



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

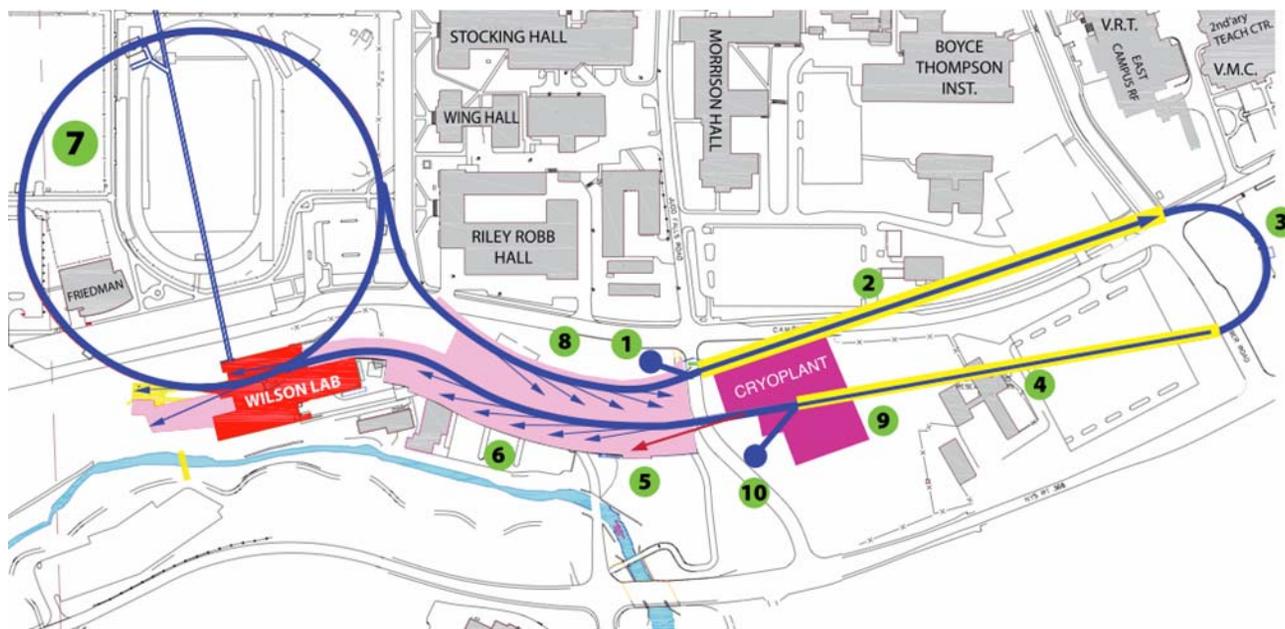
Bruce Dunham, for the Cornell ERL Team

September 11, 2013



# Outline

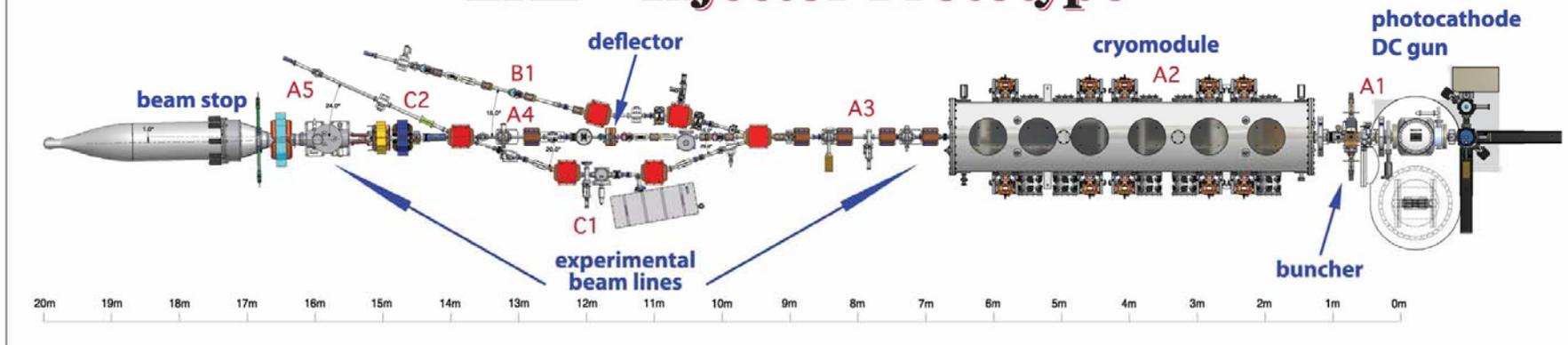
- Overview
- High Brightness Results
- High Power Operations and Results
- Conclusion



- Our long-term goal is to build an ERL-based x-ray light source to replace our existing machine (CESR/CHES).
- 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



## ERL – Injector Prototype



ERL Injector Prototype:  
Achievements to date:

- 75 mA average current @ 4 MeV
- 0.3  $\mu\text{m}$  emittance @ 77 pC, 8 MeV



# Injector Requirements

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

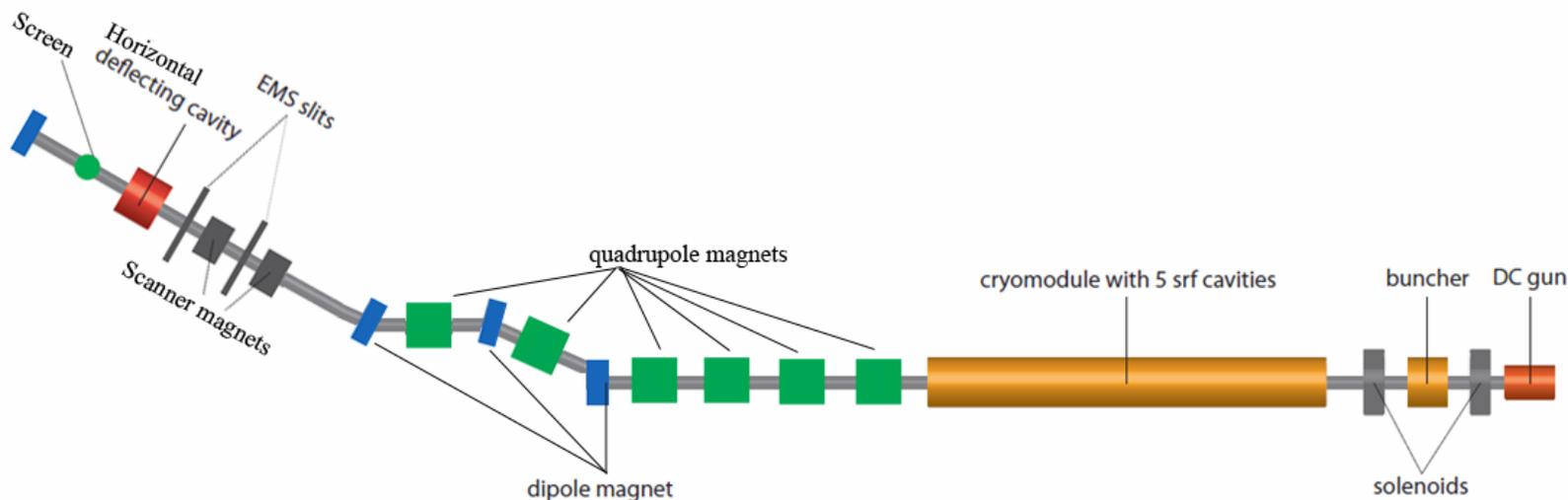


# Emittance Measurement Results



## Goals for Experiment

- Measure low emittances at the end of the merger  
Emittances  $\leq 0.3$  micron, bunch Length  $\leq 3$  ps, energy Spread  $\sim 1e-3$
- 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





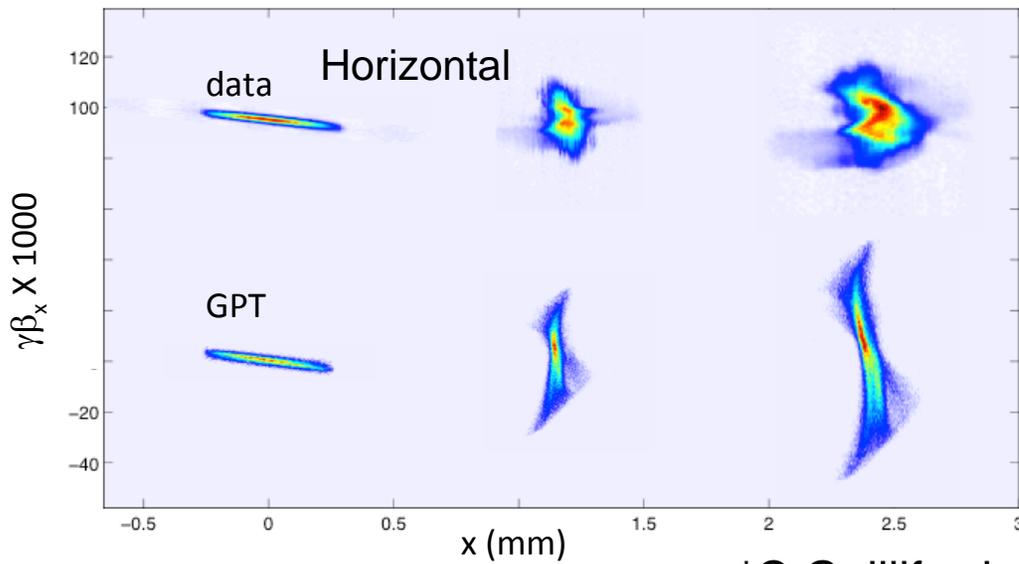
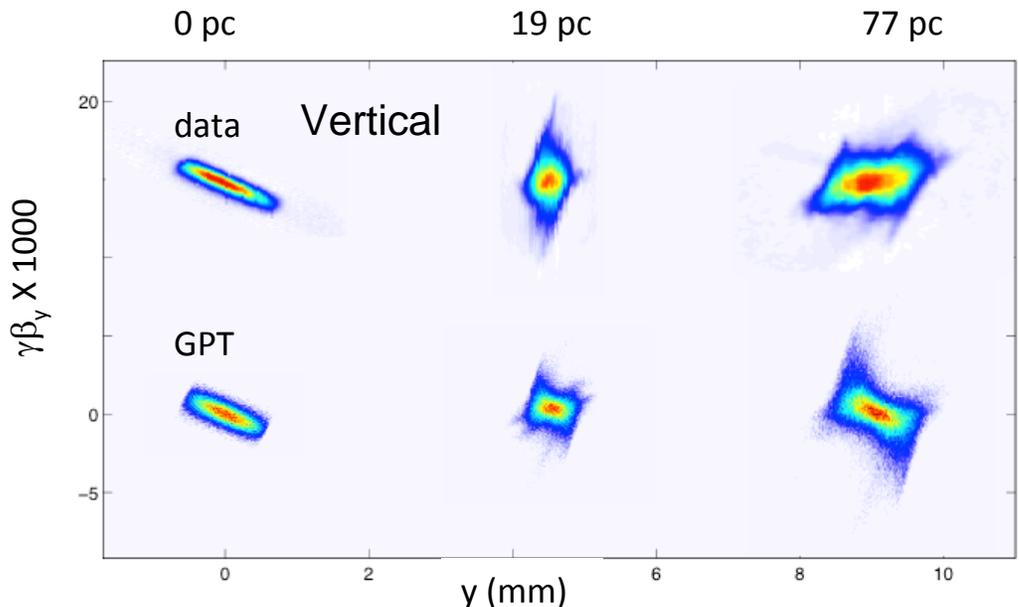
## Baseline Measurement at 'zero' charge

### 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:

## Vertical Phase Space

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)

## Horizontal Phase Space

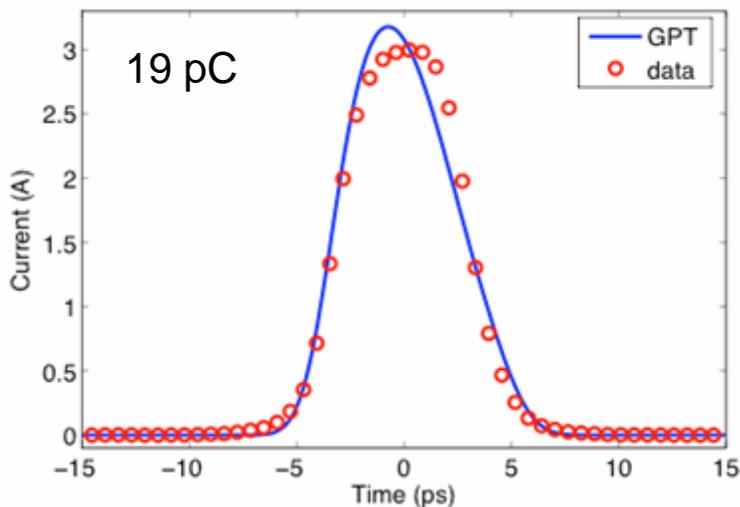
Data Type	en(100%) [microns]	en(90%) [microns]
Projected (EMS)	0.33(0.69)	0.23(0.51)
GPT	0.31 (0.72)	0.19(0.44)

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

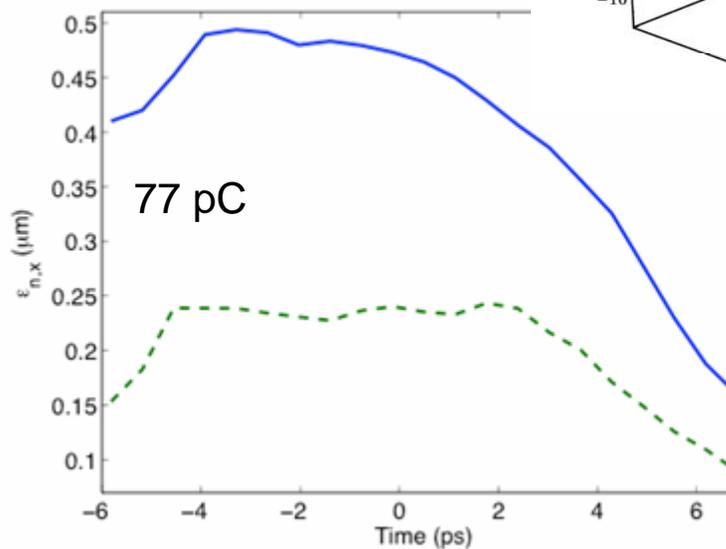
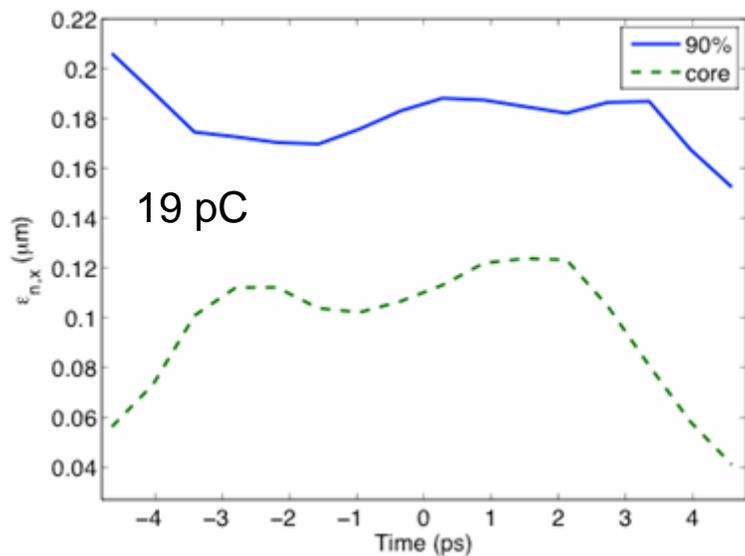
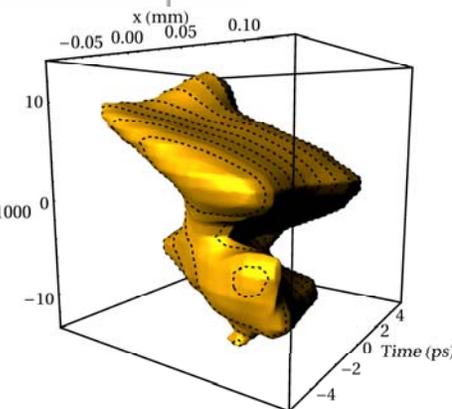
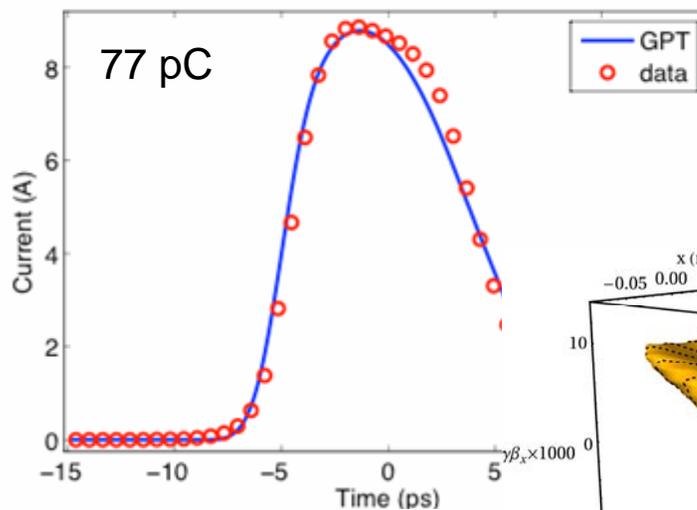


# Slice Emittance and Bunch Length

GPT:  $\sigma_t = 2.2$  ps, data:  $\sigma_t = 2.1$  ps



GPT:  $\sigma_t = 3.1$  ps, data:  $\sigma_t = 3.0$  ps





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

The screenshot displays the GPT GUI interface with several panels:

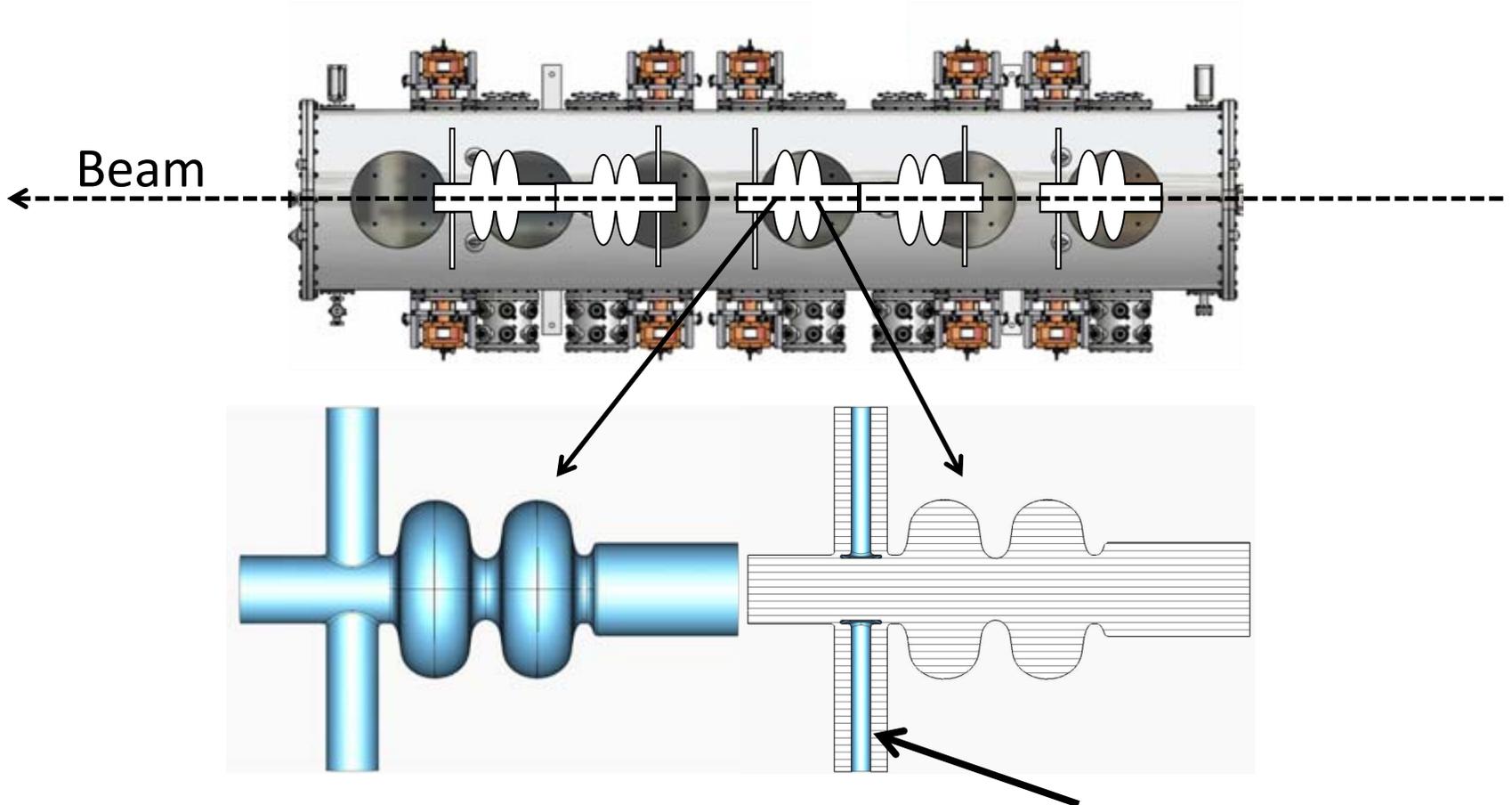
- Beamline and Save/Restore:** Includes a dropdown for 'Select Beamline Type' (a1a2a3b1) and buttons for 'Load Saved Settings', 'Save Settings', 'Load Machine State', and 'Reset to defaults'.
- GPT Simulation Settings:** A table with columns 'Name', 'Value', and 'Units'.
 

Name	Value	Units
nps	20000	[#]
Qtot	-77	[pC]
space_charge	1	[0/1]
xyrms	0.4700	[mm]
trms	7.9610	[ps]
xoffset	0	[mm]
yoffset	0	[mm]
global_phase	0	[deg]
dtmax	100	[ps]
FinalGamma	15	[1/A]
couplers	1	[0/1]
- Calculated Settings:** Shows 'Beam Energy: 7.154 MeV' and 'Pinhole Diameter: 2 mm'. It includes explanatory text about energy setting and assumptions.
- Run GPT Simulation:** Features buttons for 'Phase GPT', 'Just Set Energy', and 'Run GPT', along with instructions for particle simulation.
- Plot Data:** Includes 'Screen Options' (Name: B1 1st Slit, Type: X Phase Space) and '2D Plot Style' (Density, Scatter). A 'Plot Data' button and 'Make new figure' checkbox are also present.
- Beam Element Settings:** A table with columns 'Element', 'PV Name', 'Command Value', 'Readback Value', 'Units', 'Simulation Value', and 'Z Position'.
 

Element	PV Name	Command Value	Readback Value	Units	Simulation Value	Units	Z Position	
1	GA1GVH01	349.3000	349.3000	(kV)	349.3000	(kV)	0	
2	MA1SLA01	Current	-3.7000	-3.7069	(A)	0.0309	(T)	0.3030
3	RA1CTB01	Cavity Voltage	60	60	(kV)	0.9569	(MV/m)	0.7140
4	RA1CTB01	On-crest Cavity Phase	175.8100	175.8100	(deg)	148.4674		0.7140
5	RA1CTB01	Relative Cavity Phase	-90.0000	-90.0000	(deg)	-90.0000		0.7140
6	MA1SLA02	Current	2.3000	2.3023	(A)	-0.0192	(T)	1.1280
7	RA2CTC01	Cavity Voltage	1491	1491	(kV)	12.7983	(MV/m)	2.0470
8	RA2CTC01	On-crest Cavity Phase	-61.2000	-61.2000	(deg)	9.1949		2.0470
9	RA2CTC01	Relative Cavity Phase	-10.0000	-10.0000	(deg)	-10.0000		2.0470
10	RA2CTC02	Cavity Voltage	1900	1900	(kV)	16.3090	(MV/m)	2.8330
11	RA2CTC02	On-crest Cavity Phase	43.2000	43.2000	(deg)	356.1229		2.8330
12	RA2CTC02	Relative Cavity Phase	-7	-7.0000	(deg)	-7		2.8330
13	RA2CTC03	Cavity Voltage	1.3860e+03	1.3860e+03	(kV)	11.8970	(MV/m)	3.6960
14	RA2CTC03	On-crest Cavity Phase	161.0900	161.0900	(deg)	256.8649		3.6960
15	RA2CTC03	Relative Cavity Phase	-3.6621e-06	-3.6621e-06	(deg)	-3.6621e-06		3.6960
16	RA2CTC04	Cavity Voltage	1386	1386	(kV)	11.8970	(MV/m)	4.4820
17	RA2CTC04	On-crest Cavity Phase	97.1322	97.1322	(deg)	284.5580		4.4820
18	RA2CTC04	Relative Cavity Phase	2.1484e-06	2.1484e-06	(deg)	2.1484e-06		4.4820
19	RA2CTC05	Cavity Voltage	1500	1500	(kV)	12.8755	(MV/m)	5.3450
20	RA2CTC05	On-crest Cavity Phase	-47.4085	-47.4085	(deg)	193.1202		5.3450
21	RA2CTC05	Relative Cavity Phase	-20	-20.0000	(deg)	-20		5.3450
22	MA3QUA01	Current	-3.8000	-3.8014	(A)	-3.0390	(T/m)	6.5421
23	MA3QUA02	Current	9.8000	9.8020	(A)	7.8375	(T/m)	7.1421
24	MA3QUA03	Current	4.9000	4.8950	(A)	3.9187	(T/m)	7.7421
25	MA3QUA04	Current	-8.5000	-8.4944	(A)	-6.7978	(T/m)	8.3421
26	MB1QUB01	Current	9.3000	9.3188	(A)	7.8112	(T/m)	9.7906
27	MB1QUB02	Current	9.3000	9.3281	(A)	7.8112	(T/m)	10.3296
- Status:** Displayed as 'Ready' in red text.
- Phase Space Plot:** A 2D density plot titled 'B1 1st Slit viewscreen, at z = 12.34 meters,  $\epsilon_x = 1.08$  mm-mrad,  $\sigma_x = 0.104$  mm,  $\sigma_{p_x, y} (\times 1000) = 12.2$ '. The x-axis is 'x position (mm)' and the y-axis is ' $p_{x, y} (\times 1000)$ '. A color scale on the right ranges from 0 to 40.



# 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

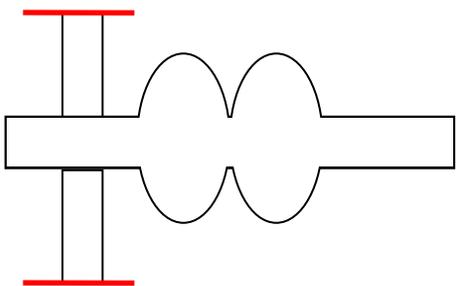
$$\vec{E} = \vec{E}_+ + \vec{E}_-$$

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

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

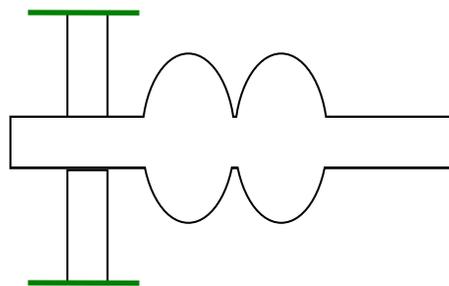
$$\vec{B}_\pm = \mp \frac{A_\pm}{cr} e^{i(\pm kx + \omega t)} \hat{\theta}$$

$$E_{\parallel} = 0$$



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

$$B_{\parallel} = 0$$

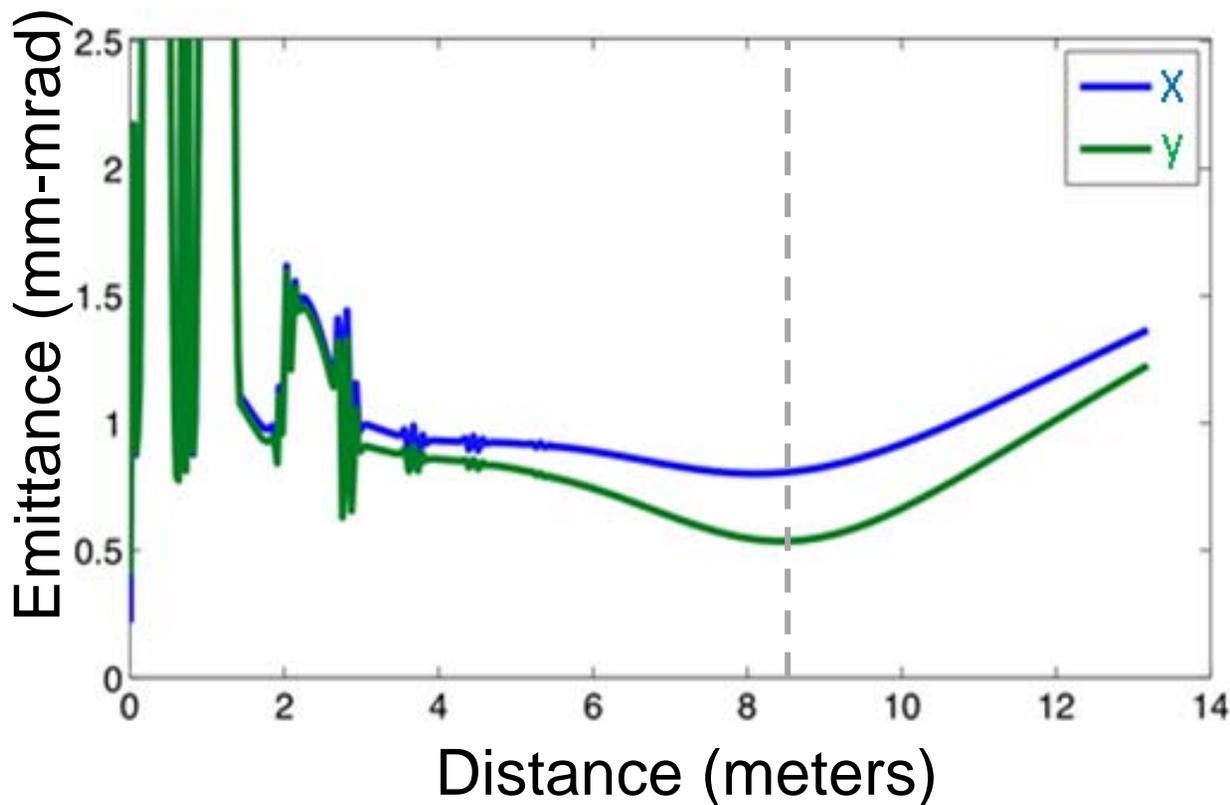


$$\begin{cases} \vec{E}^m = \frac{A^m}{r} \cos(kx) \hat{r} \\ \vec{B}^m = -i \frac{A^m}{cr} \sin(kx) \hat{\theta} \end{cases}$$

- Normalize result to match real forward and reflected power



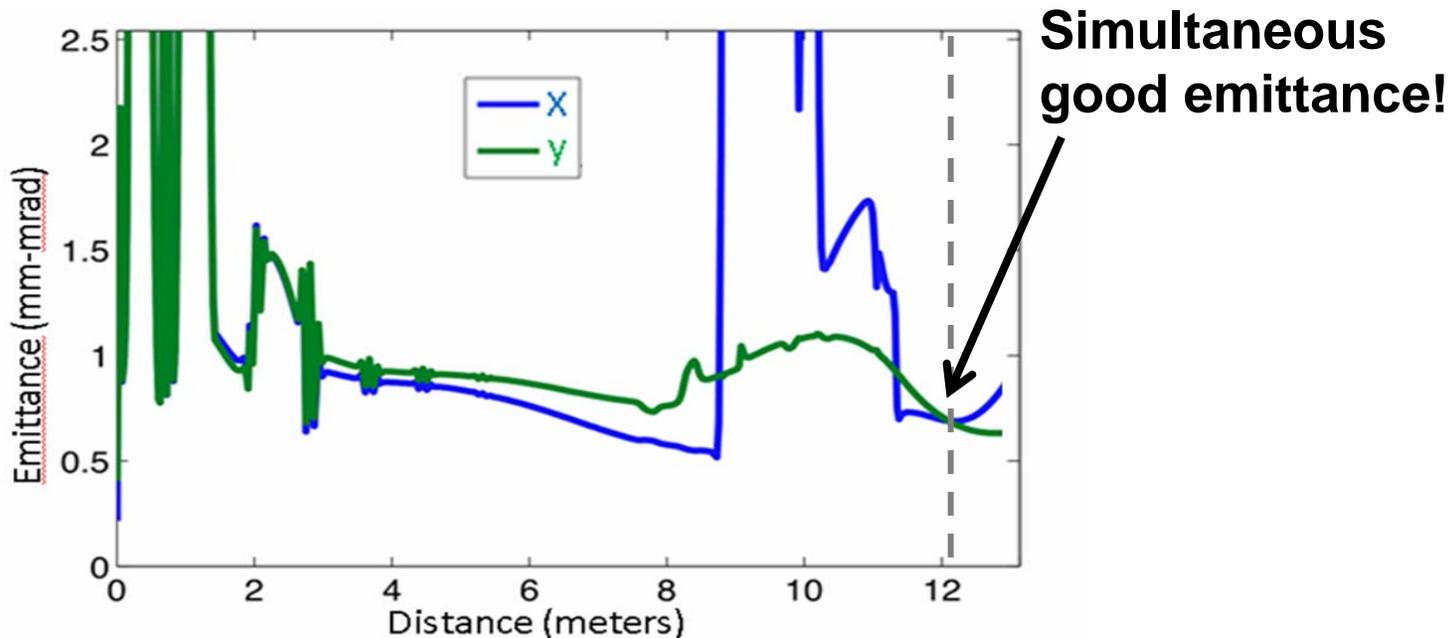
- Strong asymmetry after first cavity couplers
- Beam size asymmetry is accurately reproduced in the lab
- At minimum y emittance, the x emittance is 2x larger
- This is for a beam straight ahead (no merger)





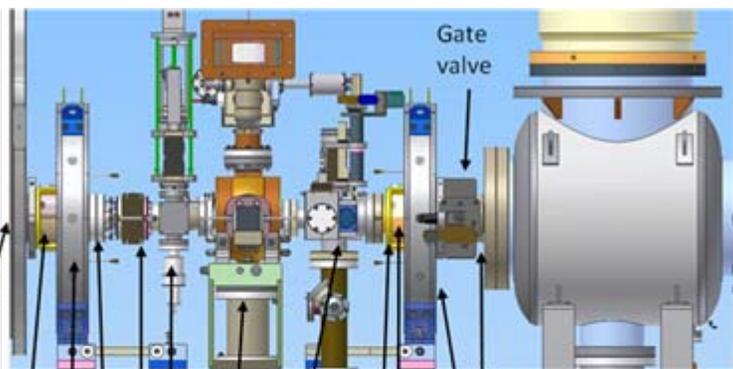
# Simulation with Merger

- Optimize emittance using a 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





# Alignment Accuracy

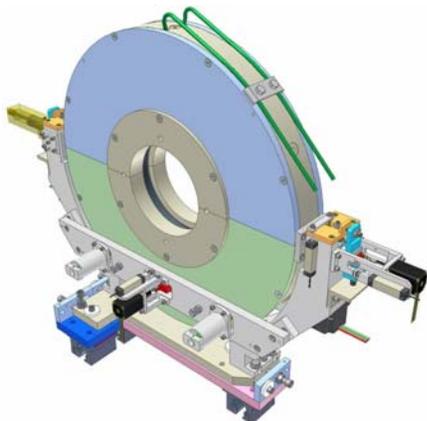


Aligning the magnetic and electrical centers of all elements to the beam axis is crucial for obtaining low emittance and minimizing aberrations.

Superconducting  
Cryomodule  
H&V corrector pair  
Solenoid #2  
RF sealed sliding joint  
RF sealed viewscreen  
RF Buncher Cavity  
Laser Input Box  
H&V corrector pair  
BPM  
Solenoid #1  
H&V corrector pair  
Photoemission Gun

## Procedure:

1. Align laser at cathode center
2. Center on buncher using correctors (+/- 10  $\mu\text{m}$ )
3. Center on first 2 SRF cavities using correctors (+/- 10  $\mu\text{m}$ )
4. Center solenoid #1 by physical adjustments (+/- 50  $\mu\text{m}$ )
5. Center solenoid #2 by physical adjustments (+/- 50  $\mu\text{m}$ )



Had to add remote  
control of the solenoids



# 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!



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



# 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  $\mu$ A

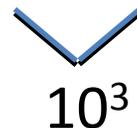
Phase space measurements:  
Non-intercepting or fully  
intercepting diagnostics

100 nA

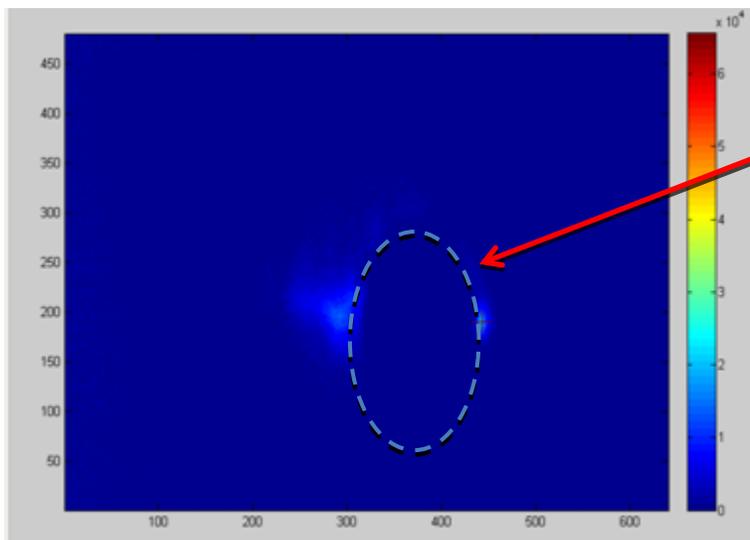
Beam setup: viewers,  
cameras

100 pA

Halo, cathode lifetime:  
viewers, PMT's



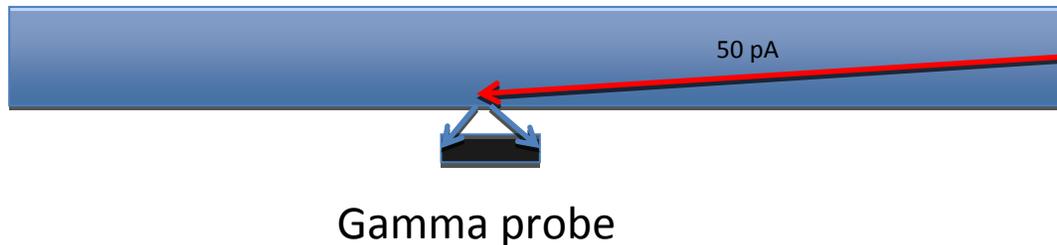
A viewer with a hole for imaging halo





# Beam Loss Estimate

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

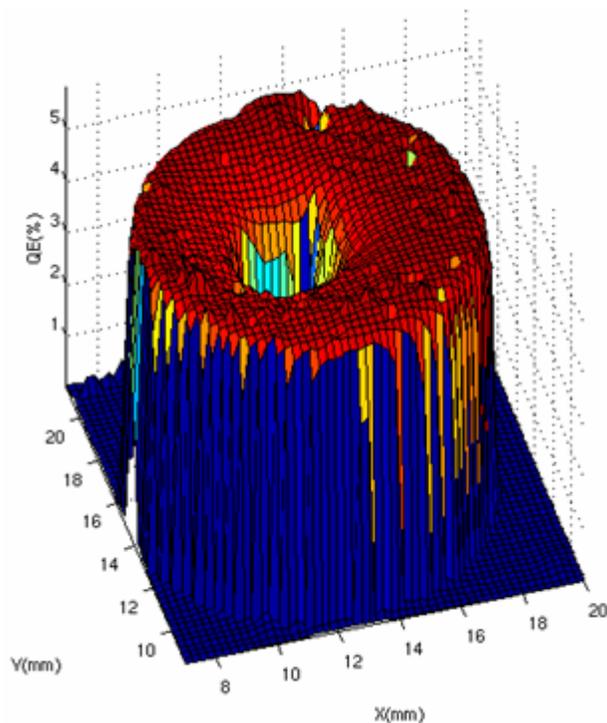


50 pA/5 MeV produces about 10 mSv/hr at an external gamma probe

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  $\sim 1$  nA out of 50 mA, or  $2 \times 10^{-8}$



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



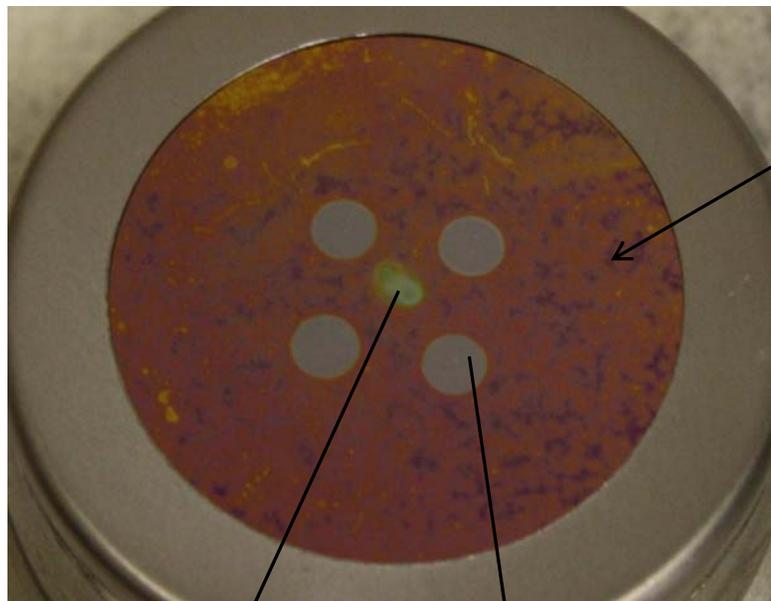
## Cause of Damage?

- 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

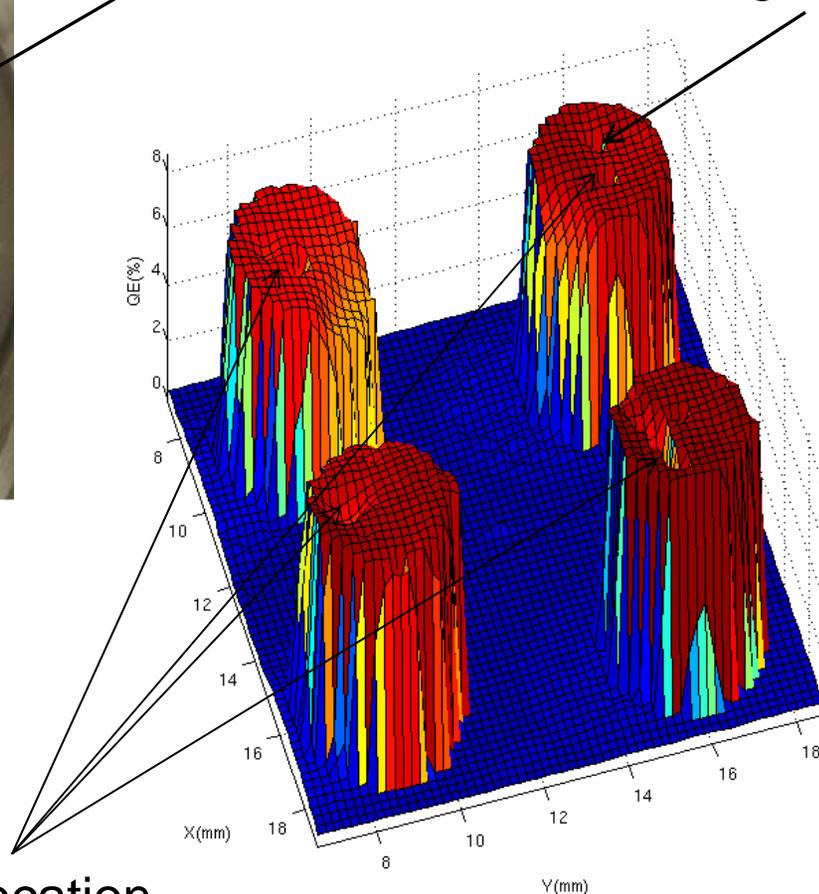


Ion damage at  
the center

Active area  
(4 spots)

Dead area (brown)

Local ion  
damage



Laser location



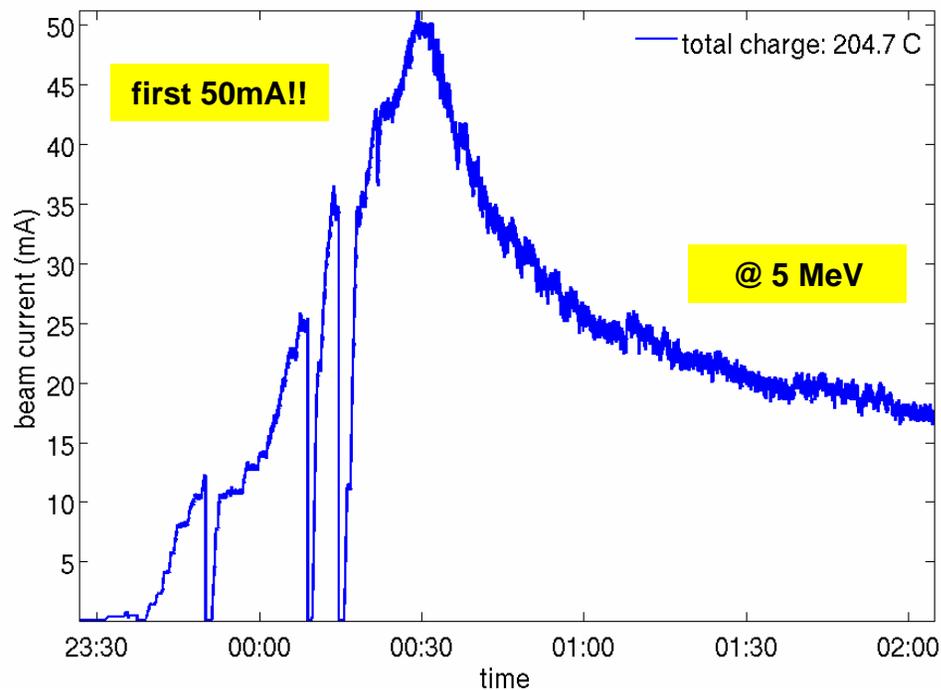
Now: the cathode we use has  
a single active area offset  
from the center



before



after

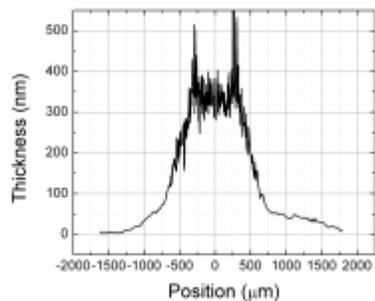
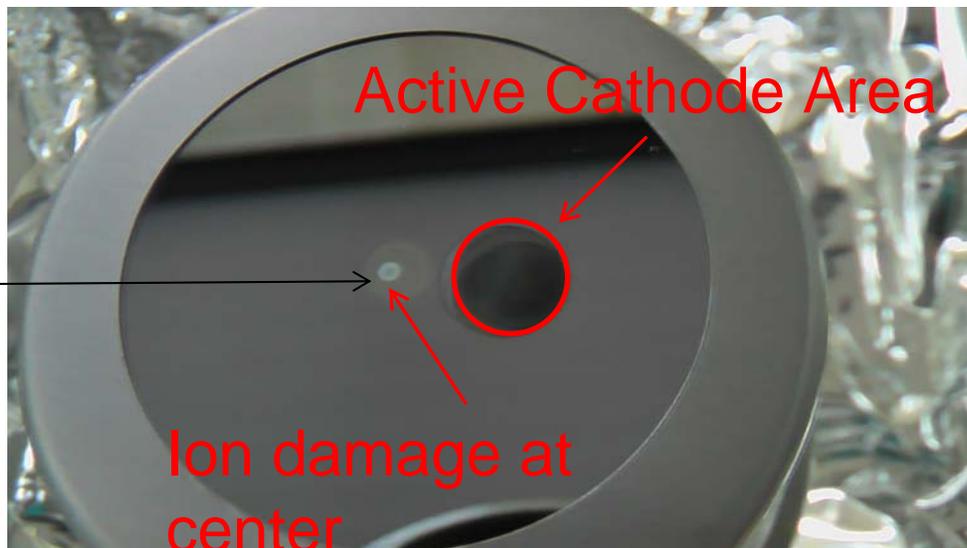
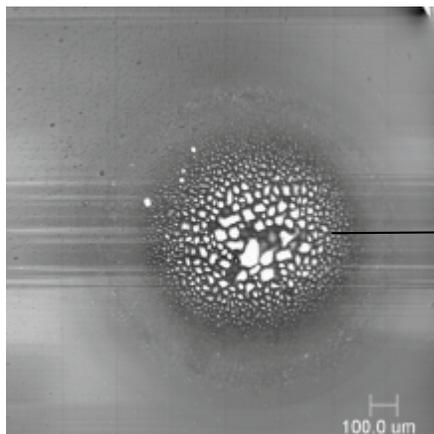


Highest ever average current  
from a GaAs photocathode!

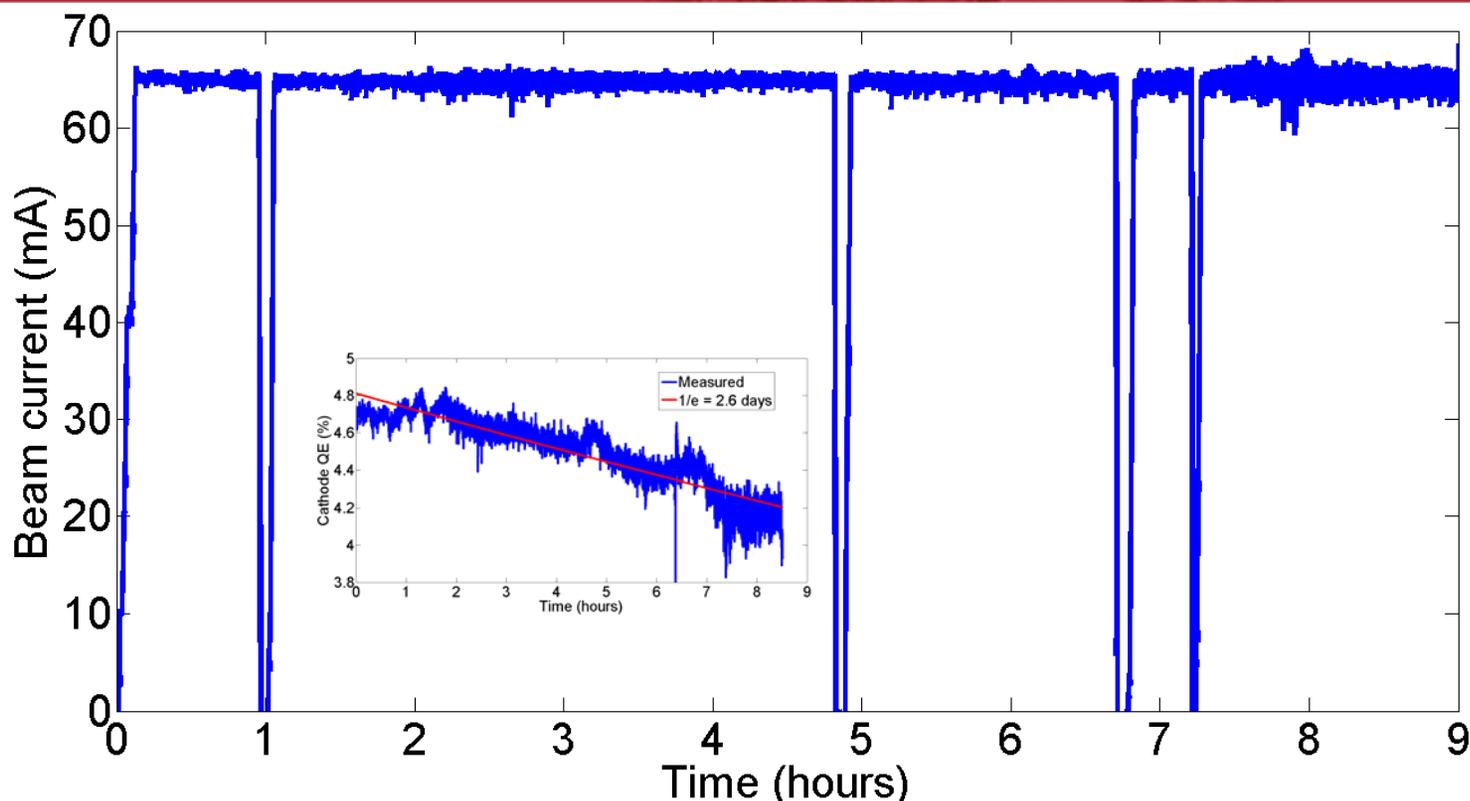


# CsK<sub>2</sub>Sb Damage

Analysis after 8 hour/ 20 mA run – CsK<sub>2</sub>Sb on Si



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



Using a Na<sub>2</sub>KSb 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)



- 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



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

This work is supported by the National Science Foundation grant  
DMR-0807731

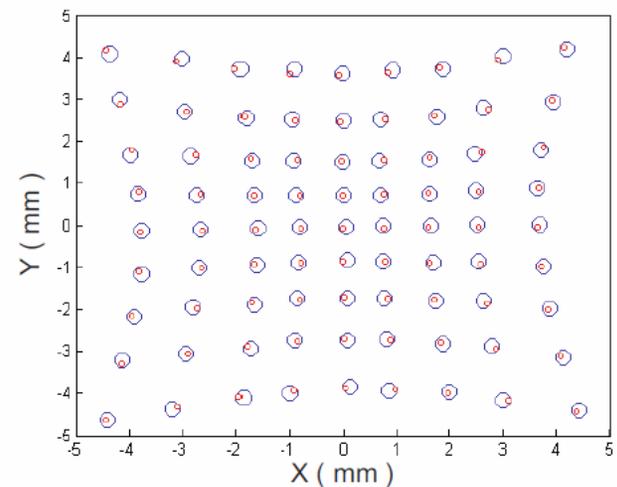


and Department of Energy grant DE-SC0003965



# Alignment effort

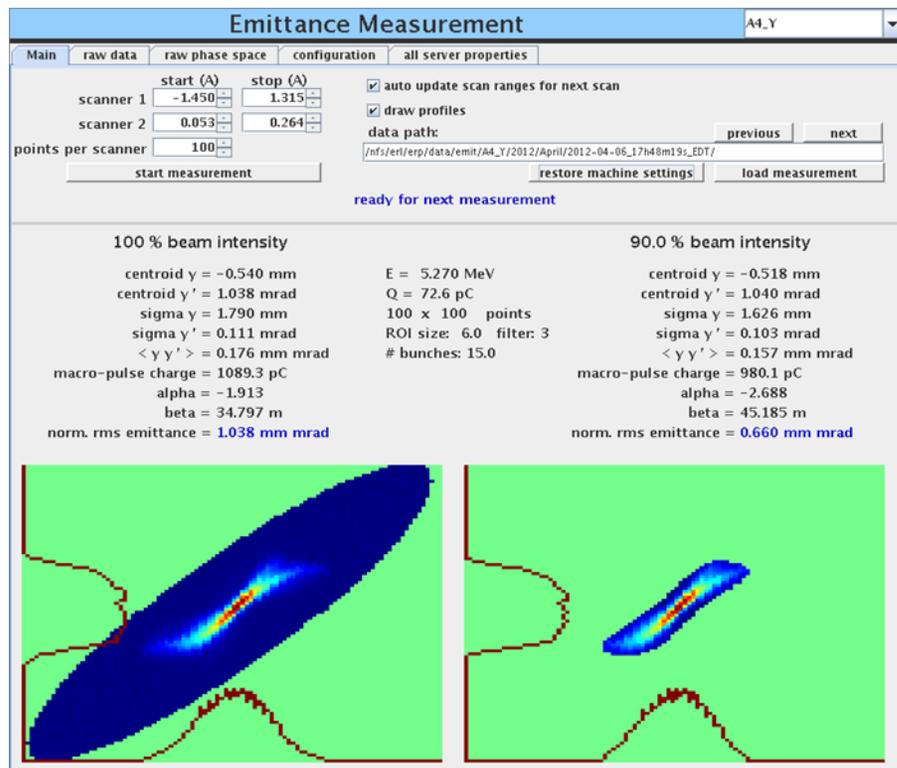
- Align DC gun by scanning laser position, measuring pin-cushion downstream.
- Align buncher and SRF cavities using correctors, making sure beam does not move when turned on/off.
- Align solenoids by scanning current, using motors to move/tilt magnets.
- Slice emittance is a sensitive tool to verify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



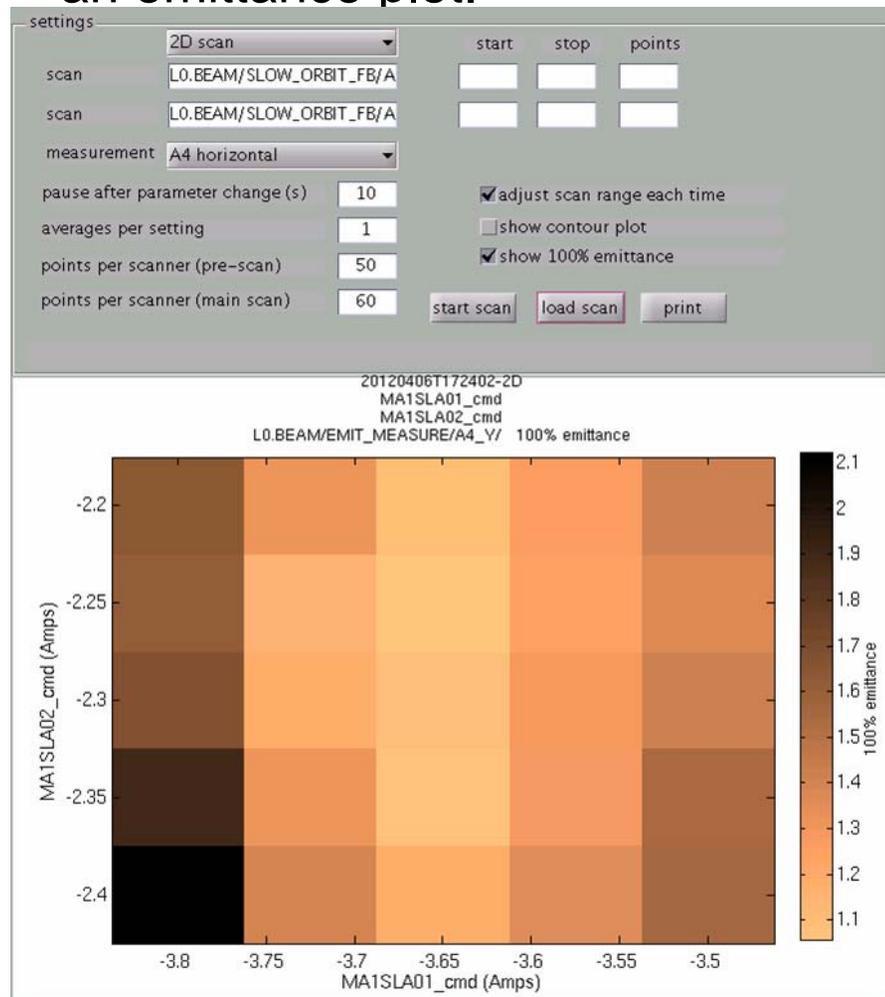


# Emittance Scans

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



Single emittance scan GUI





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



Bruce Dunham, Cornell University



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

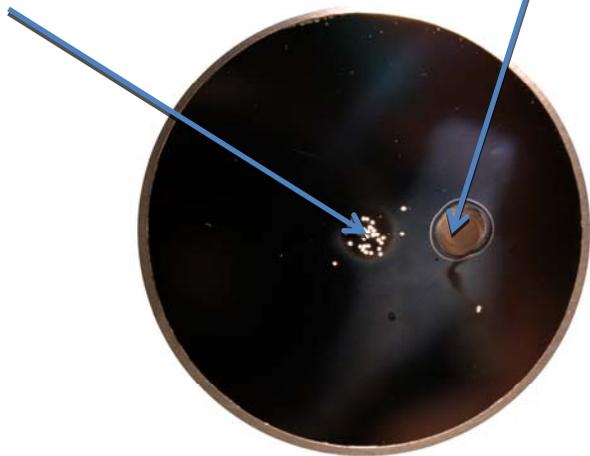


Bruce Dunham, Cornell University



Ion damage  
limited to the  
central area

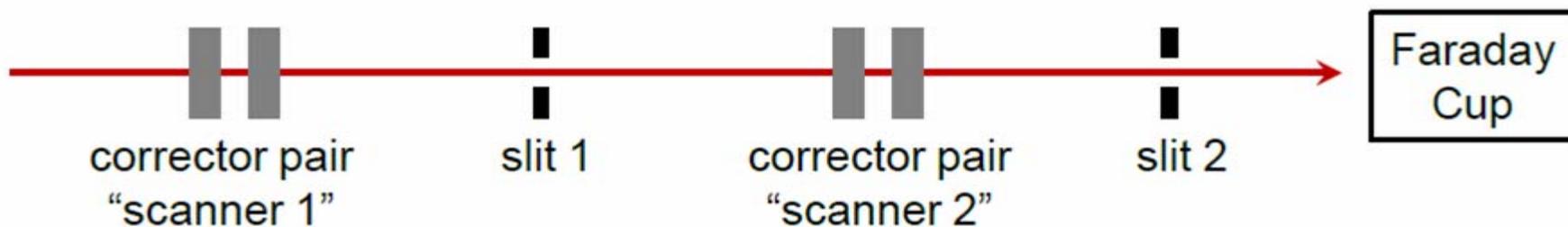
Active area is offset  
from the center



Front surface of the  
cathode ( $\text{CsK}_2\text{Sb}$  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

