HIGH BRIGHTNESS AND HIGH AVERAGE CURRENT PERFORMANCE OF THE CORNELL ERL INJECTOR

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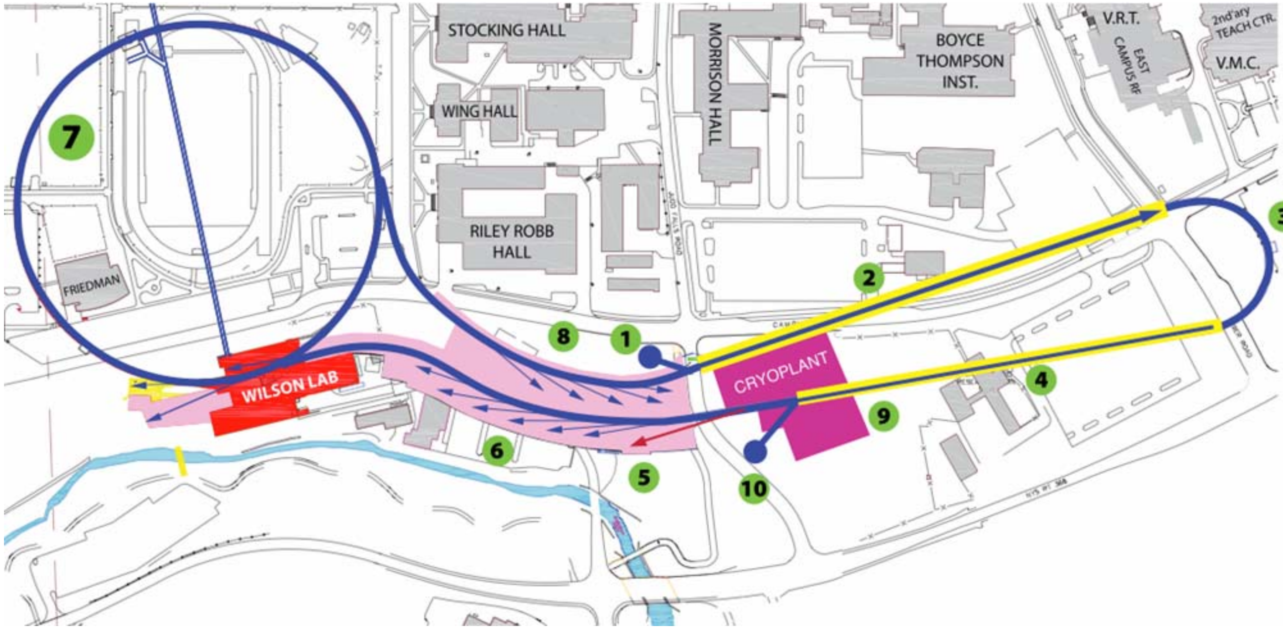
Outline

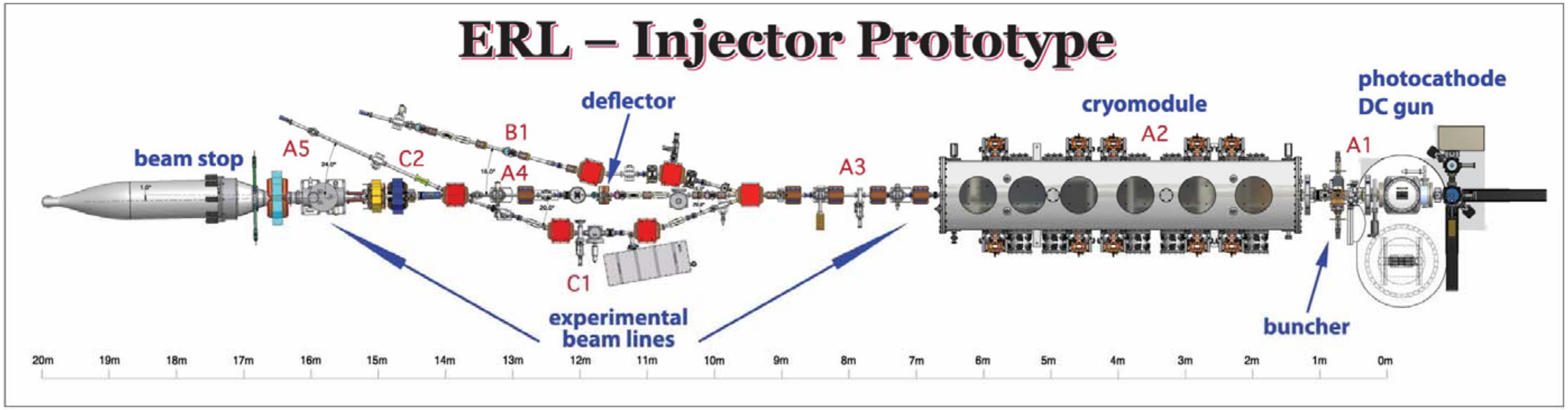
- Overview
- High Brightness Results
- High Power Operations and Results
- Conclusion

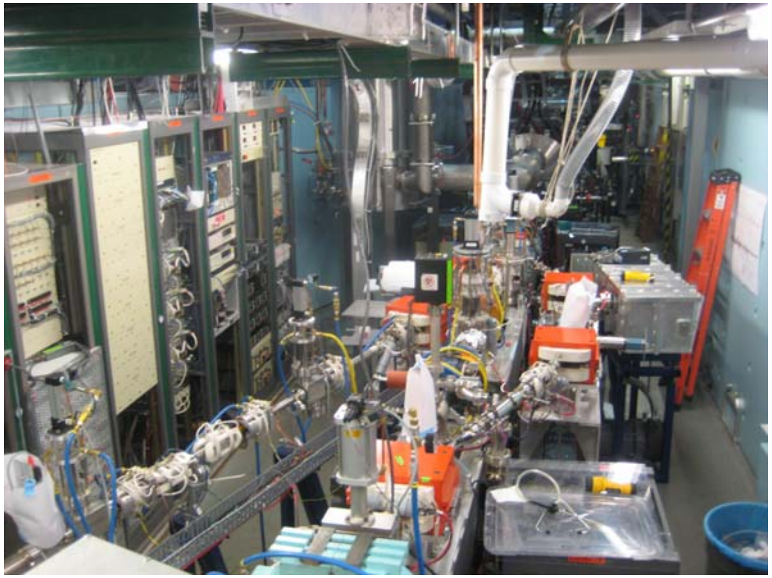
ERL @ Cornell



- Our long-term goal is to build an ERL-based x-ray light source to replace our existing machine (CESR/CHESS).
- Our proposal is complete and ready to go . . .
- In the meantime, we are working on prototypes for the injector, SRF cavities, and undulators, plus gun and cathode R&D

Cornell ERL Injector





ERL Injector Prototype:
Achievements to date:

- ➢*75 mA average current @ 4 MeV*
- ➢*0.3 μm emittance @ 77 pC, 8 MeV*

Injector Requirements

Parameter	Metric	Status	Notes
Average Current	100 mA	(yellow)	75 mA (1300 MHz)
Bunch Charge	77 pC	(green)	Pulsed mode (50 MHz)
Energy	5 to 15 MeV	(green)	14 MeV max (due to cryo limits)
Laser Power	> 20 W	(green)	> 60 W at 520 nm (1300 MHz)
Laser Shaping	beer can dist.	(green)	Adequate for now
Gun Voltage	500 kV	(yellow)	Currently operating at 350 kV
Emittance	< 2 μm (norm, rms)	(green)	Ultimate ERL goal 0.3 μm, with merger
Operational Lifetime	> 1 day	(green)	Recent improvements with new cathodes

Emittance Measurement Results

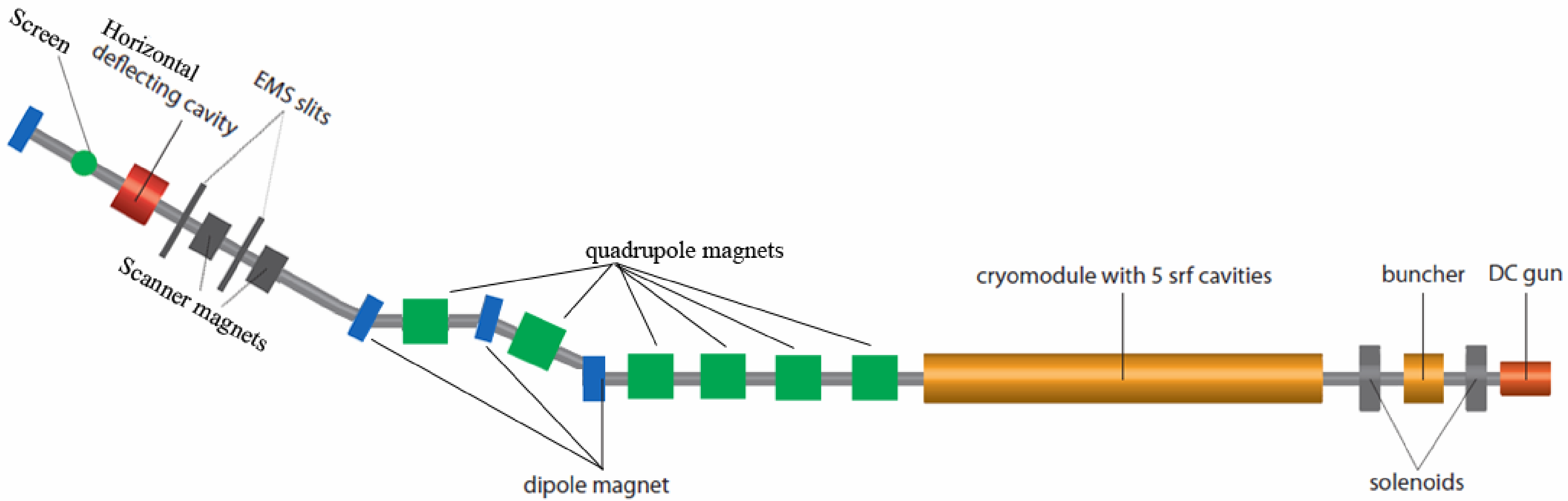
Goals for Experiment

- Measure low emittances at the end of the merger

  Emittances ≤ 0.3 micron, bunch Length ≤ 3 ps, energy Spread ~ 1e-3

- Demonstrate $\varepsilon_{n,x} \propto \sqrt{q}$, take 19 pC and 77 pC data, corresponds to 25 and 100 mA

- Demonstrate agreement between measurement and simulation



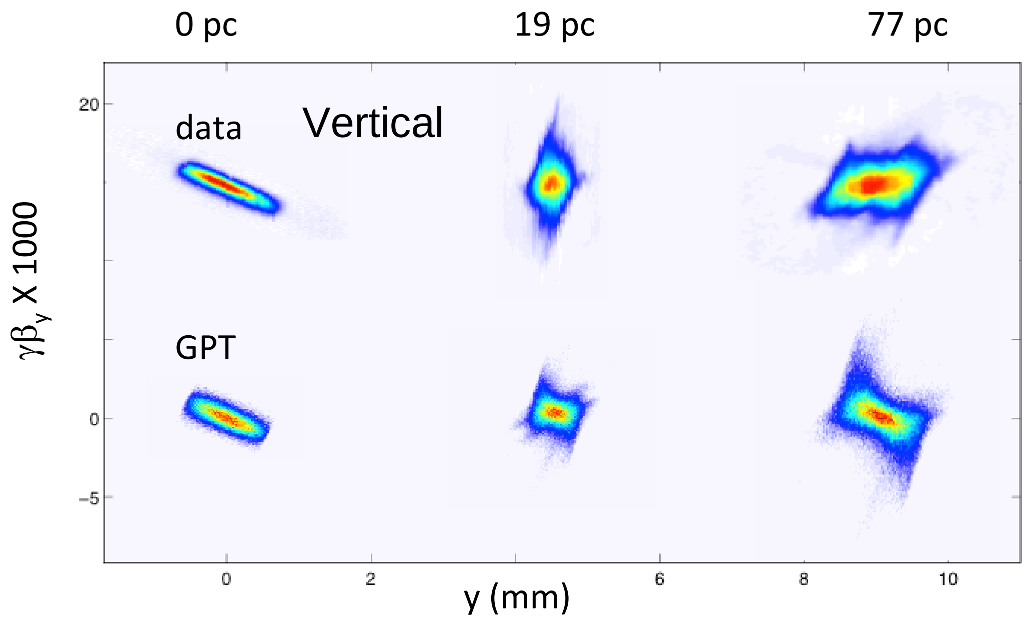
Baseline Emittance

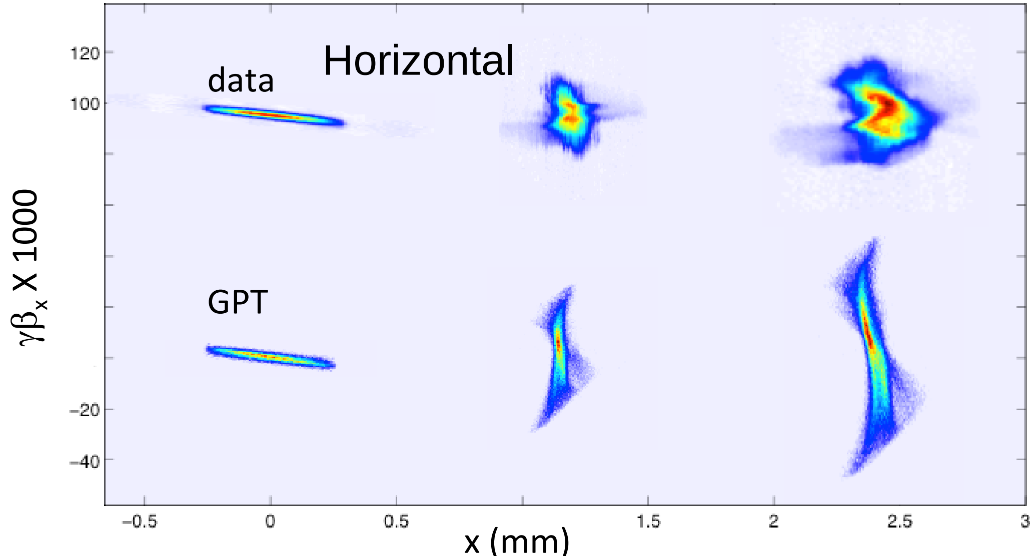
Baseline Measurement at 'zero' charge

Three methods for comparison

Measurement	Horizontal Emittance [microns]	Vertical Emittance [microns]
Solenoid Scan after the gun (350kV)	0.12	0.11
Projected emittance (EMS) in merger(8 MeV)	0.11	0.12
Slice emittance (EMS) in merger (8 MeV)	0.11	N/A

Emittance Results – Projected





Projected Emittance for 19 (77) pC @ 8MeV:

<u>Vertical Phase Space</u>

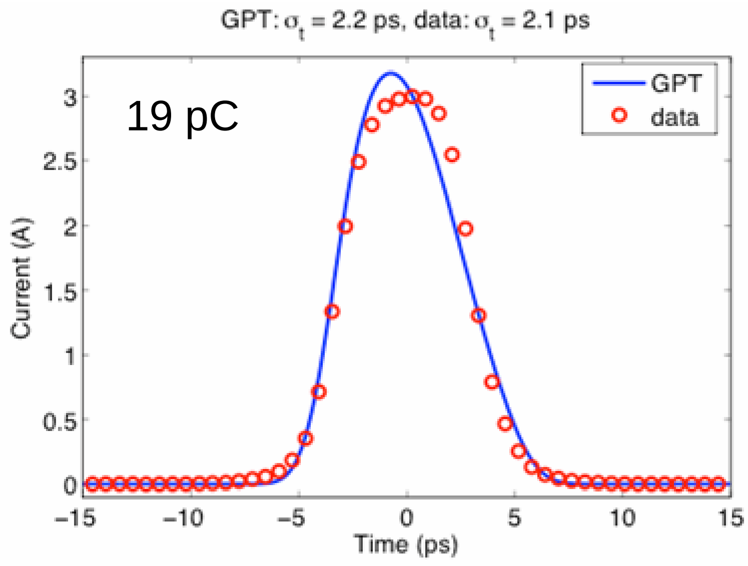
Data Type	en(100%) [microns]	en(90%) [microns]
Projected (EMS)	0.20(0.40)	0.14(0.29)
GPT	0.16(0.37)	0.11(0.25)

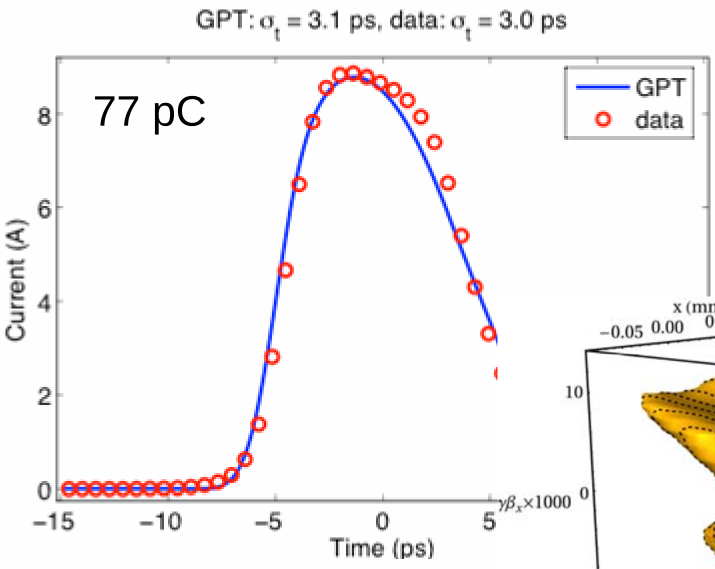
<u>Horizontal Phase Space</u>

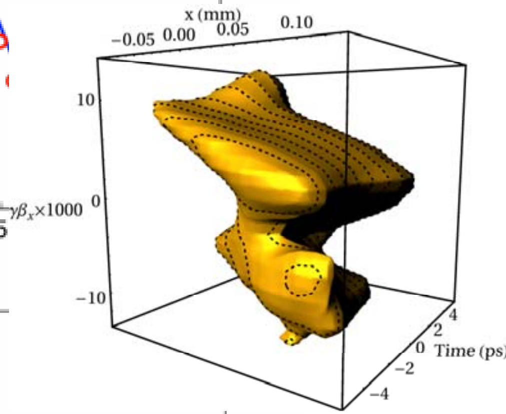
Data Type	en(100%) [microns]	en(90%) [microns]
Projected (EMS)	0.33(0.69)	0.23(0.51)
GPT	0.31 (0.72)	0.19(0.44)

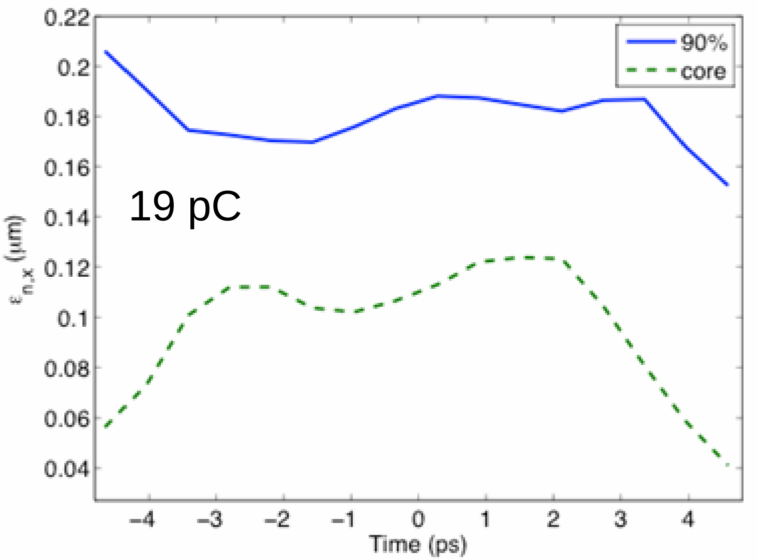
*C Guilliford, *et al*, PRST-AB **16**, 073401 (2013)

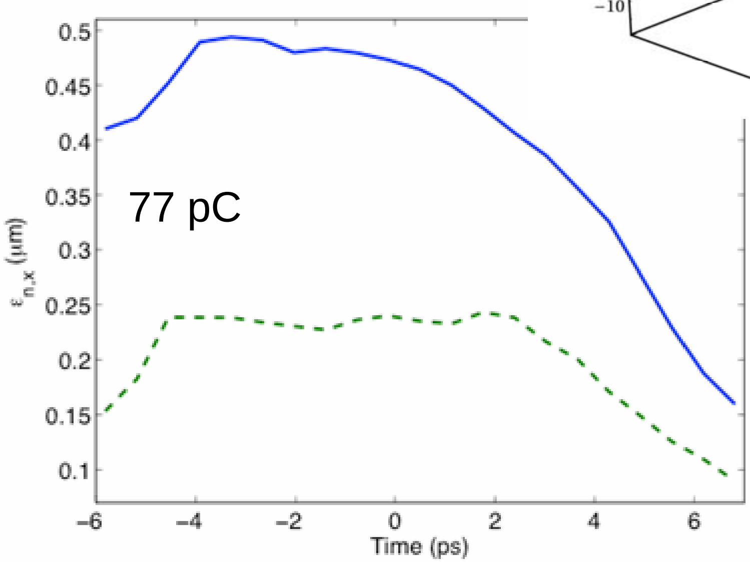
Slice Emittance and Bunch Length





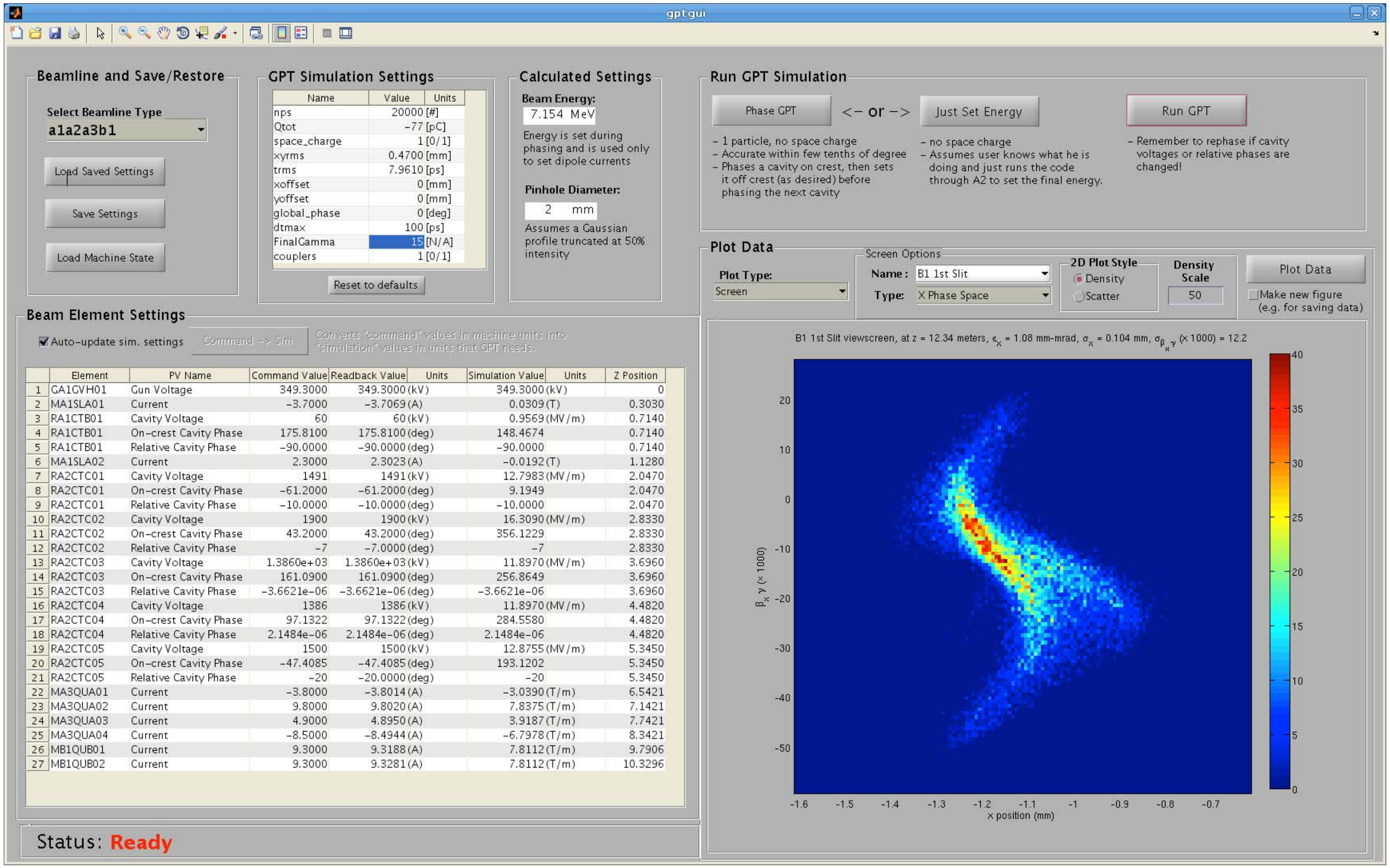




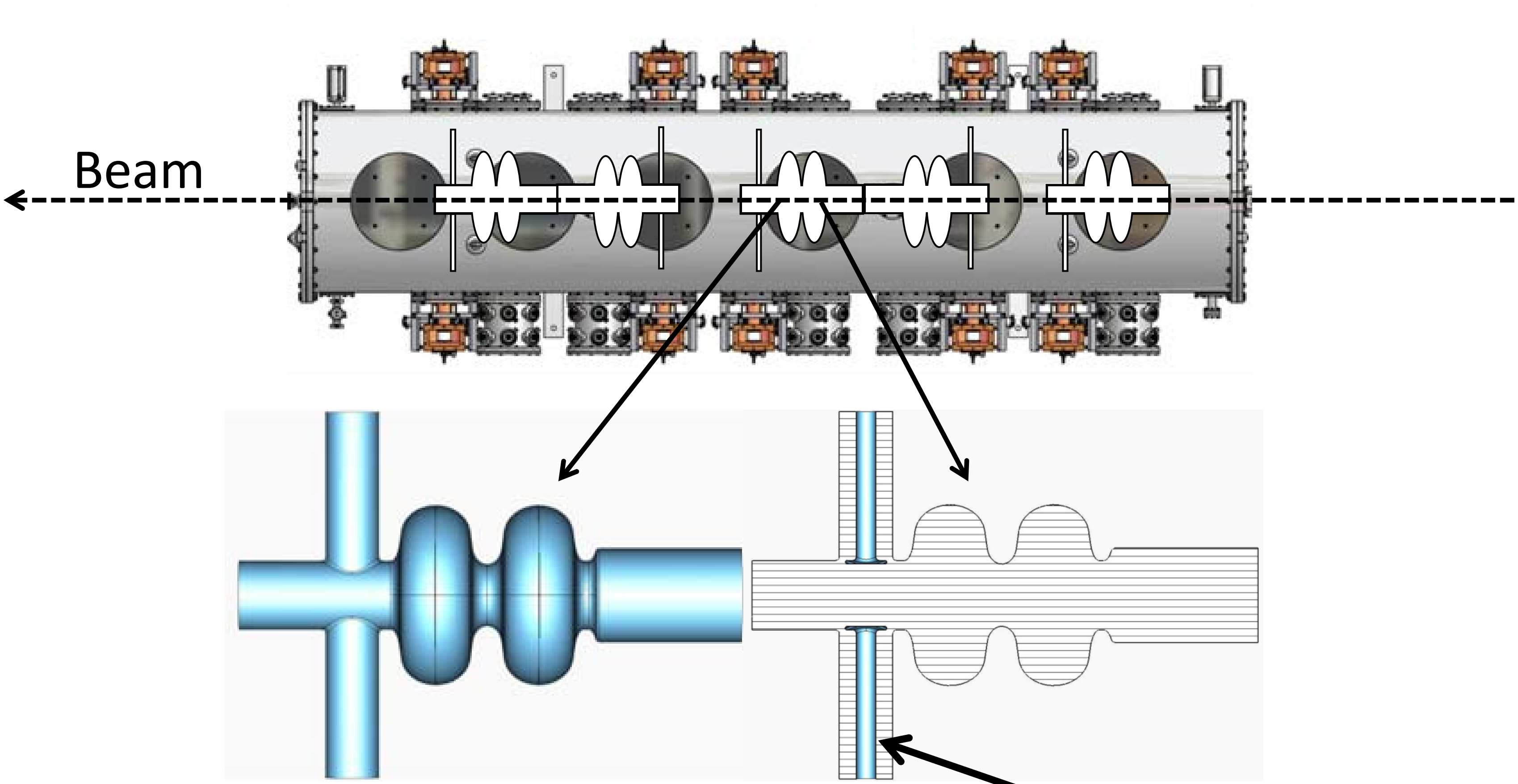


GPT – Machine Interface

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



SRF Cavity Couplers



Coupler antennas only in x-direction!

No dipole kick, but we see ‘quadrupole’ focusing

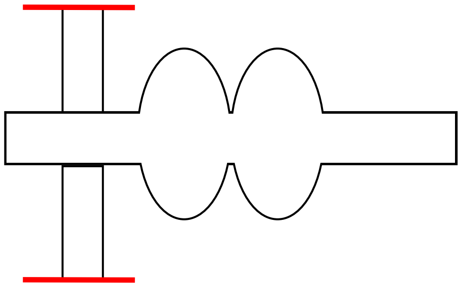
Models for GPT

- Existing software allows magnetic or electric boundary conditions
- Create traveling wave as superposition

$$\vec{E} = \vec{E}_+ + \vec{E}_- \qquad \vec{B} = \vec{B}_+ + \vec{B}_-$$

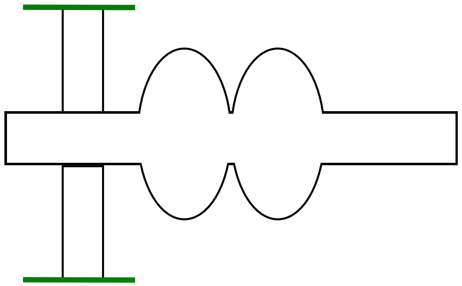
$$\vec{E}_\pm = \frac{A_\pm}{r} e^{i(\pm kx + \omega t)} \hat{r} \qquad \vec{B}_\pm = \mp \frac{A_\pm}{cr} e^{i(\pm kx + \omega t)} \hat{\theta}$$

$E_\parallel = 0$



$$\begin{cases} \vec{E}^e = \dfrac{A^e}{r} \sin(kx) \hat{r} \\ \vec{B}^e = i \dfrac{A^e}{cr} \cos(kx) \hat{\theta} \end{cases}$$

$B_\parallel = 0$

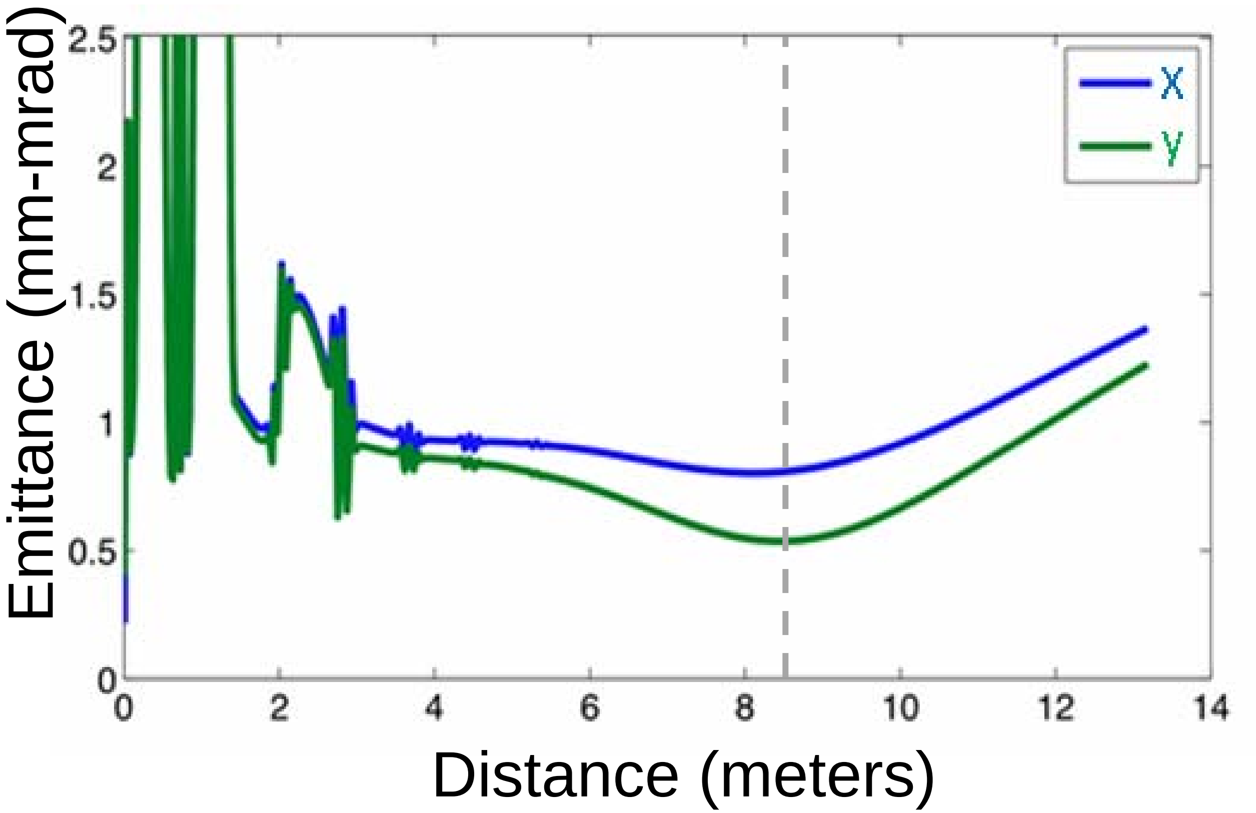


$$\begin{cases} \vec{E}^m = \dfrac{A^m}{r} \cos(kx) \hat{r} \\ \vec{B}^m = -i \dfrac{A^m}{cr} \sin(kx) \hat{\theta} \end{cases}$$

- Normalize result to match real forward and reflected power

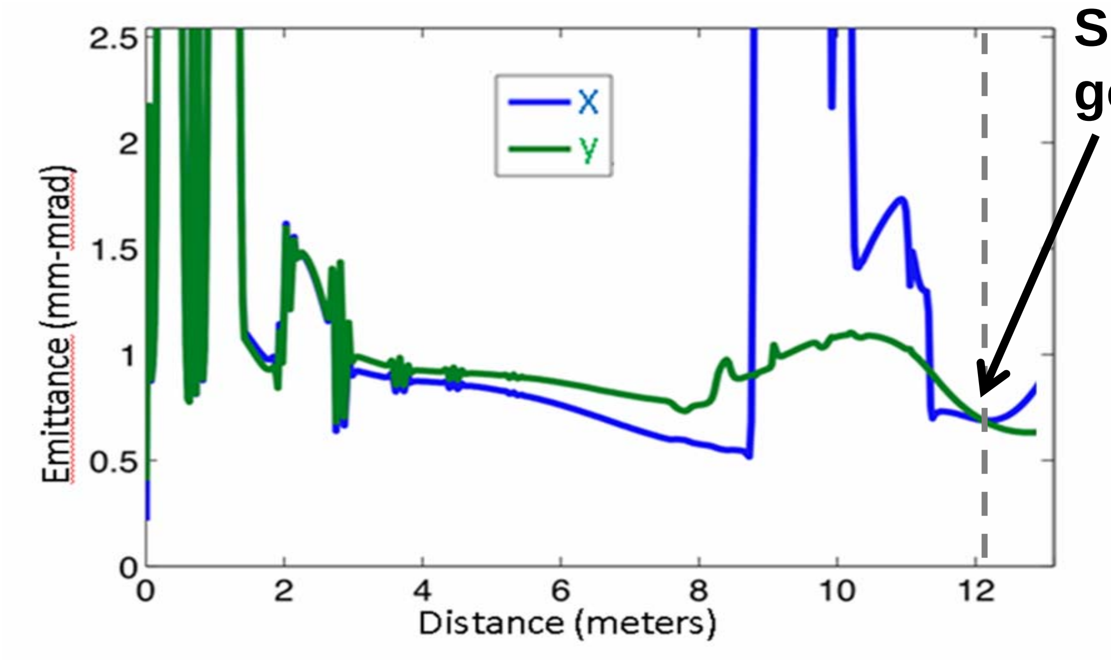
GPT Simulations

- Strong asymmetry after first cavity couplers
- Beam size asymmetry is accurately reproduced in the lab
- At minimum y emittance, the x emittance is 2x larger
- This is for a beam straight ahead (no merger)



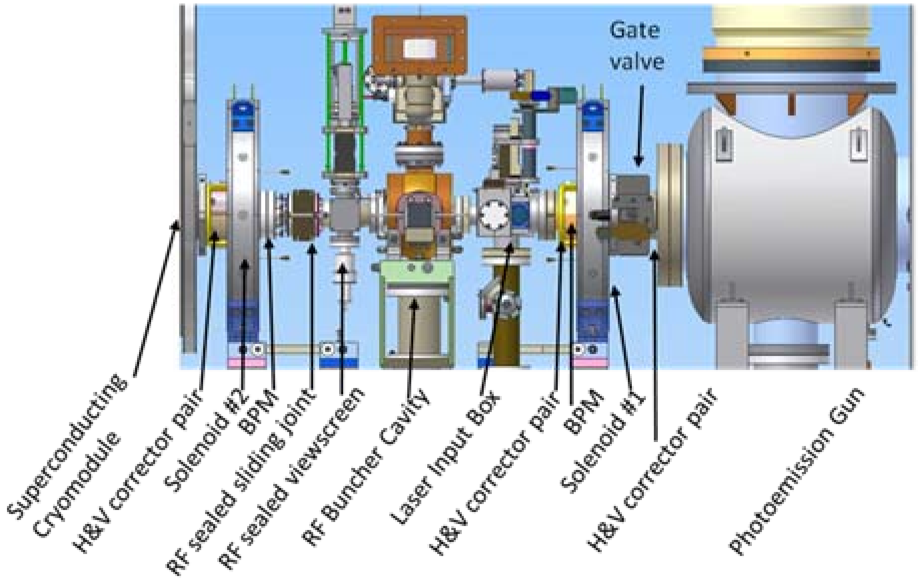
Simulation with Merger

- Optimize emittance using a using a genetic algorithm
- In the merger, the emittance asymmetry can be (mostly) removed, using the asymmetry provided by the dipoles
- Also, optimizations show that a beam energy of 12-13 MeV is needed to maintain minimum emittance in x/y before injection into the main linac

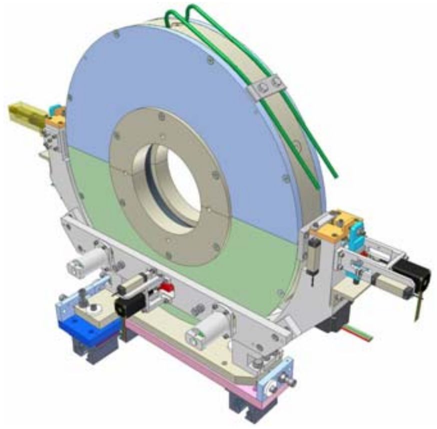


Simultaneous good emittance!

Alignment Accuracy



Aligning the magnetic and electrical centers of all elements to the beam axis is crucial for obtaining low emittance and minimizing aberrations.



Had to add remote control of the solenoids

Procedure:

1. Align laser at cathode center
2. Center on buncher using correctors (+/- 10 um)
3. Center on first 2 SRF cavities using correctors (+/- 10 um)
4. Center solenoid #1 by physical adjustments (+/- 50 um)
5. Center solenoid #2 by physical adjustments (+/- 50 um)

Emittance – What is important?

- Alignment
- Laser shaping
- Accurate simulation tools + genetic algorithm optimizations
- Adequate number of ‘knobs’
- Gun voltage: 350 kV is adequate, optimum value is ~450kV (for our system)
- We are already very close to recovering the cathode thermal emittance! Better cathodes are needed!

High Current Results

What is important for running high currents?

- Halo is a major problem (tuning, radiation shielding and machine protection)
- Beam dump monitoring and protection
- Fast shutdown – want to block the laser before anything else trips . . .
- Catching transients (due to FE, ions, scattering, ...) for troubleshooting
- RF trips (mostly due to couplers)
- Feedback for bunch charge, laser position and beam orbit
- Current measurement
- Measurements of RF response to the beam, HOM's
- Monitoring HV power supply ripple and frequency response
- Vacuum monitoring, fast and slow
- Personnel protection
- Overall machine stability

Dynamic Range and Halo

100 mA
Design current:
Non-intercepting or minimally intercepting diagnostics

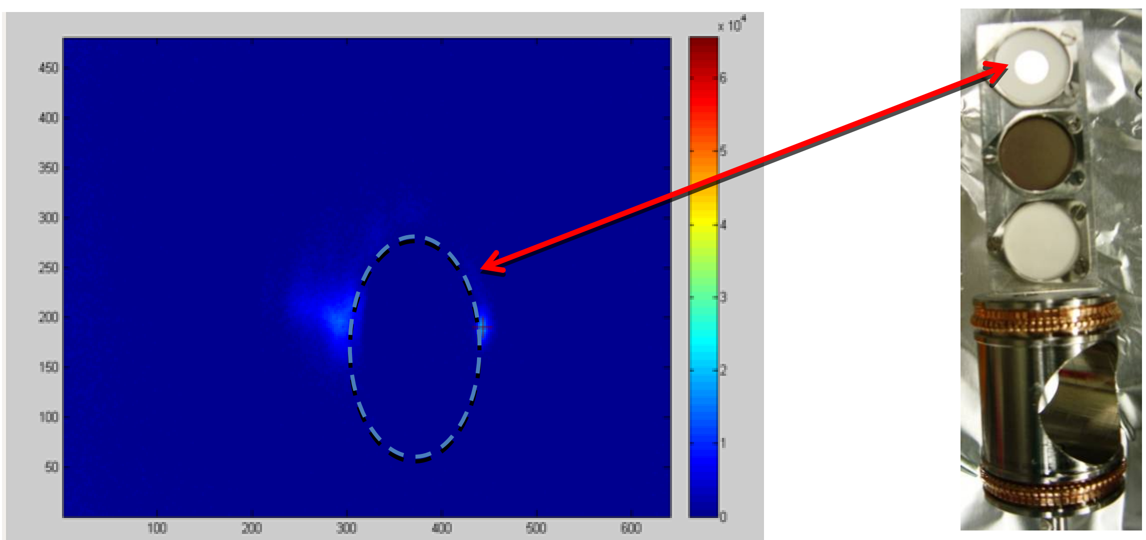
100 μA
Phase space measurements:
Non-intercepting or fully intercepting diagnostics

100 nA
Beam setup: viewers, cameras

100 pA
Halo, cathode lifetime:
viewers, PMT's

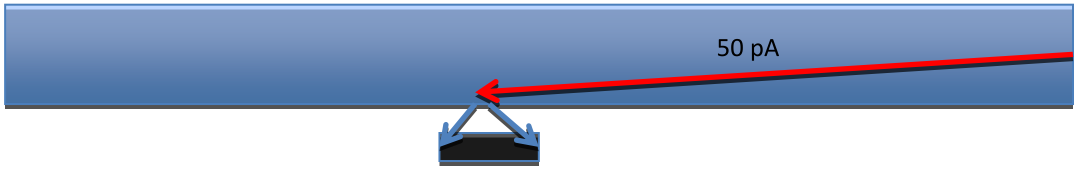
10^3 10^3 10^3 → 10^6 to 10^9

A viewer with a hole for imaging halo



Beam Loss Estimate

To 'calibrate' the beam loss , used radiation measurements – steered a 50 pA, 5 MeV beam onto a beam pipe



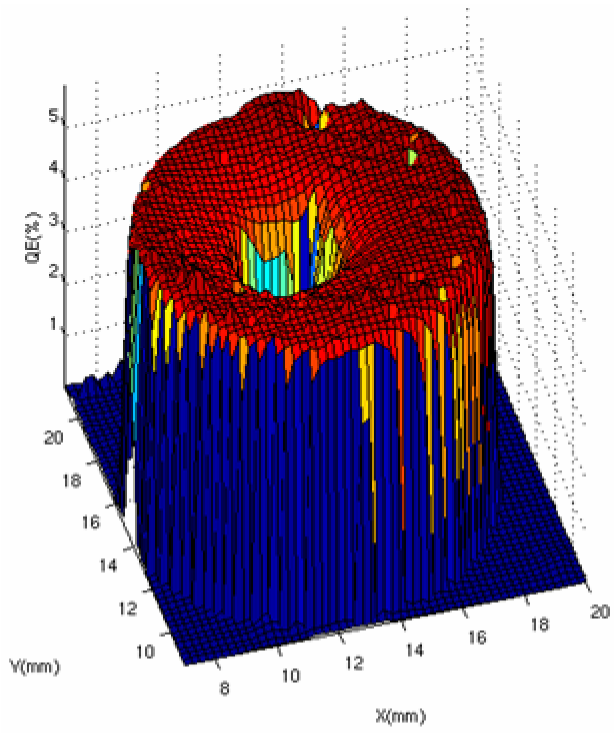
Gamma probe

50 pA/5 MeV produces about 10 mSv/hr at an external gamma probe

For the best beam setup, we typically observe from 0 to 40 mSv/hr along the length of the beamline. From this, we estimate a total beam loss of ~1 nA out of 50 mA, or $2x10^{-8}$

GaAs Damage

Non-recoverable QE damage on GaAs at the cathode center (at high current)– cannot be recovered by heat treatment and reactivation



Cause of Damage?

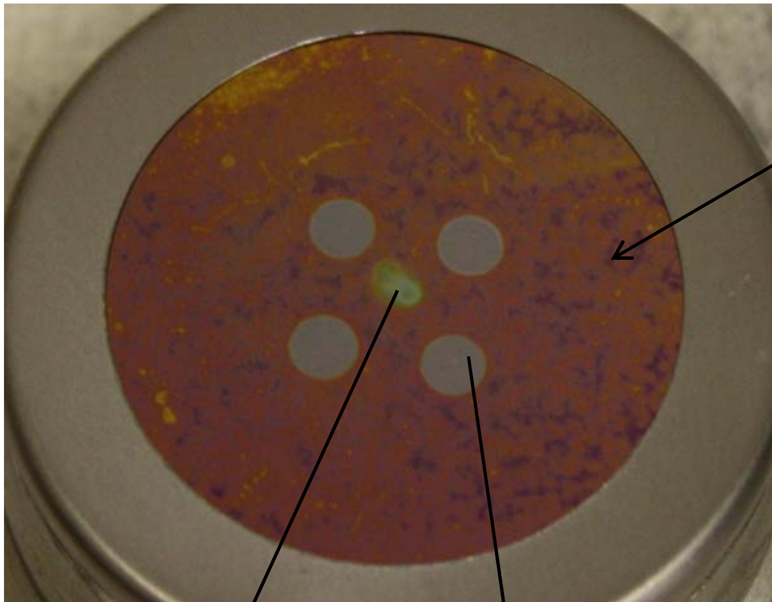
- Ion Backbombardment
- Ion implantations
- Rise in vacuum pressure
- Field emission/arcing

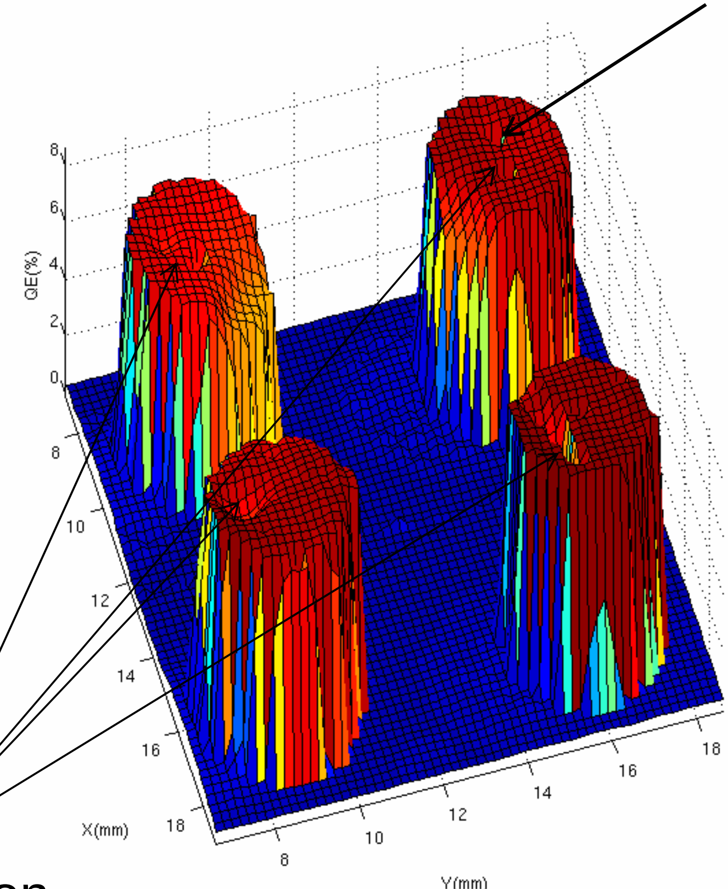
Conclusion: The cathode center cannot be used for high current operation

Off-Center Cathodes - GaAs

Dead area (brown)

Local ion damage





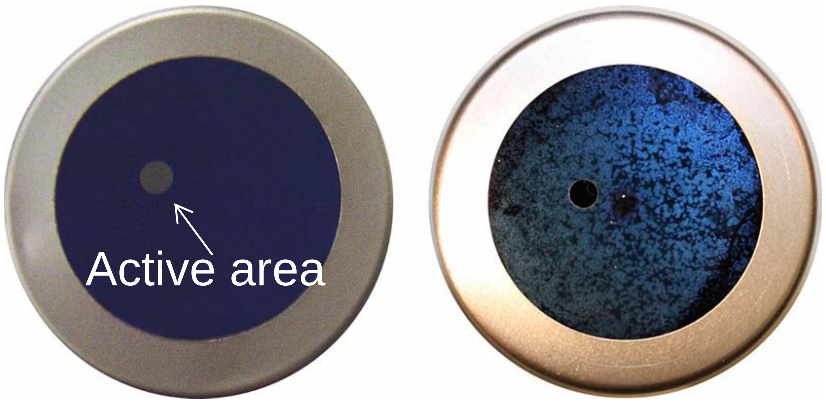
Ion damage at the center

Active area (4 spots)

Laser location

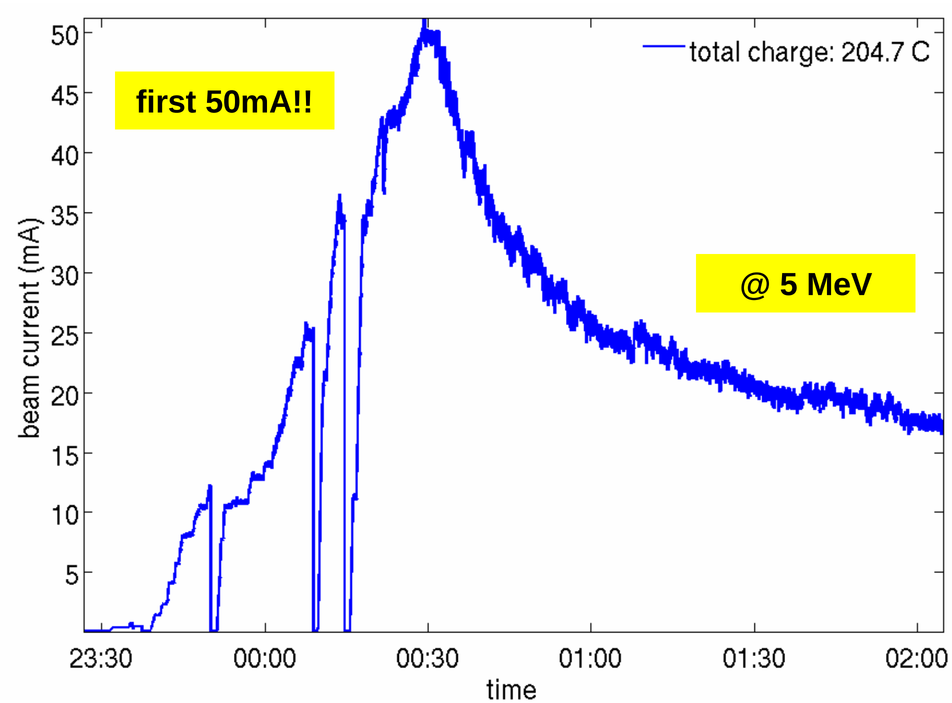
High Currents - GaAs

Now: the cathode we use has a single active area offset from the center



before

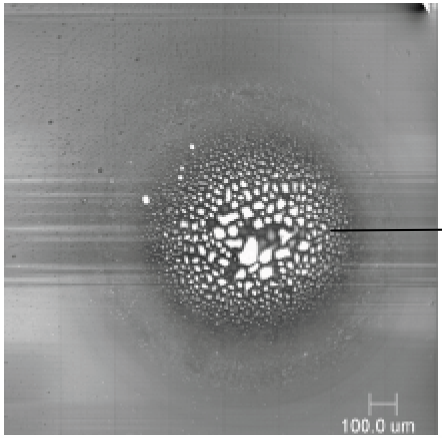
after

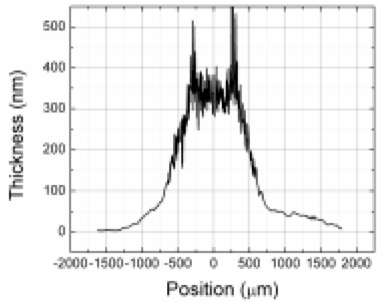


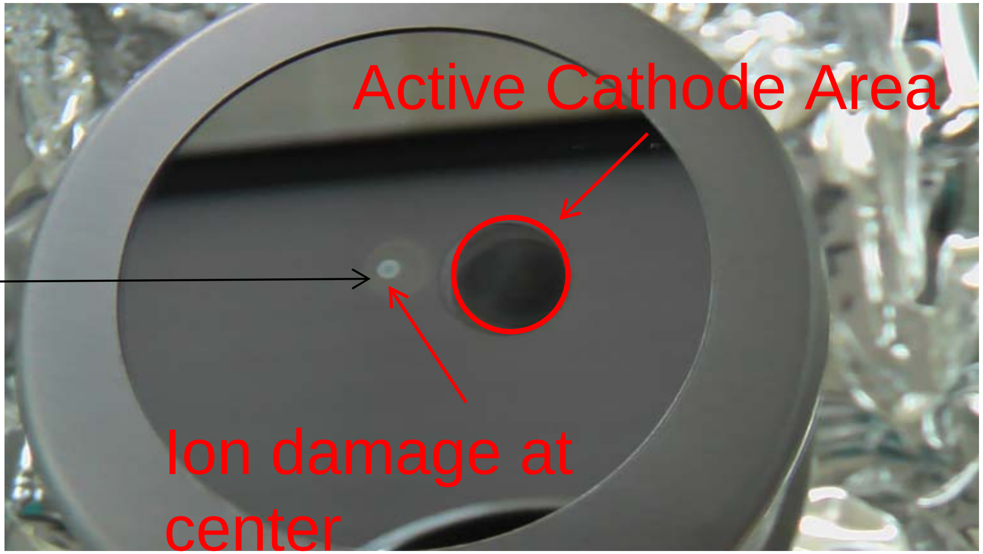
Highest ever average current from a GaAs photocathode!

CsK_2Sb Damage

Analysis after 8 hour/ 20 mA run – CsK_2Sb on Si

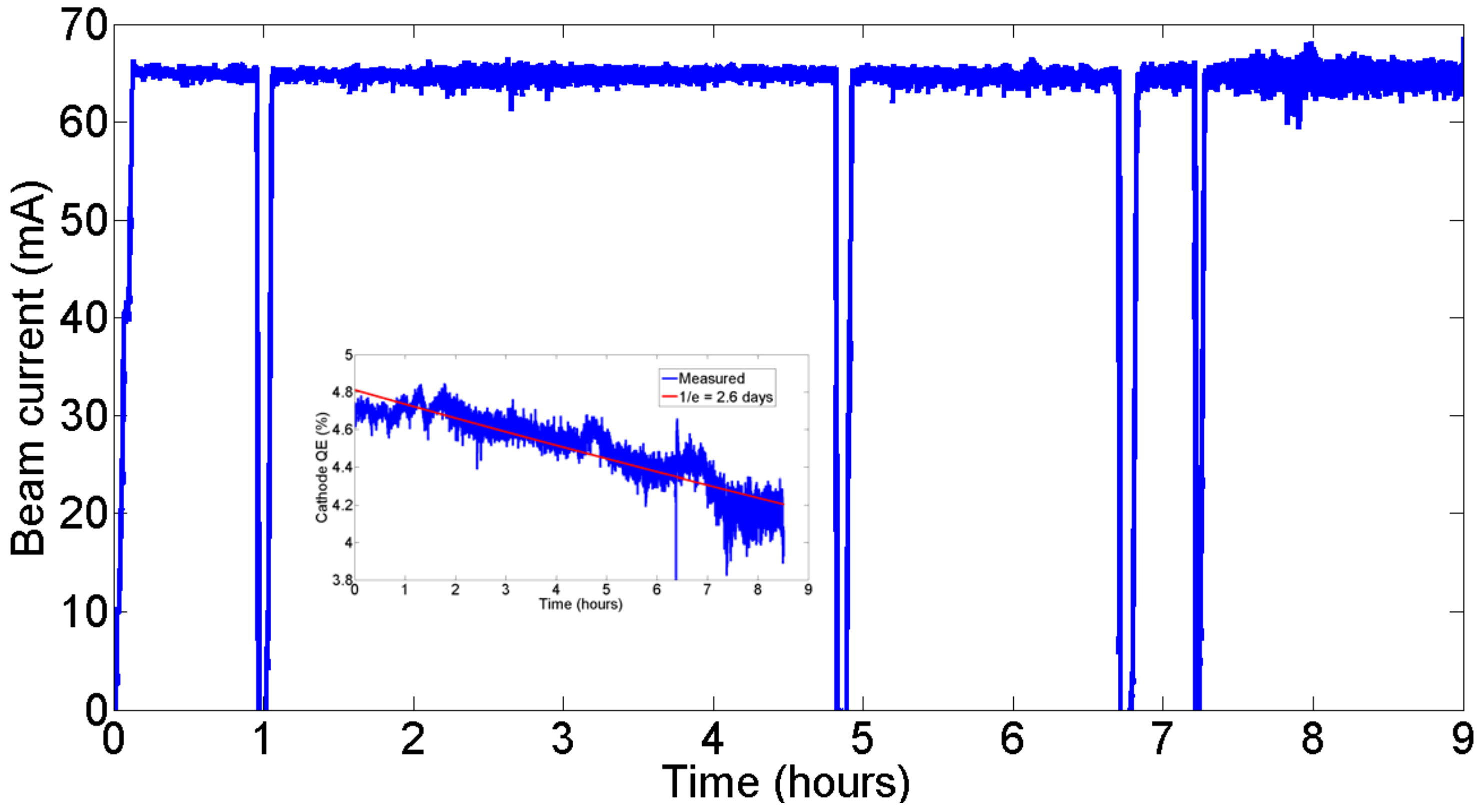






Large bump in the middle from ion damage! Eventually causes field emission, making the cathode unusable

High Currents – Na_2KSb



Using a Na_2KSb photocathode, ran over 8 hours at 65 mA (2000 C) with a 2.6 day 1/e cathode lifetime. Reached as high as 75 mA for a short time.

*L. Cultrera, *et al*., *Appl. Phys. Lett*., 103, 103504 (2013)
*B. Dunham, *et al*., *Appl. Phys. Lett*., 102, 034105 (2013)

Lessons Learned

- High average currents with good lifetime from a photocathode are a reality
- Low emittance (near thermal) beams (with reasonable bunch charge) from a DC gun/SRF booster are a reality
- Extremely high DC voltages are not necessary to achieve our requirements (350 kV okay)
- Space charge simulations + genetic optimizations match experiments accurately
- Halo/beam loss can be maintained at or below 1 part in 10^7 to 10^8
- Cathodes are still the key for any photoemission gun

Conclusion

Just in the last year . . .

- *Average current of 75 mA* from a photoinjector demonstrated – new record!
- Demonstrated feasibility of high current CW operation (65 mA for >8 hours from a single cathode spot)
- Emittance specification achieved

DC photoemission guns with SRF boosters provide proven performance for high average current, high-brightness beams for moderate bunch charge applications

Acknowledgements

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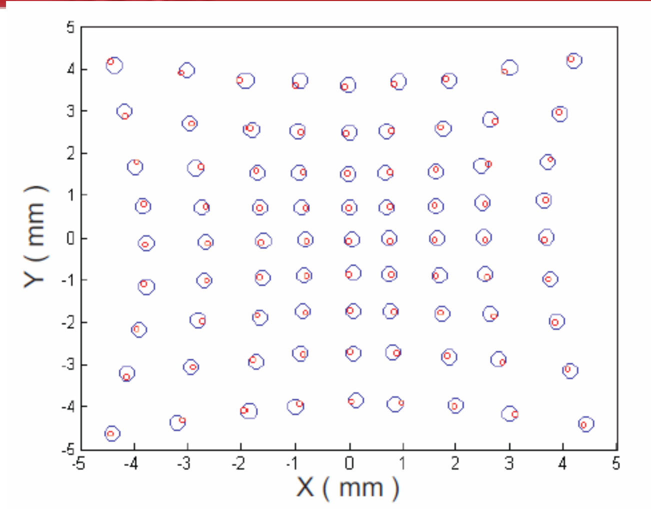
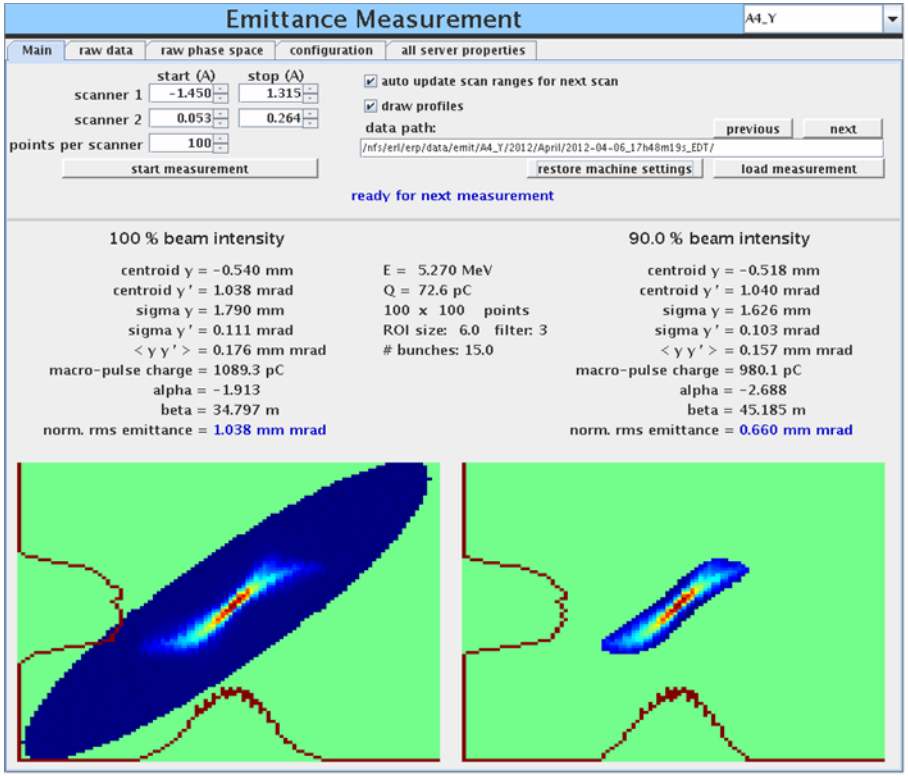
Alignment effort



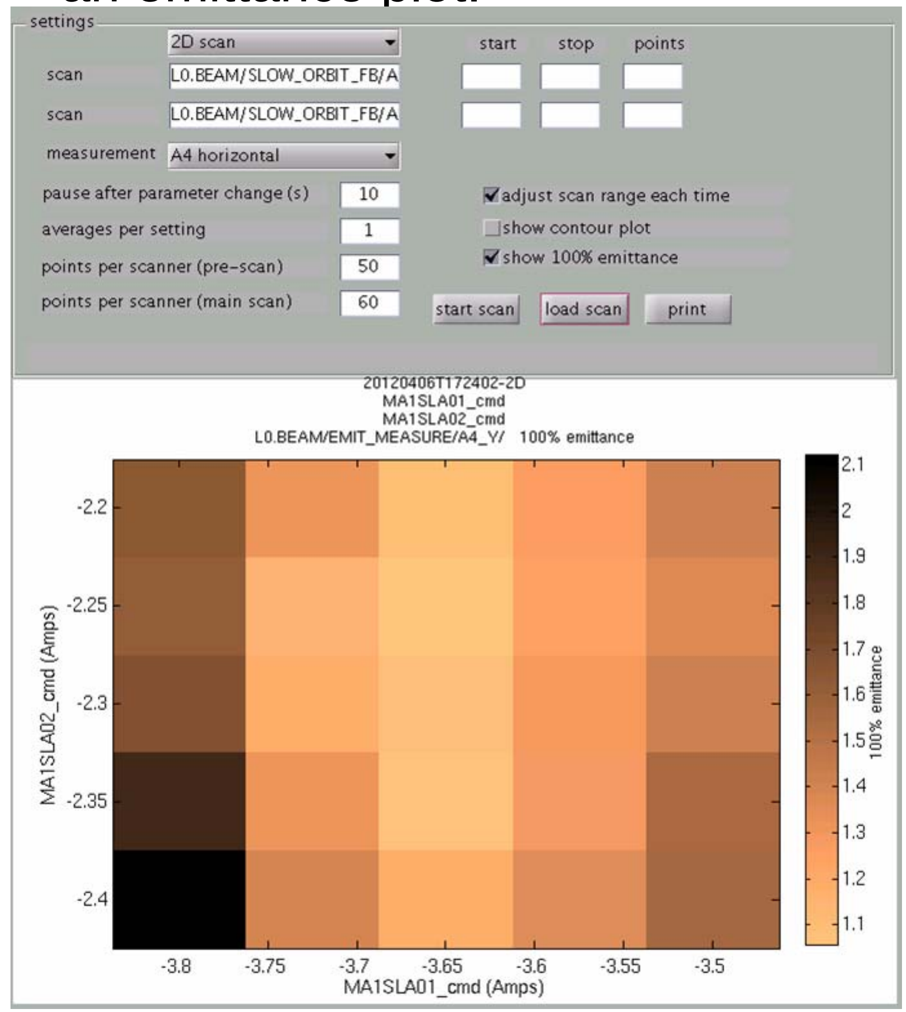
- Align DC gun by scanning laser position, measuring pin-cushion downstream.
- Align buncher and SRF cavities using correctors, making sure beam does not move when turned on/off.
- Align solenoids by scanning current, using motors to move/tilt magnets.
- Slice emittance is a sensitive tool to verify good machine alignment, as all misalignments lead to an emittance change.

Emittance Scans



Single emittance scan GUI

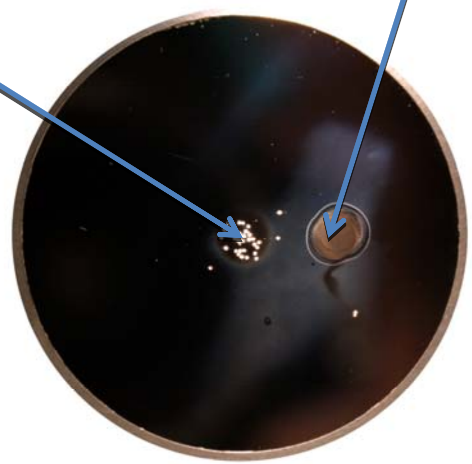
This GUI performs 1D and 2D parameter scans and displays an emittance plot.



Cathode Damage

Ion damage limited to the central area

Active area is offset from the center



Front surface of the cathode (CsK_2Sb on Si) after use.

Emittance Measurement System (EMS)

Leave the slits stationary and scan the beam across them. Can measure charge ranges from 0.1 pC up to 100 pC. Measurements take ~10 seconds.

This turns our injector into an analog computer for performing multi-parameter optimizations.

By adding a deflection cavity after the slits, we can also do slice emittance measurements