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

Physics and technology of high-brightness high-power photoinjectors for beam coolers and electron ion colliders

Luca Cultrera

PI: Ivan Bazarov
Cornell University

Relevance

- Address major outstanding technological and beam physics issues of **critical importance to <u>high intensity sources</u> as required by the EIC**
- The landscape of successfully operating high current photoinjectors **is extremely modest**, **none of them have demonstrated** parameters as required for EIC (coolers or collider)

Project Goals

- 1 & 2 nC bunch low-emittance operation from DC gun injector (done)

PHYSICAL REVIEW SPECIAL TOPICS—ACCELERATORS AND BEAMS **18,** 083401 (2015)

Operational experience with nanocoulomb bunch charges in the Cornell photoinjector

Adam Bartnik,* Colwyn Gulliford,† Ivan Bazarov, Luca Cultera, and Bruce Dunham
CLASSE, Cornell University, Ithaca, New York 14850, USA
(Received 3 April 2015; published 19 August 2015)

- High average current running @ high charge (progress made)
- Physics of ion trapping & clearing (good progress made)

PHYSICAL REVIEW ACCELERATORS AND BEAMS **19,** 034201 (2016)

Detection and clearing of trapped ions in the high current Cornell photoinjector

S. Full,* A. Bartnik, I. V. Bazarov, J. Dobbins, B. Dunham, and G. H. Hoffstaetter
CLASSE, Cornell University, Ithaca, New York 14853, USA
(Received 22 July 2015; published 3 March 2016)

Milestones

- **1) Nano-coulomb bunch high-current generation**
  - Prepare the **new laser system** for beam operation (both pulsed and 100% duty factor) that has sufficient energy per pulse (≥mJ) to generate high charge bunches with appropriate transverse and longitudinal profiles.
  - Generate **1 and 2 nC bunches and characterize the beam emittance** (both transverse and longitudinal) and the bunch length at a reduced repetition rate (<kHz).
  - Operate with **50 mA average beam** current for 1 nC bunches.
- **2) Ion effect for high intensity electron beams**
  - Develop a **new simulation tool for ions**, which combines existing fast space charge routines in GPT along with adiabatic-invariant-based simulator for ions.
  - Determine the **equilibrium ion density** both by direct **measurement** and by examining the creation and clearing rates of ions using clearing electrodes.
  - Measure **beam properties both with and without ion mitigation strategies**, specifically clearing electrodes, clearing gaps, and beam shaking, and compare to the simulations.

Budget

Summary of expenditures by fiscal year (FY):

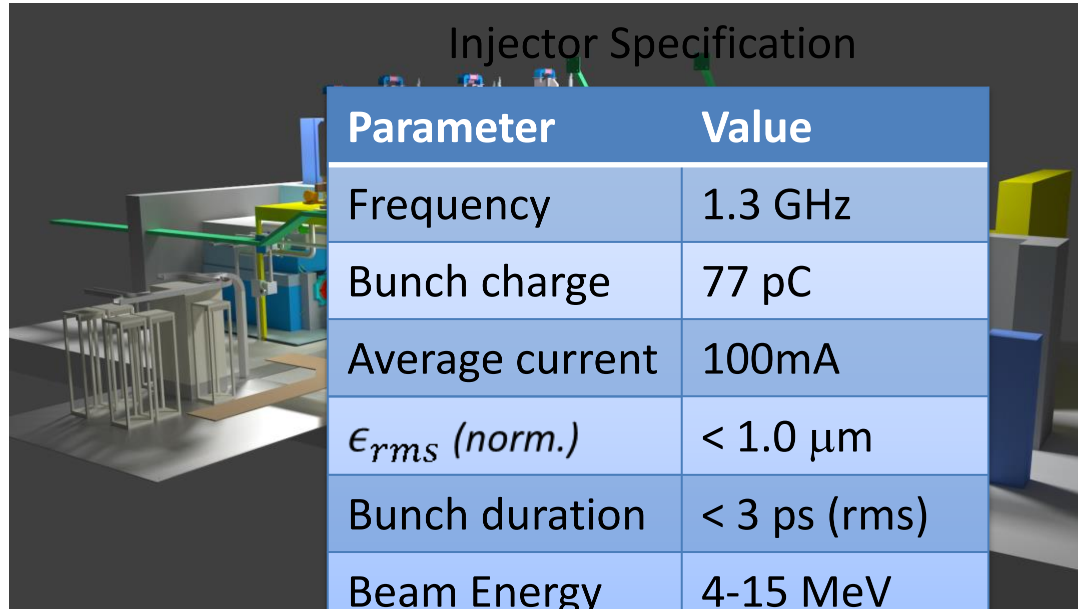
	FY10+ FY11	FY12+FY13	FY14+ FY15	FY16	Totals
a) Funds allocated			170,000	170,000	340,000
b) Actual costs to date			170,000	138,688	308,668

Original Design

Original design: ERL injector

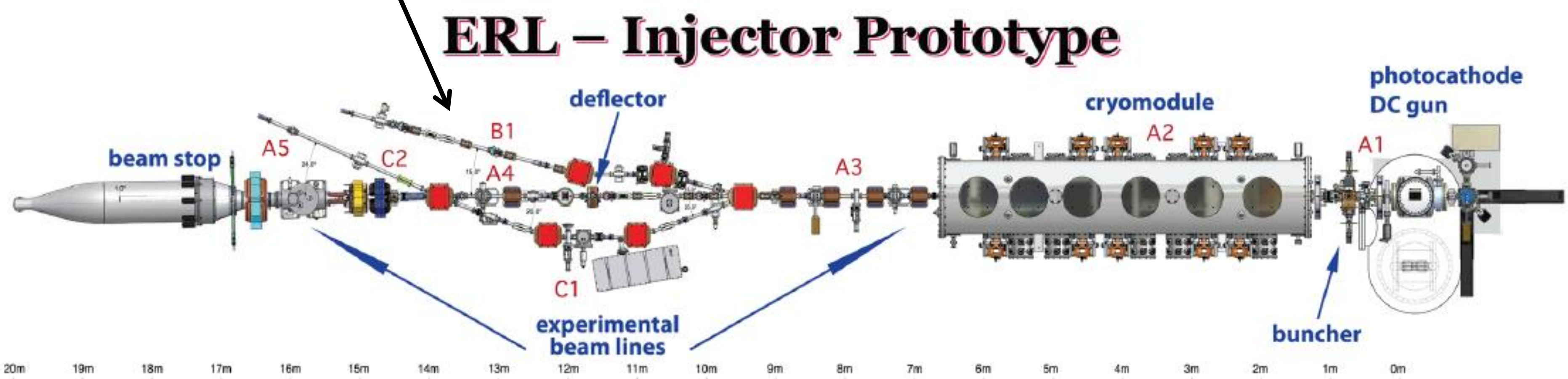
- Moderate charge
- High current

- Note: merger section (B1)



Injector Specification

Parameter	Value
Frequency	1.3 GHz
Bunch charge	77 pC
Average current	100mA
ϵ_{rms} *(norm.)*	< 1.0 μm
Bunch duration	< 3 ps (rms)
Beam Energy	4-15 MeV



Injector for ERL operation

Emittance measurements[1] (merger section, 7 MeV)

- 350 kV Gun Voltage
- Met requirements for ERL

Bunch charge	Bunch length	Horz Emit. (100%)	Vert Emit. (100%)
19 pC	2.1 ps	0.33 μm	0.20 μm
77 pC	3.0 ps	0.69 μm	0.40 μm

Asymmetry Due to the Merger?

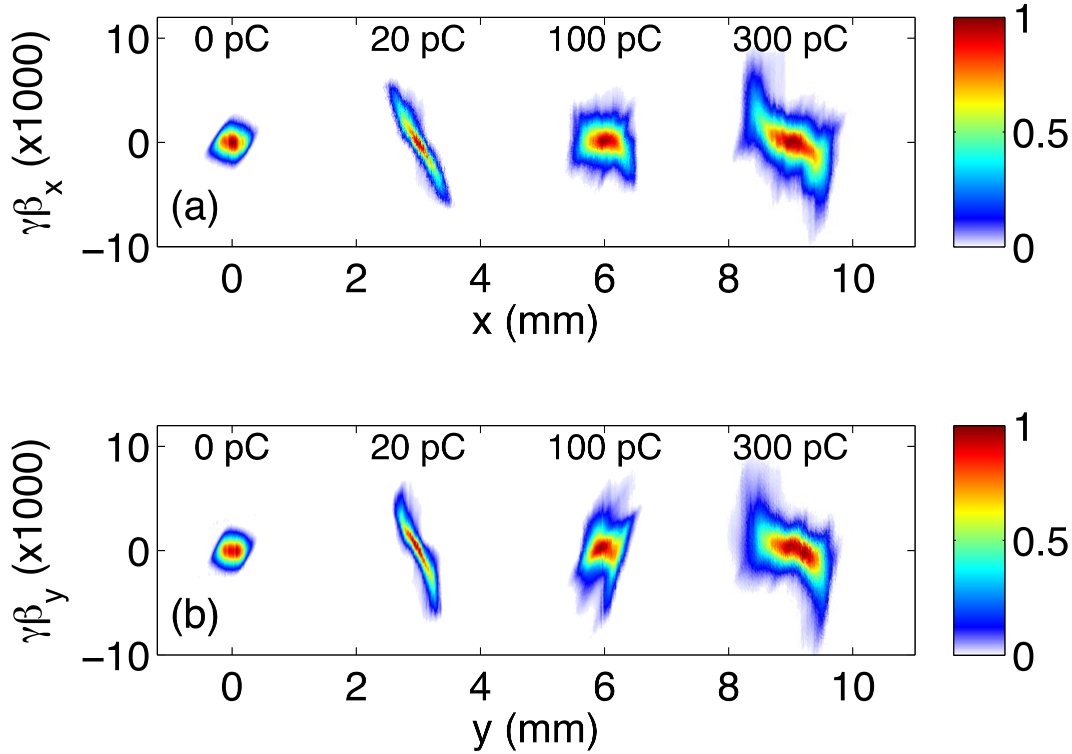
High current operation[2,3] (straight section, 4 MeV)

- Up to 75 mA peak, reliable operation at 65 mA
- > 60 hour cathode lifetime at 65 mA (NaKSb)
- 250 kV Gun Voltage

1. Gulliford el al., Phys. Rev. ST Accel. Beams **16**, 073401 – 2013
2. Cultrera el al., Appl. Phys. Lett. **103**, 103504 (2013)
3. Dunham el al., Appl. Phys. Lett. **102**, 034105 (2013)

Injector for FEL operation (LCLS-II)*

- Met spec at 20/100/300 pC 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	58%
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%

C. Gulliford, Appl. Phys. Lett. 106 (2015) 094101

**These measurements were supported by SLAC*

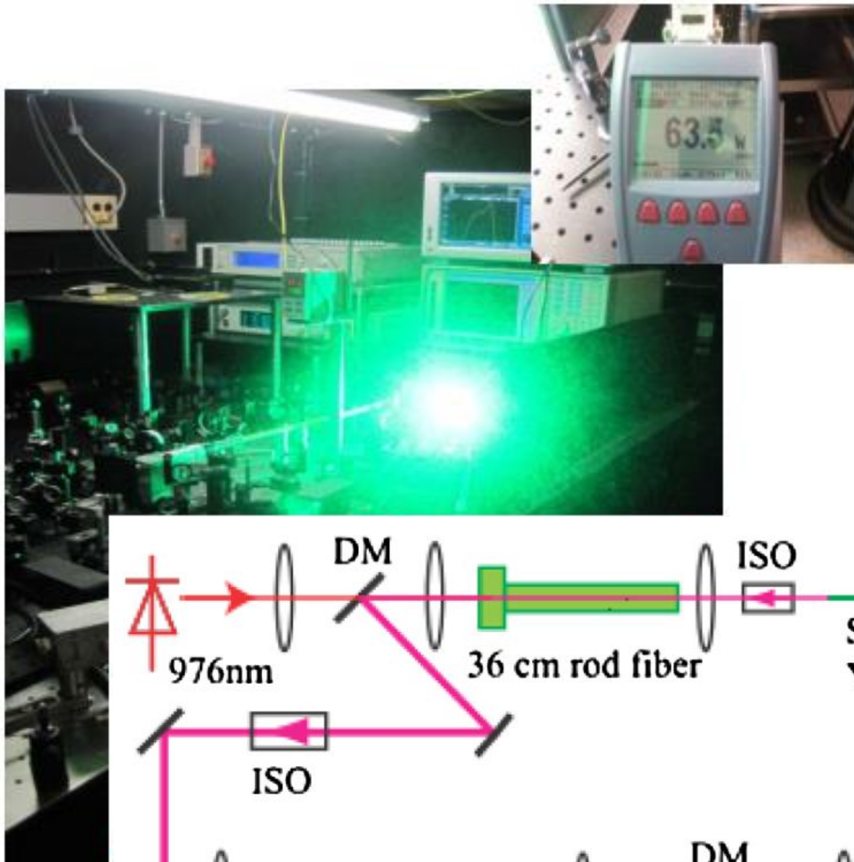
Primary Question

Can the injector provide similar performance in parameter ranges appropriate for the **EIC**?

- Much higher bunch charges (up to **2 nC**)
- More relaxed emittance requirements
- No requirement for short bunch length
- High current (up to **50 mA** @ 50 MHz repetition rate, 1 nC)
    - Requires running off center on cathode

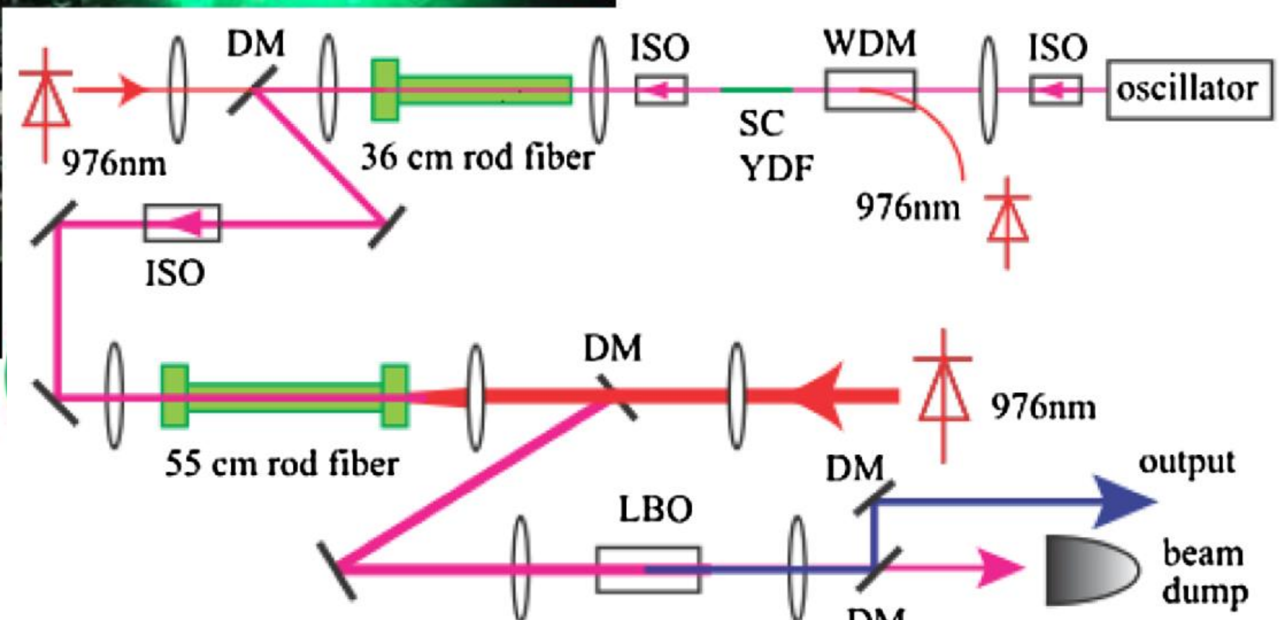
Nano-coulomb bunch high-current generation

Laser upgrade for nC bunches



- Drive laser was incapable of reaching pulse energies needed for nC bunches

- Upgraded using Yb-doped rod amplifiers
    - Capable of 150 W average power (IR) and 1 MW peak power
    - Limited to 50 W due to damage threshold of downstream optics

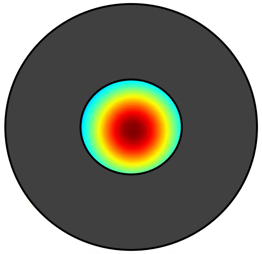


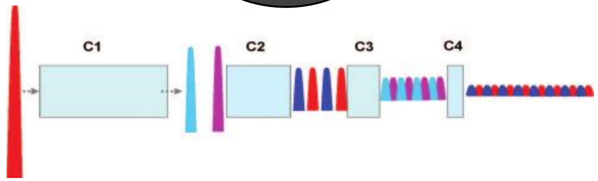
Zhi Zhao, et. al, JOSA B, **31**, 33-37 (2014)

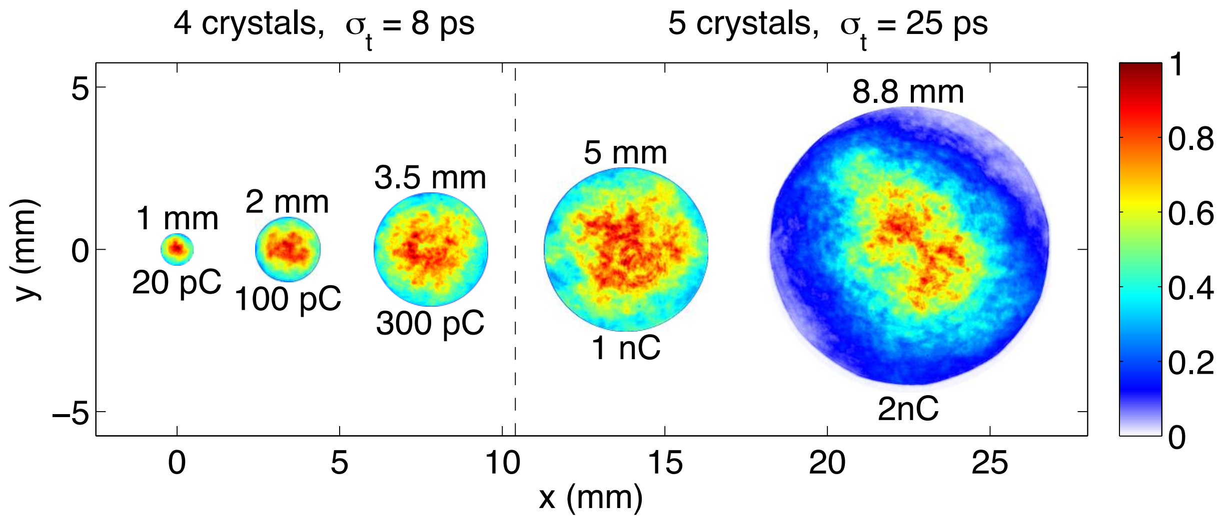
Laser Characterization

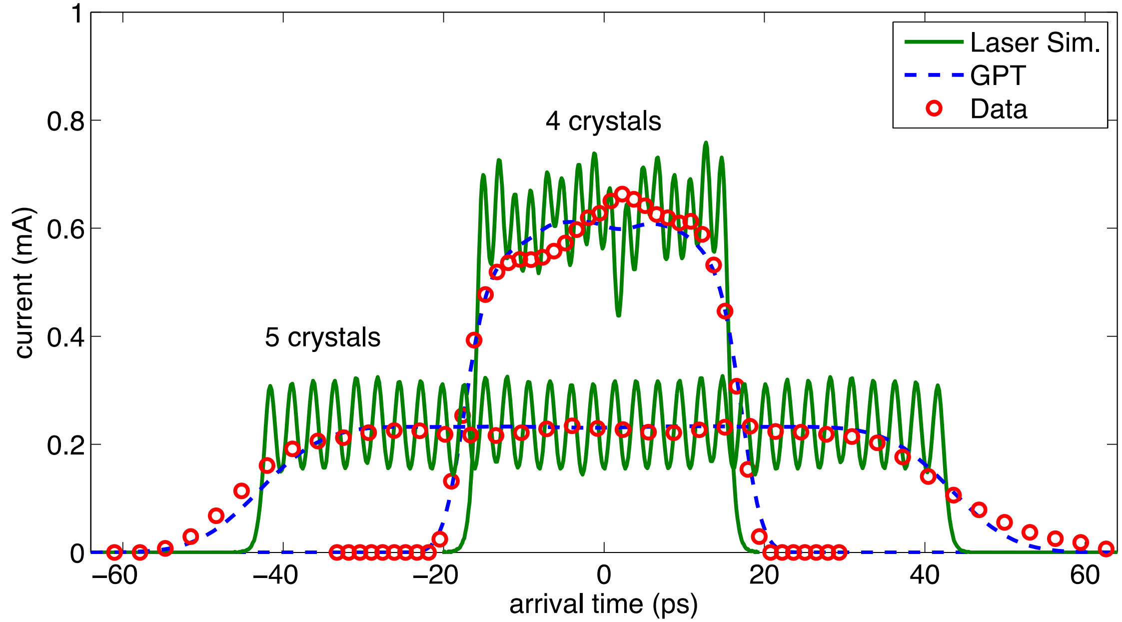
Laser beam size scales as $\sqrt{Q}$

- Need **D > 6 mm** for 1nC
- Lengthen pulse:
  - 8 ps -> **25 ps**
- Optimizer chooses D = 5 mm
- For 2 nC, D = 7 mm
- In practice, need D = 8.8 mm to get enough charge



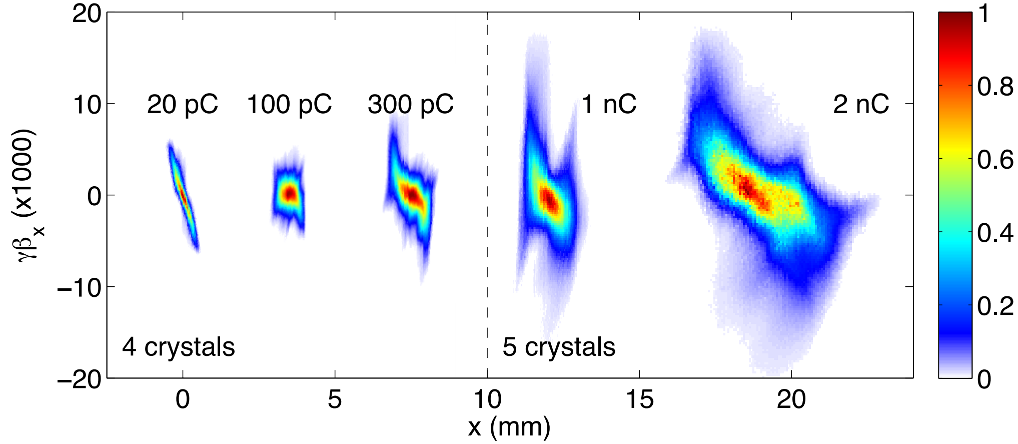


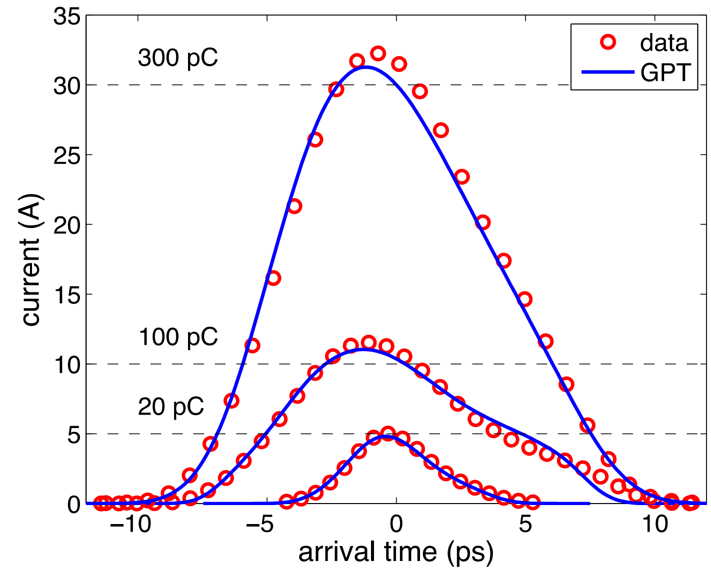




Results

1 nC: 1.6 μm, 2 nC: 4.4 μm (95%)





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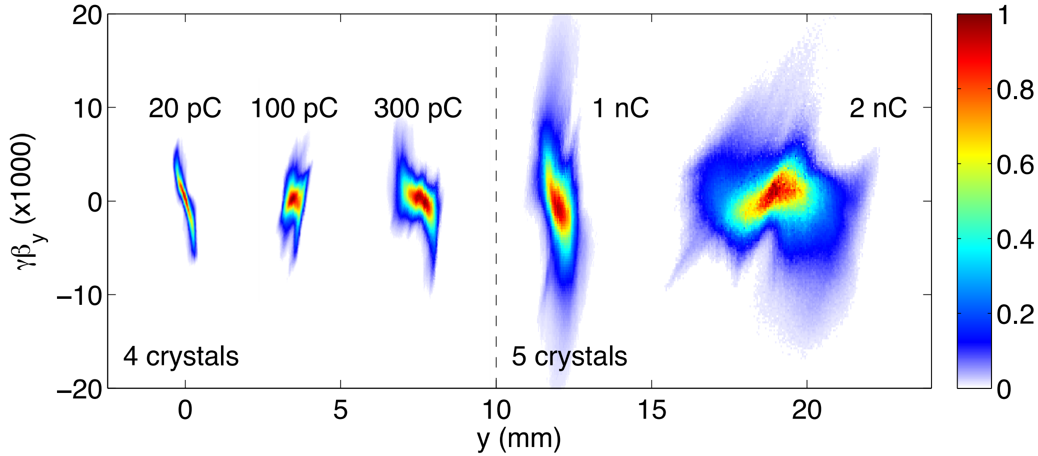
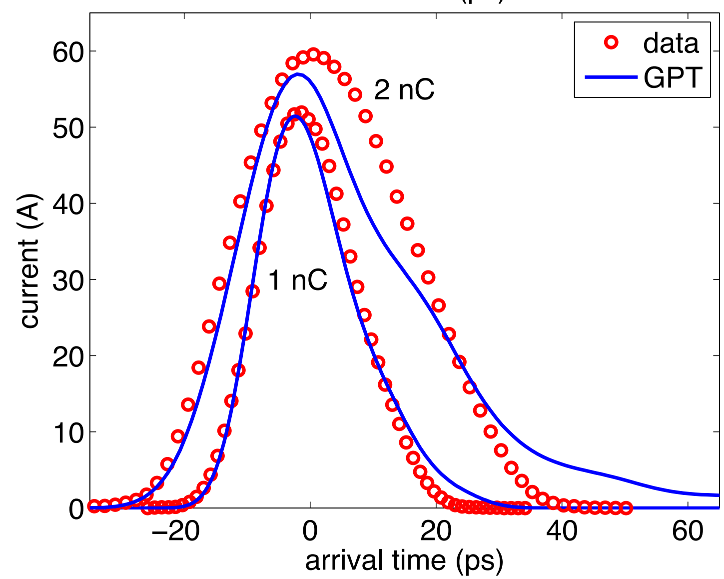


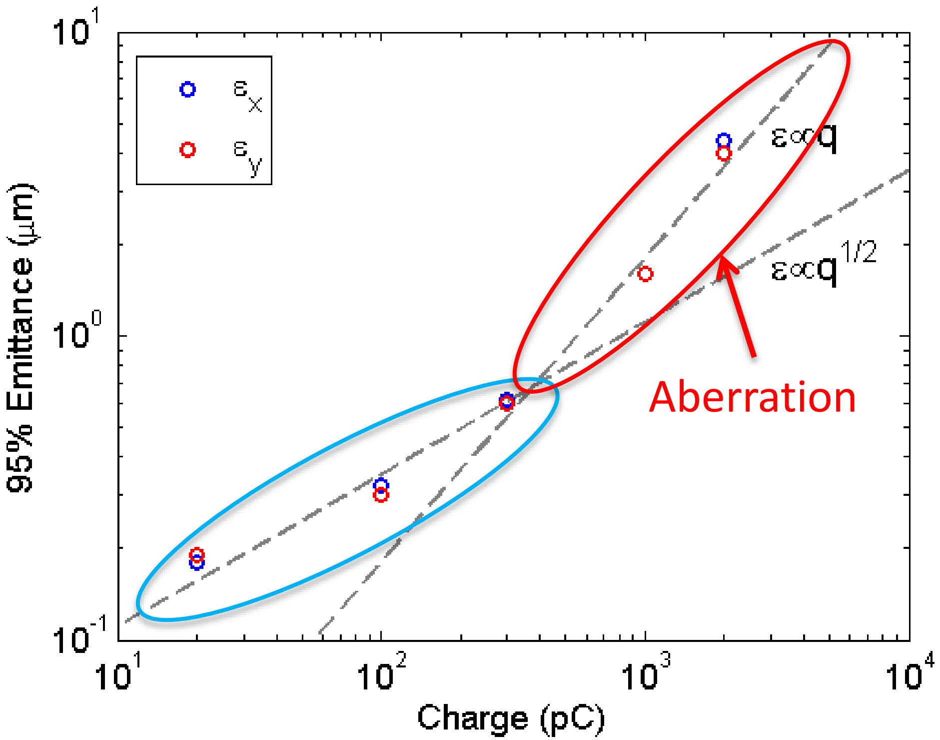


A. Bartnik et al., PRSTAB 18 (2015) 083401

Emittance Summary

Trend becomes more linear around 300 pC…

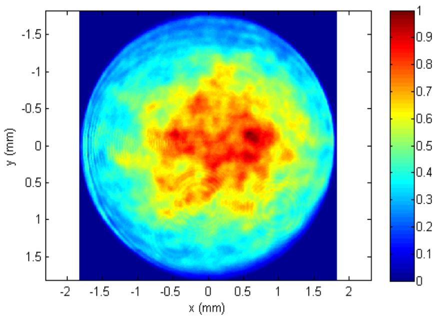
Q (pC)	Peak current (A)	Emittance (95%, µm)
20	5	H: 0.18 V: 0.19
100	11.5	H: 0.32 V: 0.30
300	32	H: 0.62 V: 0.60
1000	50	H: 1.6 V: 1.6
2000	56	H: 4.4 V: 4.0

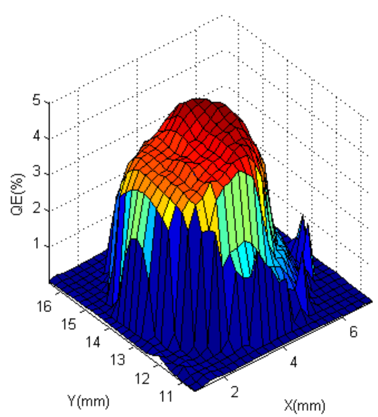


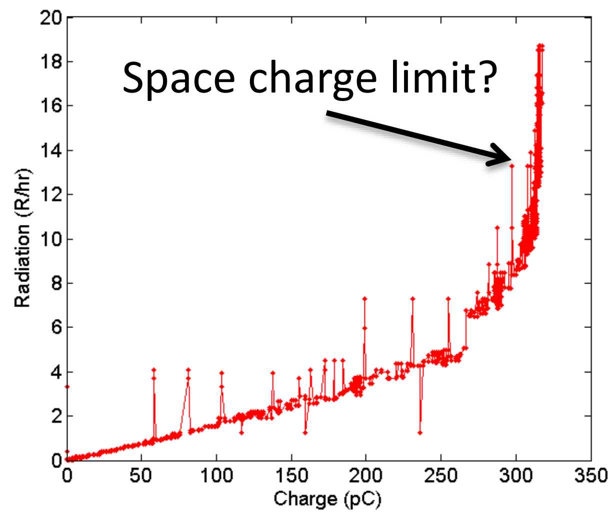
High current operation

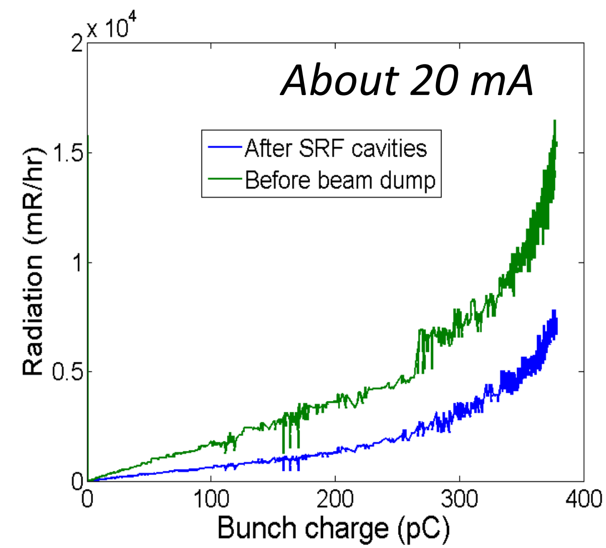
- Would like a 5 mm diameter active area cathode, offset from gun center
- 1st off-center cathode available had a roughly 3.5 mm active area
- See dramatic increase in radiation around 320 pC
  - Made laser size bigger: same problem at 375 pC
- In simulation, begin to lose particles at cathode around 400 pC

Laser profile during high current









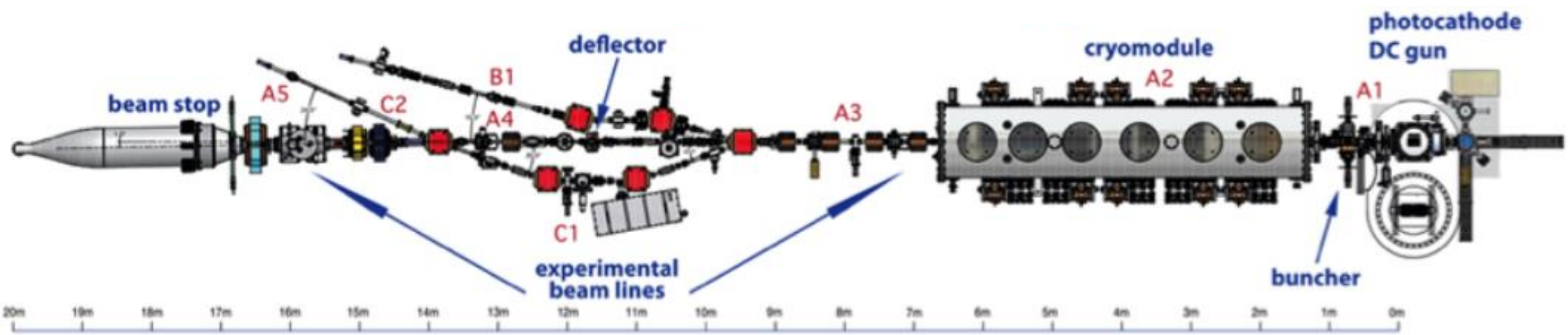
Cathode used for High Current Operation

- Active area offset ~ 5 mm from gun center
- Active area width ~ 3 mm diameter

CU Injector Status

Since the last meeting…

- Disassembled our injector
- Sent SRF cryomodule across campus for maintenance
- Made a gun-only beamline for high current reliability tests
- Disassembled that beamline
- Brought the cryomodule back
- Rebuilt the full injector in a new location with another DC gun
- Fixed the HV power supply that got broken
- Injector re-commissioning



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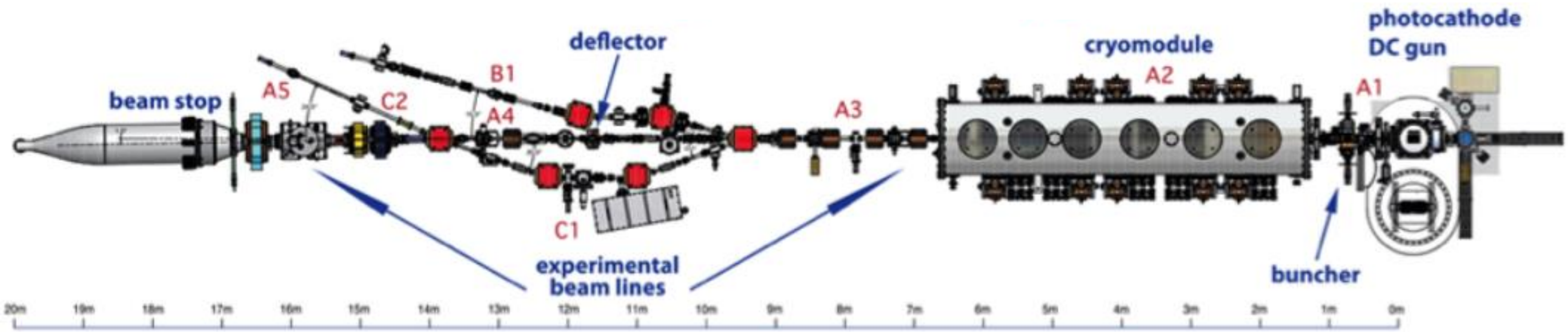
Used a few cathodes here…



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

Why we had to move?

The Cornell-BNL FFAG-ERL Test Accelerator

White Paper

Ivan Bazarov, John Dobbins, Bruce Dunham, Georg Hoffstaetter, Christopher Mayes, Ritchie Patterson, David Sagan

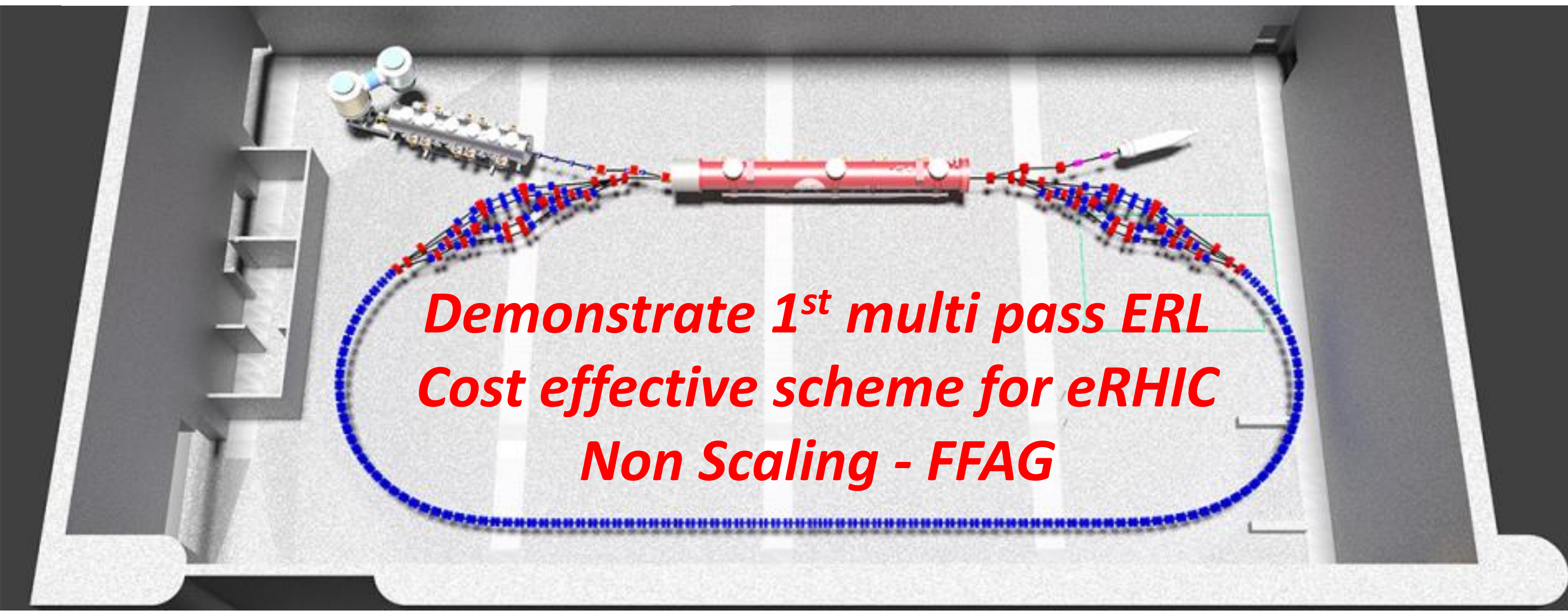
Cornell University, Ithaca NY

Ilan Ben-Zvi, Scott Berg, Michael Blaskiewicz, Stephen Brooks, Kevin Brown, Wolfram Fischer, Yue Hao, Wuzheng Meng, François Méot, Michiko Minty, Stephen Peggs, Vadim Ptitsin, Thomas Roser, Peter Thieberger, Dejan Trbojevic, Nick Tsoupas.

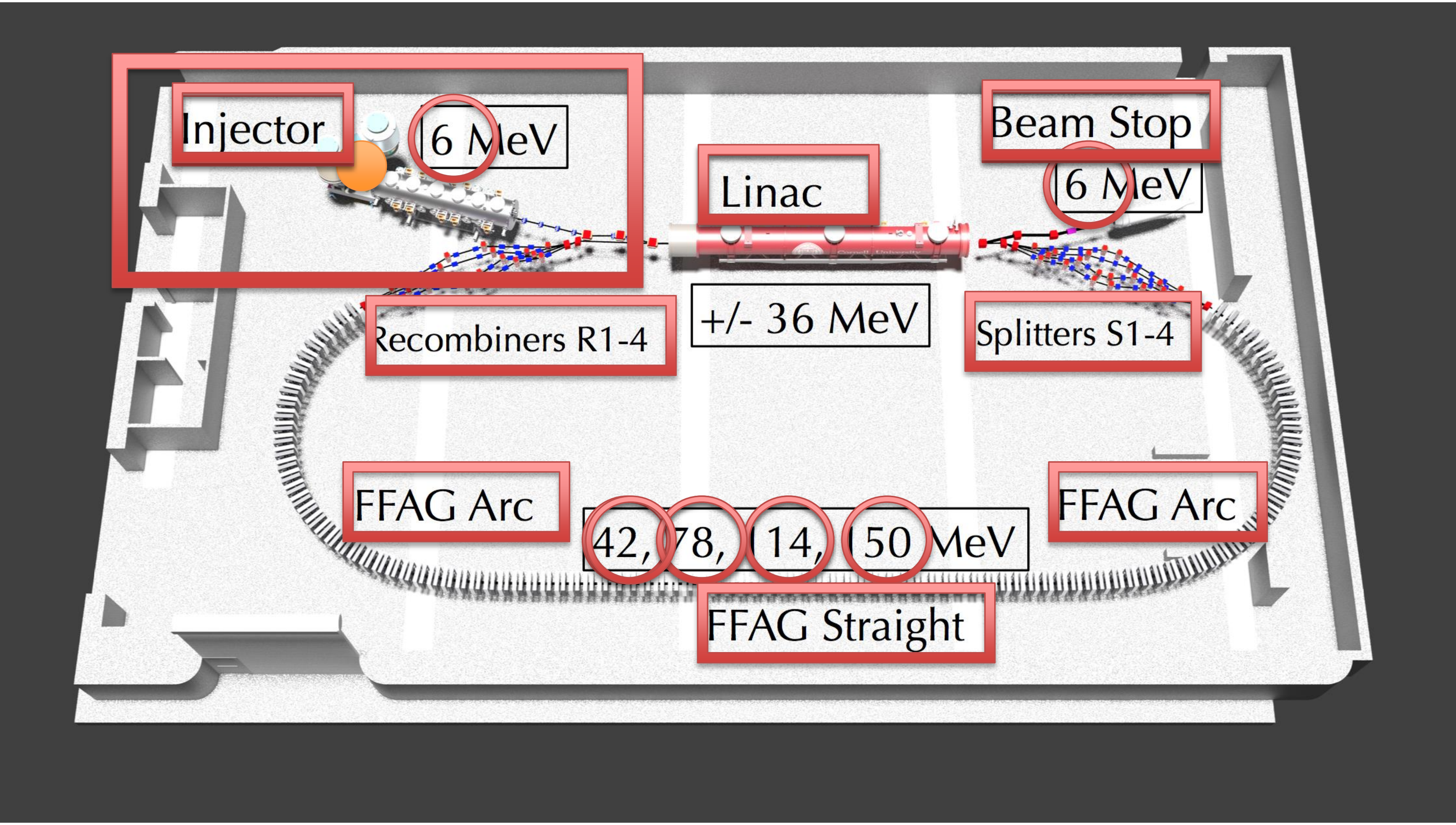
Brookhaven National Laboratory, Upton NY

CBETA

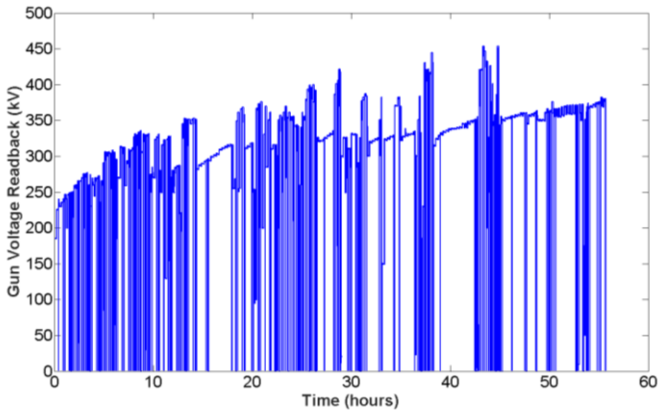
CORNELL-BNL ERL TEST ACCELERATOR

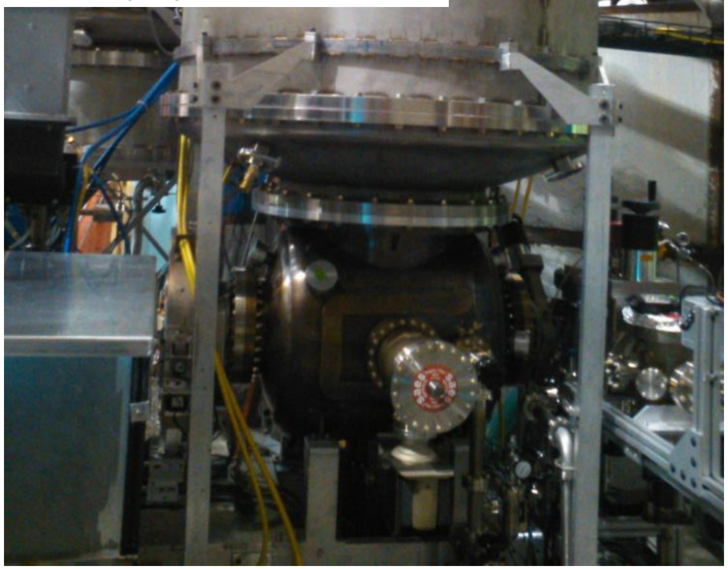


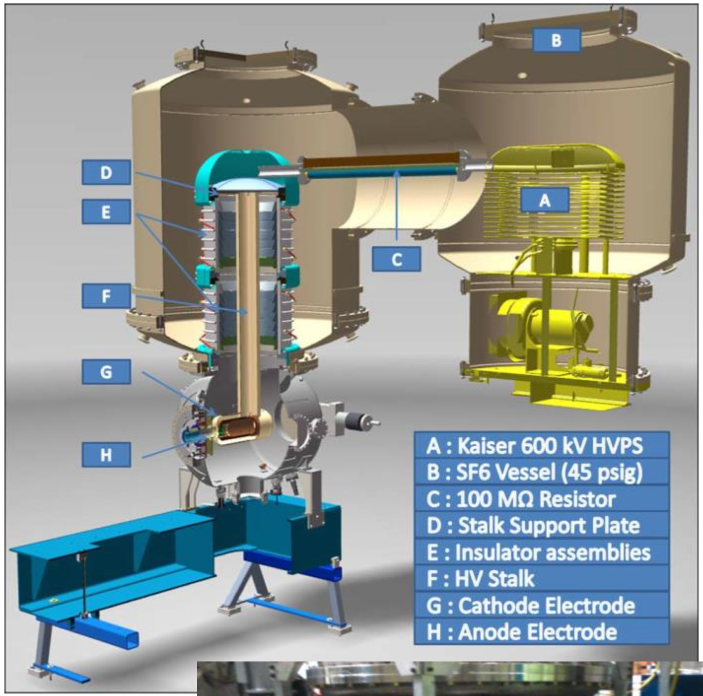
CBETA 4 pass ERL FFAG



New DC gun

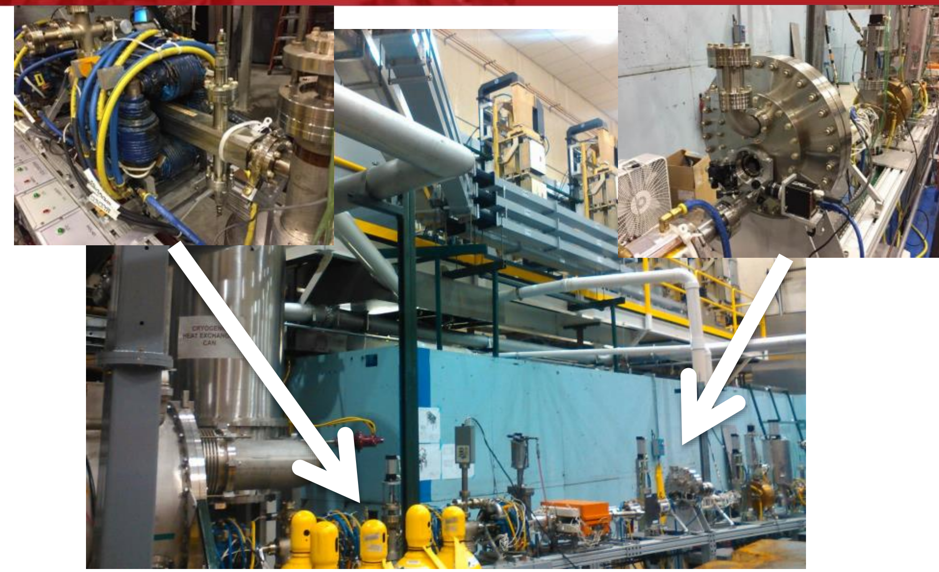


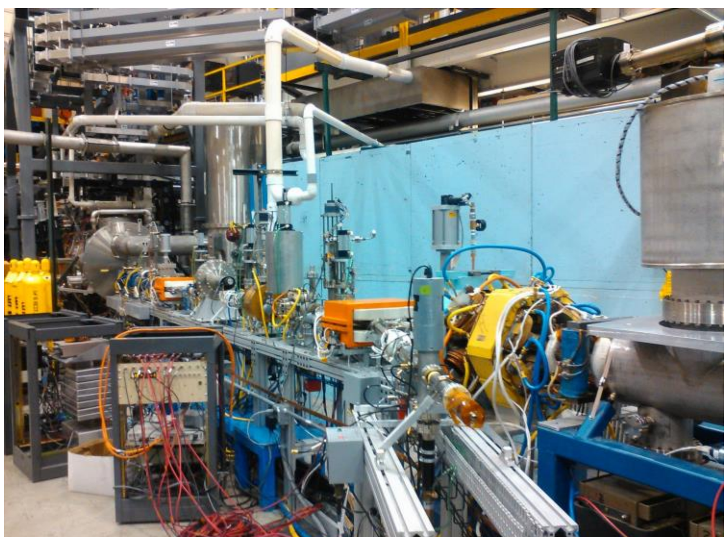




- Segmented ceramic insulator => Higher voltage
- **Biased anode => Longer cathode lifetime**

Injector after the move





EIC Cathode Challenges

Challenge	Comment	Status
Lifetime ~10,000 C	50 mA (done but NOT 1 nC @ 50 MHz!!)	Not yet done
QE > 1%	50 mA @ 1% => QE ≈ 10 W of laser power	Solved
Localized, offset active area	Roughly = laser size, reduces halo	Solved
QE spatially flat		Solved
Response time < 1 ps	Long tails will be lost in RF	Solved

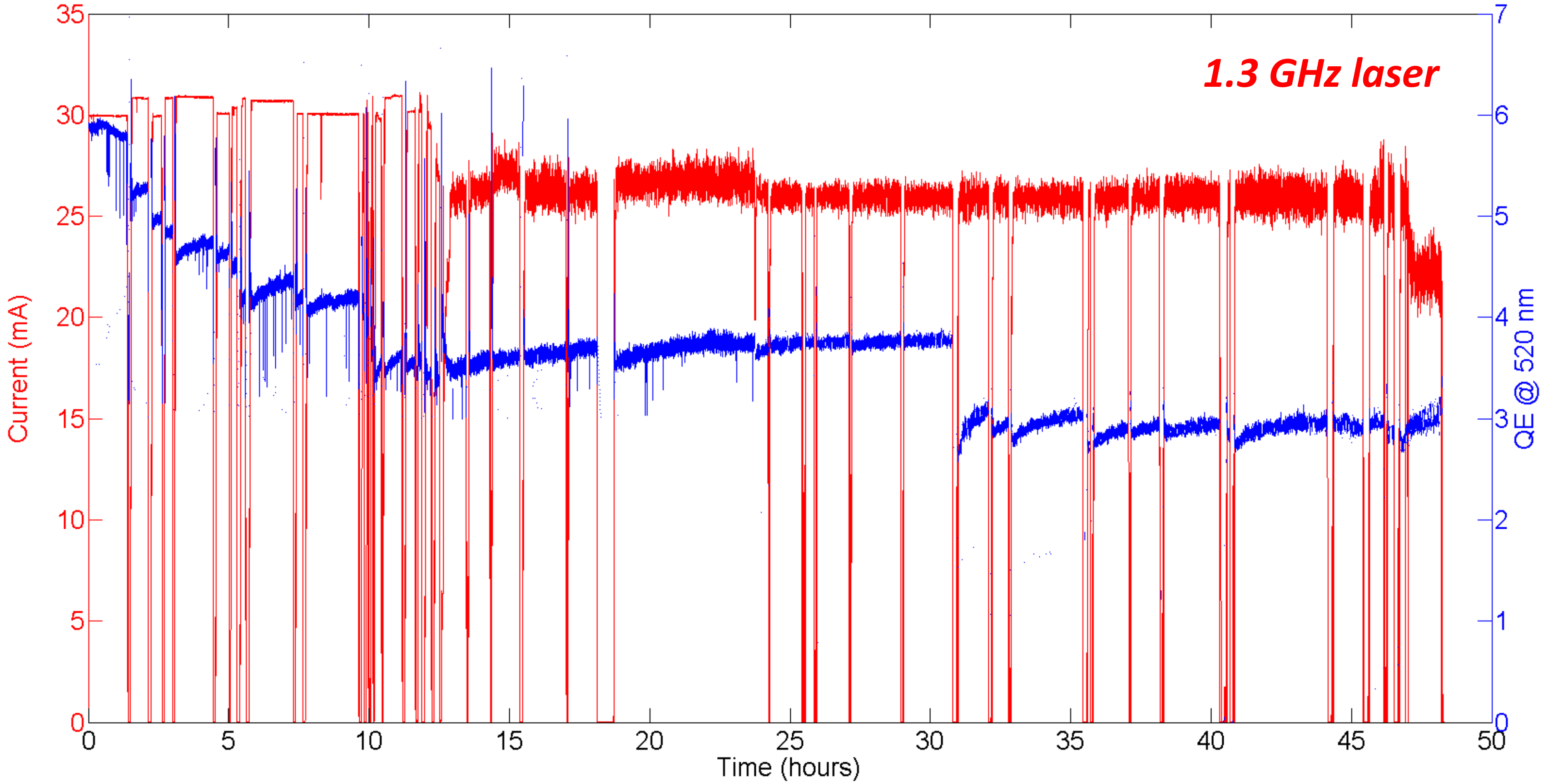
Not yet proven at high charge per bunch !!

The biggest remaining challenge for high current machines is not ruining the cathode that is provided.

Offset cathode over 2 days

The cathode experienced many machine trips, roughly 1-2/hour

- Most were SRF Cavity "coupler arc"
- QE decreases a little bit after each trip

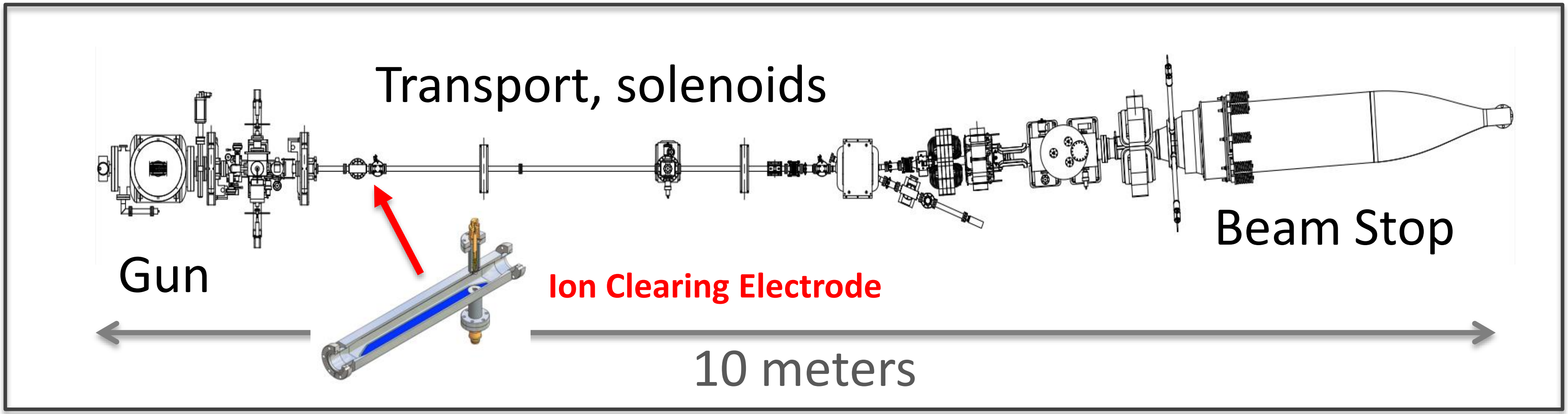


Gun Test Beamline

During maintenance on our SRF booster linac, we constructed a simplified “gun test” beamline.

- 350 kV
- 1.3 GHz @ 15 pC = 20 mA

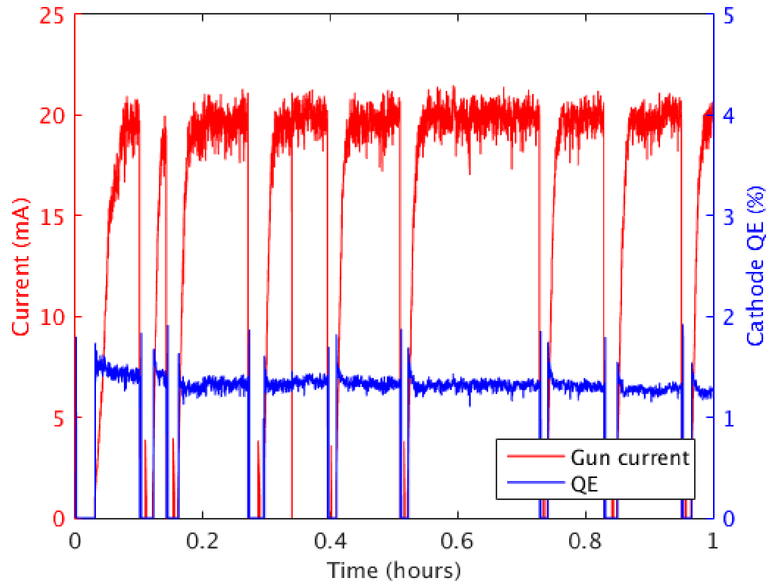
Expectation: No SRF = No trips

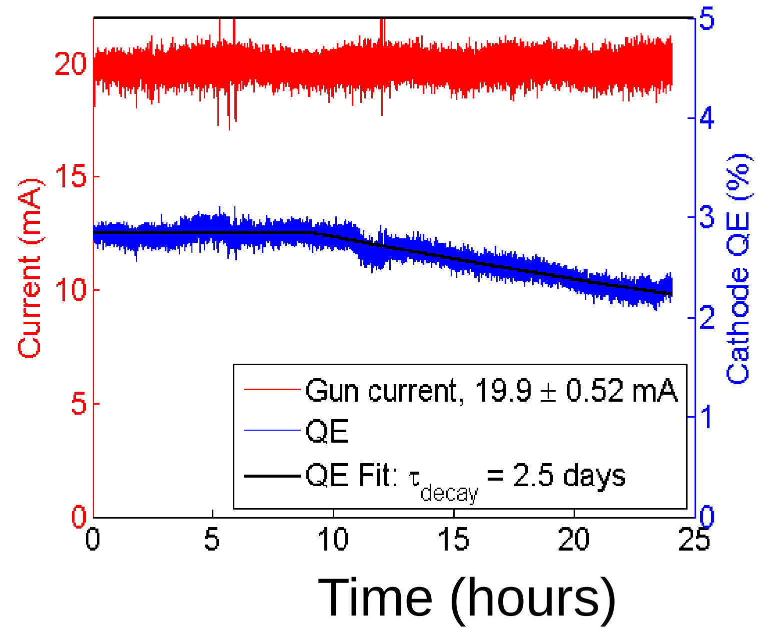


Gun Test Beamline

Surprise! The machine tripped **10x more often** with only the gun.

- Upon further inspection, an error was discovered in our previous reasoning– it was possibly always the gun.

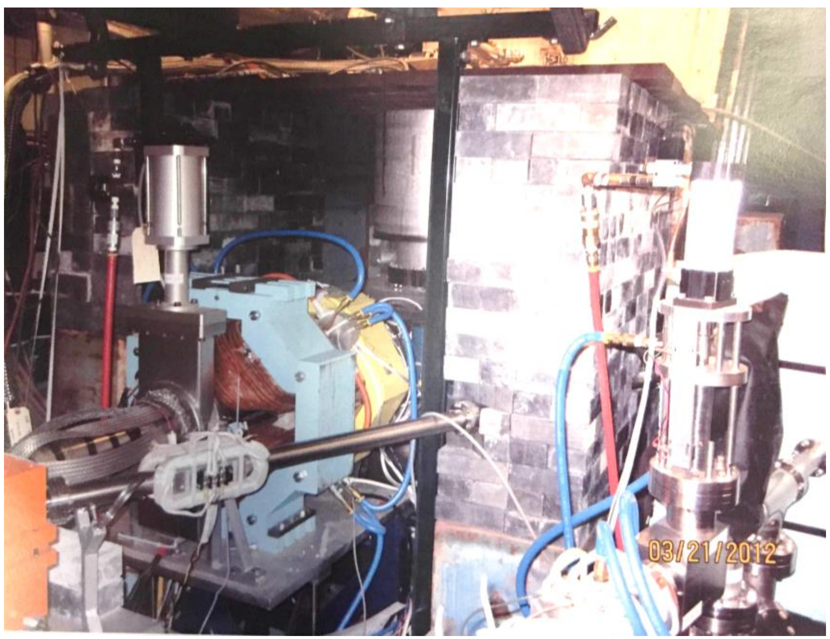


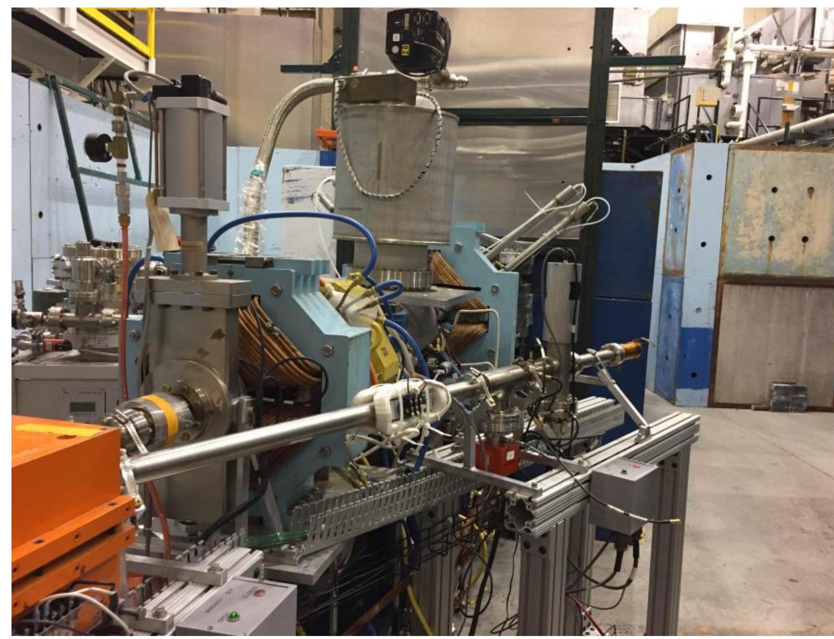


With ion clearing electrode
24 hours at 20 mA with no trips!!

Road towards 50 mA?

- **As of today** injector is ready to go
- Ramping up the current at mA levels
- **More radiation shielding** around the dump is likely to be needed to further increase current levels

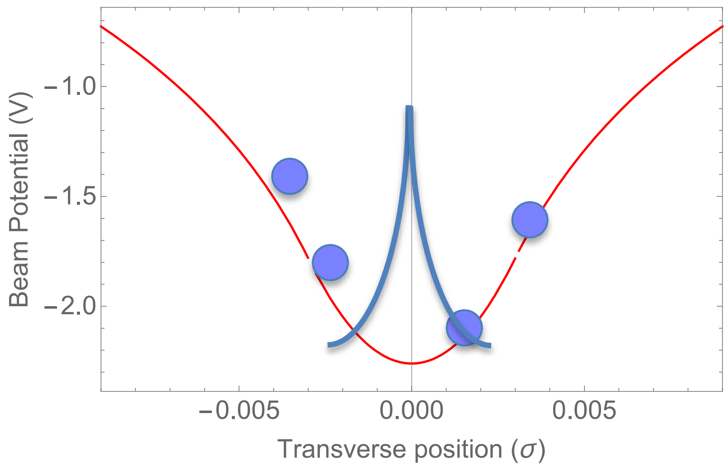


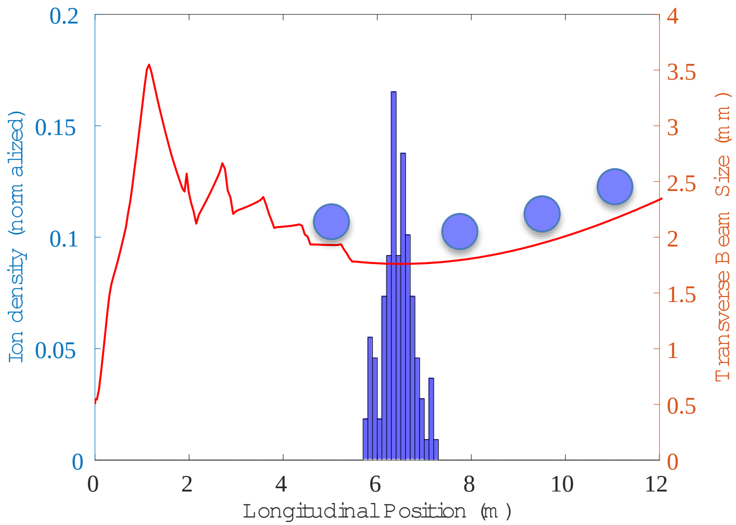


Ion effect for high intensity electron beams

What is ion trapping?

- Electron beam ionizes residual gas via collision ionization
- Ions get trapped inside the negative potential well of the beam.
- Oscillate transversely with a characteristic frequency
- Accumulate sharply in center of beam
- Also drift longitudinally towards beam potential minima





EIC Ion trapping conditions

Two primary trapping conditions:

1) Trapped ion mass number
   - Found by considering focusing in bunches and drifting outward between bunches

Number of electrons per bunch

Distance between bunches

1nC
50 MHz
~ 2 mm

$$A_{\text{ion}} \geqslant \frac{n_{\text{e}} r_{\text{p}}}{4(\sigma_x + \sigma_y)\sigma_y} \Delta L_{\text{g}} = 3.6\text{e-}4$$

<< 1 !!

2) Ion oscillation frequency
   - Oscillation of ion in beam's potential
   - Trapping occurs if $\omega_{ions} << f_{beam}$
   - Experimentally verified formula

$$\omega_{ions} = \sqrt{\frac{2r_p c}{e} \frac{I_{beam}}{A_{ion}\sigma_{beam}^2}}$$

Avg. Current	Transverse Beam size	Ion oscillation frequency	Beam repetition rate
50 mA	~2 mm	~125 kHz (N_2) <<	50 MHz

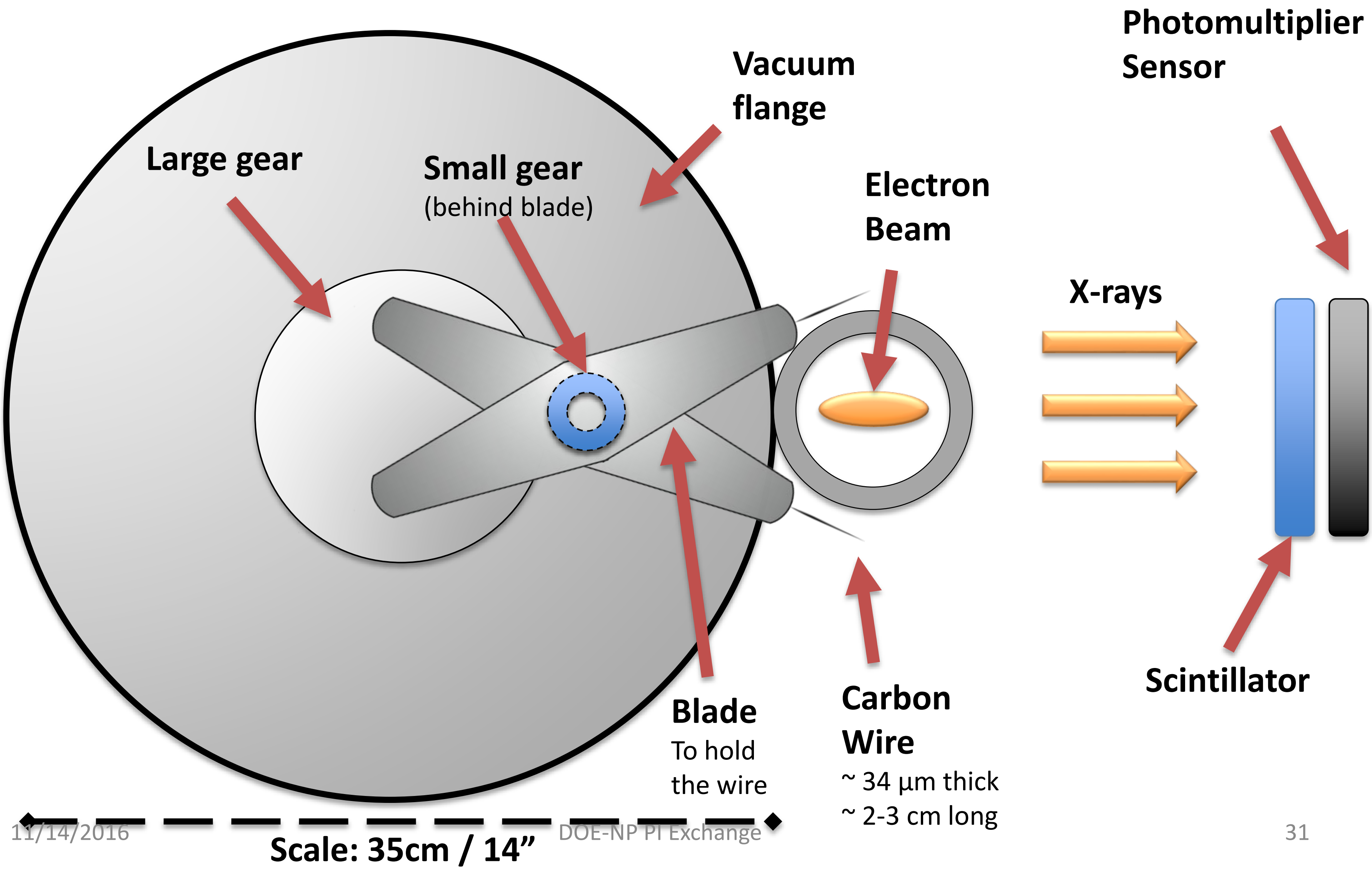
Measurements at High Power

- We're one of the first to explore this regime experimentally
  - Ions have been studied extensively using simulations, but experimental data is rare.
- We can't measure beam directly
  - Interceptive diagnostics melt above 1 mA
  - No synchrotron/diffraction radiation (low energy linac)
  - New fast wire scanner wasn't available
- We look for ions instead
- **We used 3 diagnostics**
  - **BPM + spectrum analyzer**
  - **Ion clearing electrode + picoammeter**
  - **Radiation monitors**

Flying Wire

Operating principle

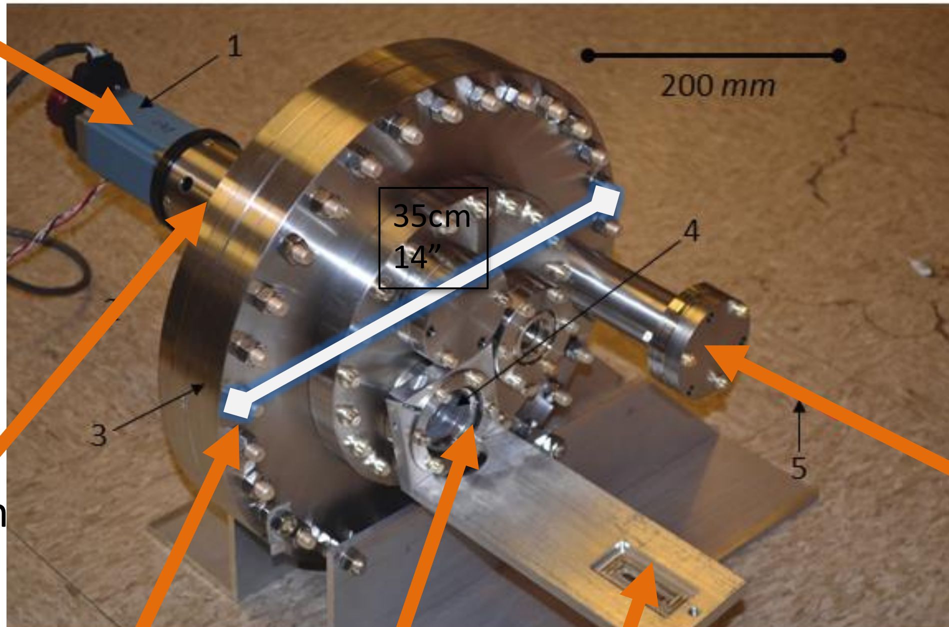
Detection



Flying Wire

Stepper motor

Ferrofluidic Rotary feedthrough

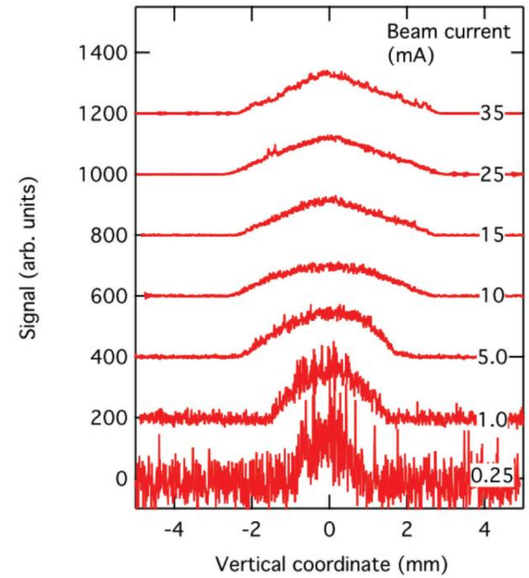


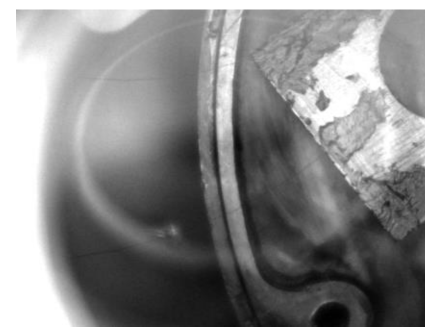
Beam pipe

Vacuum flanges

Viewports

Camera mount

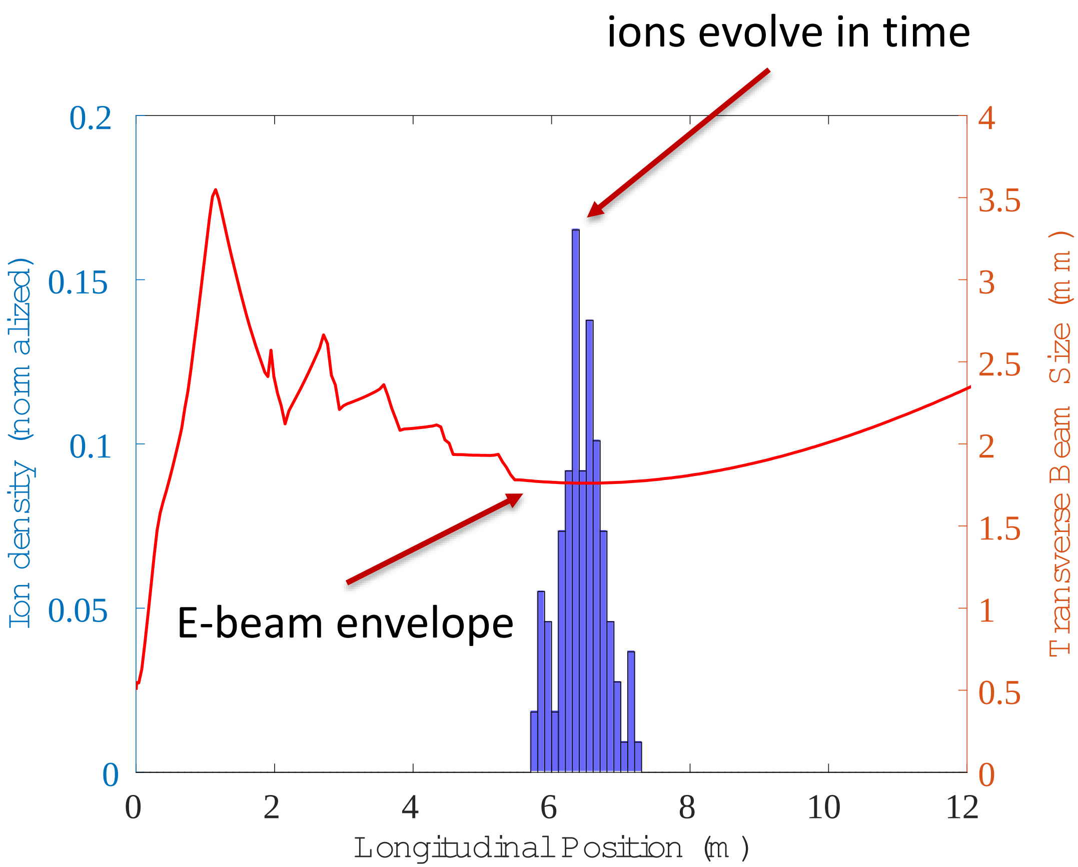




- The wire kept breaking, **problem now solved**
- Poor tensile strength of carbon wires

Simulation results

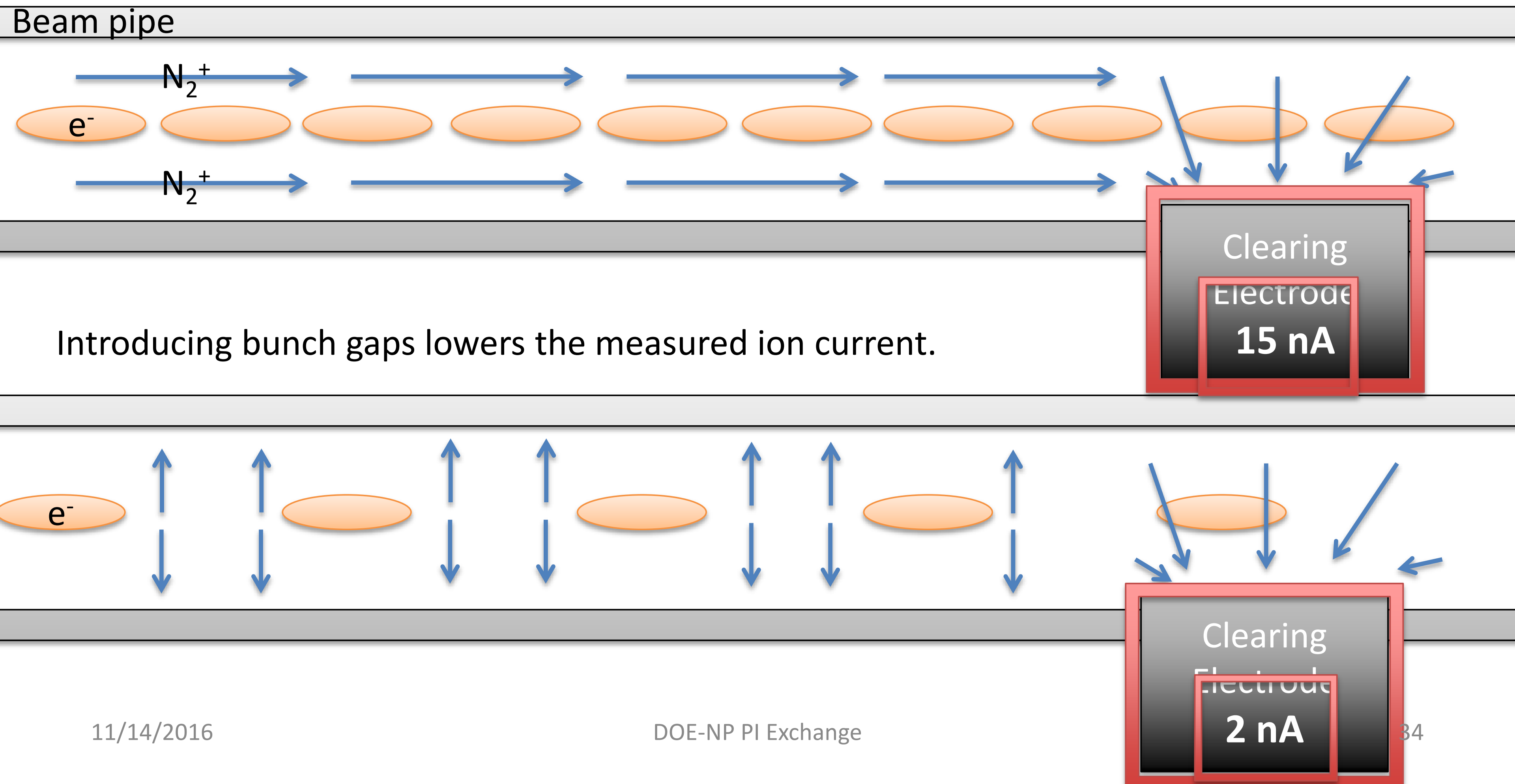
- Developed ion-electron tracking simulation software.
- It showed that ions drift longitudinally, and accumulate at beam size minima, as expected.
- Useful for deciding locations of clearing electrodes.



Clearing electrode setup

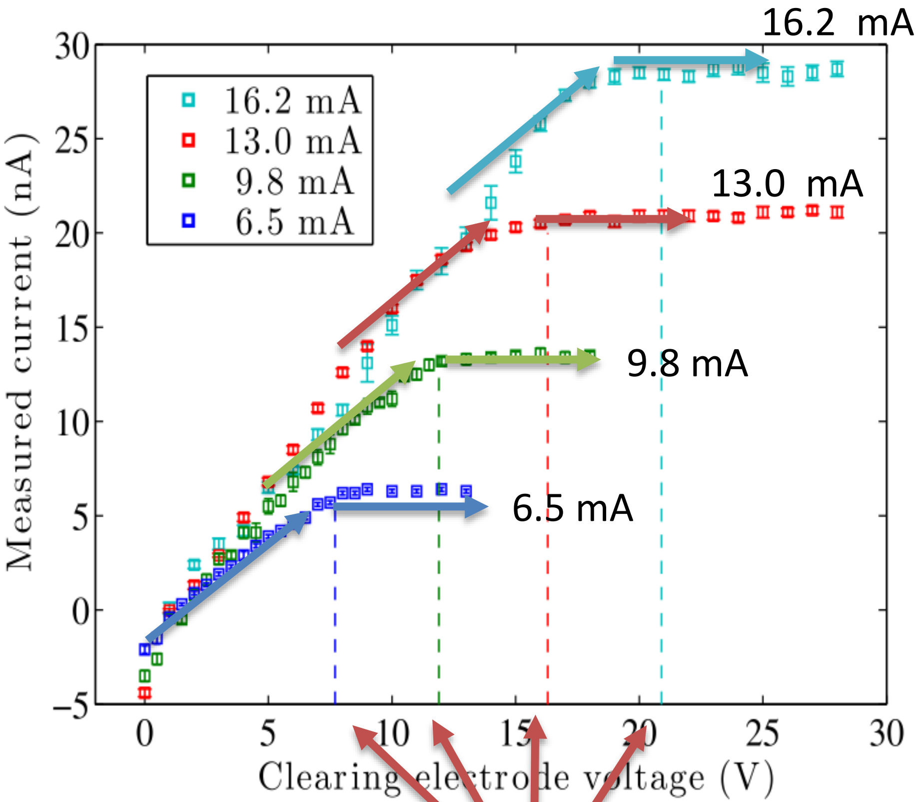
Clearing electrode and Bunch gap measurements

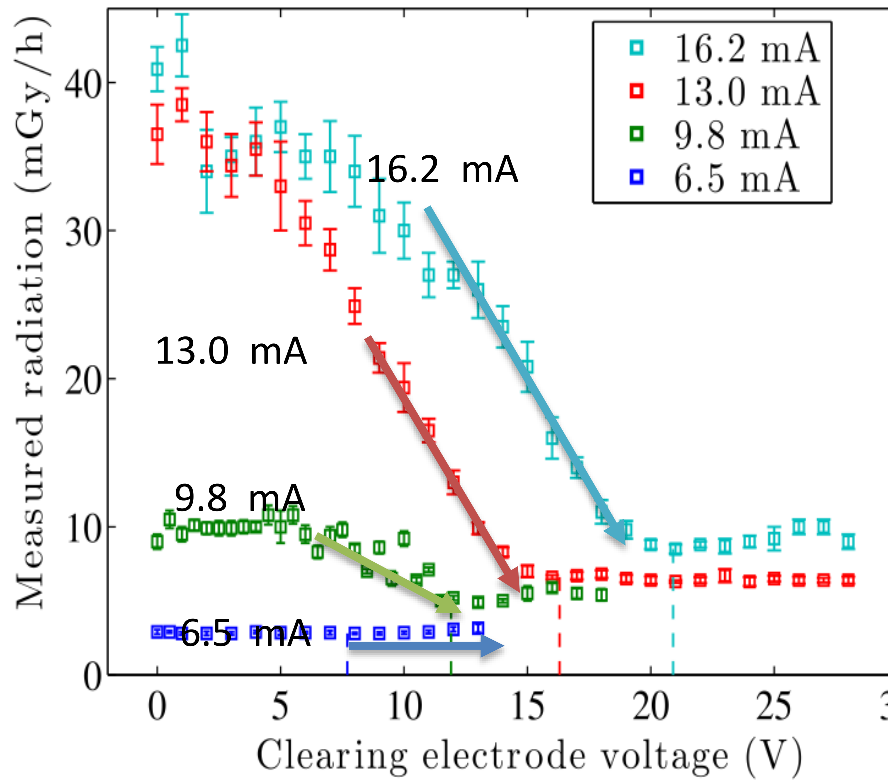
During CW operation, ions remain trapped, drift towards and are measured by the clearing electrode.



Clearing electrode tests

Measured ion current striking the clearing electrode





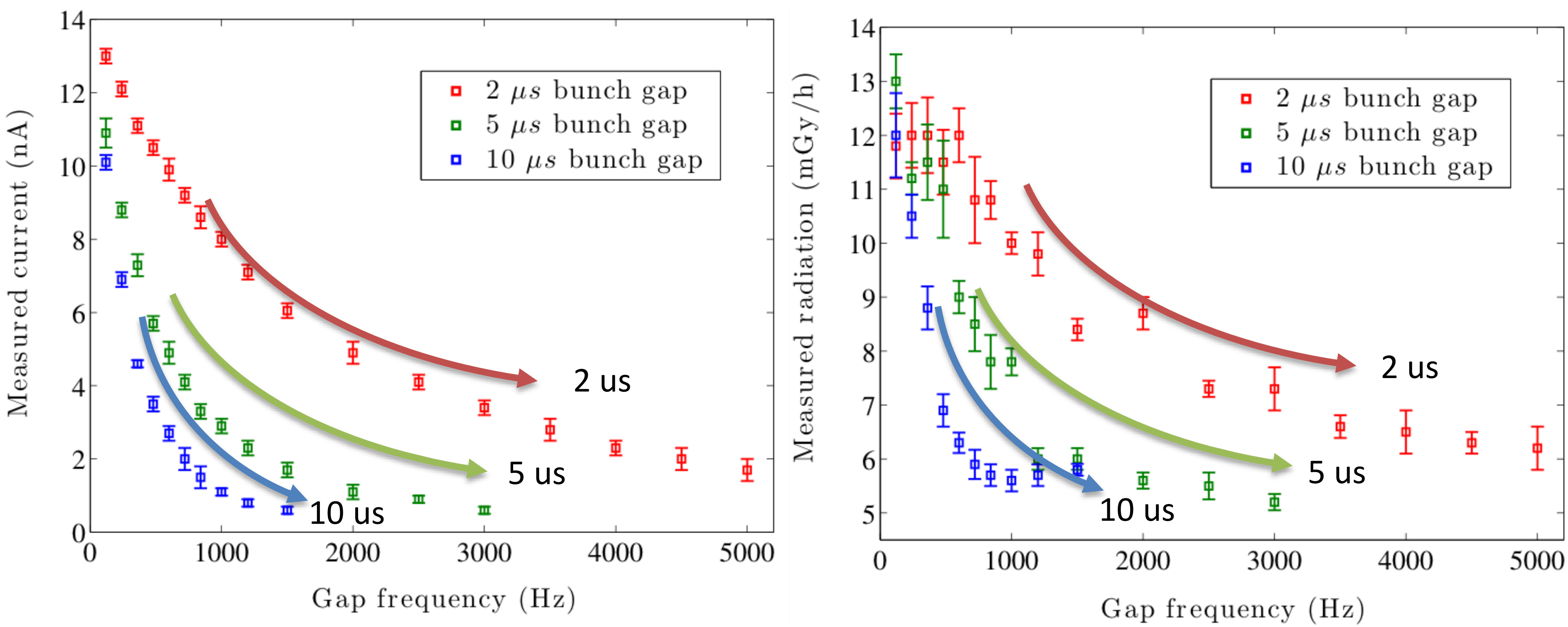
$$V_{electrode} \geq \frac{I}{2\pi\epsilon_0 c}\frac{d}{\sigma_b}$$

Clearing electrode separation

Transverse beam size

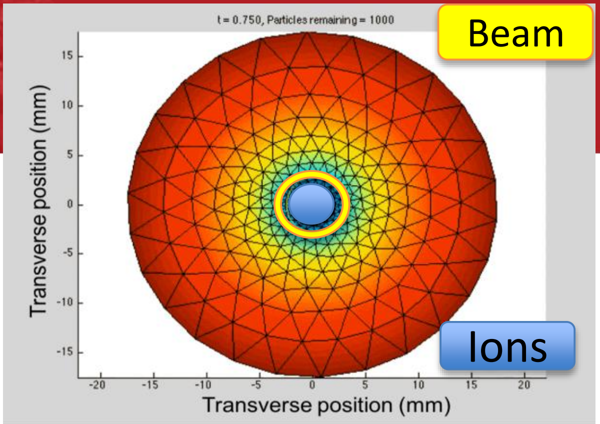
Bunch gap measurements

Beam current held fixed at 10 mA



Confirms that the ions are being cleared by the gaps, and not just the clearing electrode

Beam shaking

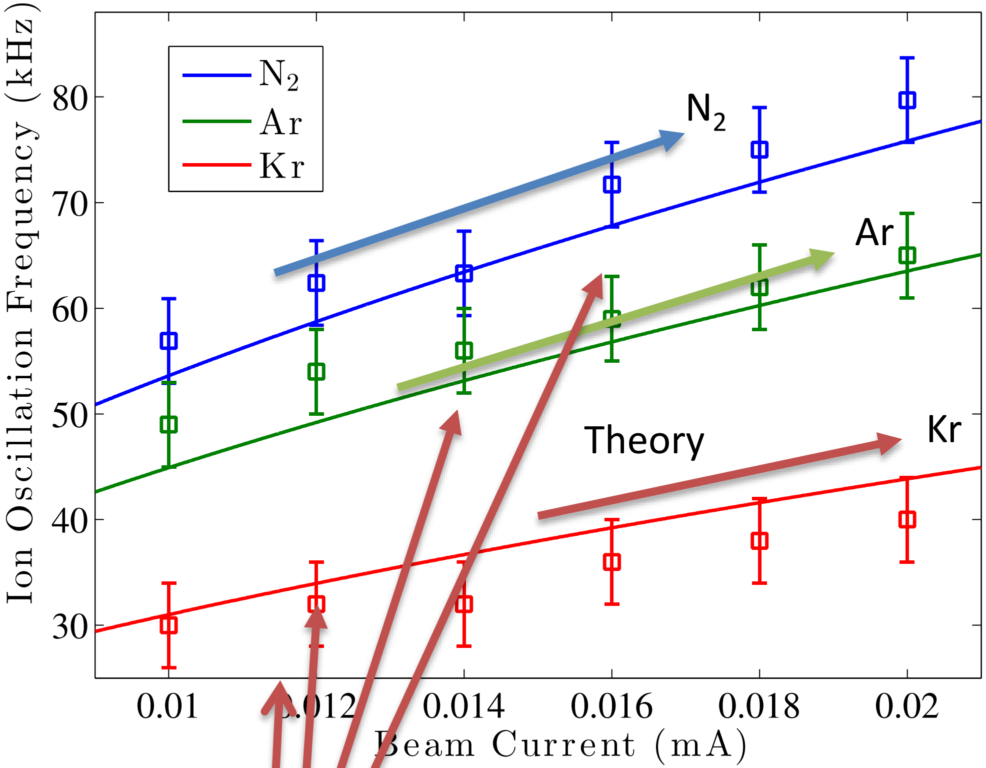


Shaking at the resonance frequency results in a reduction of background radiation.

After leaking gas, our radiation readings increased.

When we sinusoidally shake the beam with the clearing electrode at the ion oscillation frequency, the radiation levels drop significantly.

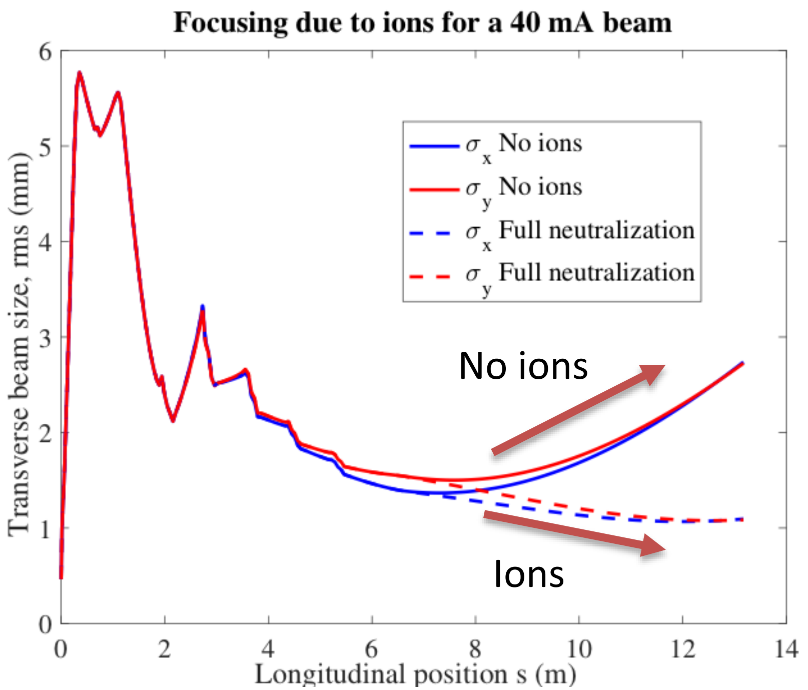
This was a known mitigation scheme in the 1980's at CERN's antiproton accumulator.

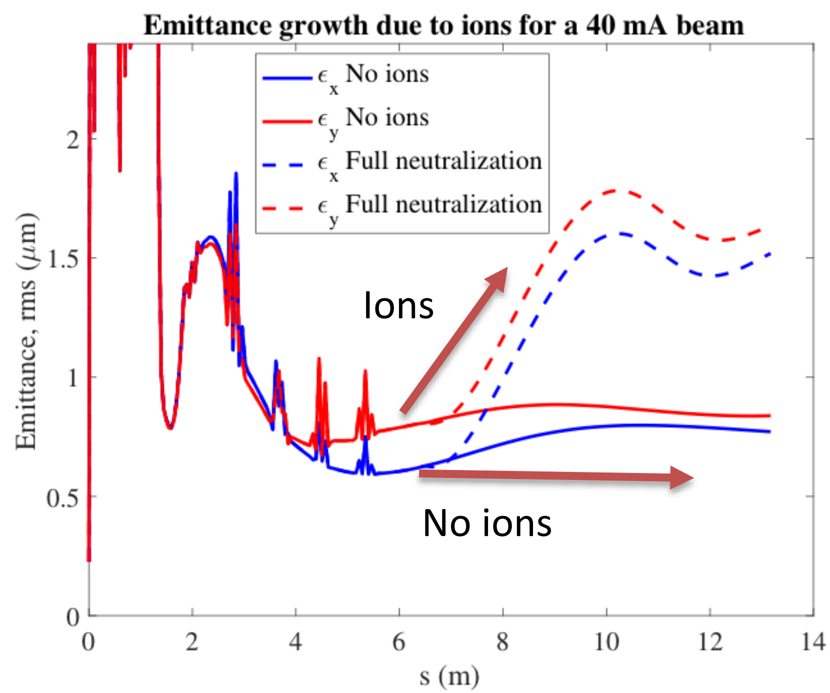


$$\omega_{ions} = \sqrt{\frac{2r_p c}{e} \frac{I_{beam}}{A_{ion}\sigma_{beam}^2}}$$

Ion effects on beam

- Assume ion column is a very long charge distribution throughout the accelerator, with a Gaussian transverse distribution
- Ions act like a lens, leading to (non-linear) focusing
- In theory, can compensate, but in practice cannot be corrected with linear optics – so let's get rid of them
- Reducing ionization fraction to ~1% eliminates focusing





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

Conclusions

- **1) Nano-coulomb bunch high-current generation**
  - Prepare the **new laser system** for beam operation (both pulsed and 100% duty factor) that has sufficient energy per pulse (≥mJ) to generate high charge bunches with appropriate transverse and longitudinal profiles.
  - Generate **1 and 2 nC bunches and characterize the beam emittance** (both transverse and longitudinal) and the bunch length at a reduced repetition rate (<kHz).
  - Operate with **50 mA average beam** current for 1 nC bunches.
- **2) Ion effect for high intensity electron beams**
  - Develop a **new simulation tool for ions**, which combines existing fast space charge routines in GPT along with adiabatic-invariant-based simulator for ions.
  - Determine the **equilibrium ion density** both by direct **measurement** and by examining the creation and clearing rates of ions using clearing electrodes.
  - Measure **beam properties both with and without ion mitigation strategies**, specifically clearing electrodes, clearing gaps, and beam shaking, and compare to the simulations.

Thanks to Cornell High-Brightness Beam Group

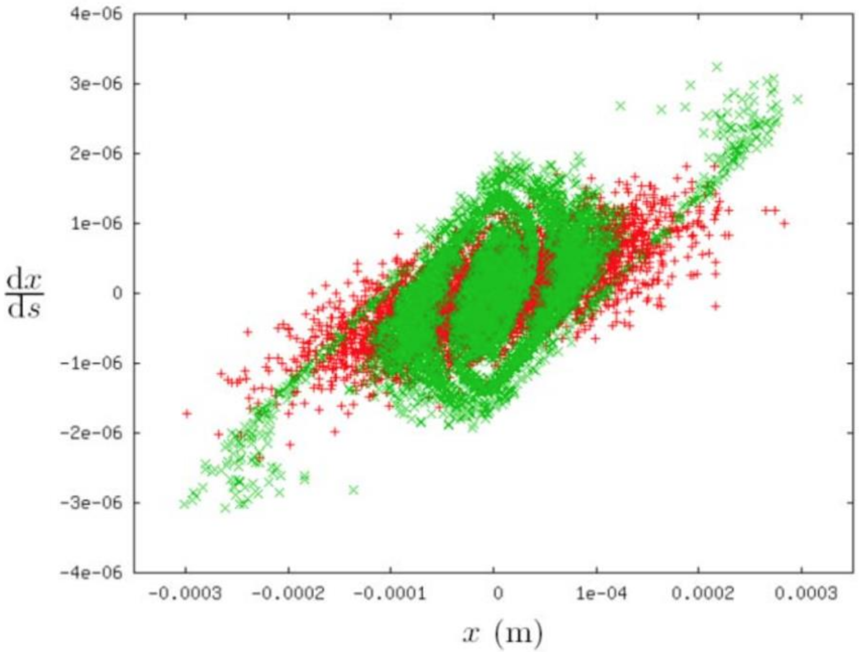
Thank you for the attention !

Detrimental Effects of ions

Ion clearing methods are **required** for stable beam operation above 20 mA.

- Without clearing methods, the machine will trip every 15 – 75 mins.
- Ions can also cause:
  - Emittance growth
  - Beam halo/losses
  - Incoherent tune shifts/spread
  - Betatron phase errors (ion focusing)
  - Charge neutralization (e.g. operational drifts/machine safety)
  - Beam instabilities (ex. Fast Ion Instability)

G.H. Hoffstaetter, C. Spethmann , Phys. Rev. ST AB, Volume 11, 014001 (2008)

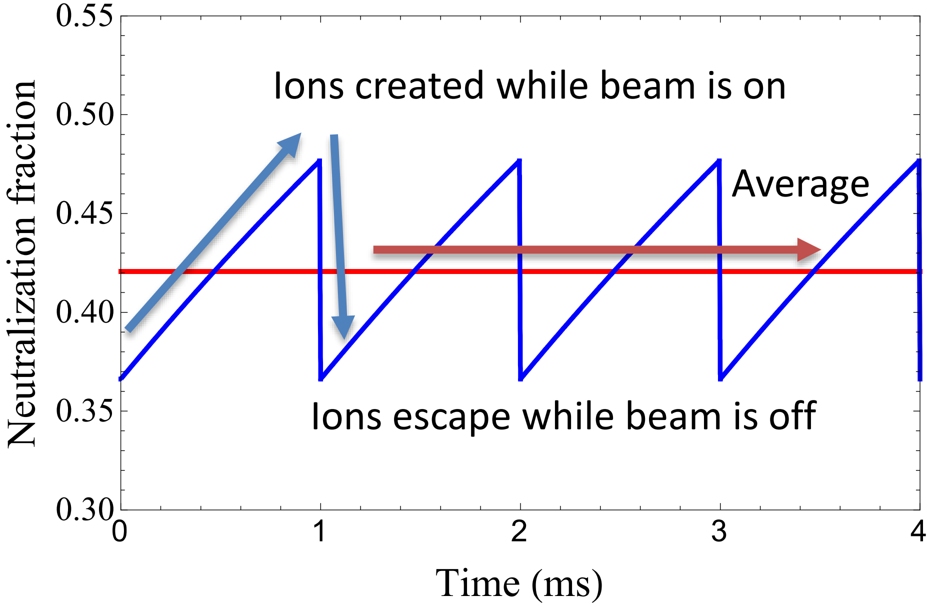


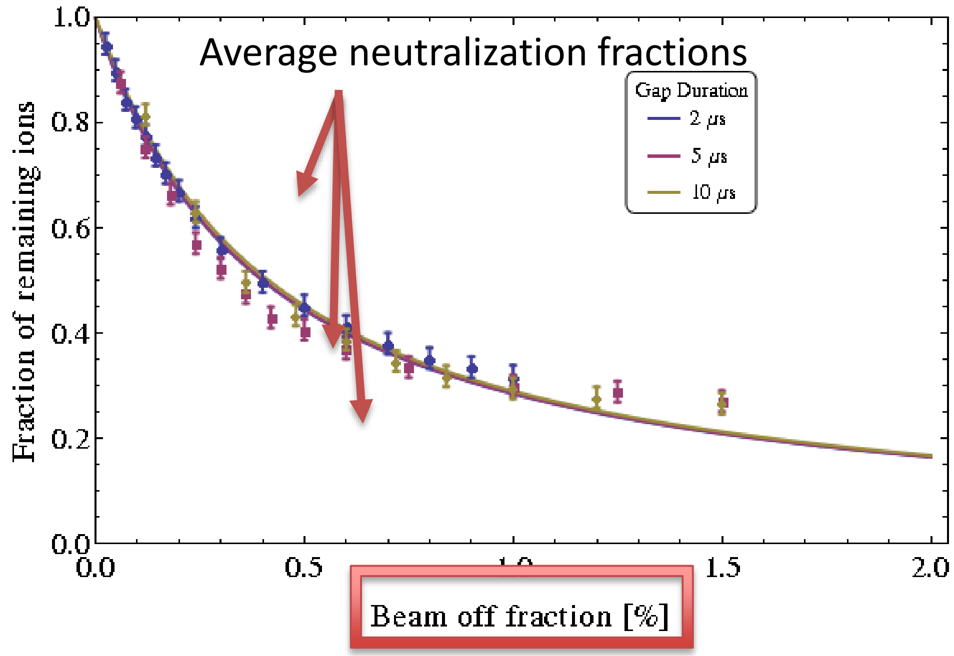
Simulated Phase space in Cornell ERL design

Green – After traversing 200 m ion field

Red – Normal operation

Measurement analysis





Our model: The ion density…

1) Increases via collision ionization while the beam is on.

2) Decays exponentially during the bunch gaps.

3) We measured the average neutralization fraction.

$$f_{avg} = \frac{1}{1 + \left(\frac{\tau_1}{\tau_2}\right)\left(\frac{T_2}{T_1}\right)}$$

Amount of clearing depends only on total time beam is turned off.

Flexibility!