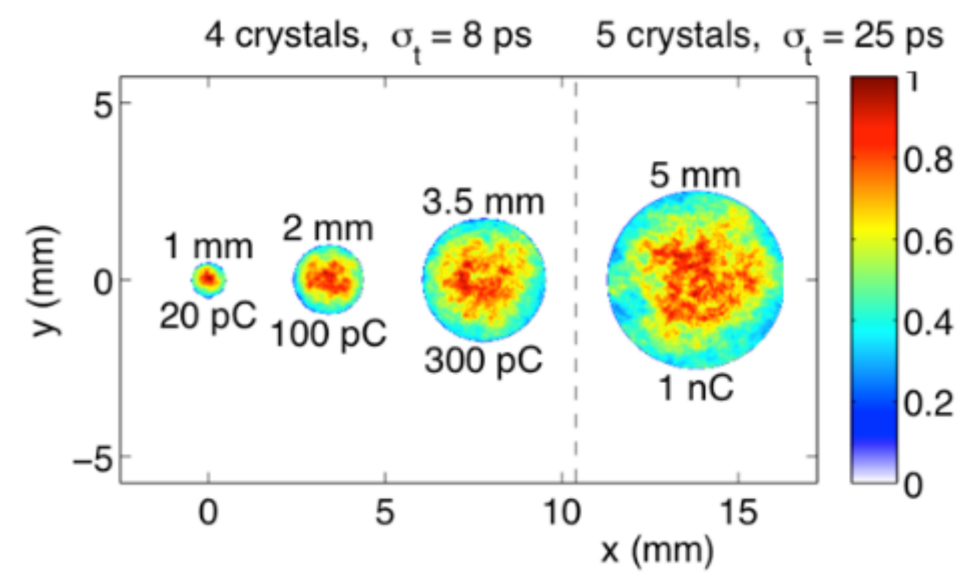
- 1 nC, laser size > 6 mm

Solution:

- Lengthen laser pulse:
  - 4 crystals -> 5 crystals
  - 8 ps -> 25 ps

- 1 nC, optimal D = 5 mm
  - Feasible!
  - (more on this later…)





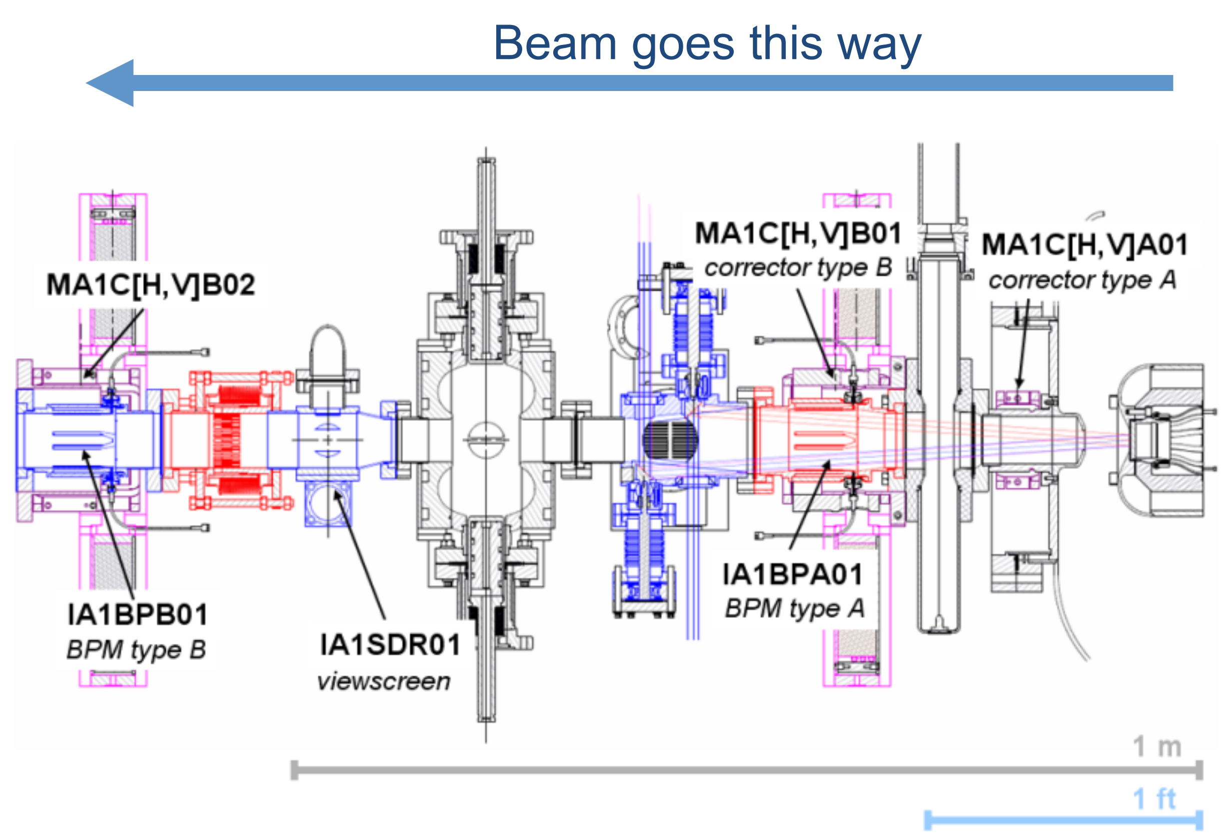
Gun Section Layout

How do we commission our gun (low-energy) beamline?

Concerns
- Stray fields
- Instabilities
- Cathode irregularities

Component List
- 2 Solenoids
- 1 Bunching cavity
- 1 BPM in each solenoid
- 1 Viewscreen

Measurements
- Position
  - Linear optics check
- Beam size
  - Emittance / MTE
- BPM arrival time
  - Absolute energy (phasing, field stability)



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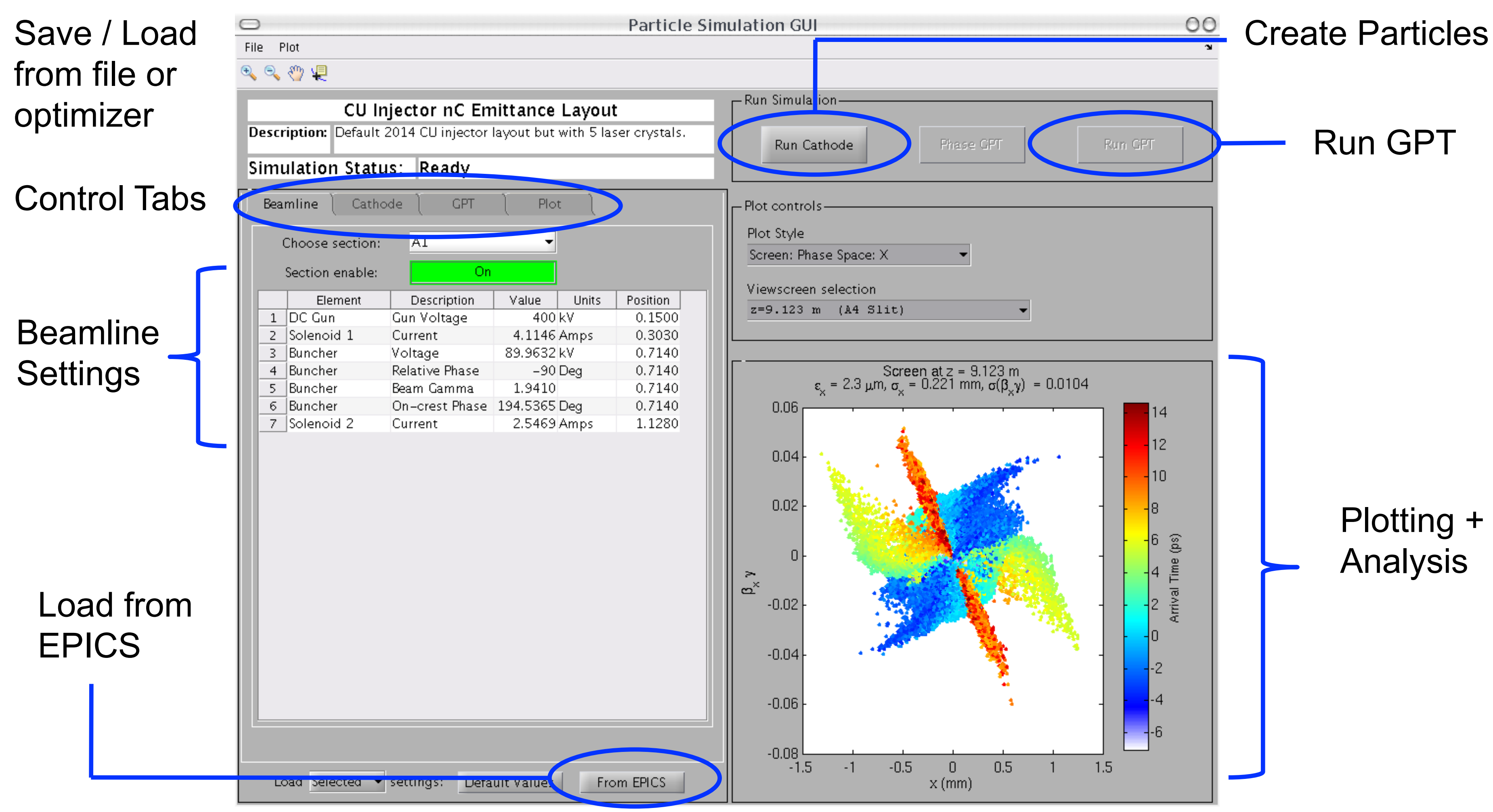
Online Modeling

GPT/ASTRA Virtual Accelerator GUI: load machine settings, load optimizer settings, save/restore, independently simulate machine in (near) real time



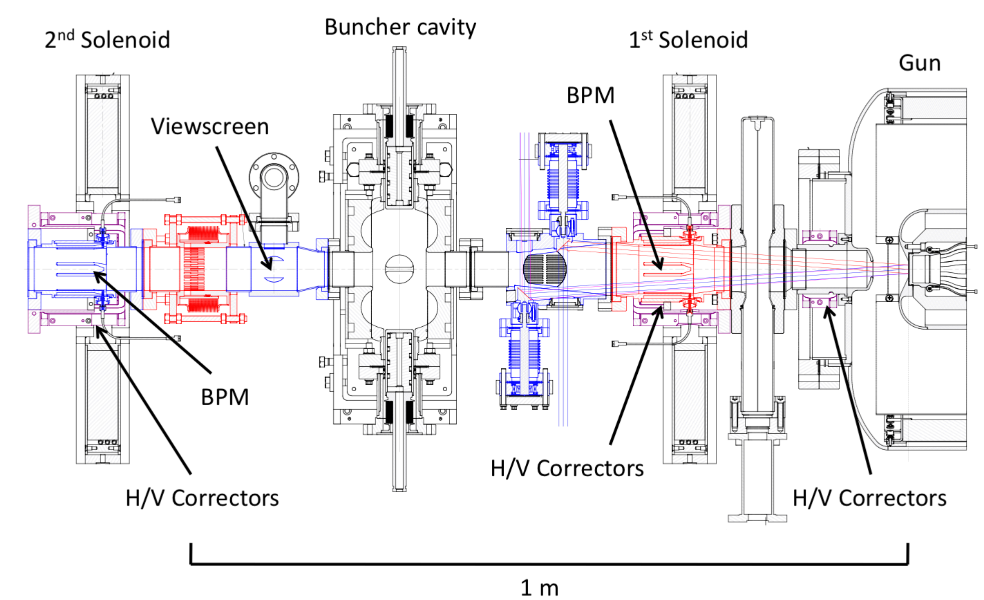
Example of Problem/Solutions

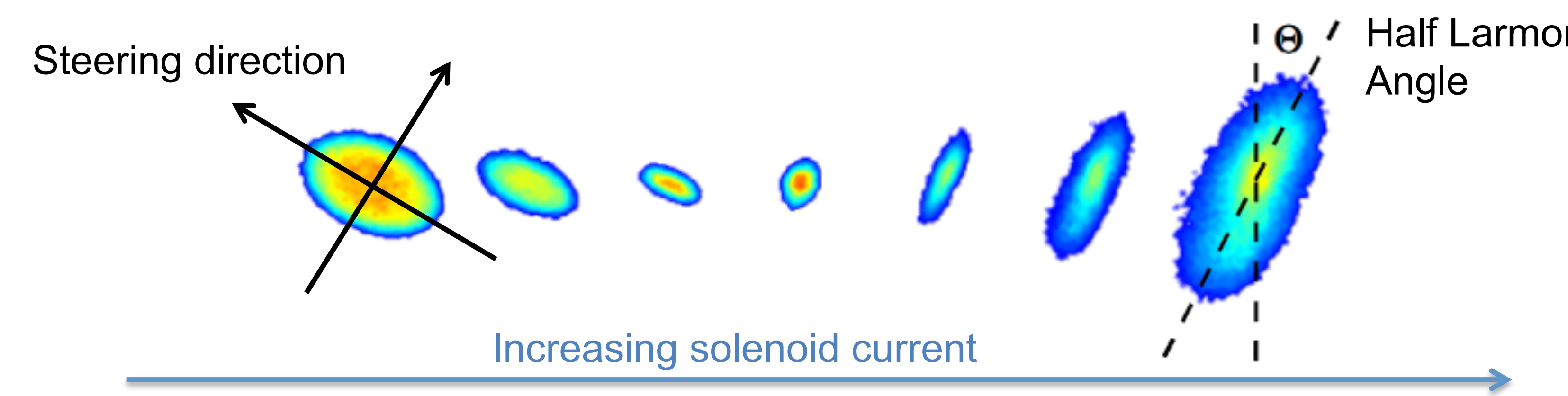
Unexpected beam asymmetry after the first solenoid

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

With 0 pC:
• Beam appears round

What is going on? Stray field?
• Can we model it?





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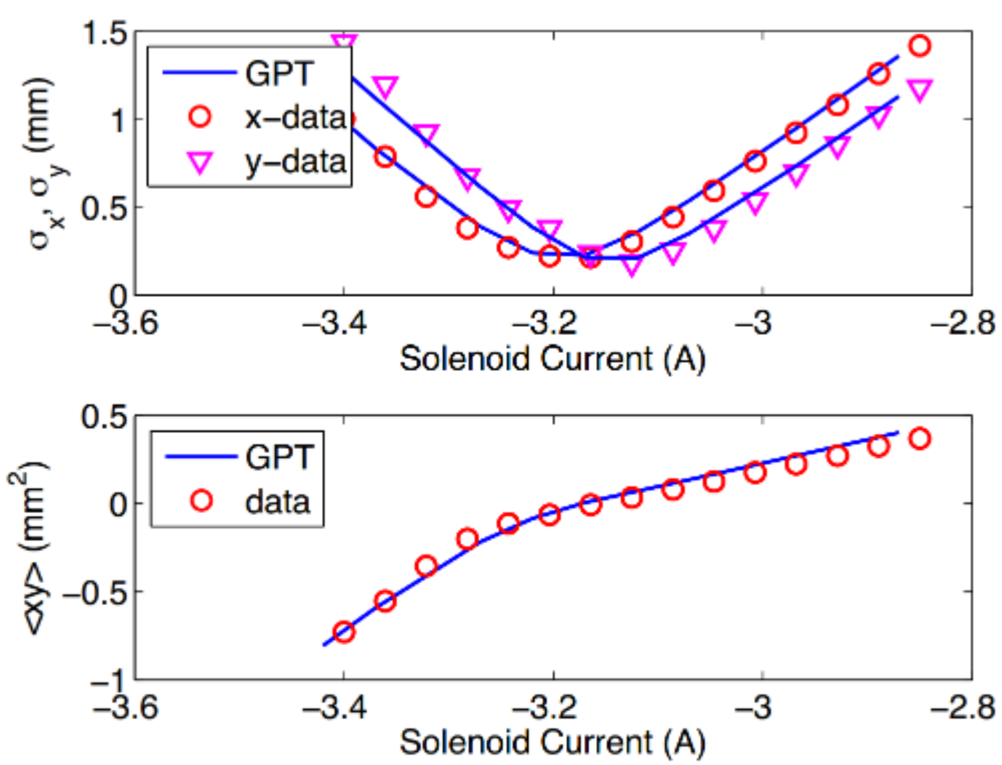
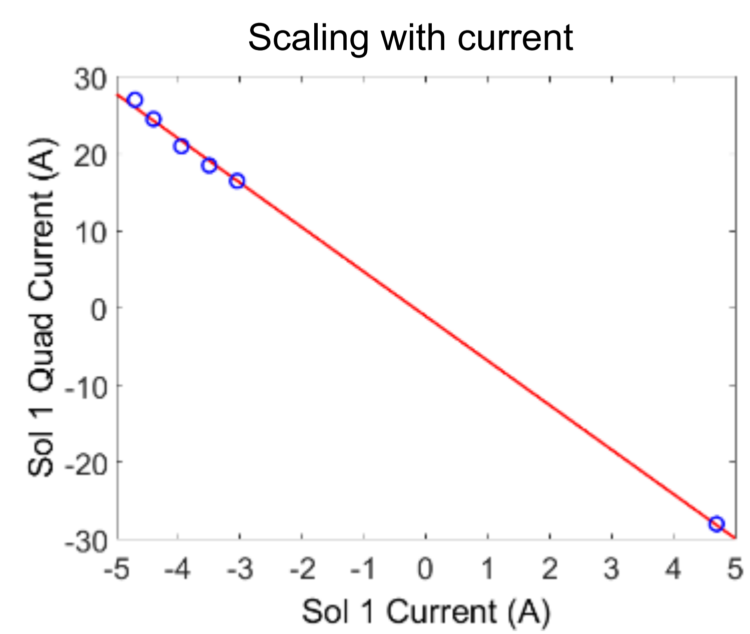
Example of Problem/Solutions

- 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
  - This is a strong enough field to wreck the emittance in simulation





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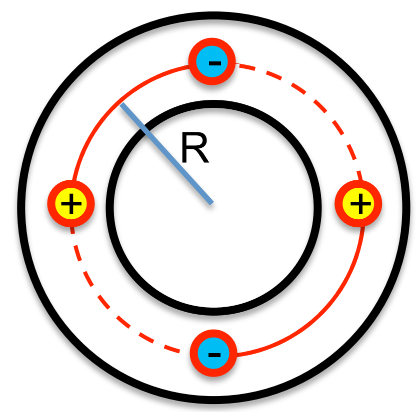
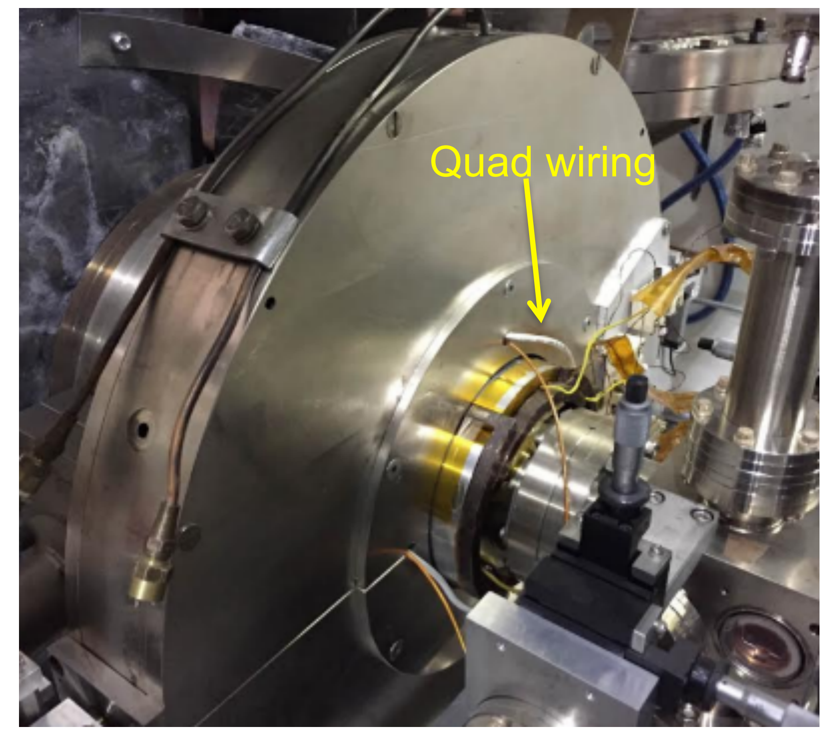
Example of Problem/Solutions

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

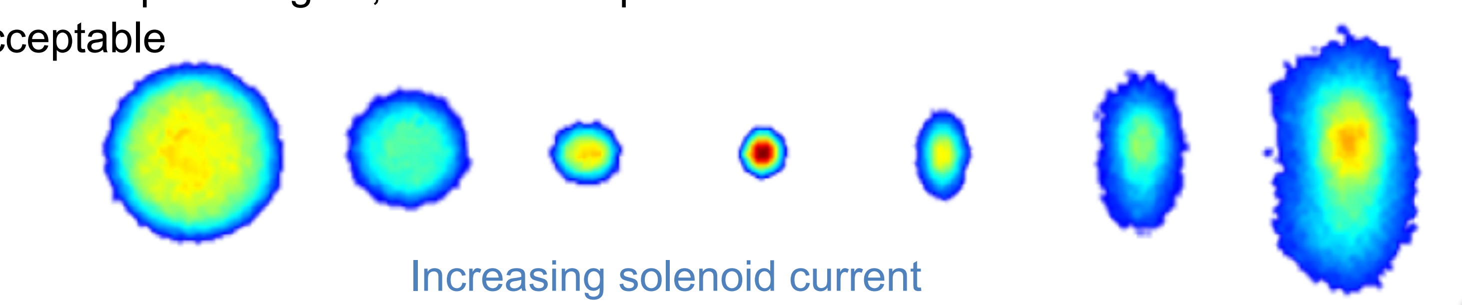
$$B_x \approx 2(NI)\mu_0 / \pi R^2 \; y$$

$$B_y \approx 2(NI)\mu_0 / \pi R^2 \; x$$





- R = 6”, L = 3”, need **40 amp-turns** of coil
  - Removed tilt with 30 amps through coil
- Remaining not-tilted quad possibly from mismatch of quad lengths, simulations predict it is acceptable



Goal I: Emittance

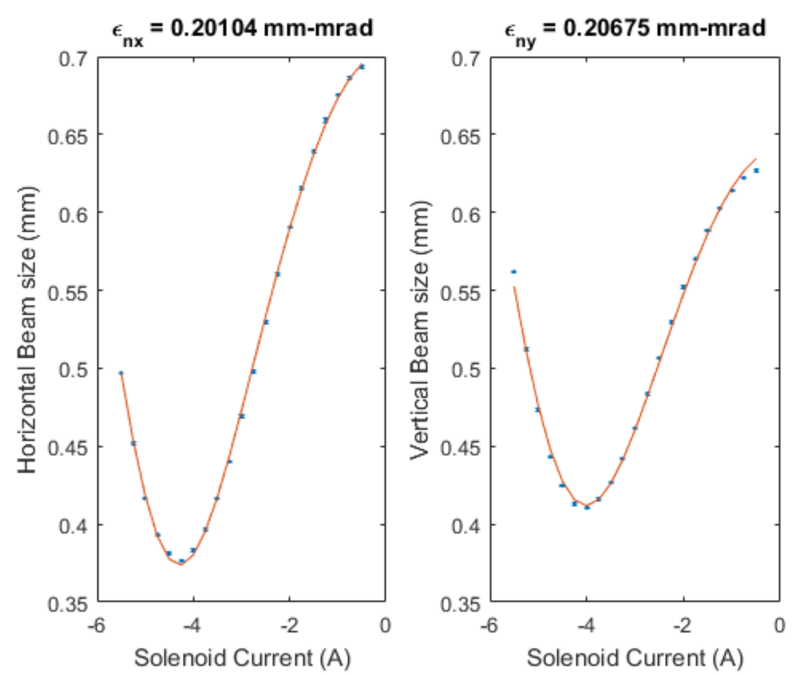
Summary of expected and measured low-energy emittance

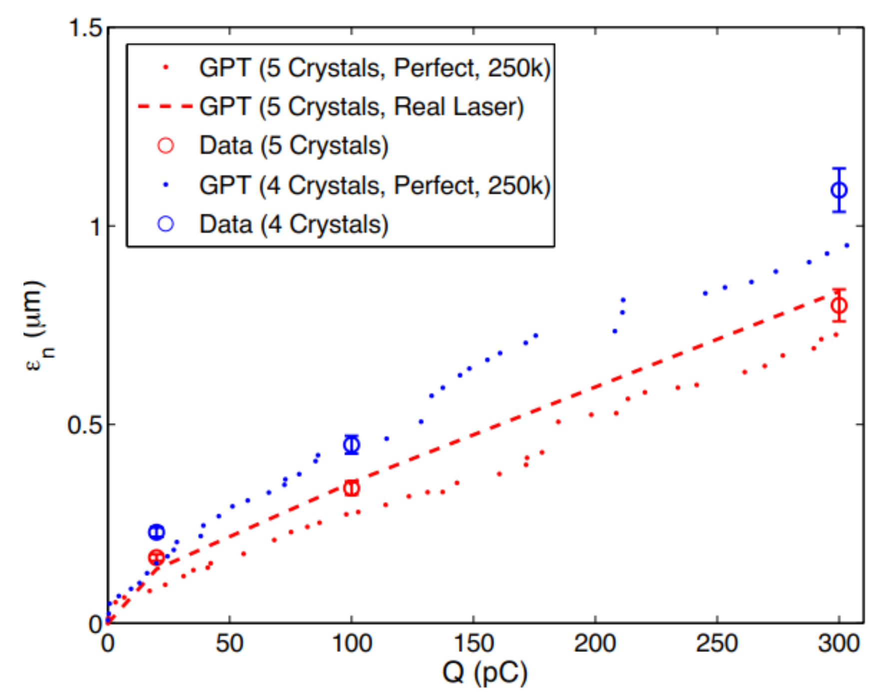
- Solenoid scan
- Laser = only free parameter
- Laser quality was primary source of emittance degradation

Met all expectations from simulation

TABLE IV. Segmented Gun Vertical Emittance Measurements for the 5 (4) Crystal Set

Bunch Charge	20 pC	100 pC	300 pC
95% $\epsilon_{n,y}$ (μm)	0.13 (0.18)	0.27 (0.35)	0.65 (0.81)
100% $\epsilon_{n,y}$ (μm)	0.17 (0.23)	0.34 (0.45)	0.8 (1.1)





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Goal 2: High Current @ 350 kV

Unexplained Machine Trips
In high average current operation (>20 mA) the Cornell Photoinjector (Gun + ICM) would experience machine trips with a frequency on the order of ~1/hour.

Isolate the gun
During extended maintenance on the ICM, a beam line was designed to isolate and test only the DC gun under high current load. Without the added complexity of the SRF booster cavities, we hoped to be able to find the cause of the trips.

Experimental Goals

1. Construct a beamline isolating the DC gun
2. Measure the trip rate with 20 mA average current
3. Identify the trip mechanism, investigate solutions
4. Run for ~24 hours without any trips at 20 mA

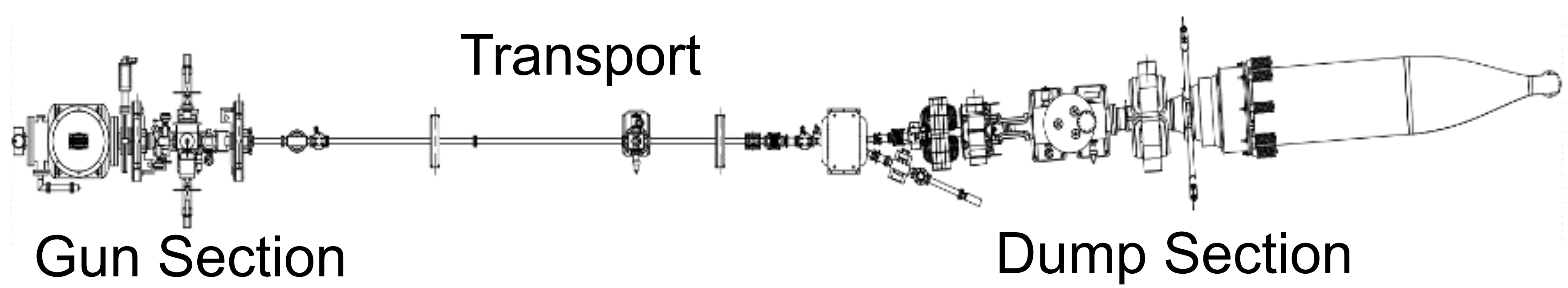
Goal 2: High Current @ 350 kV

Laser
- 1.3 GHz repetition rate
- 9 ps rms pulse length, roughly flat top

Gun Section (L = 2 meters)
- Cathode – NaKSb, QE 5-10%
- Gun – DC, 350 kV

Transport Section (L = 4 meters)
- Two additional solenoids

Dump section (L = 4 meters)
- 5 degree bend
    - Prevents line-of-sight for x-rays from dump onto cathode
- High power beam dump



Goal 2: High Current @ 350 kV

Initially, trip rate is worse
Surprisingly, the trip rate was much higher in the gun test beamline, averaging close to ~10/hour.

We found no significant dependence on gun voltage, but a strong dependence on beam current.

Assuming a power law dependence, it would be $\sim I^3$, i.e. highly nonlinear.

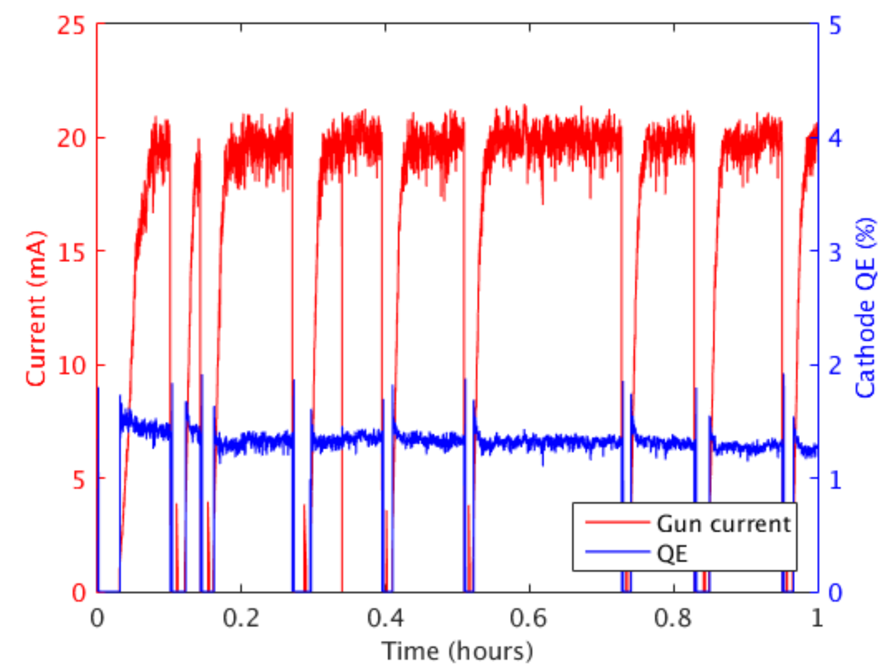


Figure 1: One hour of trips during a 20 mA gun test

Goal 2: High Current @ 350 kV

Trip Mitigation with DC Ion Clearing

(Coincidentally) a DC ion clearing electrode was added to the beamline at the beginning of the transport section.

Above ~10 V, we discovered that the trip rate was dramatically reduced, and we were able to decrease the trip rate by at least a factor of 50 with 100 V across the beam pipe.

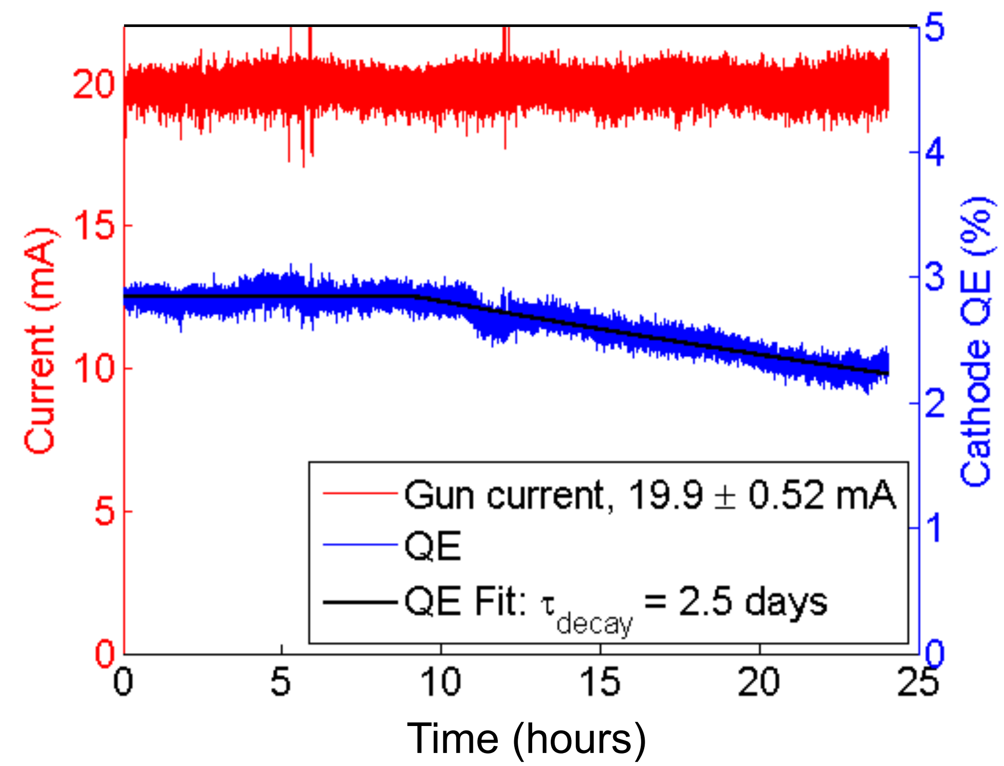


Figure 3: 20 mA run with ion clearing electrode biased at 100 V. Run was terminated without any trips after 24 hours.

Goal 2: High Current @ 350 kV

Trip Mechanism

Our current theory is that ions or charged dust particles are created somewhere after the clearing electrode, likely the beam dump. Clearing them before they are transported to the cathode can mitigate machine trips to acceptable levels.

In previous high current tests with the ICM, moderate clearing was achieved from the ponderomotive force from the RF.

Future High Current Operation

Clearing as close to the gun as possible seems best. In the future, we plan to bias the new gun's floating anode (~100s V) as an ion barrier.

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Summary

- Gun was designed and built to deliver high rep rate ~100 pC bunches with performance competitive with SRF guns

- Gun has delivered up to 1 nC with laser size compatible with high current

- Simple diagnostics near gun, combined with online modeling are invaluable for debugging beam

- Emittance measurements at low energy went as expected, highlighting the importance of laser quality when pushing for lowest emittance

- High current was demonstrated at 20 mA for >24 hours with no machine trips, suggesting ion clearing near the gun is essential for high current