Next generation robust polarization photocathodes for EIC
and
high current photoinjectors

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Outline

- Projects description and goals;
- Relevance of the research and Jones EIC R&D report;
- Budget;
- Physics and technology of high-brightness high-power photoinjectors for beam coolers and Electron Ion Colliders;
- Next generation robust polarization photocathodes for Electron Ion Colliders;
- Conclusions.

Projects Goals

PHYSICS AND TECHNOLOGY OF HIGH-BRIGHTNESS HIGH-POWER PHOTOINJECTORS FOR BEAM COOLERS AND ELECTRON ION COLLIDERS

Task 1: Prepare a **new laser system** for beam operation (both pulsed and 100% duty factor) with sufficient energy per pulse to generate **1 and 2 nC bunches and characterize the beam emittance.** Operate with **50 mA average beam** current for 1 nC bunches.

Task 2: Develop **new simulations tool for ions**, which combines existing fast space charge routines in GPT along with adiabatic-invariant-based simulator for ions and 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.

NEXT GENERATION ROBUST POLARIZATION PHOTOCATHODES FOR EIC

Task 1: Cornell University group will experiment on the **optimal conditions to achieve the NEA** on III-V semiconductors using a **thin layer of Cs_2Te** based on the previous result from the Japanese group.

Task 2: Cornell University group will integrate in the UHV photocathode lab and **recommission the Mott polarimeter** so that the spin-polarization of photoelectrons generated from Cs_2Te-coated GaAs-based photocathodes can be measured.

Row	Proponent	Concept		Panel priority	Panel sub-priority
7	Panel	LR	High current polarized and unpolarized electron sources	High	B

Budgets

PHYSICS AND TECHNOLOGY OF HIGH-BRIGHTNESS HIGH-POWER PHOTOINJECTORS FOR BEAM COOLERS AND ELECTRON ION COLLIDERS

	FY10+F11	FY12+F13	FY14+F15	FY16+F17	Totals
a) Funds allocated			170,000	170,000	340,000
b) Actual costs to date			170,000	170,000	353,000

NEXT GENERATION ROBUST POLARIZATION PHOTOCATHODES FOR EIC

	FY10+F11	FY12+F13	FY14+F15	FY16+F17	Totals
a) Funds allocated				150,000	150,000
b) Actual costs to date				98,000	98,000

High current photoinjector

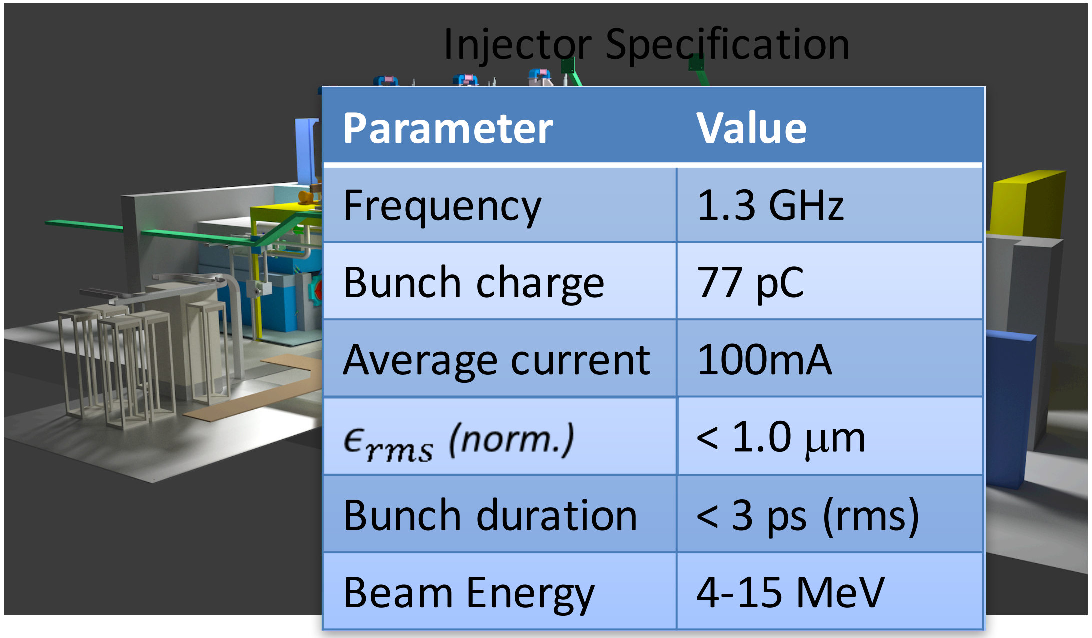
PHYSICS AND TECHNOLOGY OF HIGH-BRIGHTNESS HIGH-POWER PHOTOINJECTORS FOR BEAM COOLERS AND ELECTRON ION COLLIDERS

Original Design

Original design: ERL injector

- Moderate charge
- High current

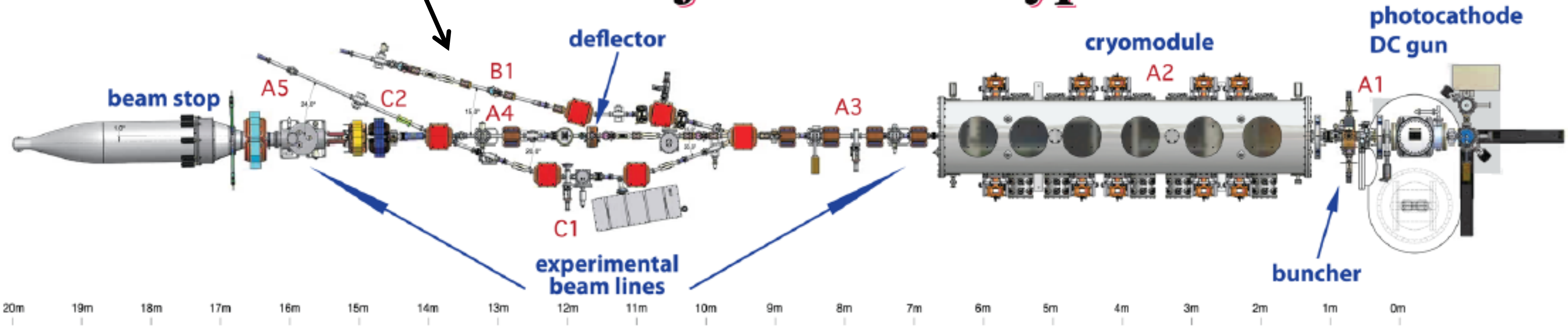
- Note: merger section (B1)



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

ERL – Injector Prototype



Injector for ERL/xFEL operation

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

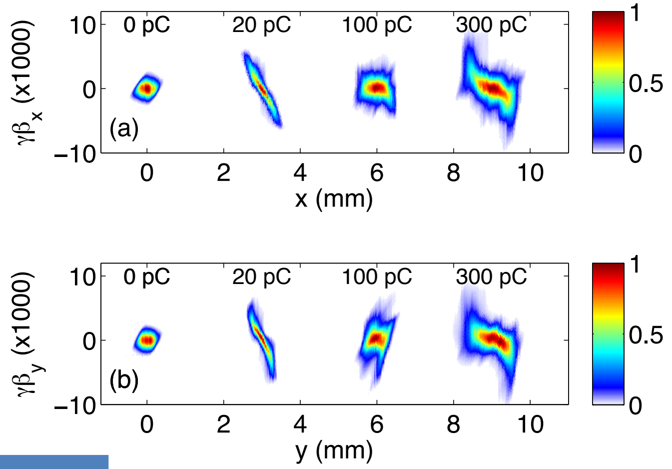
- 350 kV Gun Voltage
- **Met requirements for ERL**

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 solenoid later fixed using a small quad

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



- Met spec at 20/100/**300 pC** charges for LCLS-II[4]
- 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%**

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[1] C. Gulliford et al., Phys. Rev. ST Accel. Beams **16**, 073401 – 2013

[2] L. Cultrera et al., Appl. Phys. Lett. **103**, 103504 (2013)

[3] B. Dunham et al., Appl. Phys. Lett. **102**, 034105 (2013)

[4] C. Gulliford et al., Appl. Phys. Lett. **106** (2015) 094101

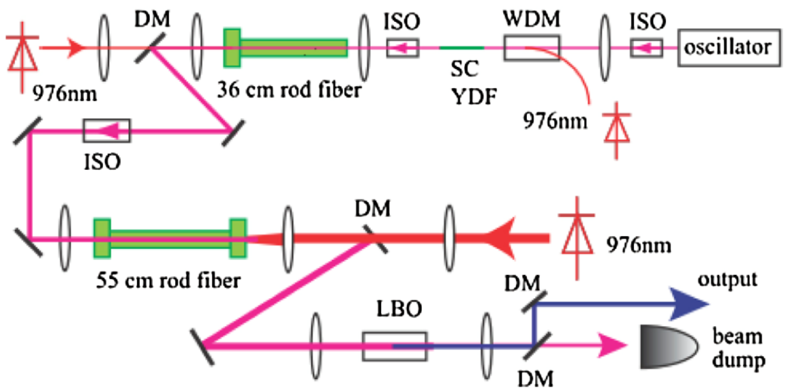
Primary Question

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

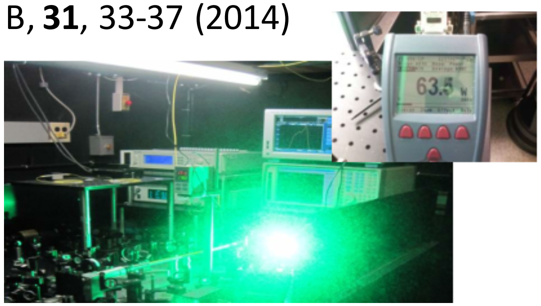
- Much higher bunch charges (up to **2 nC**)
- Relaxed emittance requirements
- No requirement for short bunch length
- High current (up to **50 mA** @ 50 MHz repetition rate, 1 nC)

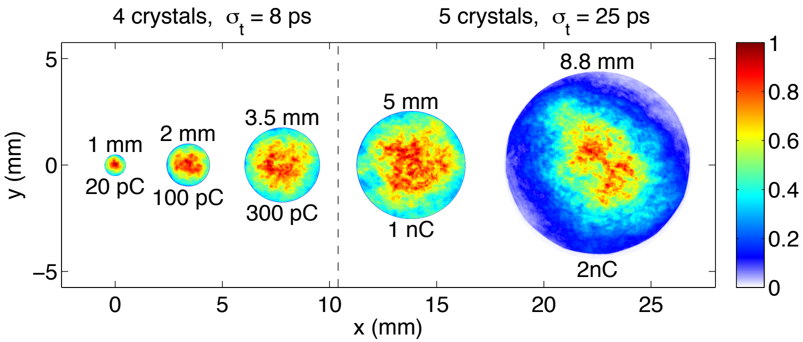
LASER UPGRADE

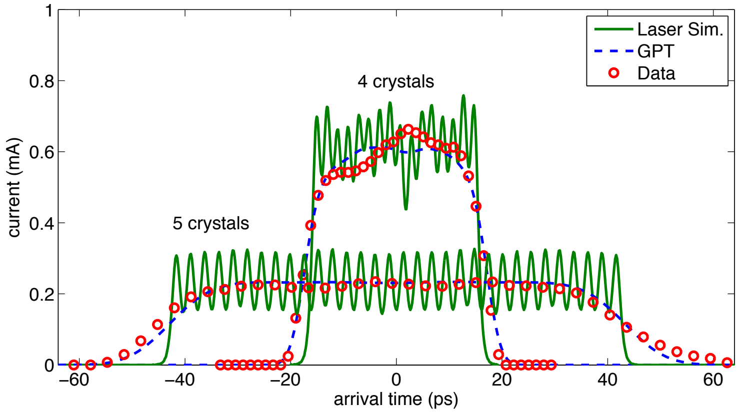
- Drive laser was incapable of reaching pulse energies needed for nC bunches
- Upgraded using Yb-doped rod amplifiers
  - Capable of 150 W average power (IR) and 1 MW peak power;
  - Limited to 50 W due to damage threshold of downstream optics;



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







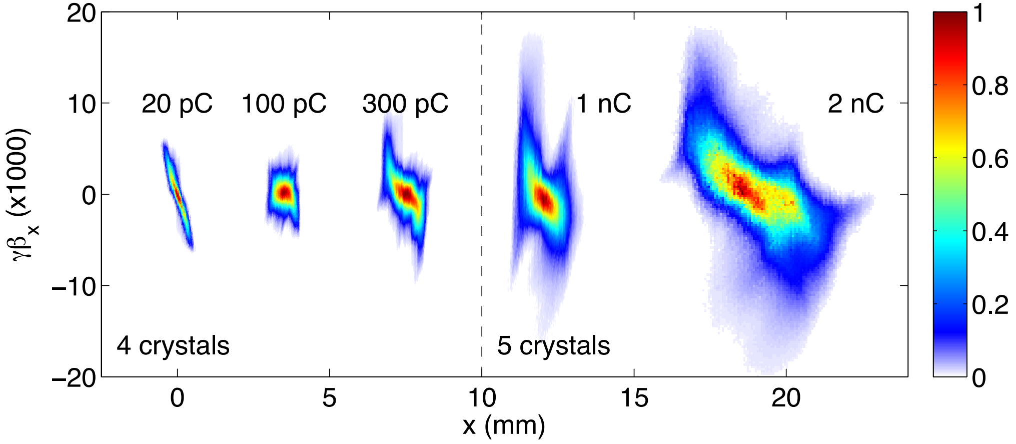
Laser beam size scales as $\sqrt{Q}$

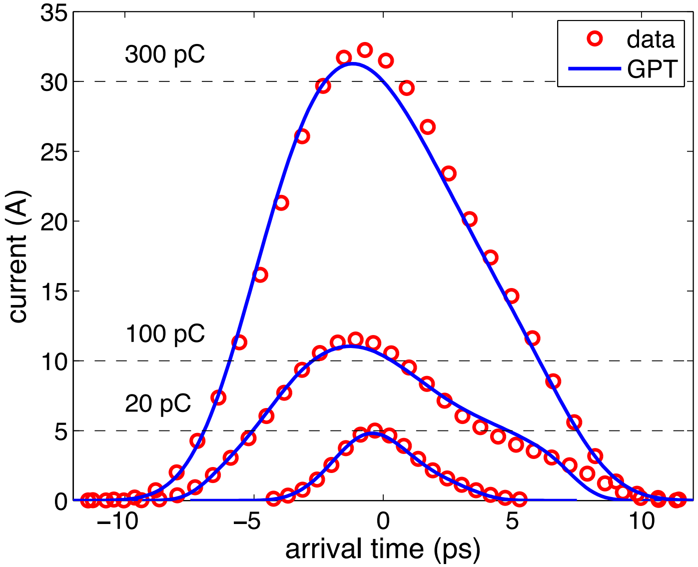
Need **D > 5 mm** for 1nC

Lengthen pulse: 8 ps -> **25 ps**

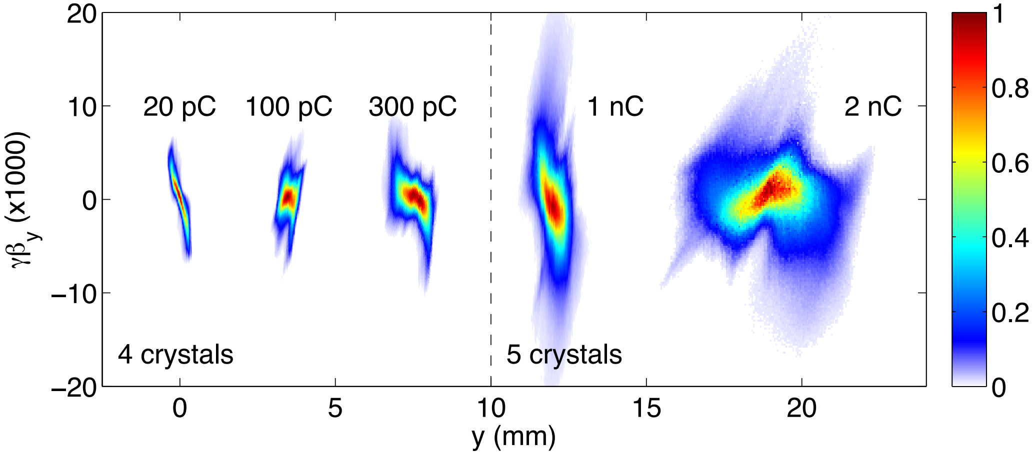
1 and 2 nC bunch results

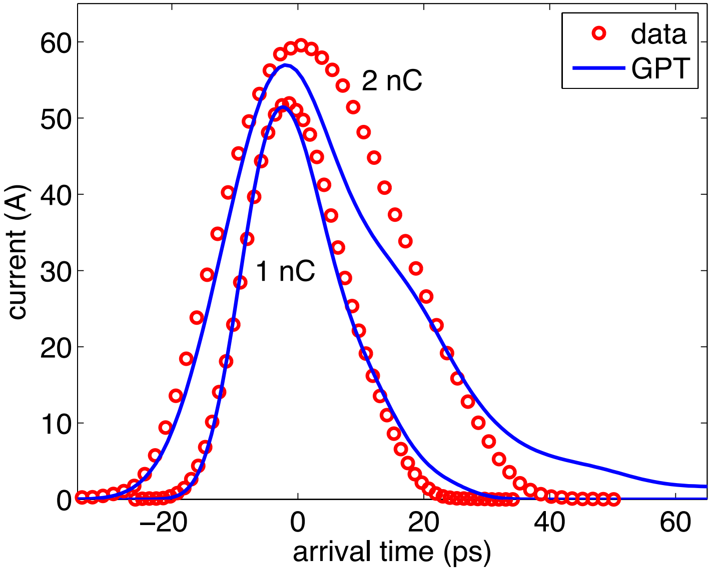
1 nC: 1.6 µm, 2 nC: 4.4 µm (95%)





1 nC: 1.6 µm, 2 nC: 4.0 µm (95%)



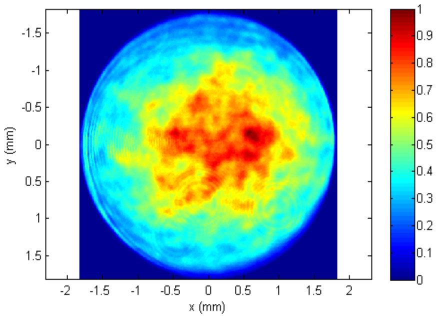


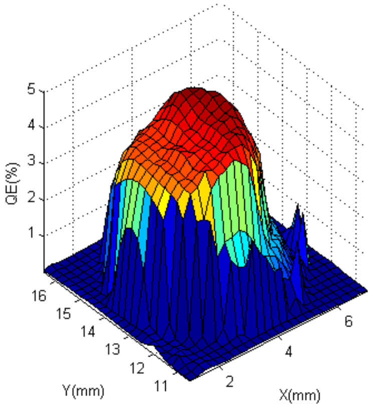
A. Bartnik et al., PRSTAB 18 (2015) 083401

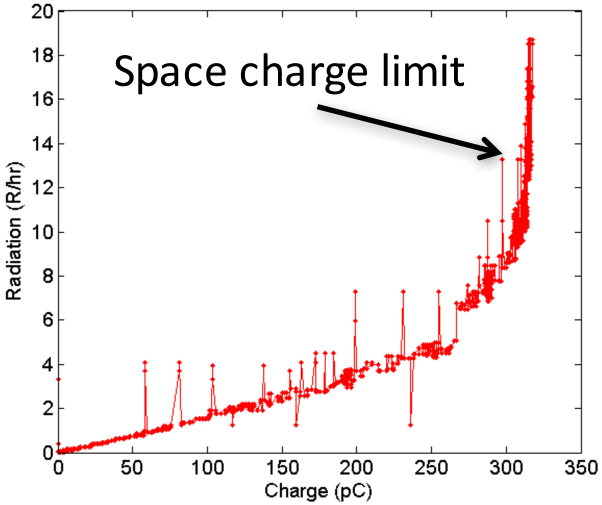
High current operation

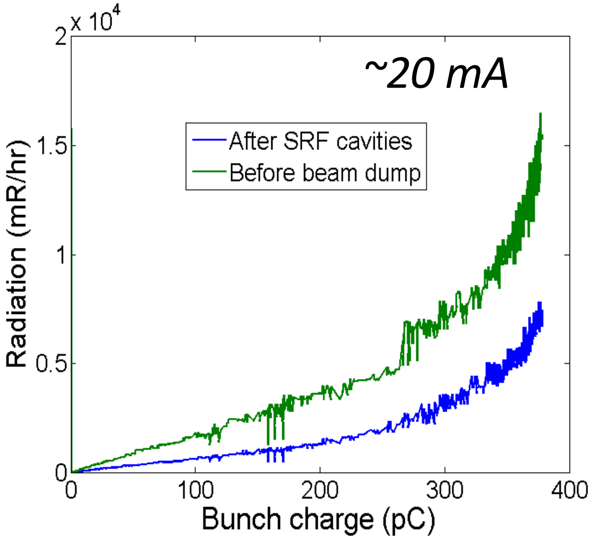
- Would like a 5 mm diameter active area cathode, offset from gun center
- 1st off-center cathode available had a roughly 3.5 mm active area
- See dramatic increase in radiation around 320 pC
    - Made laser size bigger: same problem at 375 pC
- In simulation, begin to lose particles at cathode around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

Laser profile during high current





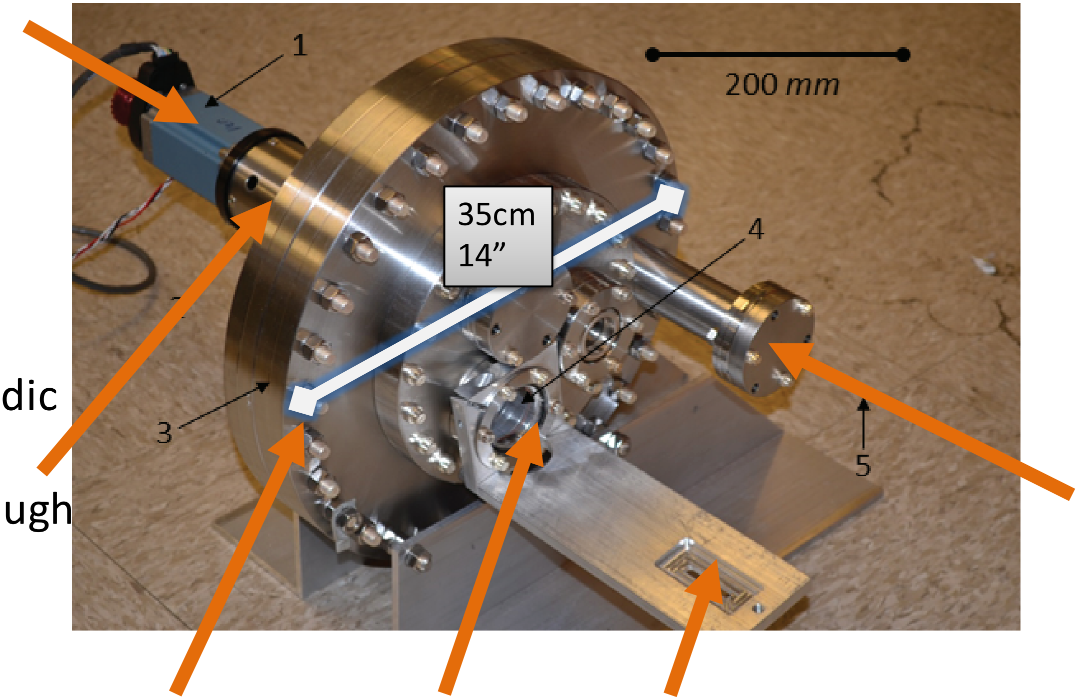




Cathode used for High Current Operation

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

Flying Wire



Stepper motor

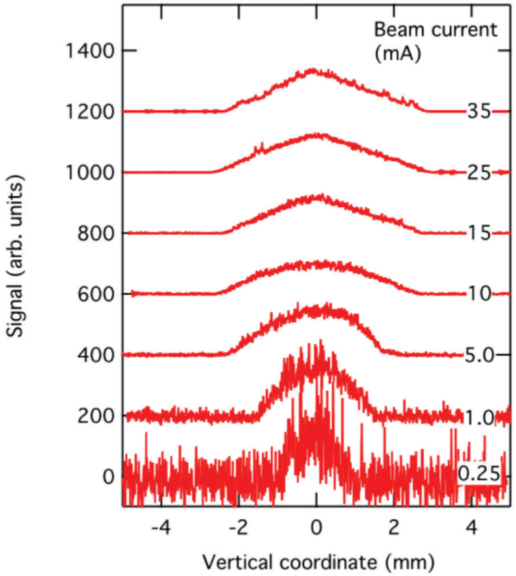
Ferrofluidic Rotary feedthrough

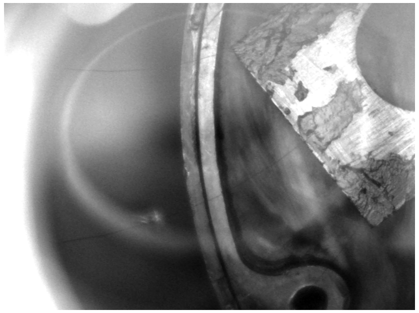
Vacuum flanges

Viewports

Camera mount

Beam pipe

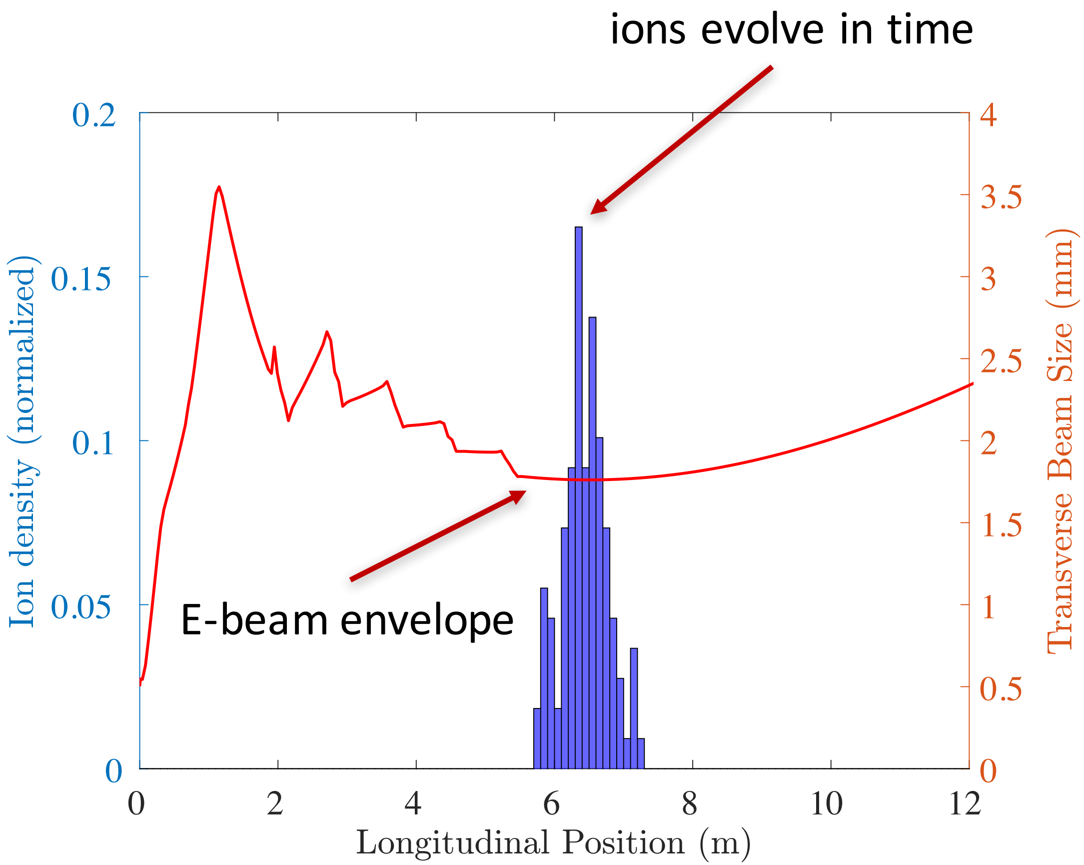




- Fast flying wire was designed, built and commissioned
- We can measure electron beam profiles at full current.

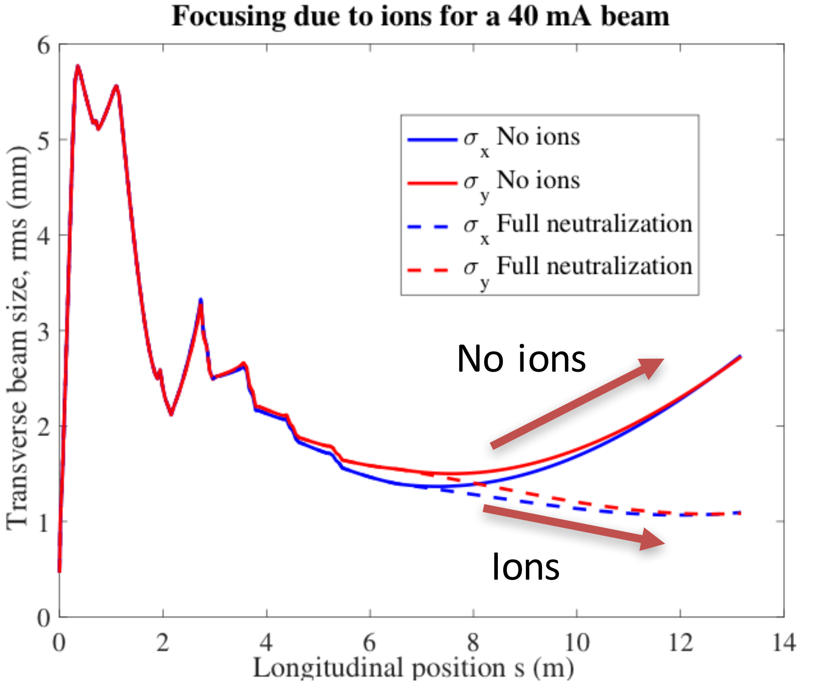
Simulation results

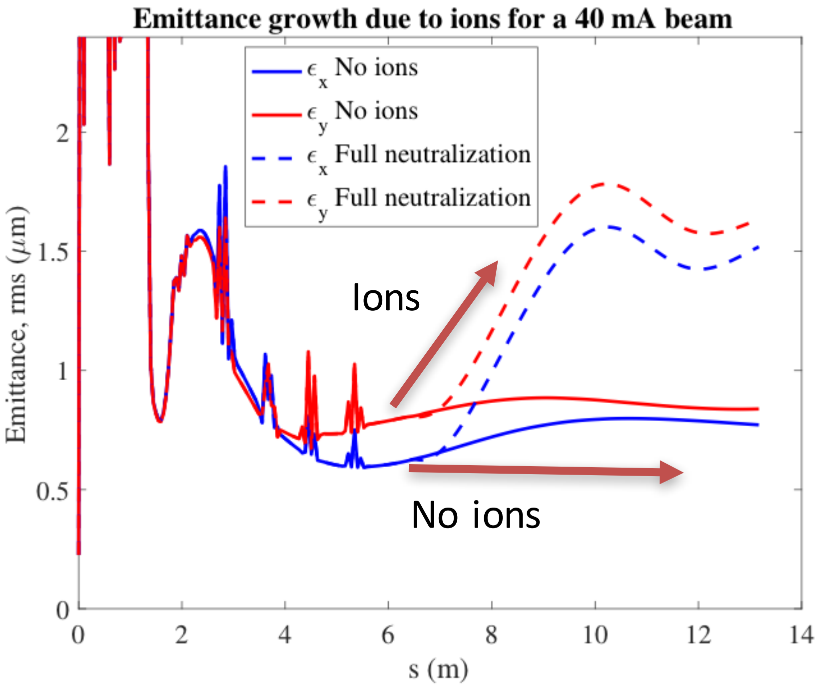
- **Developed ion-electron tracking simulation software.**
- It showed that ions drift longitudinally, and accumulate at beam size minima, as expected.
- Useful for deciding locations of clearing electrodes.



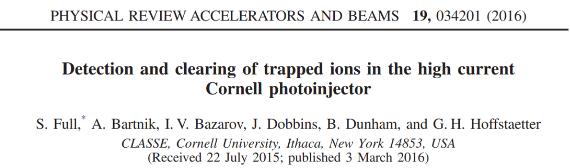
Ion effects on beam

- 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





Clearing electrode tests



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

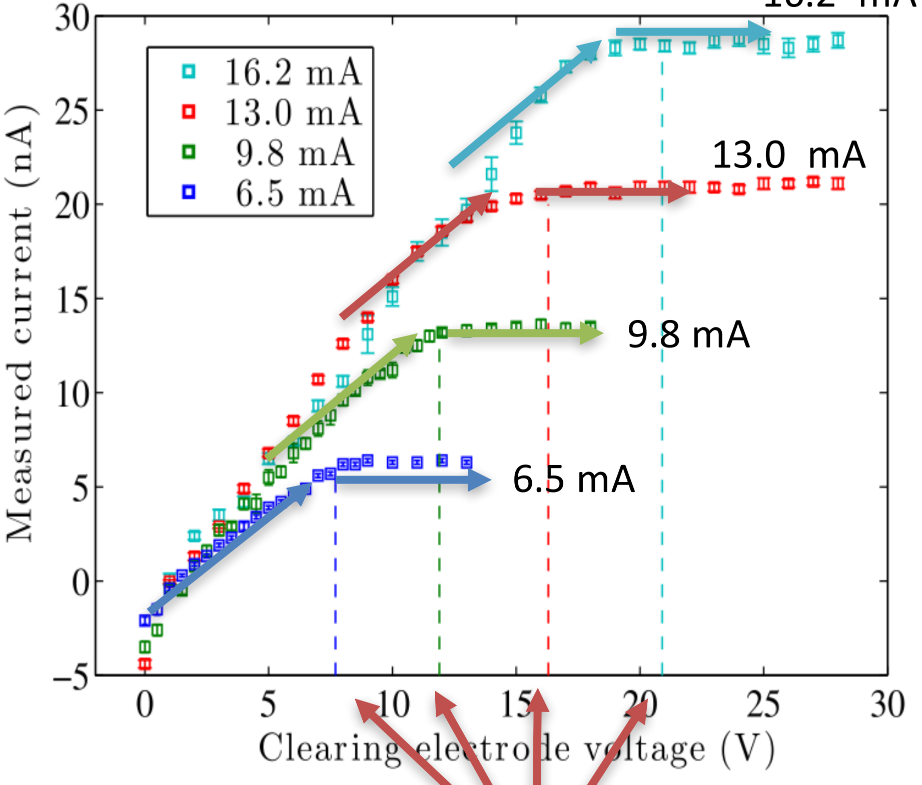
Detection and clearing of trapped ions in the high current Cornell photoinjector

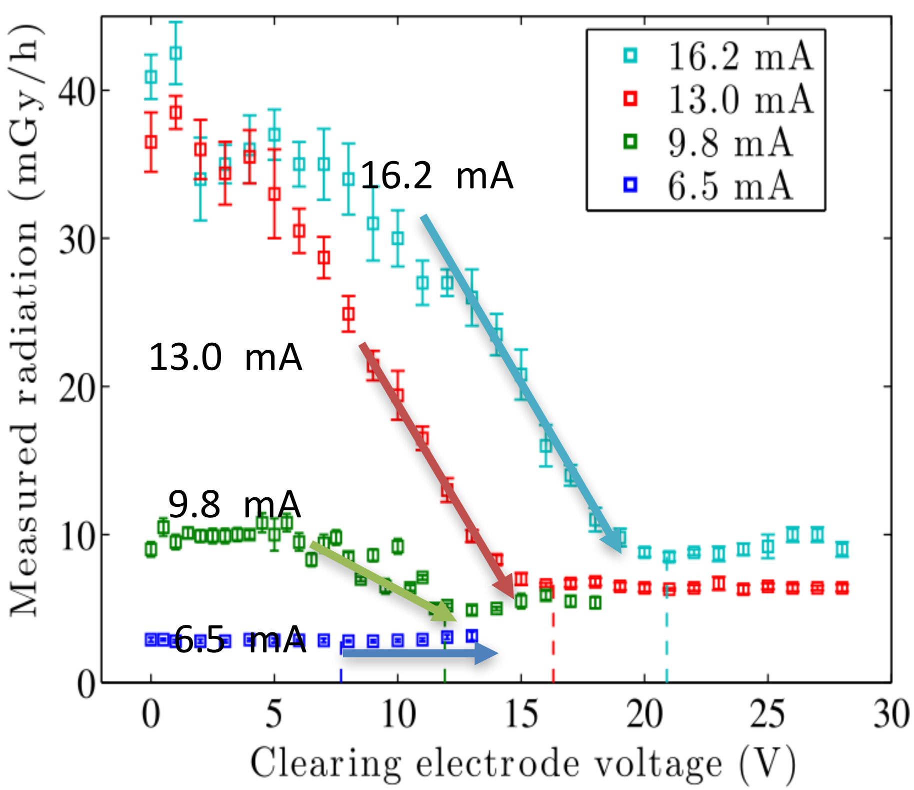
S. Full,* A. Bartnik, I. V. Bazarov, J. Dobbins, B. Dunham, and G. H. Hoffstaetter

CLASSE, Cornell University, Ithaca, New York 14853, USA

(Received 22 July 2015; published 3 March 2016)

Measured ion current striking the clearing electrode



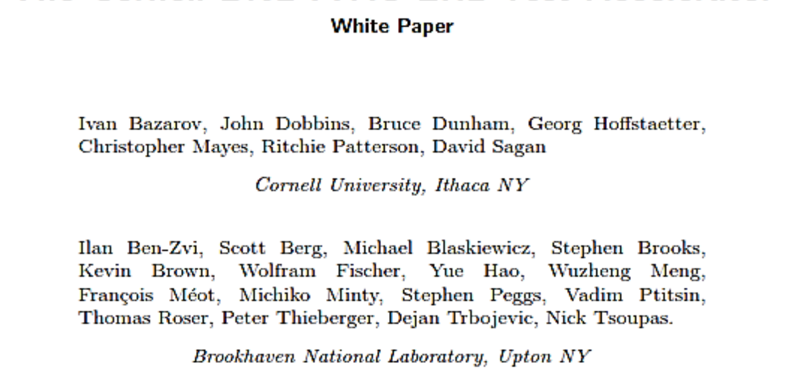


$$V_{electrode} \geq \frac{I}{2\pi\epsilon_0 c}\frac{d}{\sigma_b}$$

← Clearing electrode separation

← Transverse beam size

We had to move the injector



The Cornell-BNL FFAG-ERL Test Accelerator

White Paper

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

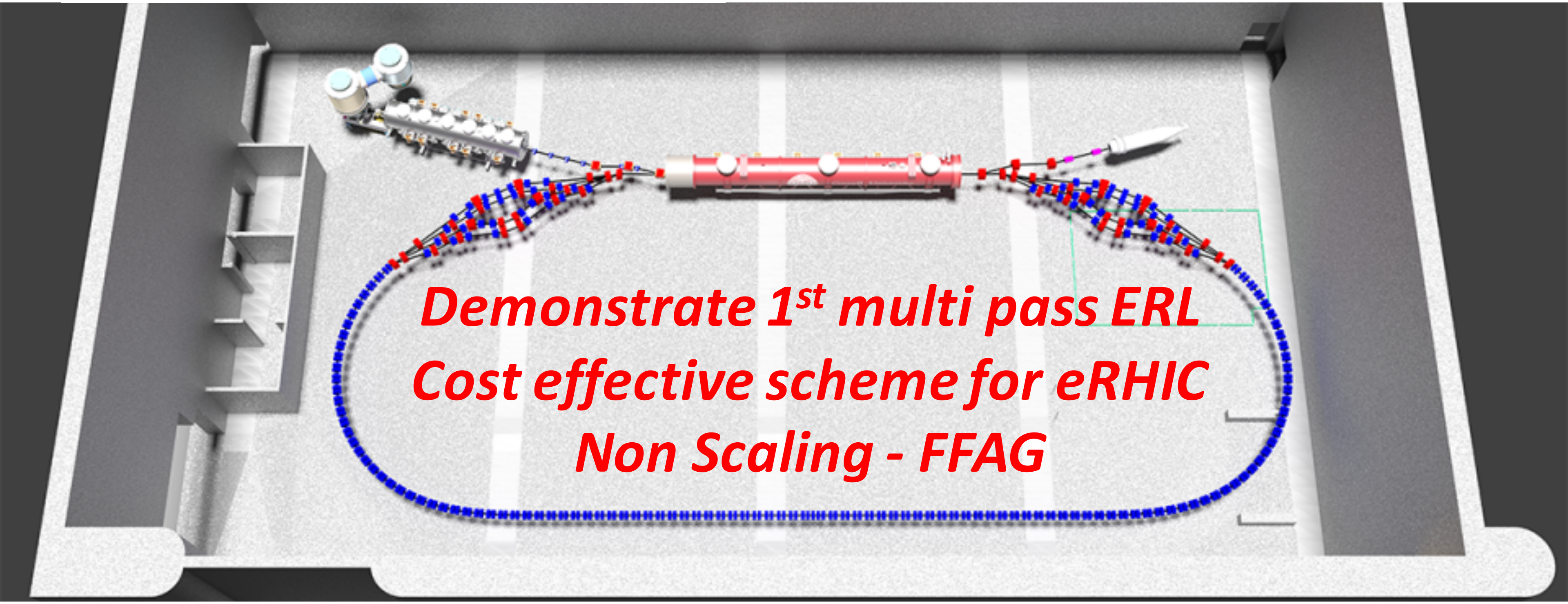
Cornell University, Ithaca NY

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



Demonstrate 1st multi pass ERL

Cost effective scheme for eRHIC

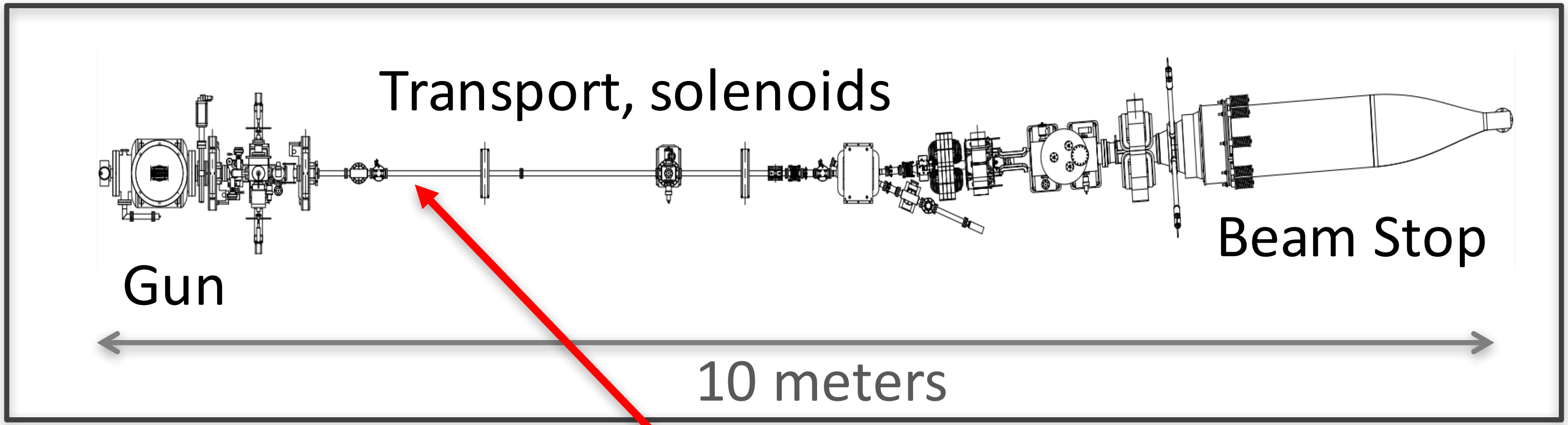
Non Scaling - FFAG

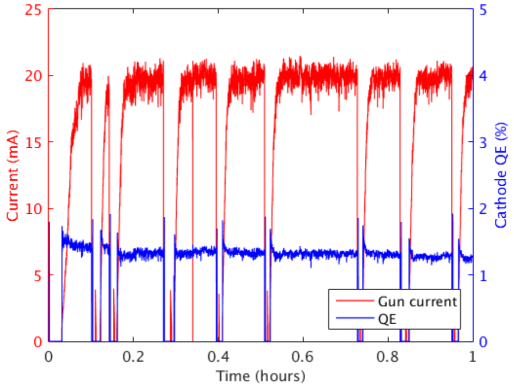
Gun Test Beamline

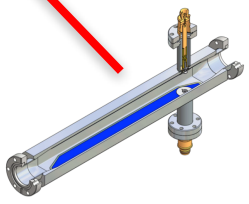
During maintenance on our SRF booster linac, we constructed a simplified “gun test” beamline.

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

Expectation: No SRF = No trips

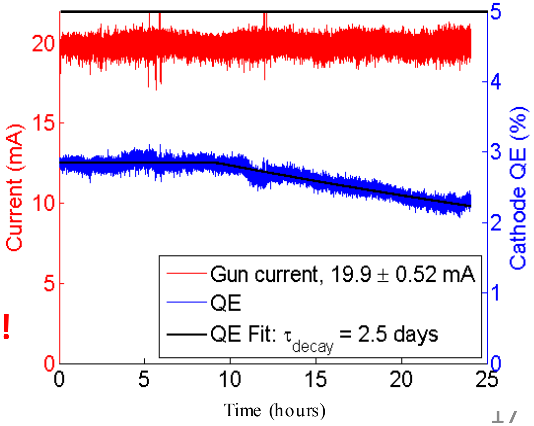






Ion Clearing

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



Injector after the move

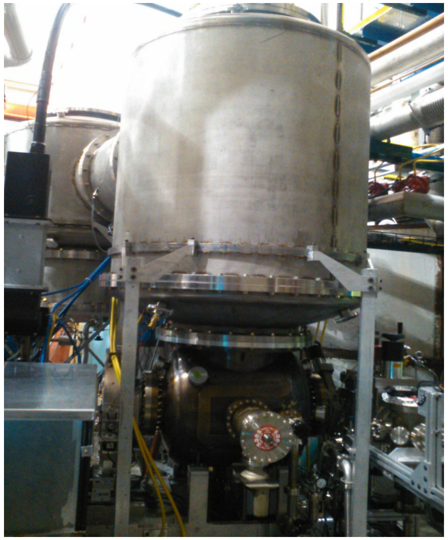
NEW GUN

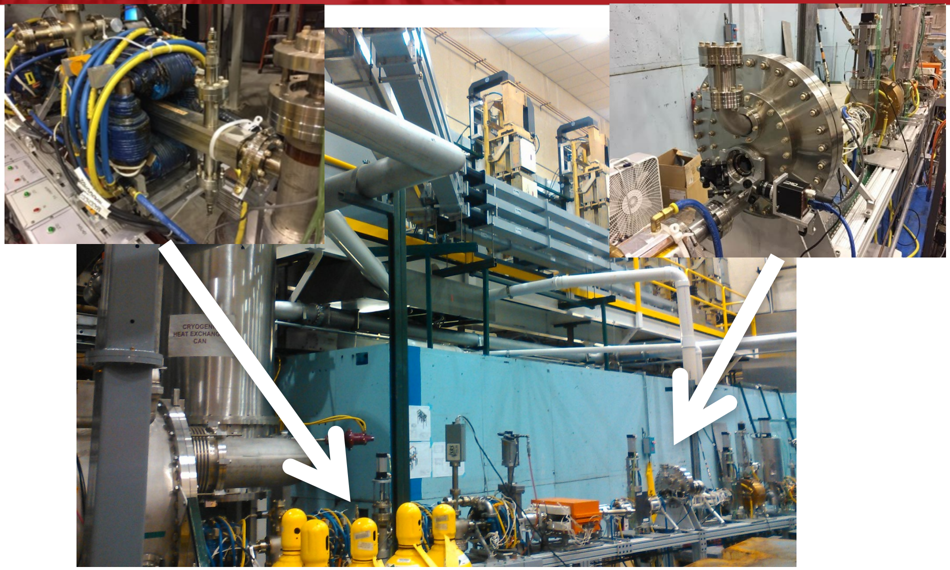
- Segmented ceramic insulator

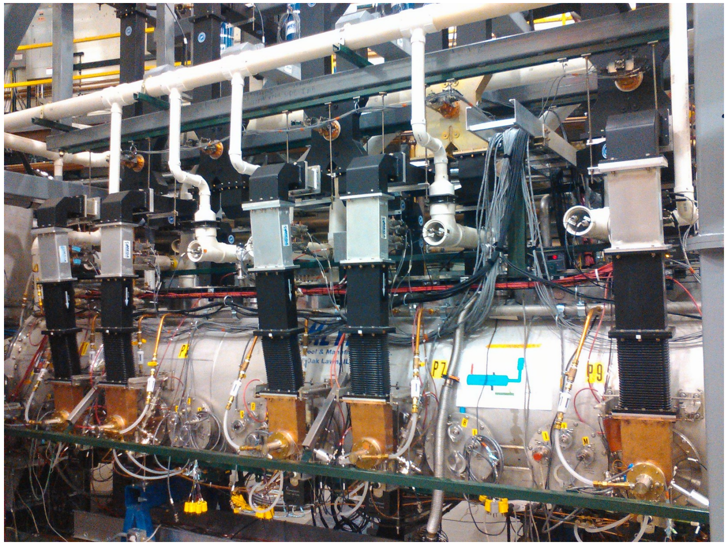
=> Higher voltage

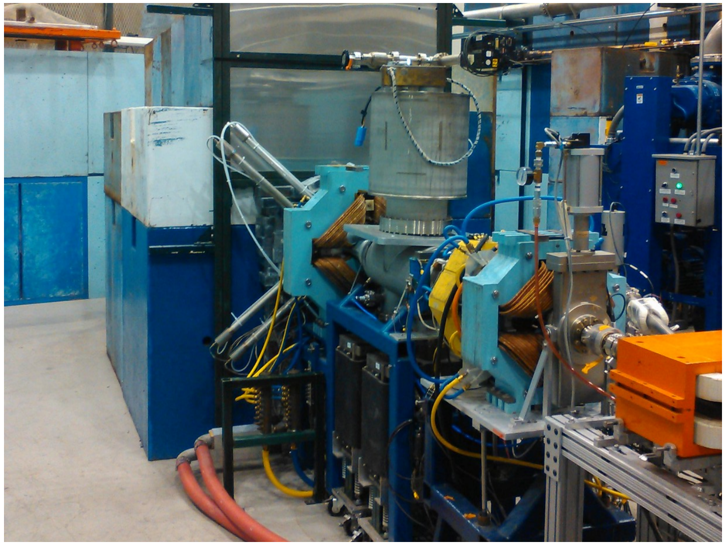
- **Biased anode**

=> Longer cathode lifetime



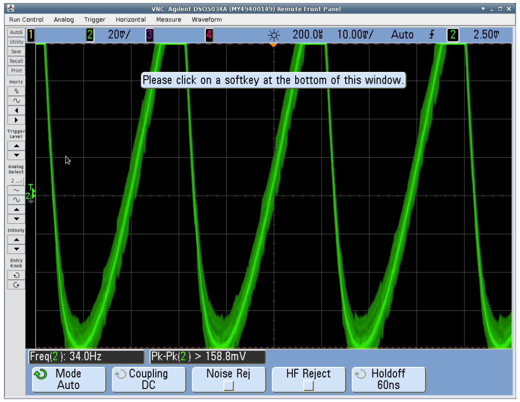






Last high current run

- Operations were delayed due to HV power supply issues:
  - Without the processing resistor the High Voltage power supply was unstable:



20mV/ 200.0µs 10.00ms/ Auto 2 2.50mV

Please click on a softkey at the bottom of this window.

Freq(2): 34.0Hz

Pk-Pk(2) > 158.8mV

Mode Auto

Coupling DC

Noise Rej ☐

HF Reject ☐

Holdoff 60ns

- Power supply’s stack circuit boards inside the SF6 tank were damage by an arcing event.
- The lack of spares forced us to run with a reduced number of stack boards resulting in an increase in output capacitance.
- Also, the control cabinets for the 2 different power supplies we own were swapped.
- Both of these issues caused the ***control loop*** to not be well matched for the current stack.

December 22nd 2016

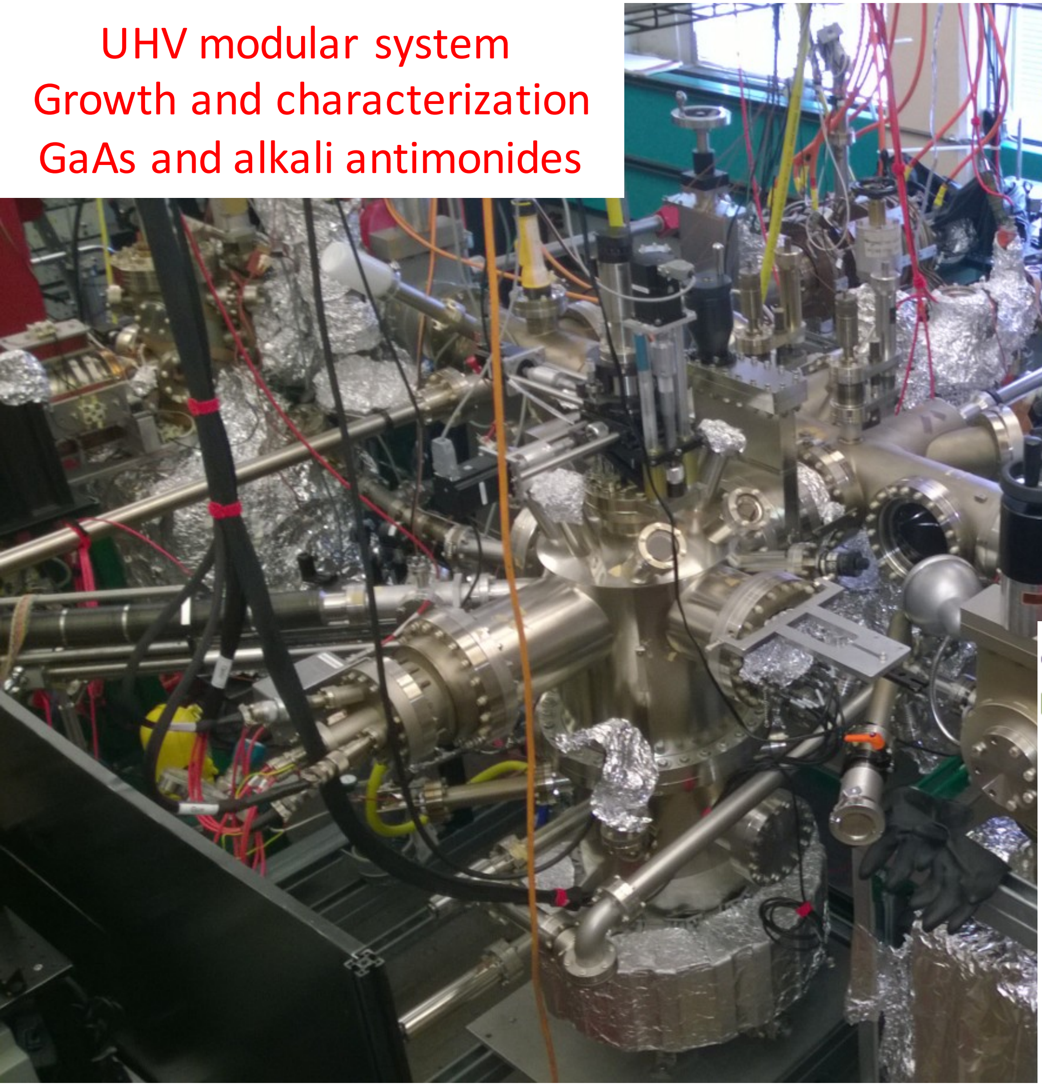
With the PS fixed we ran up to 4.2 mA before tripping the machine because SRF-cavity field trip due to cryomodule couplers.
This was our last attempt due to CBETA scheduled move of the MLC.

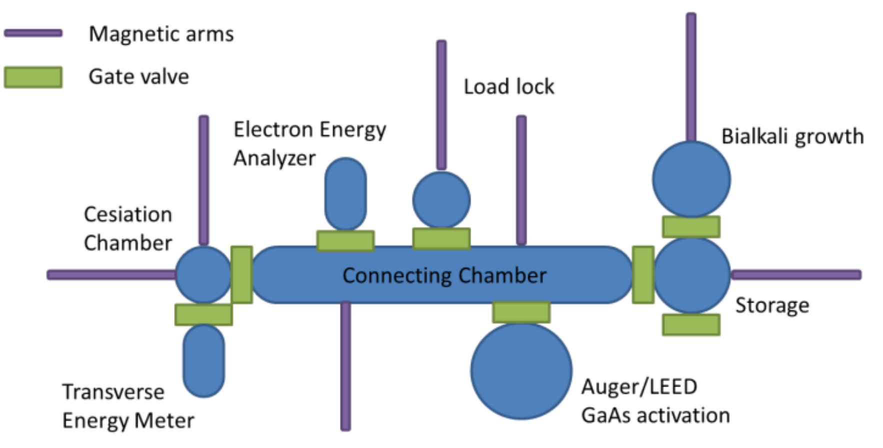
High polarization photocathodes

NEXT GENERATION ROBUST POLARIZATION PHOTOCATHODES FOR EIC

Photocathode laboratory

UHV modular system
Growth and characterization
GaAs and alkali antimonides

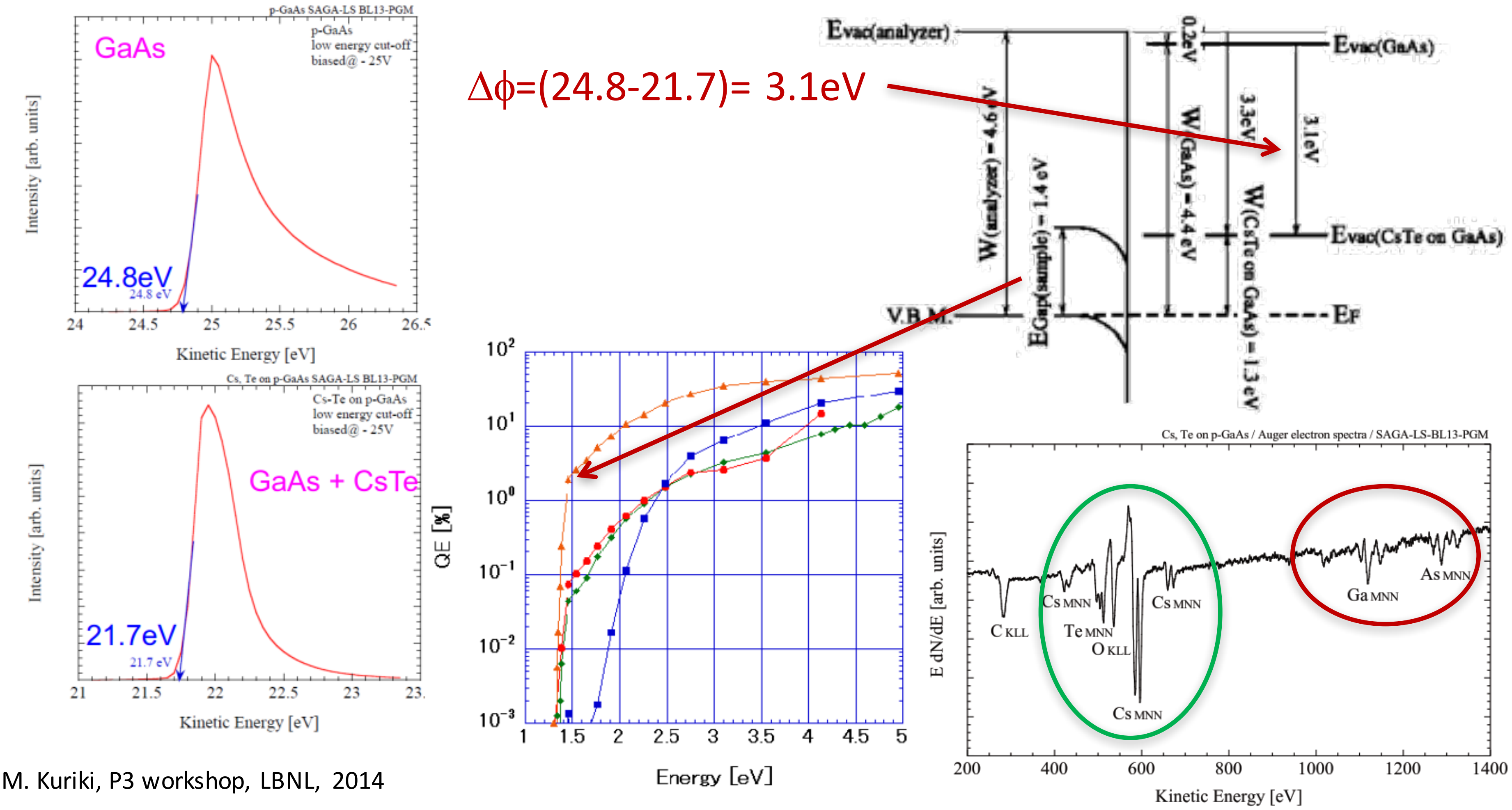




In 2014…

There are **alternative ways for generating the NEA** on GaAs that are less sensitive to vacuum conditions?

H. Sugiyama et al , *J. Phys. Conf. Series* **298** 012014 (2011)



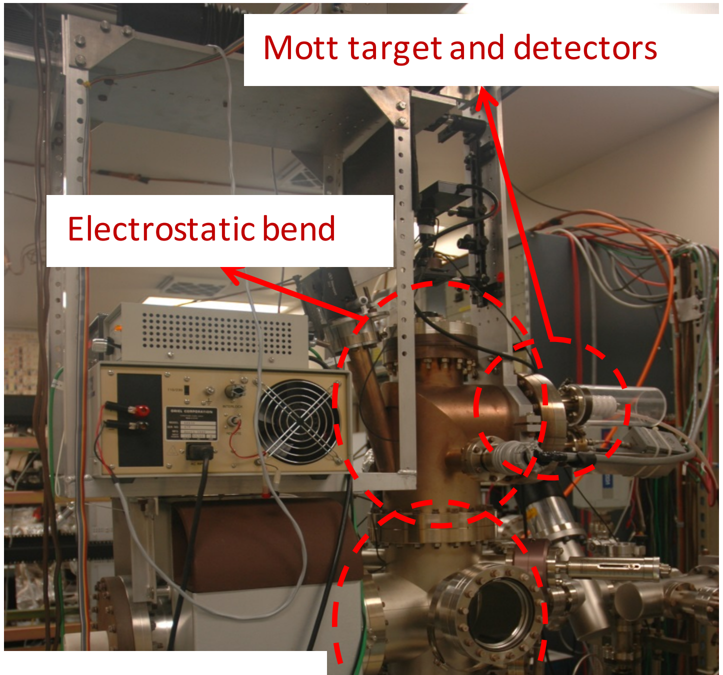
M. Kuriki, P3 workshop, LBNL, 2014

CsTe over GaAs can yield NEA!!

- *Implications of rugged NEA activation methods:*
  - *We might be able to operate at* ***higher voltage****;*
  - *Possible* ***operation in RF*** *(and SRF) guns;*
  - ***Long term*** *cathodes storage;*
  - *Cathodes transport in* ***suitcases****;*

Will the CsTe layer ***preserve the spin polarization*** *during the electron transport?*

Mott polarimeter @SLAC



Mott target and detectors

Electrostatic bend

Cesiation Chamber

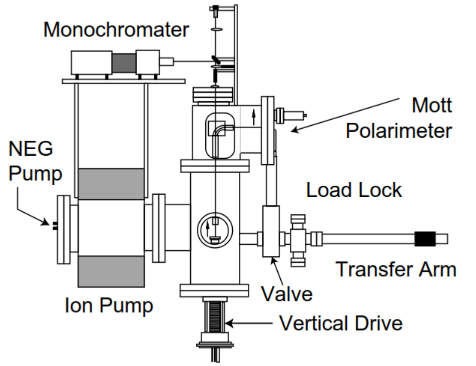
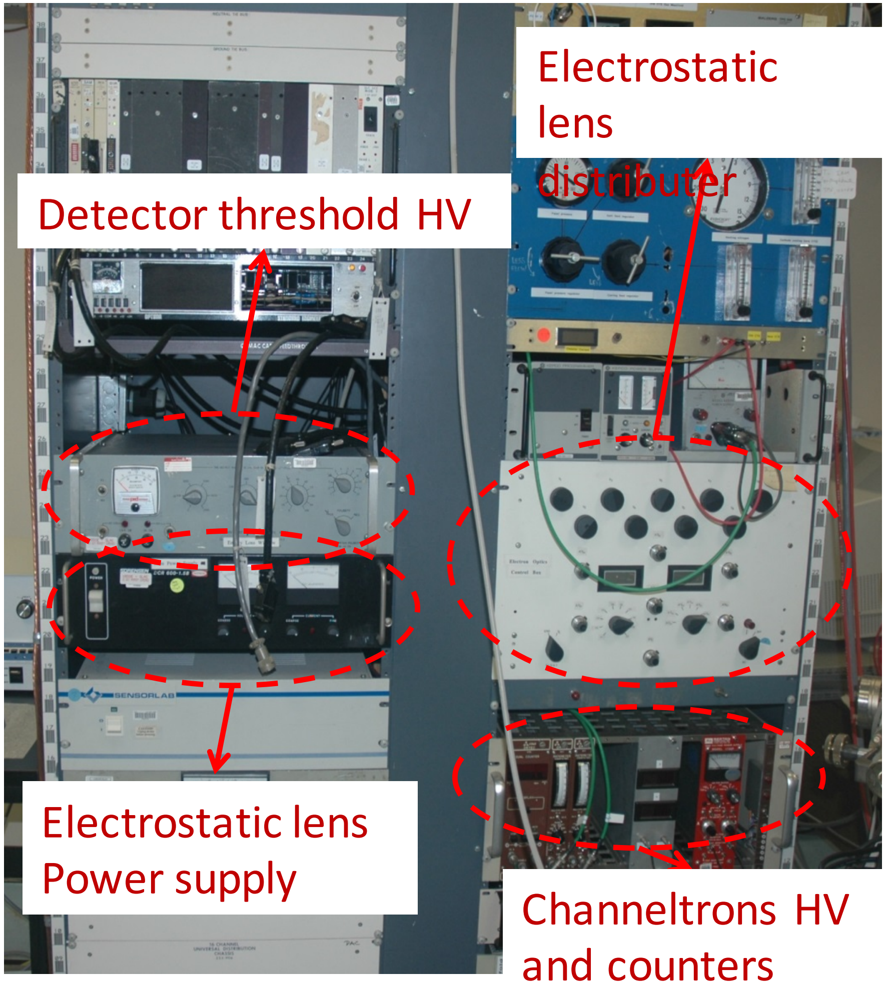


Fig. 2. Schematic diagram of the SLAC Cathode Test System showing the load lock.

In 1993!!



Electrostatic lens distributer

Detector threshold HV

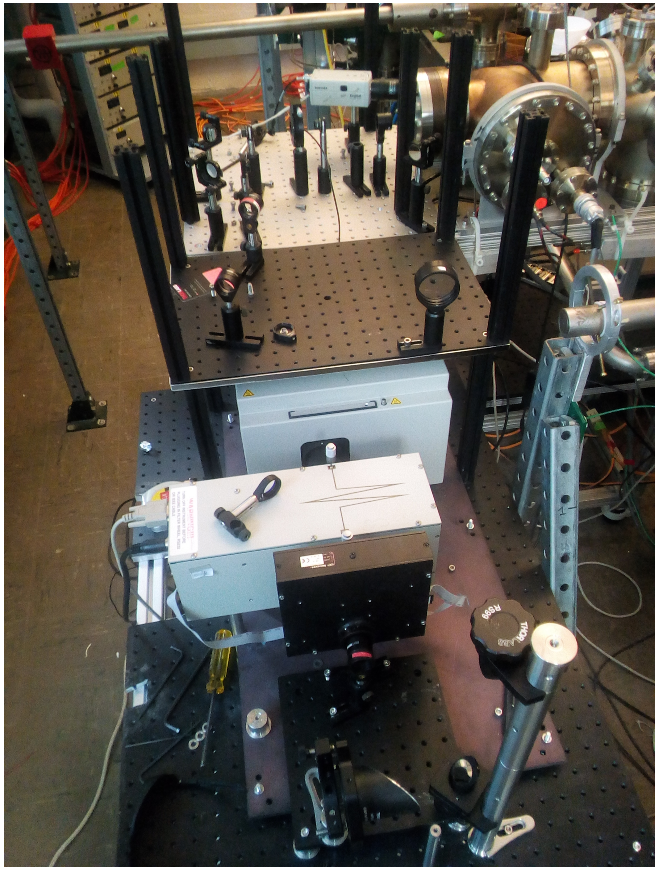
Electrostatic lens Power supply

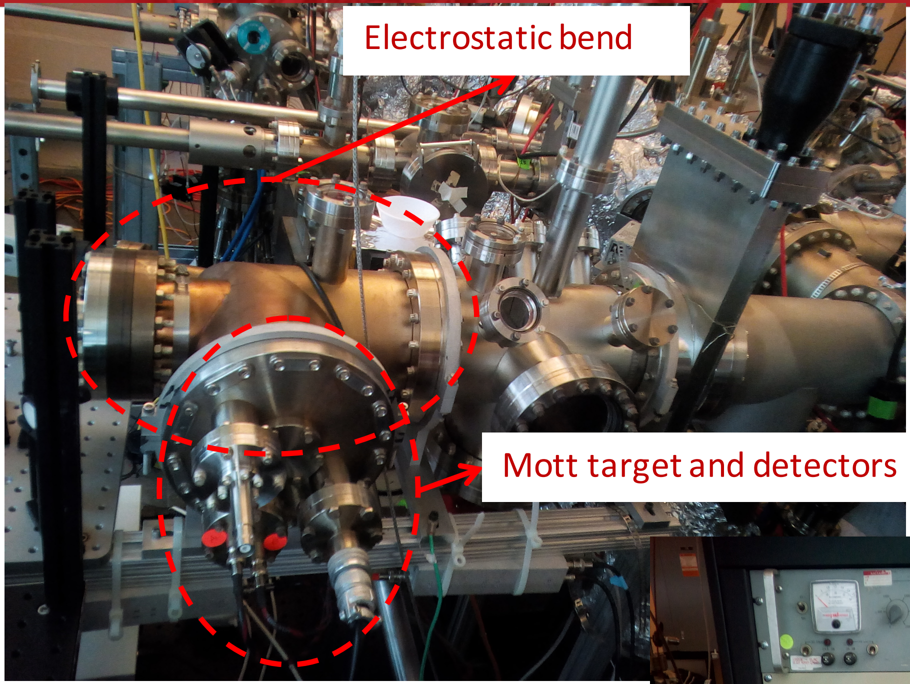
Channeltrons HV and counters

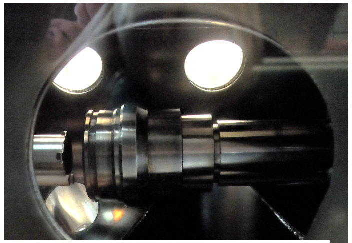
SLAC => Jlab => Cornell University

Mott polarimeter @ CU

Vacuum level is below 10^{-10} Torr







Cs_3Sb cathode

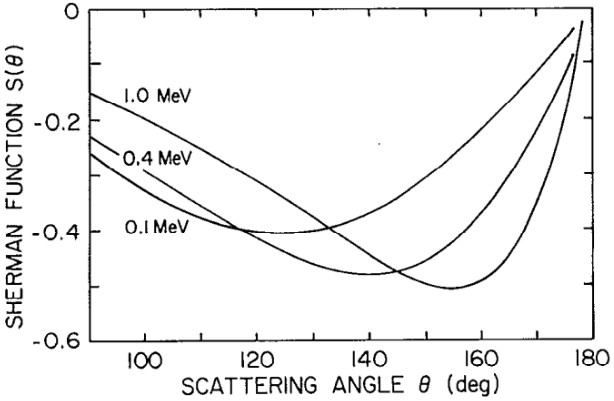
The retarding field Mott polarimeter has been refurbished upgraded and fully integrated into the photocathode lab UHV installation.

Polarization and Mott scattering

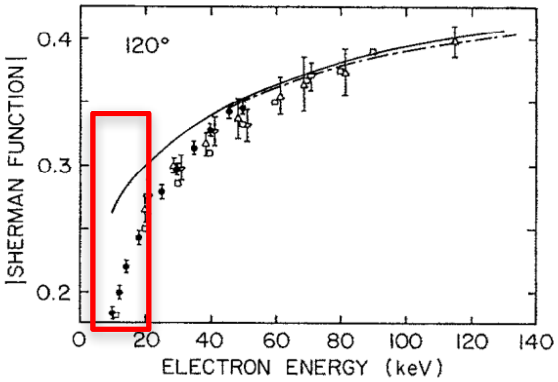
With the retarding Mott polarimeter the polarization is estimated by measuring angular asymmetry due to spin-orbit coupling in electrons elastically scattered by high Z nuclei.

$$P = \frac{N_\uparrow - N_\downarrow}{N_\uparrow + N_\downarrow} \quad \Rightarrow \quad A(\theta) = \frac{N_L - N_R}{N_L + N_R} = P \cdot S(\theta)$$

Sherman function



- Sherman function is usually computed for gold;
- The agreement with computed values is good E>50 keV;
- It takes in account a single elastic scattering (ΔE=0);



Our Mott polarimeter uses a tungsten target;

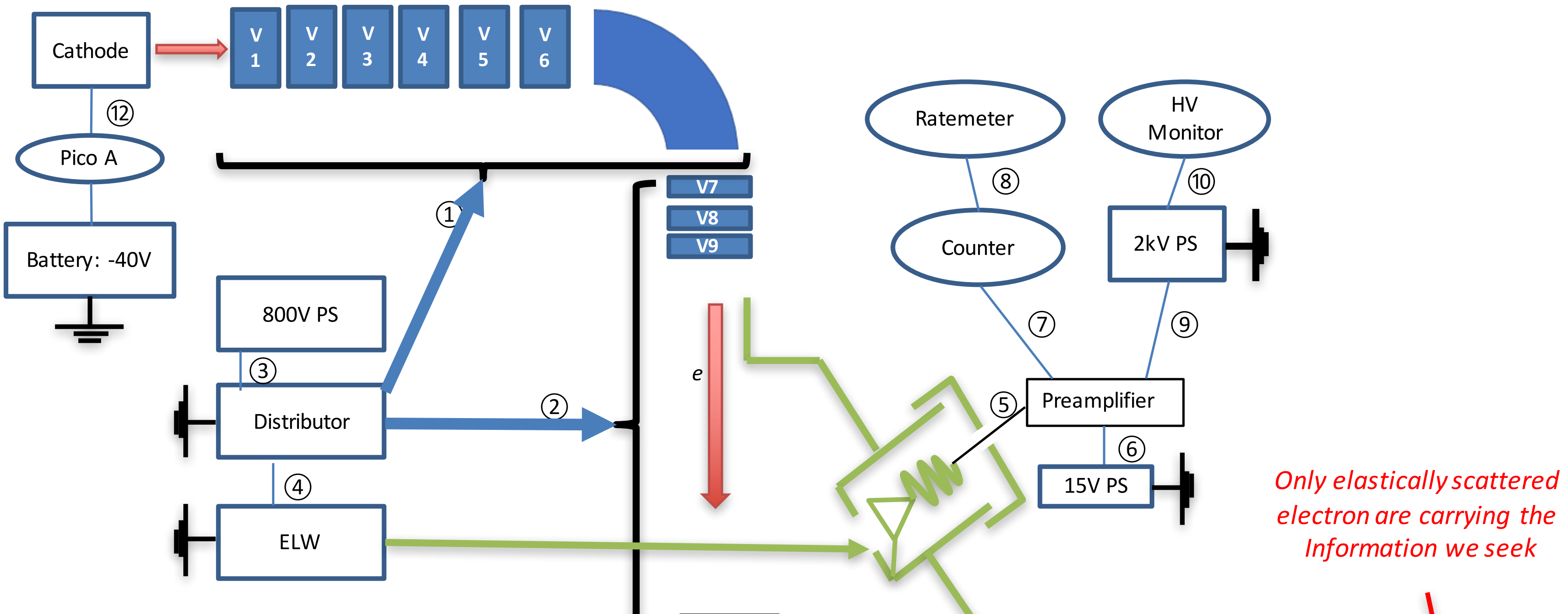
And we do not have estimates of Sherman function for our new configuration…

We need to perform a new calibration using a test sample (bulk GaAs P≅33% @780 nm).

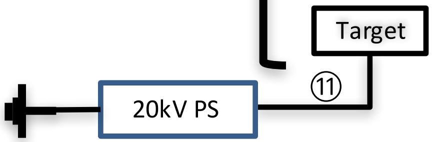
What has been done

- Refurbishing and recommissioning:
  - Initial inspection revealed that **the instrument was not anymore in the configuration it was designed**;
  - It took a while to understand how the electronic was modified with respect to the initial design;
  - Some electronic components needs to be replaced;
- This was helpful because now **we know the instrument well enough that we decided to do some improvement…**

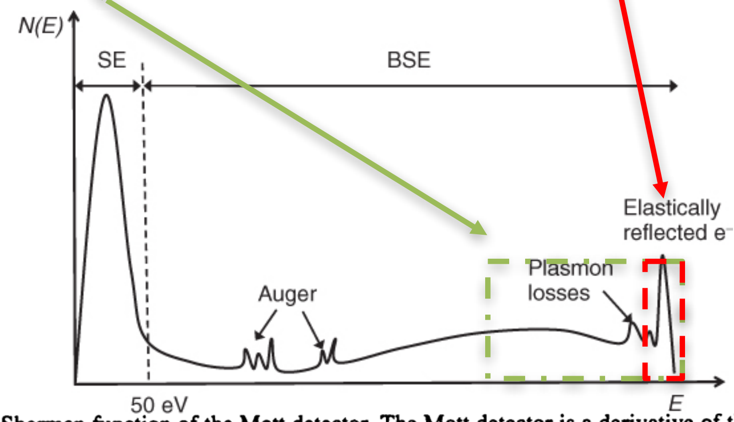
Hardware mods



Only elastically scattered electron are carrying the Information we seek

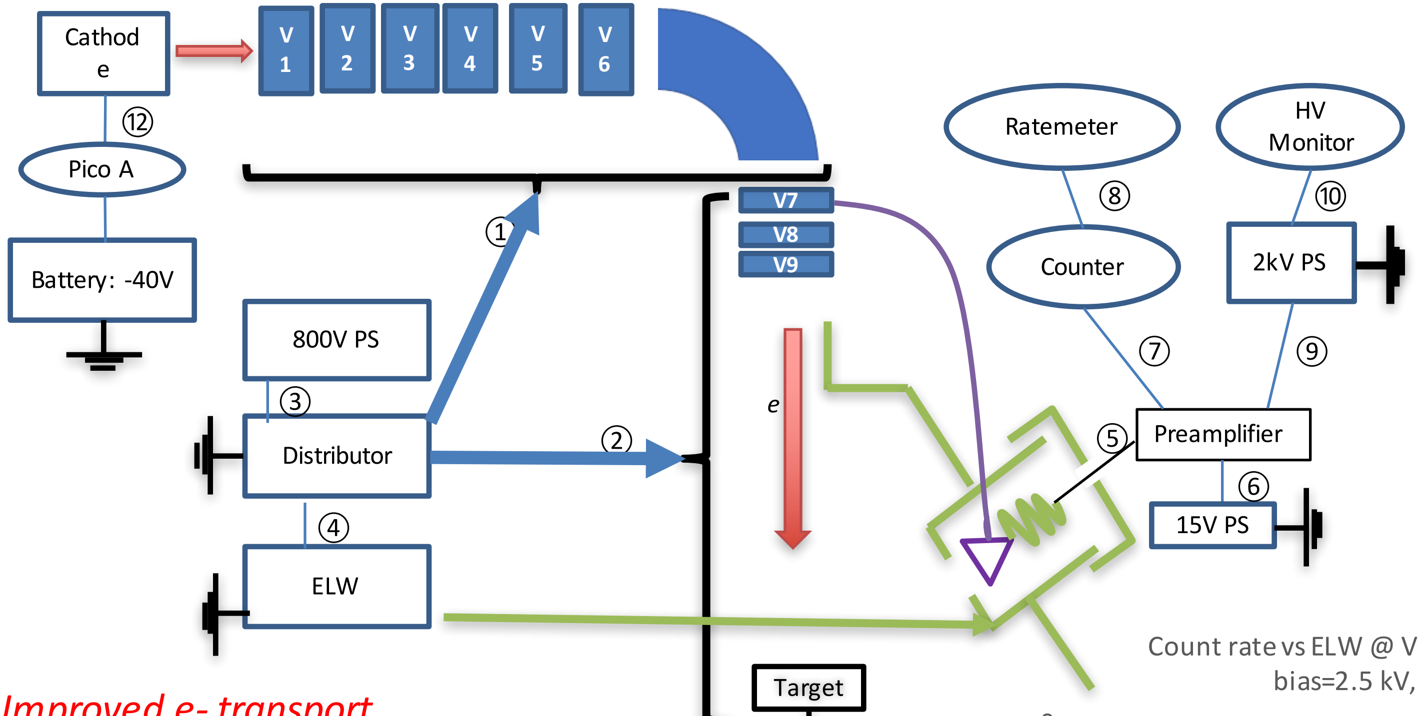


Increasing the ELW allows a better s/n ratio but then S(θ) is replaced by a n $S_{eff}(\theta)$ to take account for electrons that suffered multiple and/or inelastic scattering



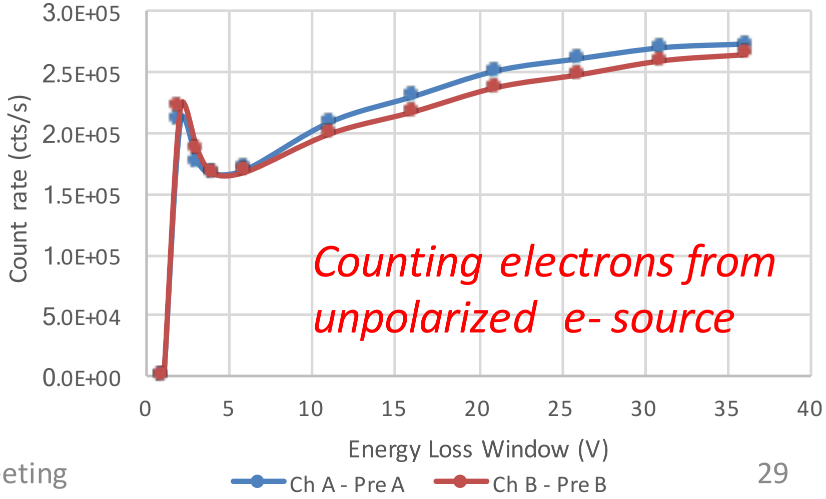
S_{EF} is the effective Sherman function of the Mott detector. The Mott detector is a derivative of the Rice micro-Mott design[4]. Calibration of this version is quoted to be accurate to 5%[5]. The Mott polarimeter on which its calibration is based is accurate to 2%[6]. For scattering at 20 keV with an energy loss window of 1000 eV, this polarimeter has $S_{EF} = 0.150$.

Energy Loss Window



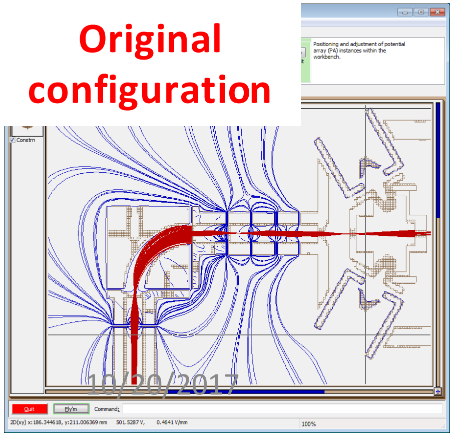
Improved e- transport
25% efficiency (x3 better)

Count rate vs ELW @ V threshold= 5.3 mV, Channeltron bias=2.5 kV, photocurrent=0.8 nA

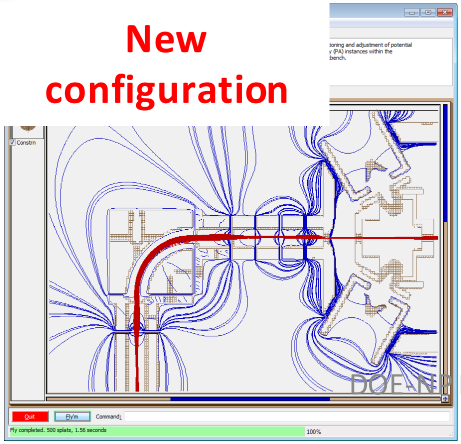


Counting electrons from unpolarized e- source

Original configuration

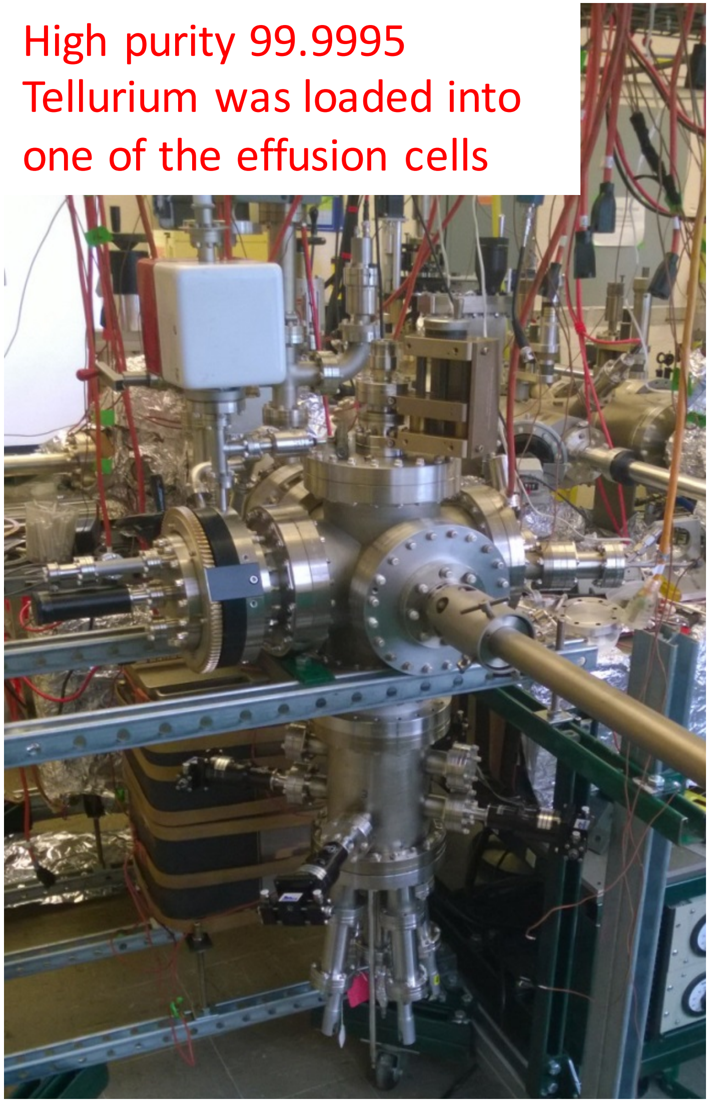


New configuration



CsTe on GaAs growth setup

High purity 99.9995 Tellurium was loaded into one of the effusion cells

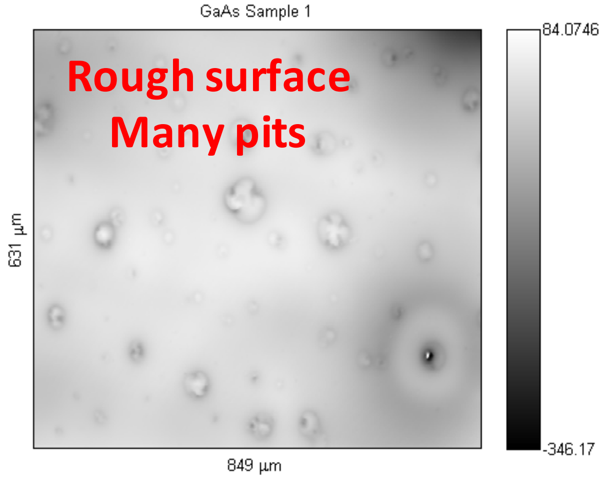


GaAs substrate samples p-type Zn doped 1e18 cm-3

Wet etch to remove oxide and passivate surface

-H_2SO_4:H_2O_2:H_2O (20:1:1) 2 min @ RT

-HCl:iPA (20:80) 3 min @ RT



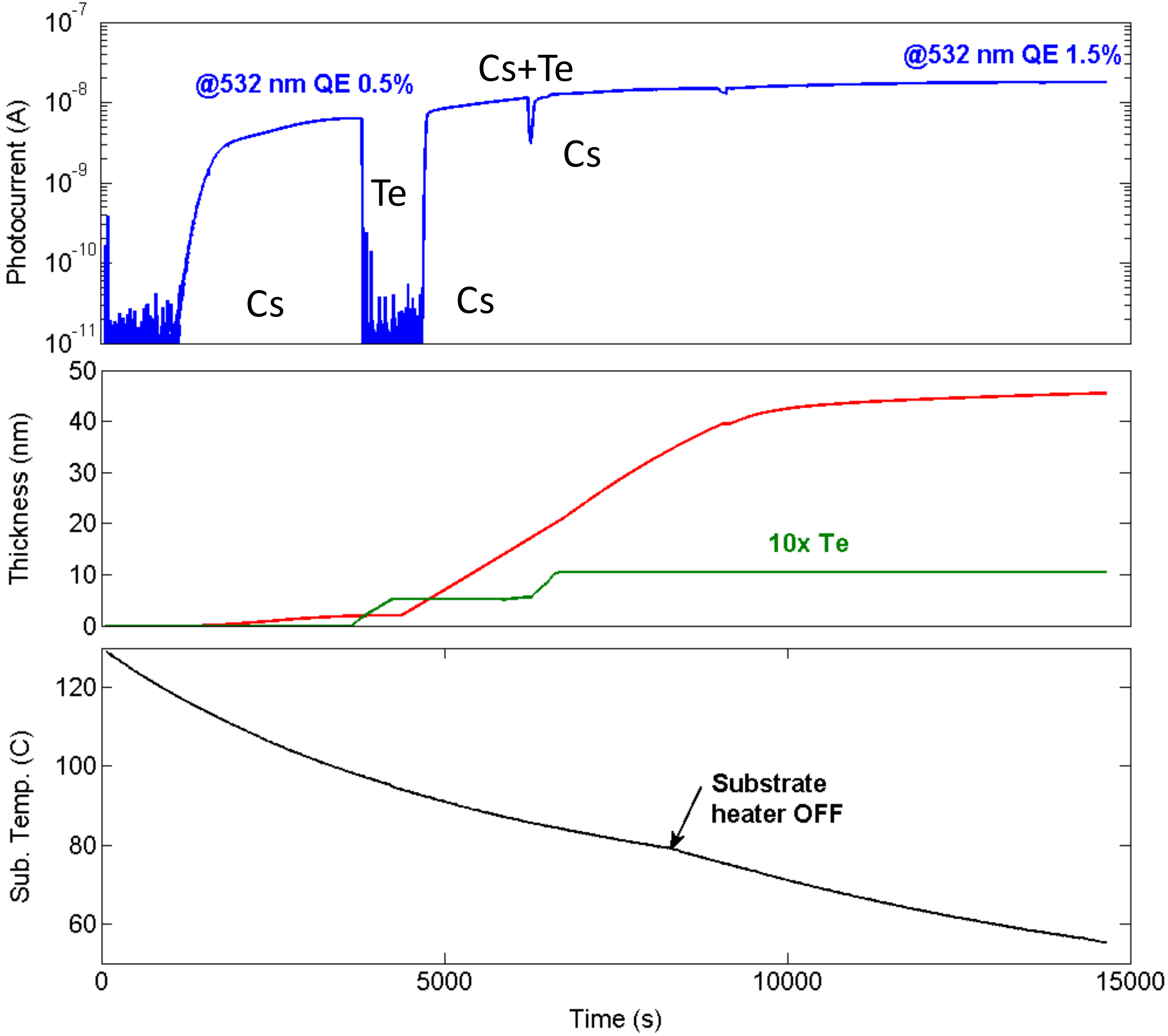
Rough surface
Many pits

Heat cleaning at 400 C overnight

Room Temperature Cs activation yields ~3% QE @ 532nm

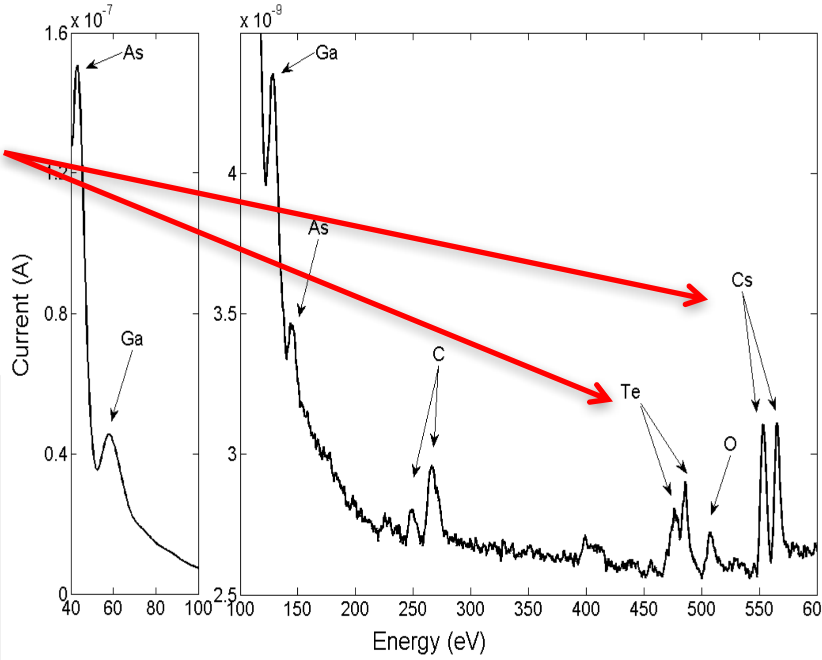
Surface is clean enough to perform activation!!

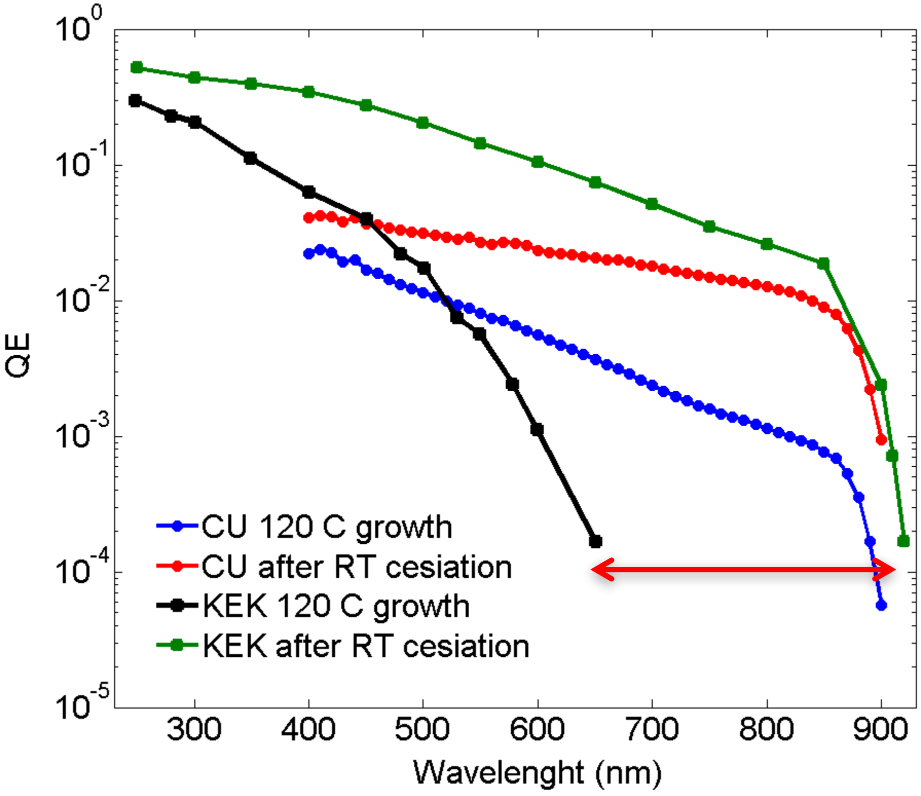
CsTe on GaAs growth procedure



CsTe on GaAs QE and Auger

- **Auger spectroscopy confirms the presence of Cs and Te over the GaAs surface**
- Ga ans As peaks are still visible meaning that the CsTe layer is thinner than few nm
- C and O peaks likely coming from the e-gun





- We do **NOT** see an emission threshold shift
- We do **NOT** get the high QE reported by Japanese group

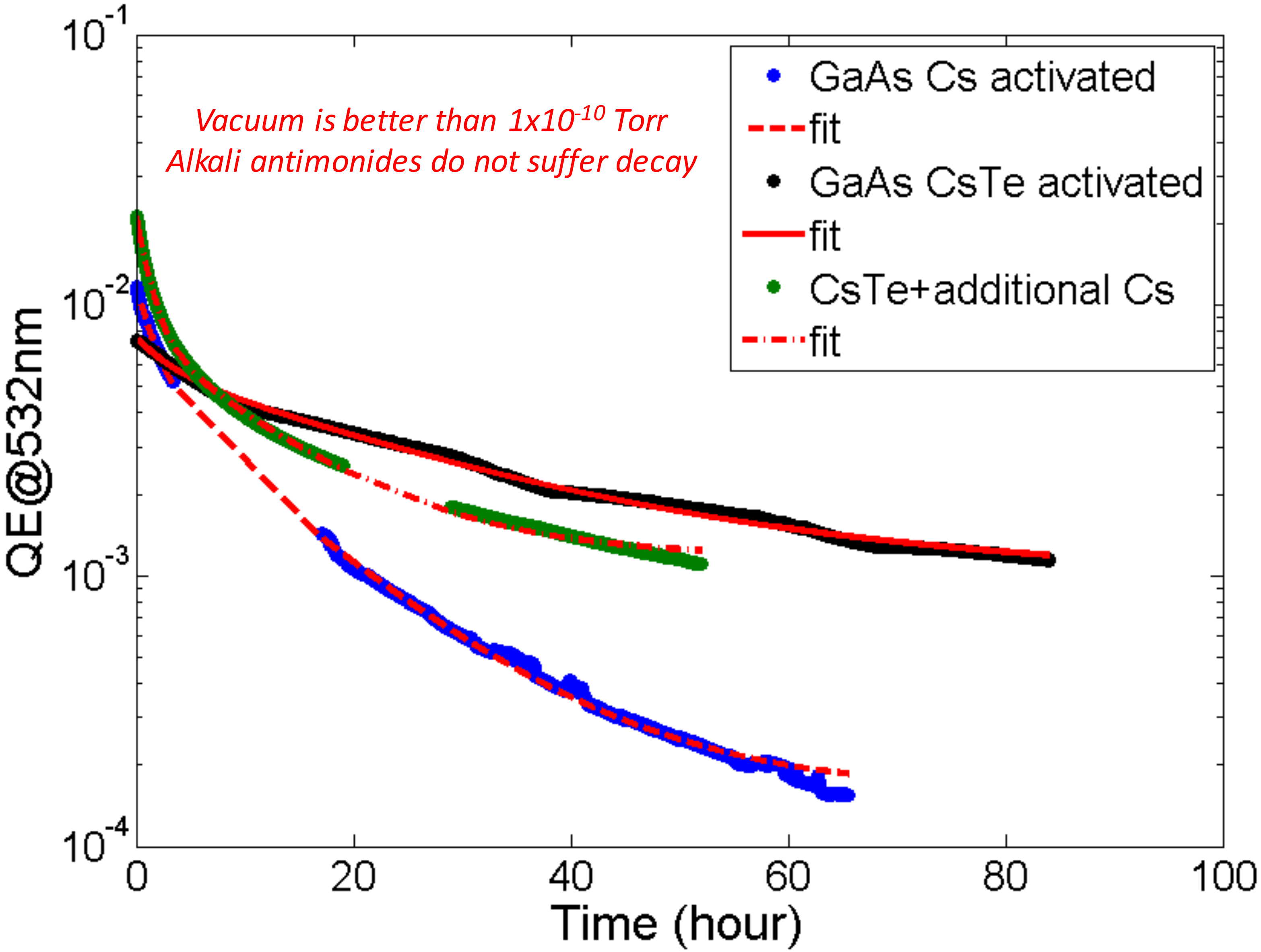
Patchy coverage of the surface?

(CsTe is expected to be less than 2 nm thick)

We need to do more surface science analyses

Look for other materials that can produce NEA

CsTe improved lifetime



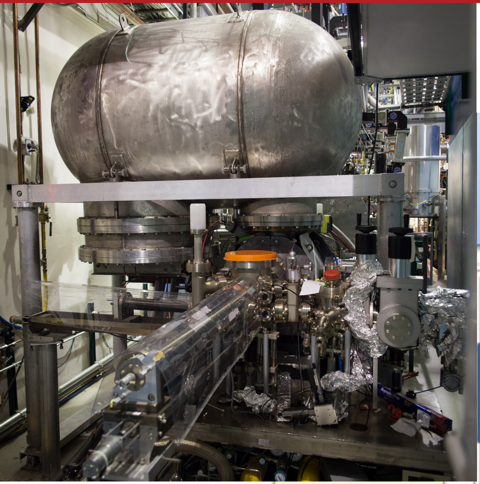
Vacuum is better than 1×10^{-10} Torr
Alkali antimonides do not suffer decay

Happening from next week

Just received and installed the 20 kV power supply

- Measure asymmetry due to beam polarization in the Mott detector at 20keV:
  - using Cs activated GaAs to measure S(θ);
  - using CsTe activated GaAs to measure polarization;
- Attempt NEA activation with thin Cs_3Sb;

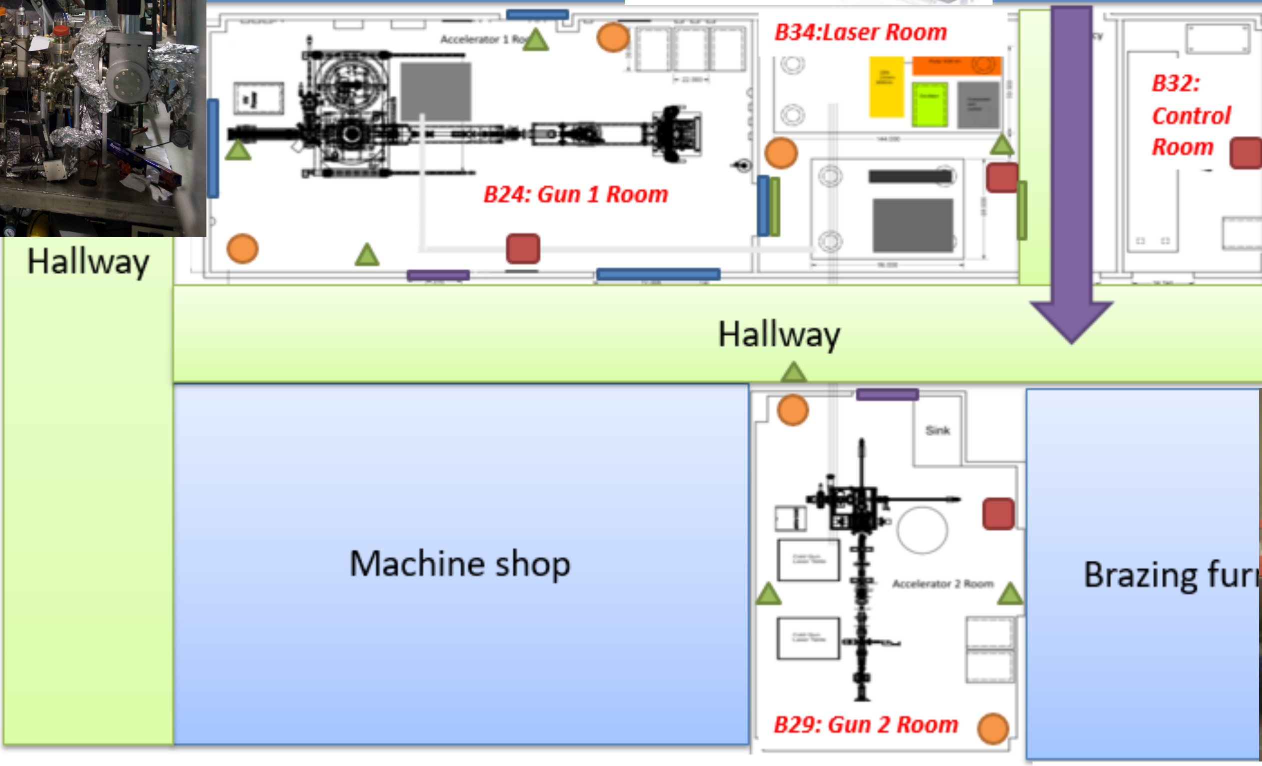
And in the near future



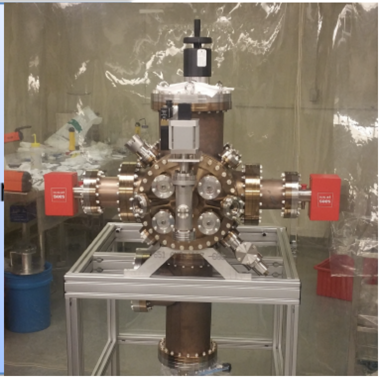
Up to 400 kV
Up to 100 mA

High power cw tunable Ar-ion laser

High average power UV-IR OPA



● Search box
■ Emergency crash
▲ Gamma Probe
▬ HV Interlocked door
▬ HV Keypad (Magnetic Lock)
▬ Laser Keypad (Magnetic Lock)



Up to 200 kV
Cooled to cryogenic T (20 K)
Compact inverted insulator design
INFN/DESY/LBNL miniplug

Conclusions

- Cornell photoinjector has generated up to 2 nC electron bunches;
- High average current have been demonstrated up to 400 pC and 20 mA level;
- We have implemented techniques to measure the effects of the ions and to clear them;
- The photocathode lab is now equipped with a polarimeter to study the production of polarized electron beam from new photocathodes;
- The photogun lab has been moved in a new location and will be soon available to perform beam studies;

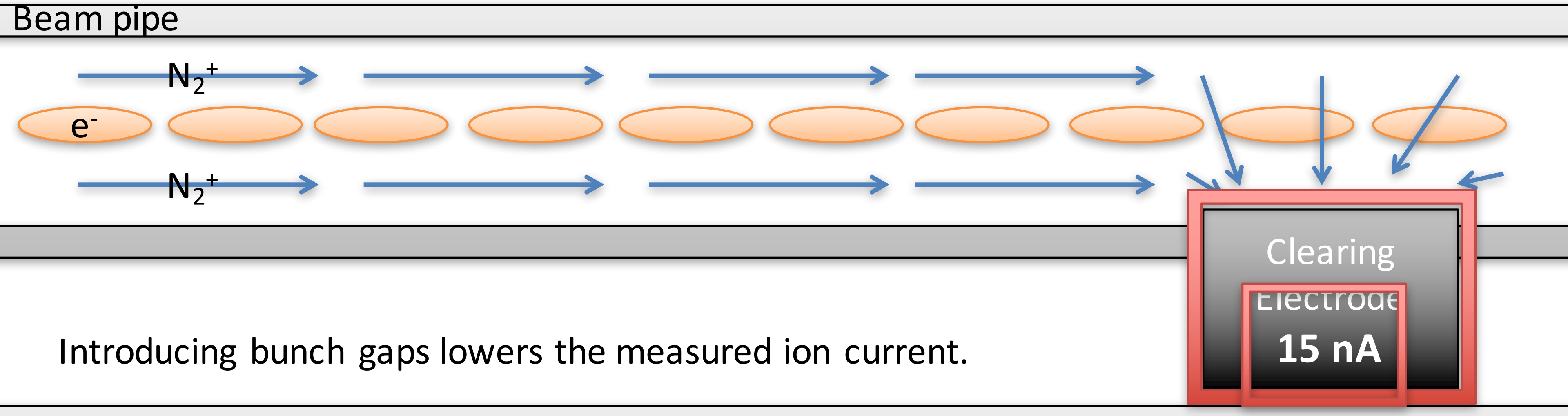
Thank you!

Gun lab as of today

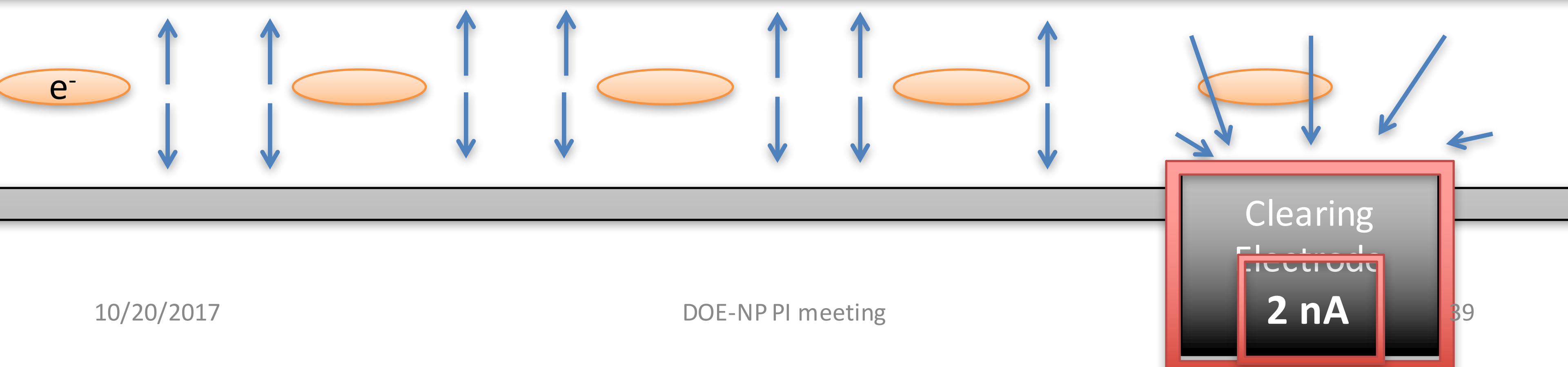
Clearing electrode setup

Clearing electrode and Bunch gap measurements

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

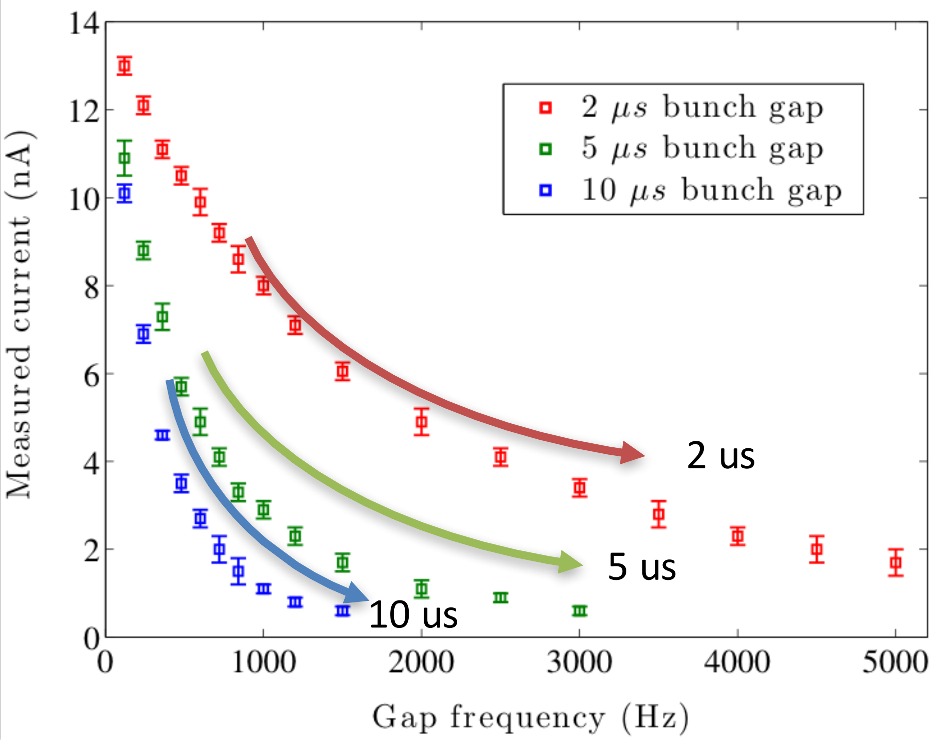


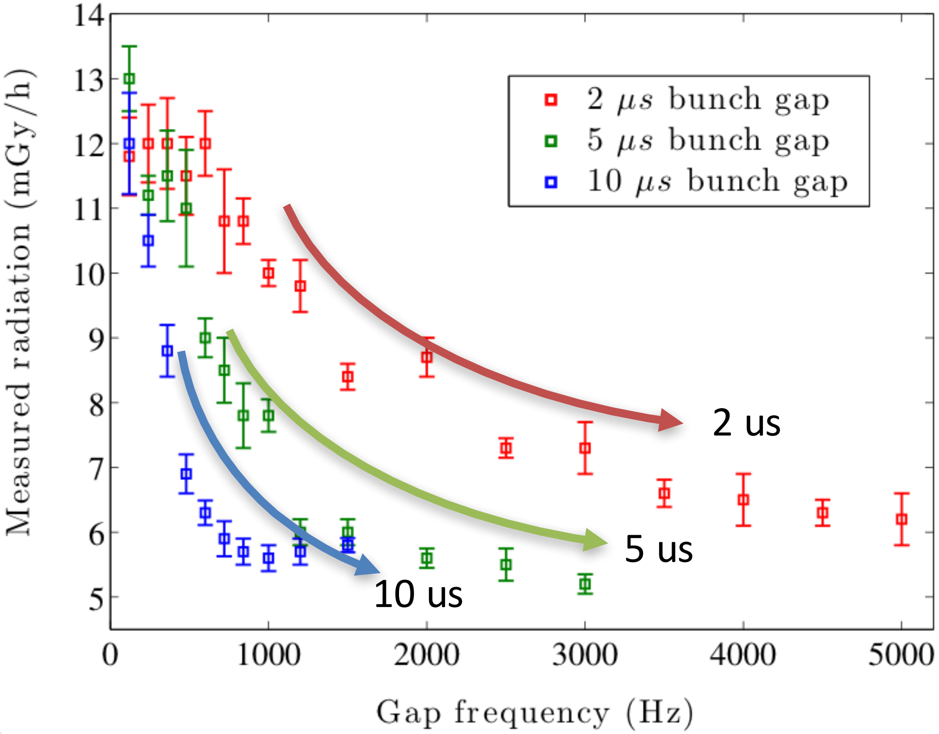
Introducing bunch gaps lowers the measured ion current.



Bunch gap measurements

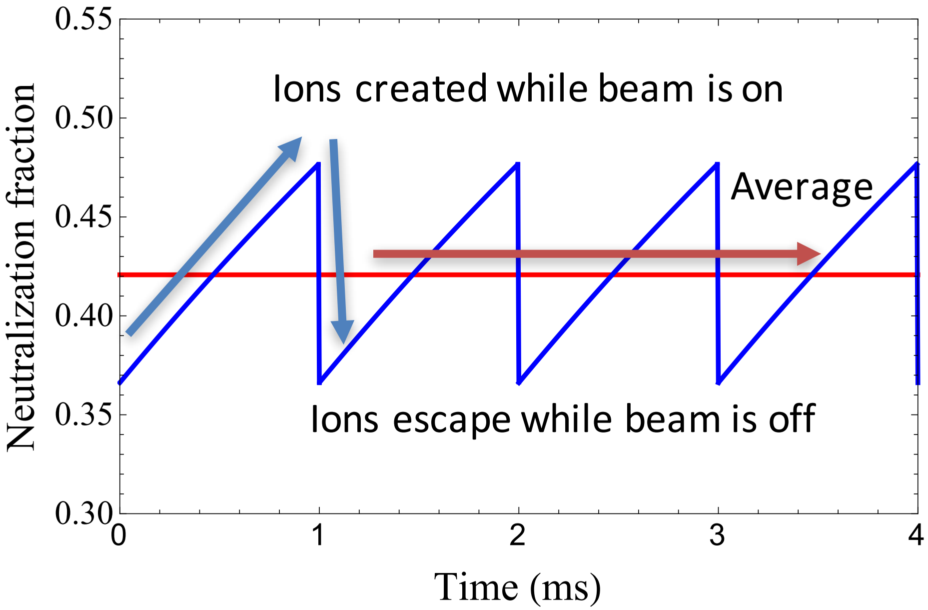
Beam current held fixed at 10 mA





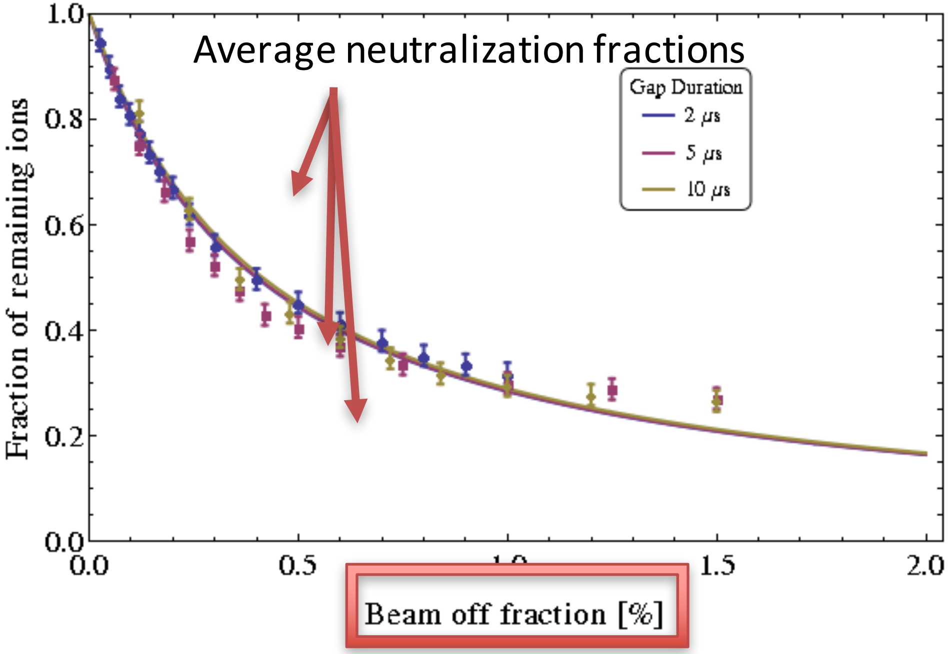
Confirms that the ions are being cleared by the gaps, and not just the clearing electrode

Measurement analysis


Ions created while beam is on

Average

Ions escape while beam is off


Average neutralization fractions

Our model: The ion density…

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

2) Decays exponentially during the bunch gaps.

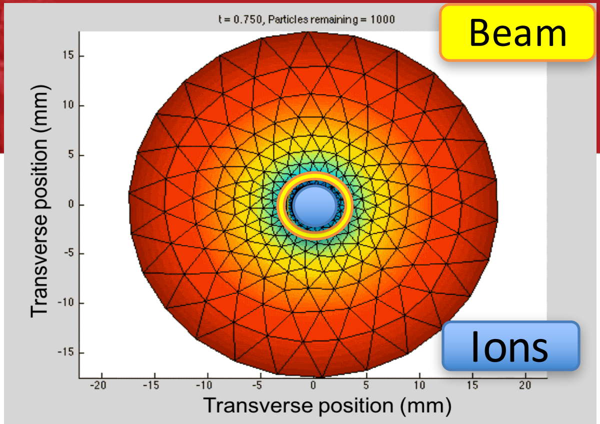
3) We measured the average neutralization fraction.

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

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

Flexibility!

Beam shaking

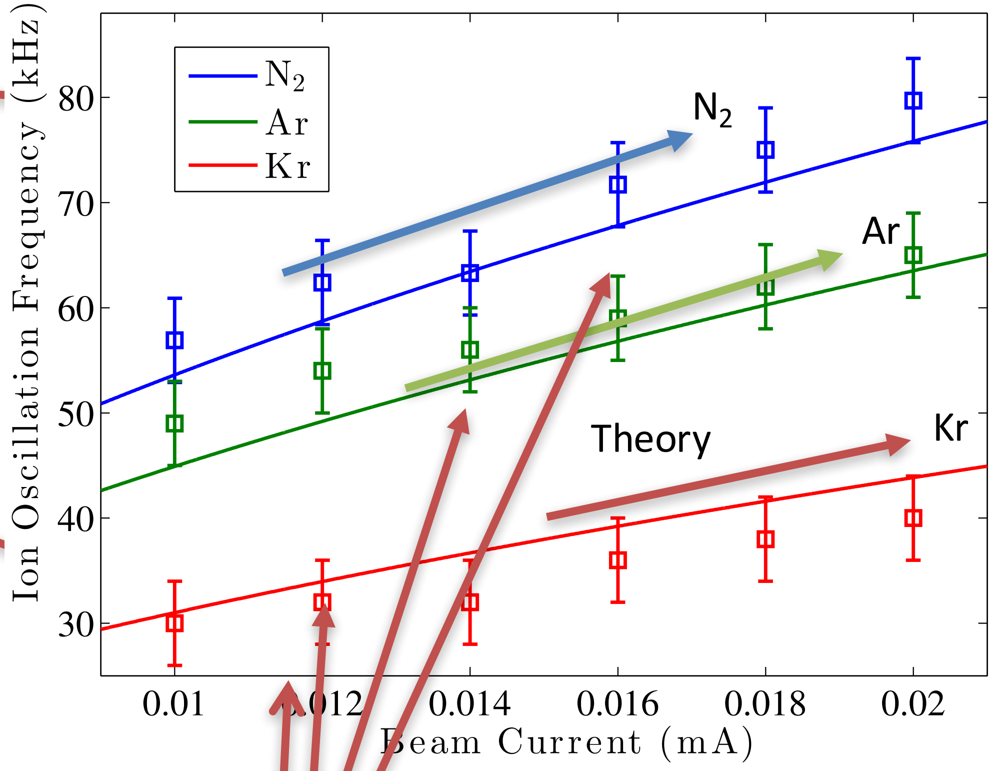


Shaking at the resonance frequency results in a reduction of background radiation.

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.



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