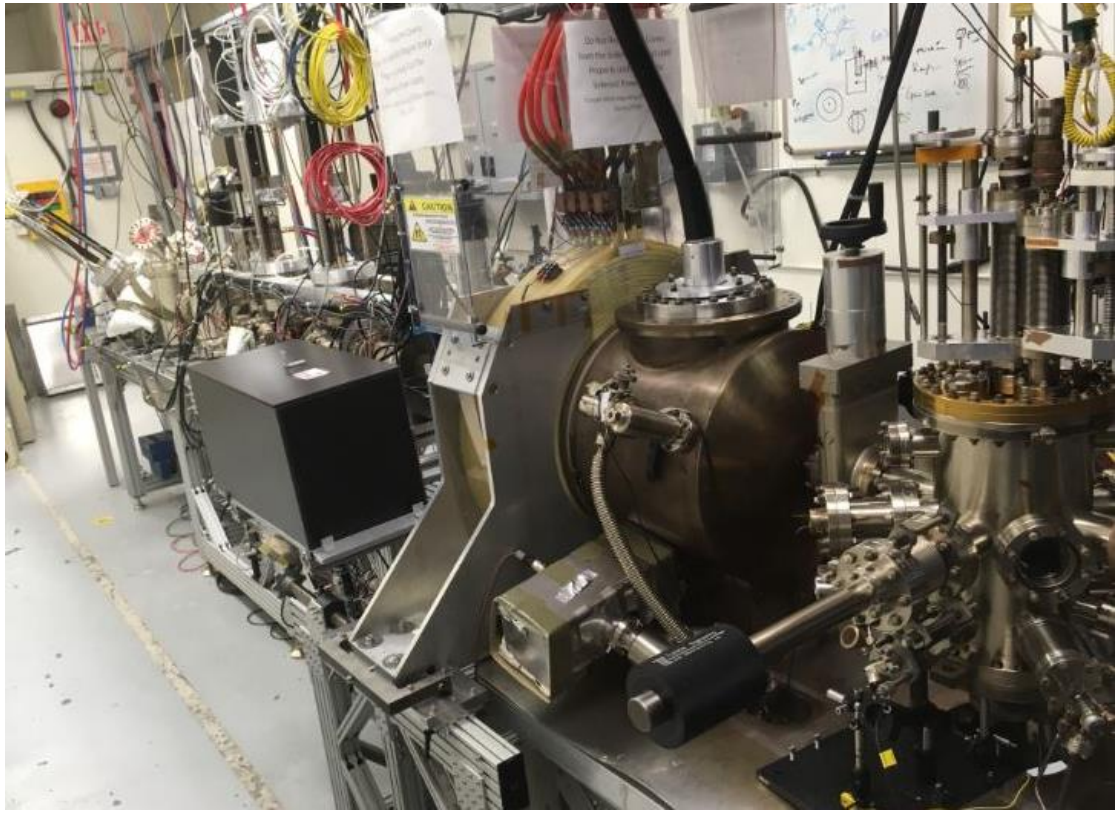
# Magnetized Electron Source for JLEIC Electron Cooler

Md Abdullah Mamun



Photocathode Physics for Photoinjectors (P3)

October 15-17, 2018

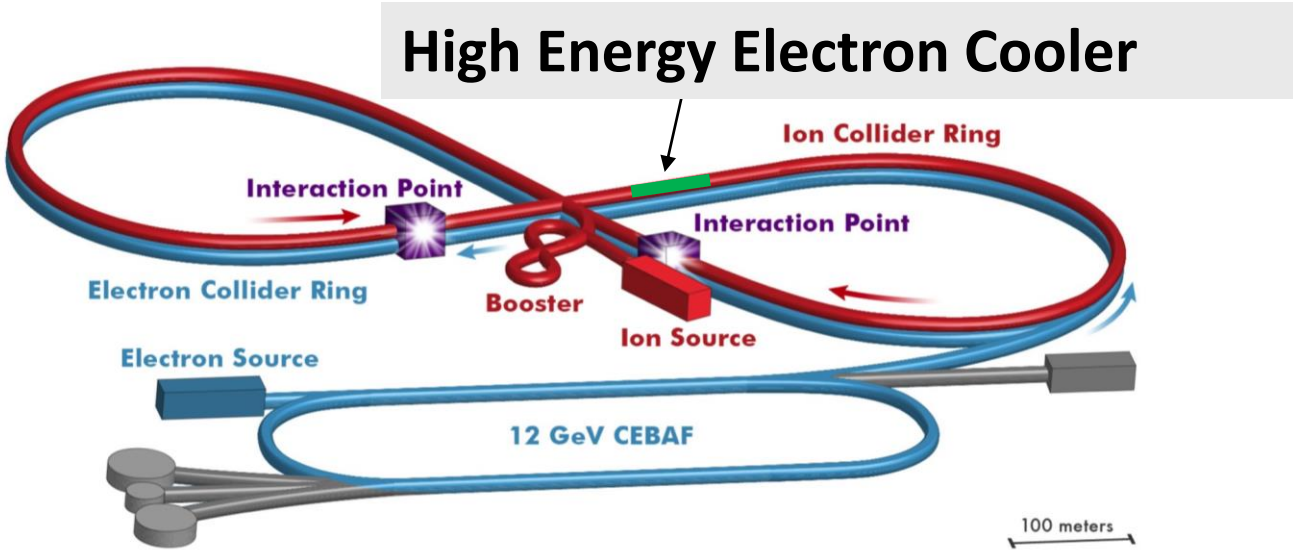
Santa Fe, New Mexico

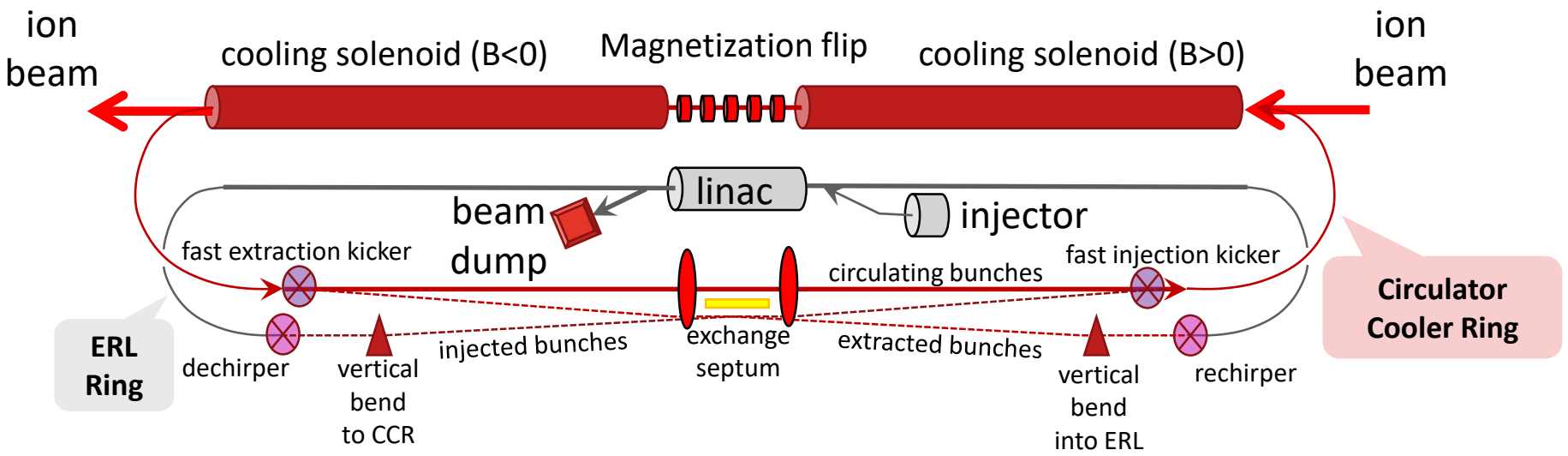
Jefferson Lab

U.S. DEPARTMENT OF ENERGY | Office of Science

JSA

# JLEIC High Energy Electron Cooler



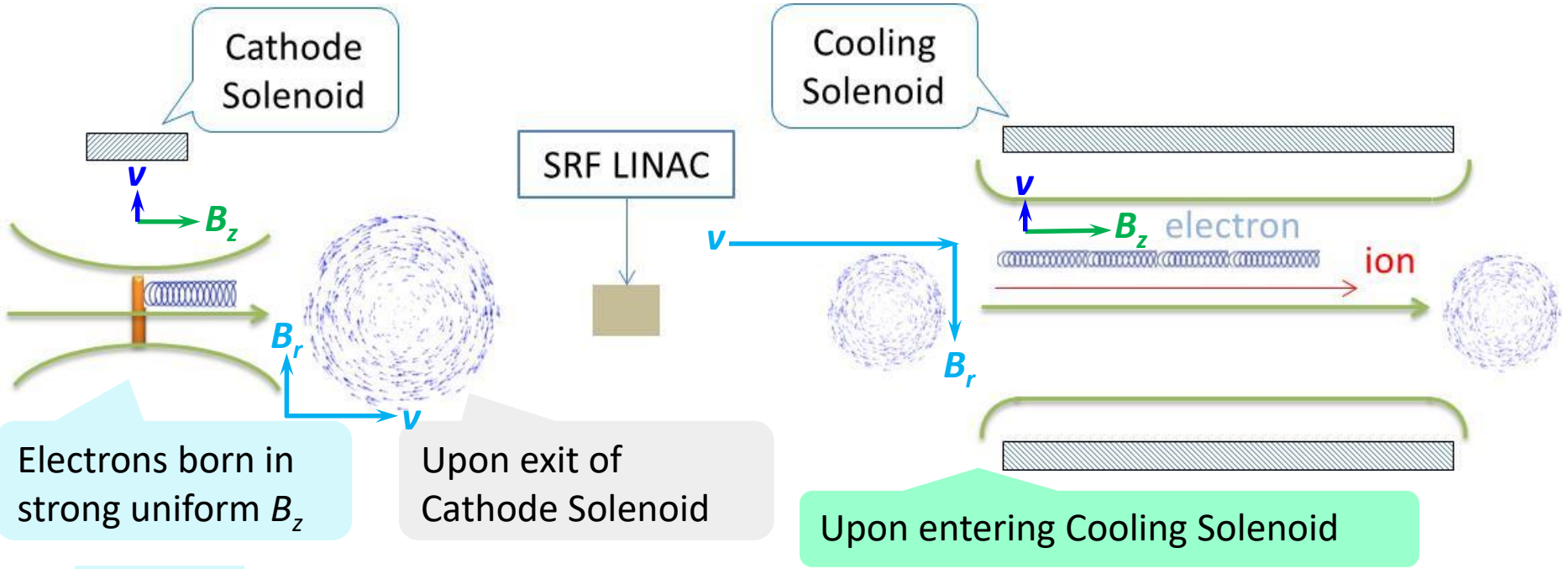
# Magnetized Bunched-Beam Electron Cooling

- Ion beam cooling in presence of magnetic field is much more efficient than cooling in a drift (no magnetic field):
  - Electron beam helical motion in strong magnetic field increases electron-ion interaction time, thereby significantly improving cooling efficiency
  - Electron-ion collisions that occur over many cyclotron oscillations and at distances larger than cyclotron radius are insensitive to electrons transverse velocity
- Long cooling solenoid provides desired cooling effect:
  - Counteracting emittance degradation induced by intra-beam scattering
  - Maintaining ion beam emittance during collisions and extending luminosity lifetime
  - Suppressing electron-ion recombination

Putting the electron beam into the cooling solenoid represents a challenge

# Magnetized Cooling Schematics

Electron beam suffers an azimuthal kick at entrance of cooling solenoid. But this kick can be cancelled by an earlier kick at exit of photogun. That is the purpose of cathode solenoid.

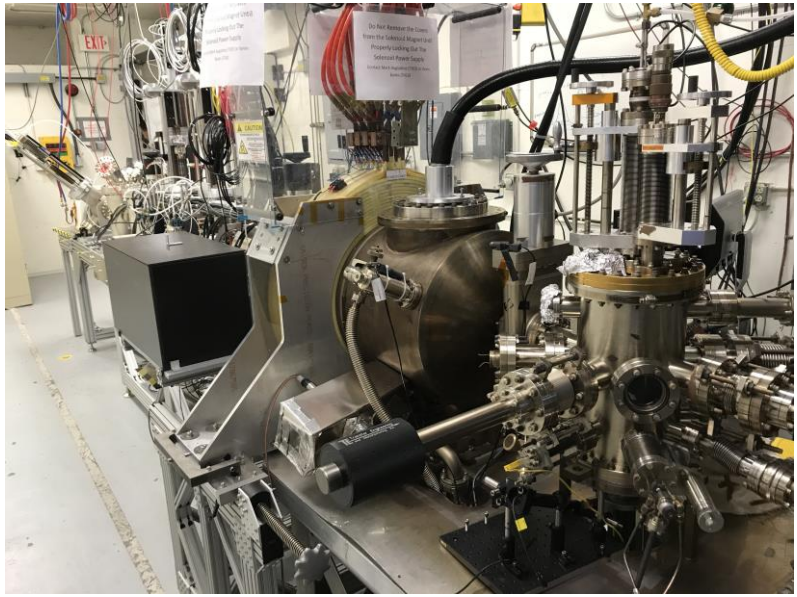



$$\langle L \rangle = \frac{eB_z a_o^2}{4} \qquad \langle L \rangle = \frac{eB_{cool} r_e^2}{4}$$

$$\frac{B_{cool}}{B_z} = \frac{a_0^2}{r_e^2}$$

# Magnetized Source for e-cooler at 30 mA

- Prototype magnetized source was funded by the Jefferson Lab LDRD program that aimed to operate up to 30 mA average current. This three-year project concluded in October 1, 2018
- Goals of the project:
  - Generating magnetized electron beam from dc high voltage photogun and measure its properties
  - Exploring impact of cathode solenoid on photogun operation
  - Simulations and measurements to provide insights on ways to optimize JLEIC electron cooler and help design appropriate source
  - JLab to have direct experience on magnetizing electron beams at high current



Magnetized beam parameters:

- $a_0$ = 0.1-1 mm, $B_z$ = 0-1.5 kG
- Bunch charge: up to 2 nC
- Frequency: 1-15 Hz , 100-500 MHz
- Bunch length: 50 ps
- Average beam currents up to 30 mA
- Gun high voltage: 200 – 350 kV

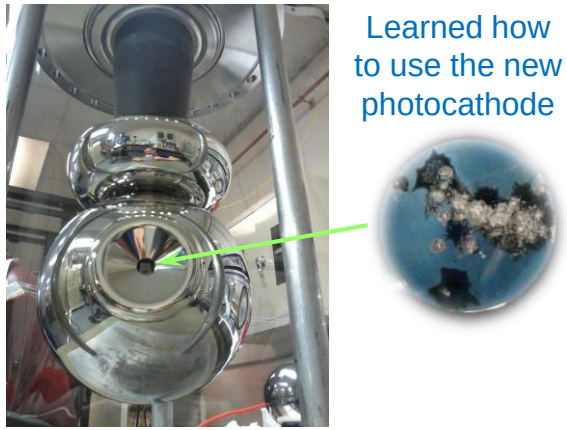
# JLEIC Magnetized Source Requirements

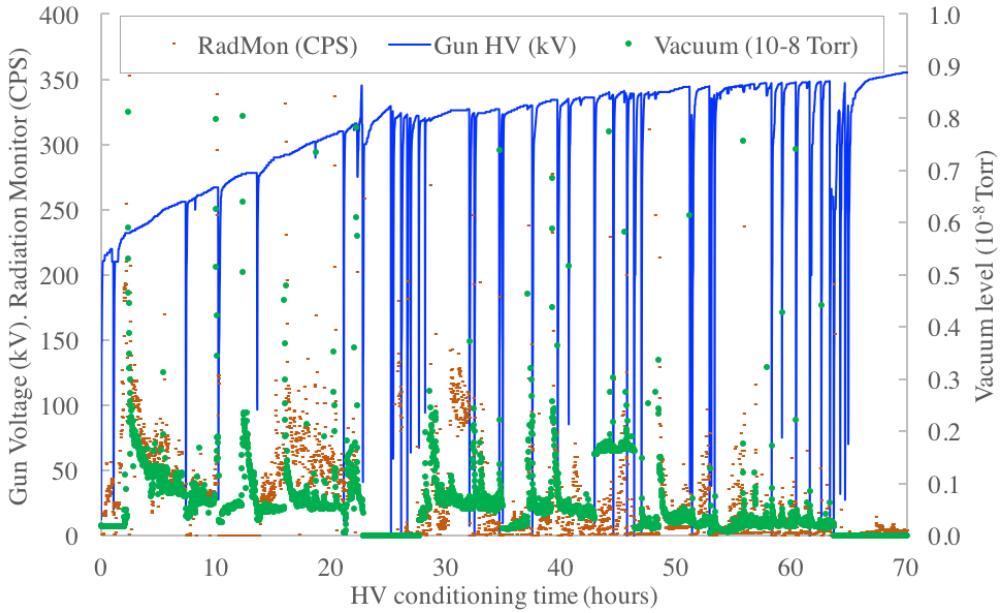
| Parameter | JLEIC | Gun Test Stand Demonstrated |
|---|---|---|
| Bunch length – Flat-top | 60 ps (2 cm) | 25 – 60 ps |
| Repetition rate | 43.3 MHz | 100 Hz – 374.3 MHz |
| Bunch charge | 3.2 nC | 0.7 nC (75 ps FWHM, 25 kHz, 225 kV, 0.76 kG) |
| Peak current | 53.9 A | 9.3 A |
| Average current | 140 mA (400 kV) | 28 mA (50 ps FWHM, 374.25 MHz, 100 kV, 0.57 kG) |
| Transverse normalized emittance | <19 microns | <2 microns |
| Normalized drift emittance | 36 microns | 26 microns |
| Cathode spot radius – Flat-top ($a_0$) | 3.14 mm | 1.70 mm |
| Solenoid field at cathode ($B_z$) | 0.50 kG | 1.51 kG |

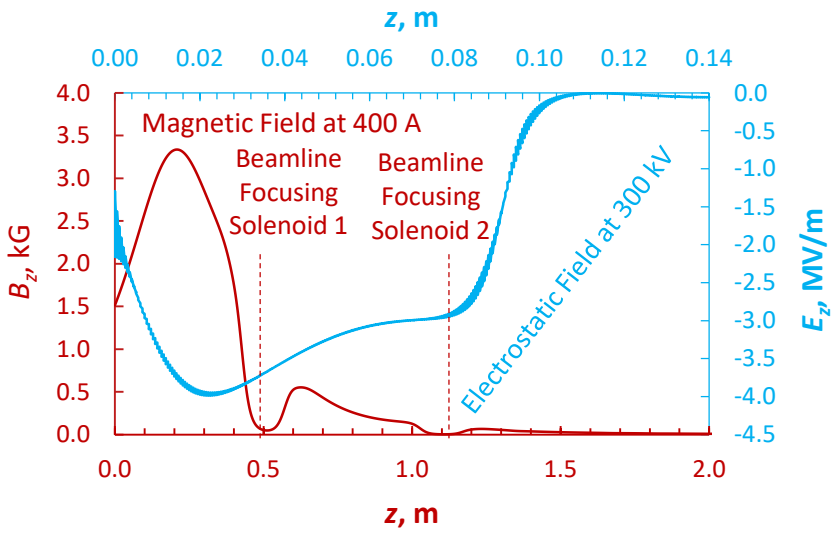
We are power supply limited: 30 mA/225 kV Spellman power supply with 3 kW max power

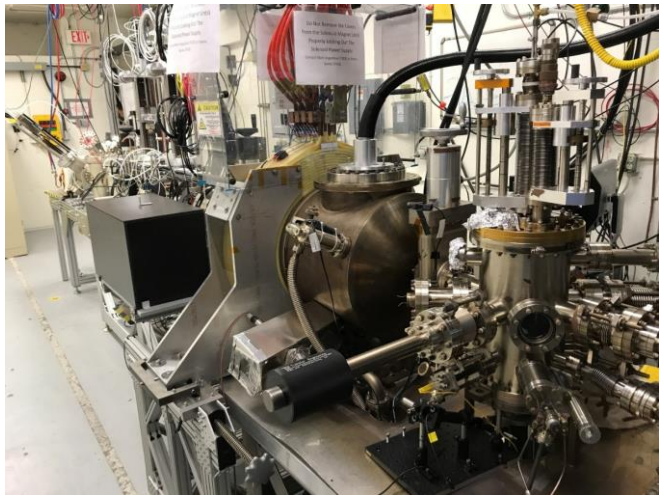
# The Gun Test Stand with 300 kV Inverted Gun and $K_xCs_ySb$ Photocathode

- Upgraded HV Chamber with new doped-alumina inverted insulator and triple point junction shield for max gradient of 10 MV/m at 350 kV
- Gun reached 360 kV in 70 hours of conditioning
- Vacuum and radiation levels indistinguishable from background at 350kV



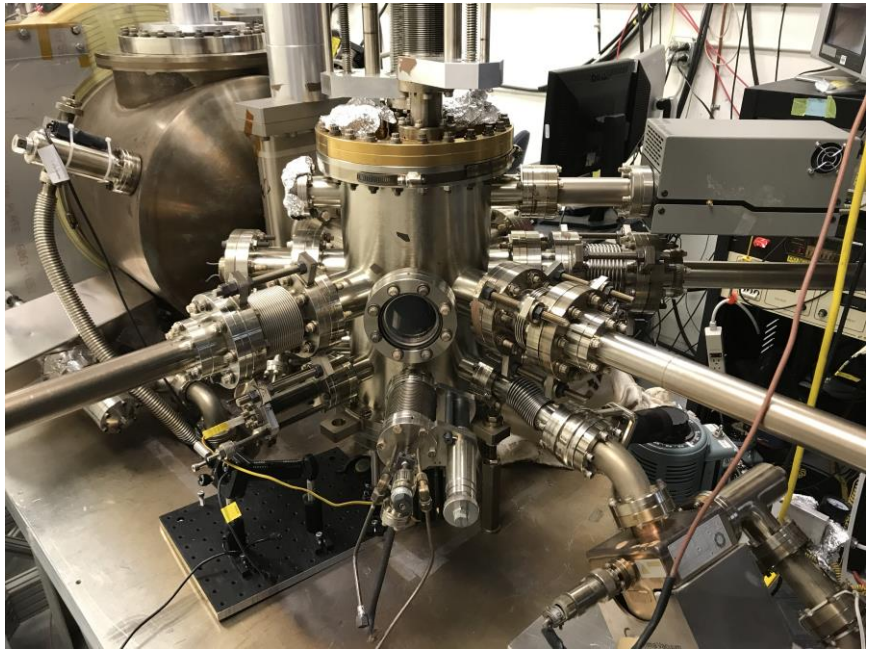



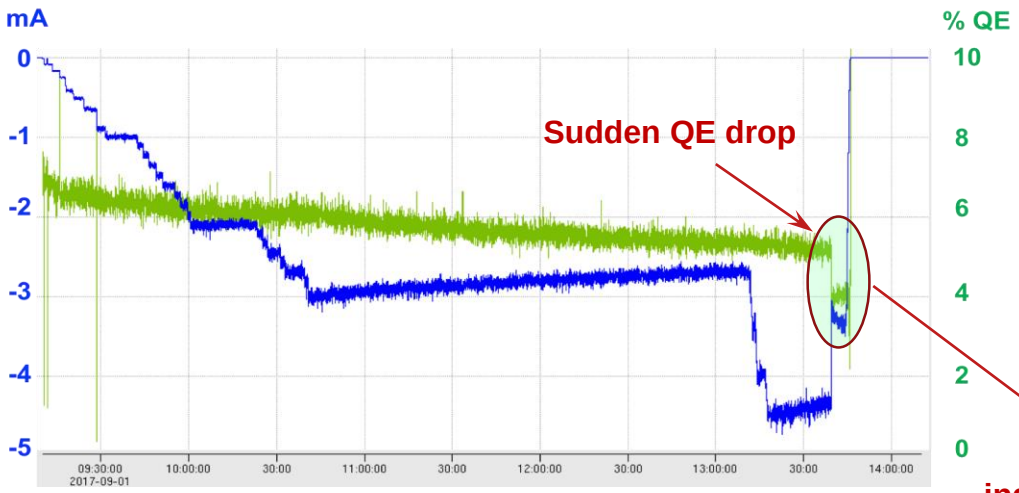



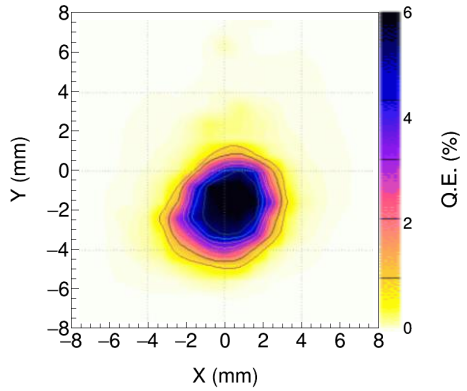



- CEBAF style Dogleg magnet power supply (400 A, 79 V)
- Can provide magnetic field to up 1.5 kG at the cathode
- Learned how to energize solenoid without exciting new field emitters
- Photogun operated at 300 kV with gun solenoid at 400 A

# Photocathode Preparation Chamber





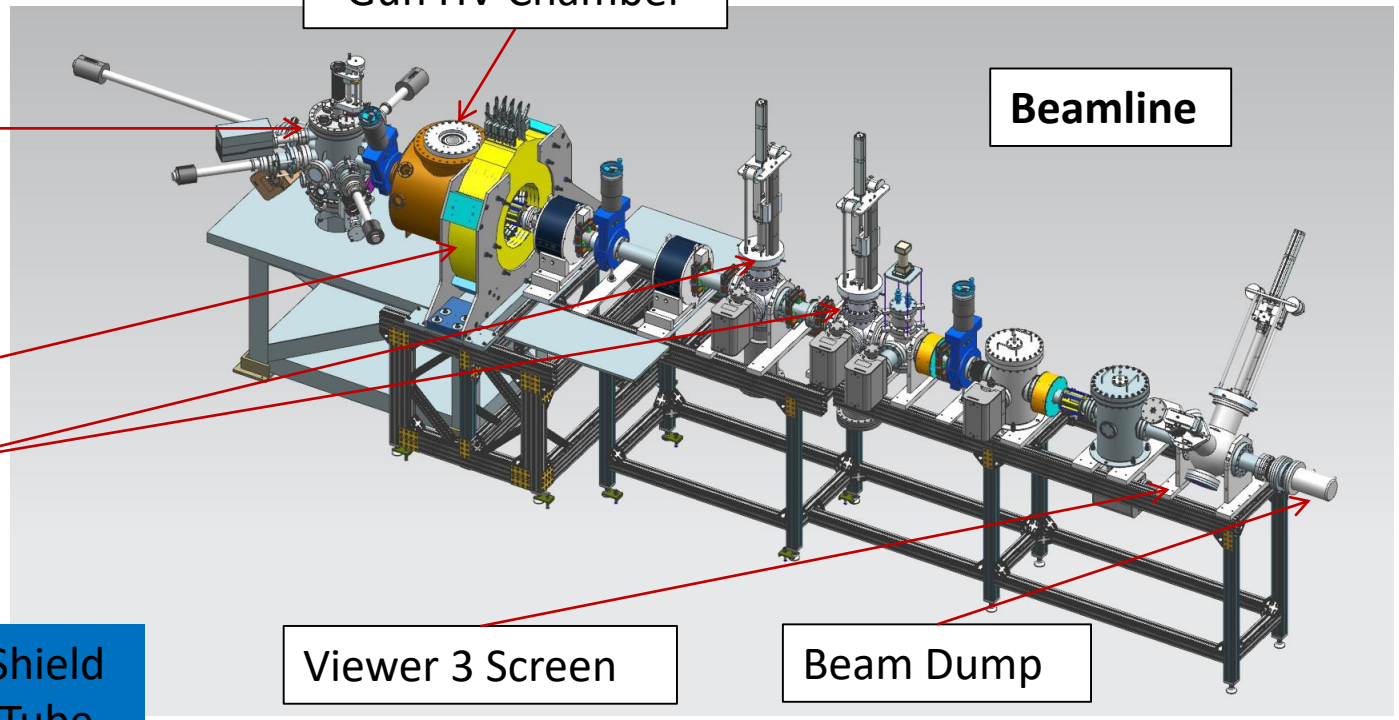

ion induced micro-arcing

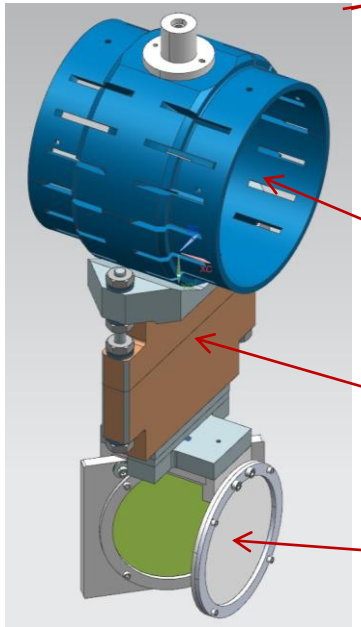
- $K_xCs_ySb$ grown with a mask – limit photocathode active area (3 and 5 mm diameter, entire photocathode can be activated too) to reduce beam halo, minimize vacuum excursions and high voltage arcing, prolong photogun operating lifetime
- Active area can be offset from electrostatic center to minimize damaging on the emission area from ion back bombardment and micro-arcing events during high current run
- Consistently fabricated photocathodes with 5-9% QE
- Moly substrate to reduce laser induced thermal desorption of chemicals during high current run
- Apply positive anode bias to prevent ion induced micro-arcing while running high current beam

# Photocathode Preparation by Co-deposition

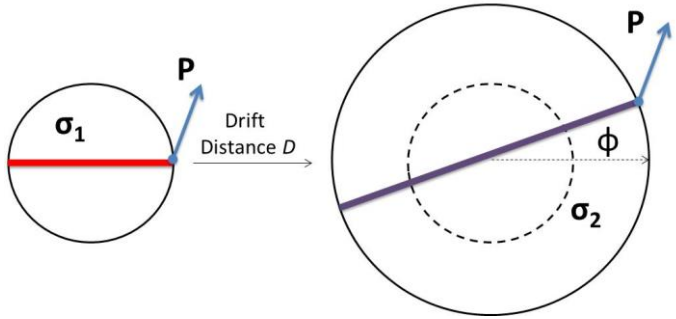
- **Co-deposition of alkalis (K and Cs)** on Sb layer using an effusion alkali source to grow bialkali antimonide photocathode
- Deposition chamber was initially baked at 200 °C for >180 h
- Vacuum with NEG pumps and an ion pump, Vacuum ~10 nA (~$10^{-10}$ Pa)
- Sb (99.9999%) , K (99.95%), and Cs (99.9+%)
- Working distance: 2 cm, – 280 V bias, low power (4 mW) laser (532 nm) and wavelength tunable light source
- Substrate temperatures: 120 °C (for Sb), dropping from 120 °C to 80 °C (for alkalis)
- Sb heater current supply from 25 A for 10-20 minutes
- **RGA as a control to monitor evaporation rate**
- Temperature kept stable at effusion source and adjusted to control alkali evaporation rate: hot air inlet tube (381 – 462 °C), dispensing tube (232 – 294 °C), and reservoir tube (153 – 281 °C)
- Chamber pressure: during bialkali deposition > $1\times10^{-6}$ Pa
  and post-deposition to ~$10^{-7}$ – $10^{-8}$ Pa
- $H_2O$ partial pressure < $2\times10^{-9}$ Pa

# Magnetized Source Schematics




Use slit and viewscreens to characterize magnetization:

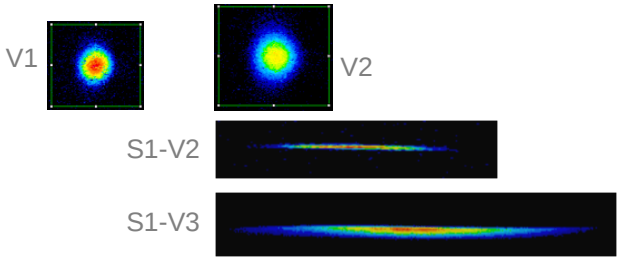



$\sigma_i$: beam size on $i$ -th viewer
$\phi$: rotation (sheering) angle

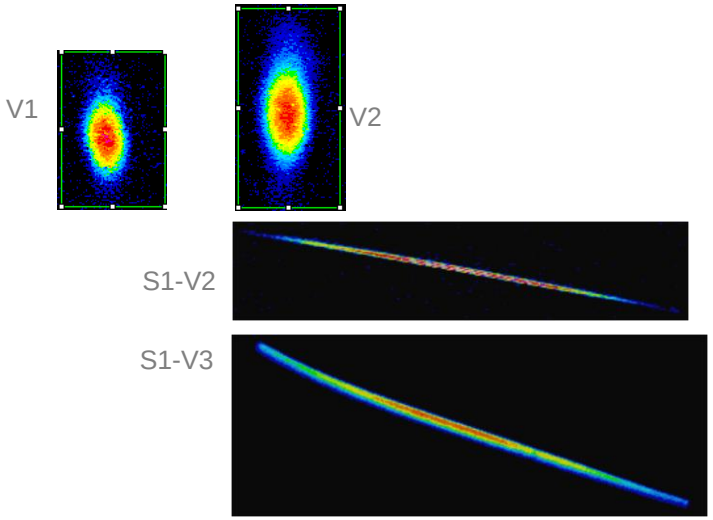
# Magnetization Measurement

## Beam and beamlet observed on successive viewers

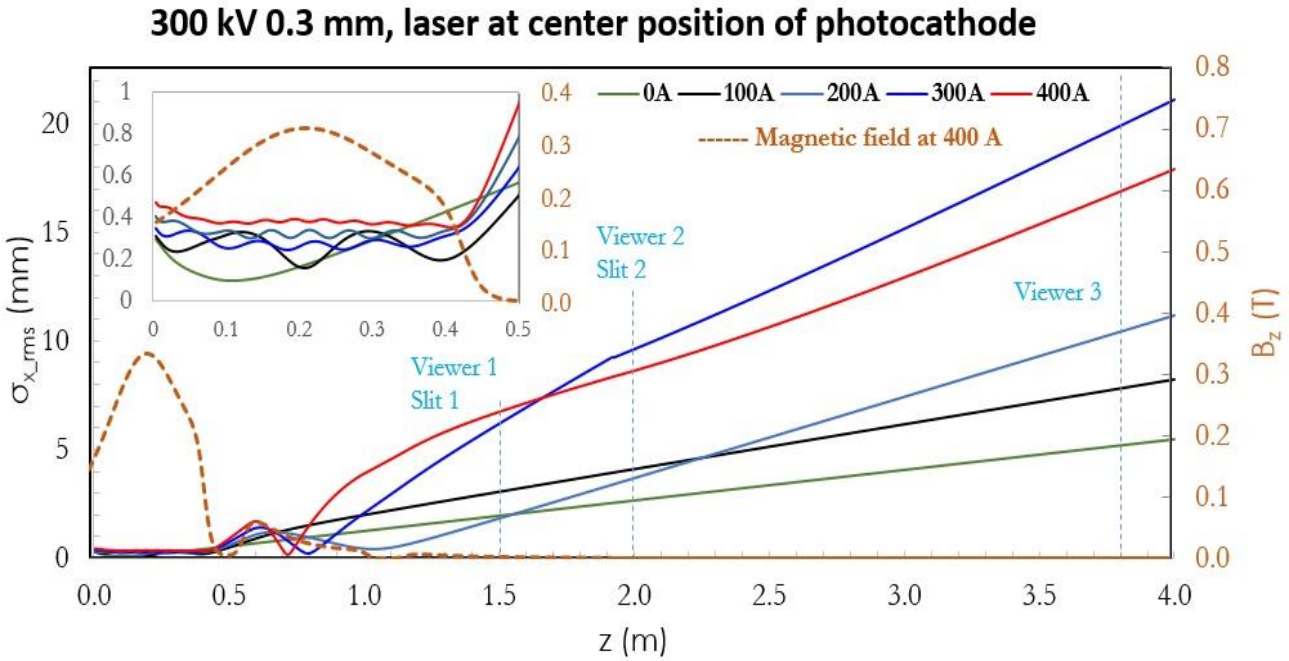
Magnetic field at photocathode = 0 G




Magnetic field at photocathode = 1514 G




## Beam size and Rotation: Experiment vs ASTRA simulation

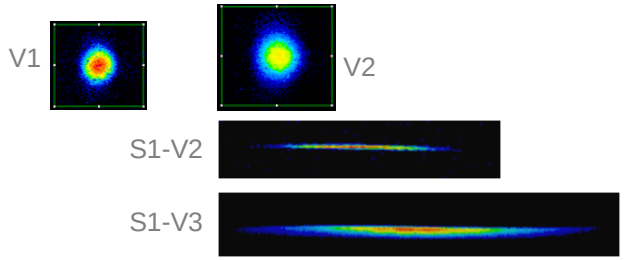



- Modelled the apparatus using ASTRA & GPT
- Larmor frequency increases with magnetic field at cathode
- Focusing by cathode magnetic field causes mismatch oscillations resulting in repeated focusing inside cathode solenoid field which affects beam size at exit of solenoid field and resulted in varying beam expansion rate in field free region

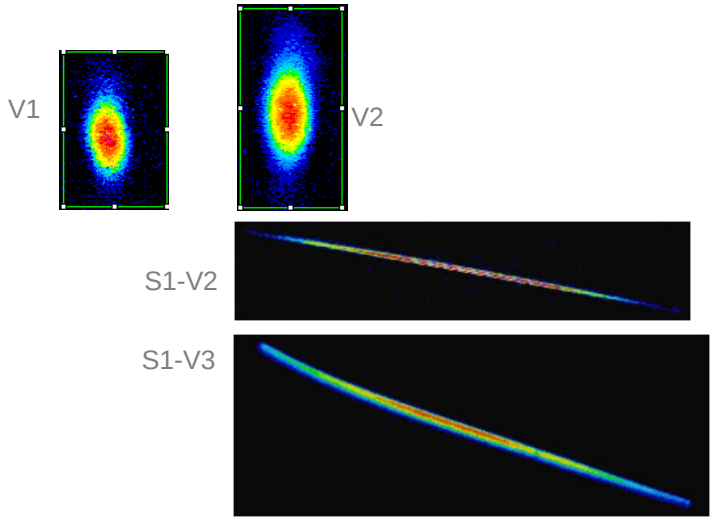
# Magnetization Measurement

## Beam and beamlet observed on successive viewers

Magnetic field at photocathode = 0 G




Magnetic field at photocathode = 1514 G

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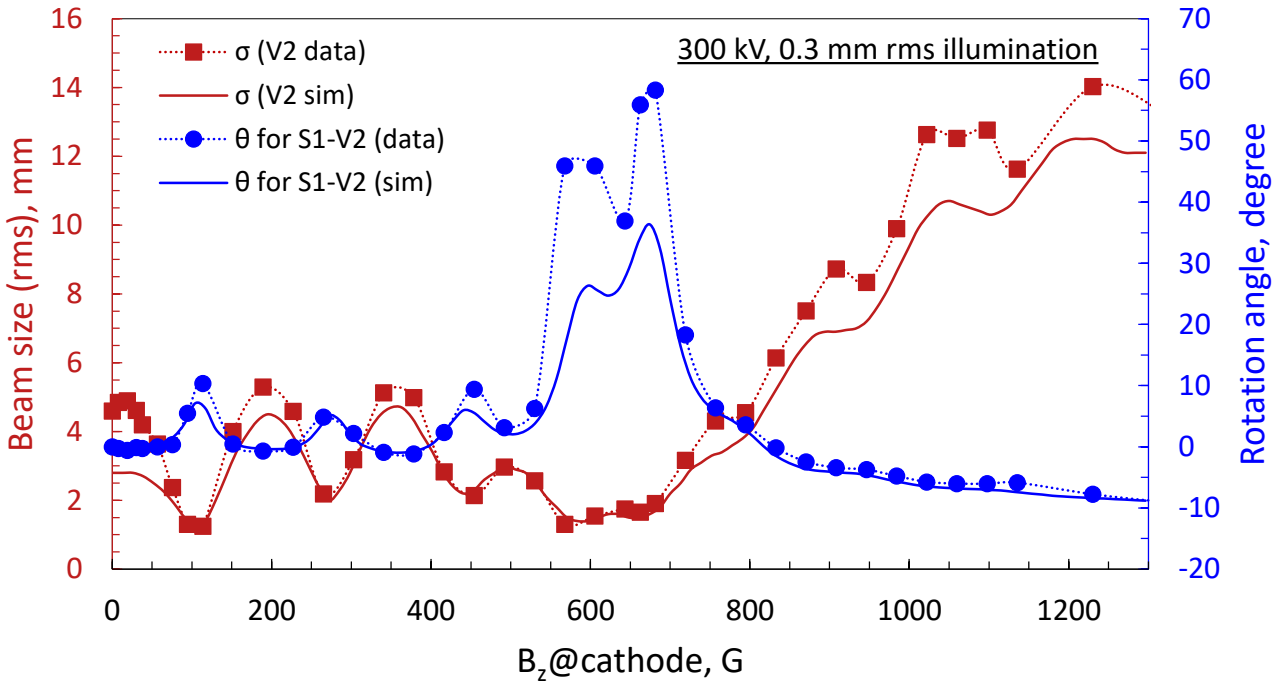
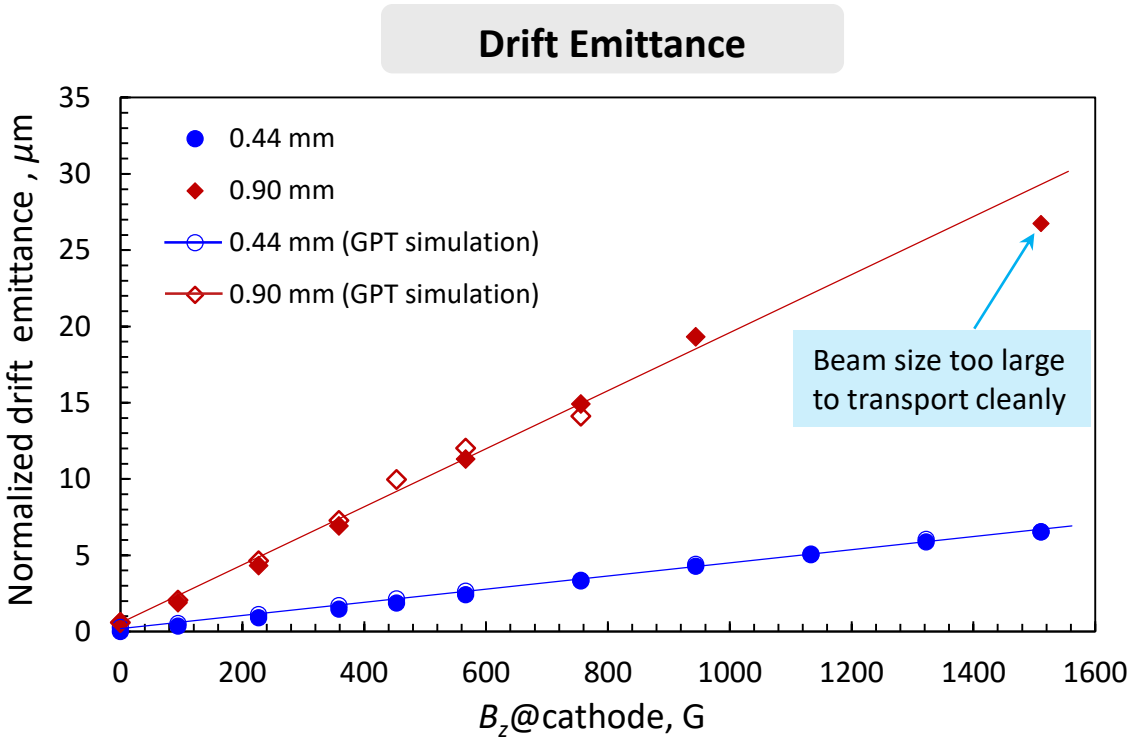
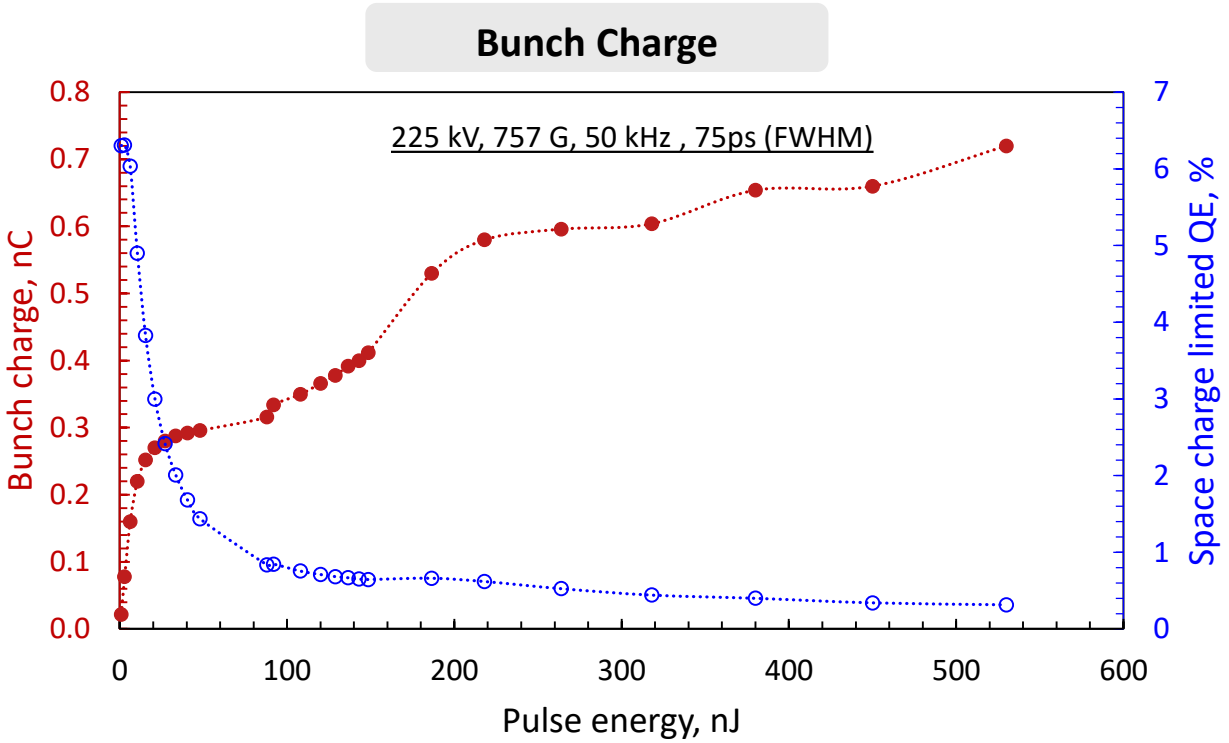



- Modelled the apparatus using ASTRA & GPT
- Larmor frequency increases with magnetic field at cathode
- Focusing by cathode magnetic field causes mismatch oscillations resulting in repeated focusing inside cathode solenoid field which affects beam size at exit of solenoid field and resulted in varying beam expansion rate in field free region
- Rotation angles are influenced by focusing in cathode solenoid

# Drift Emittance and Bunch Charge Measurement

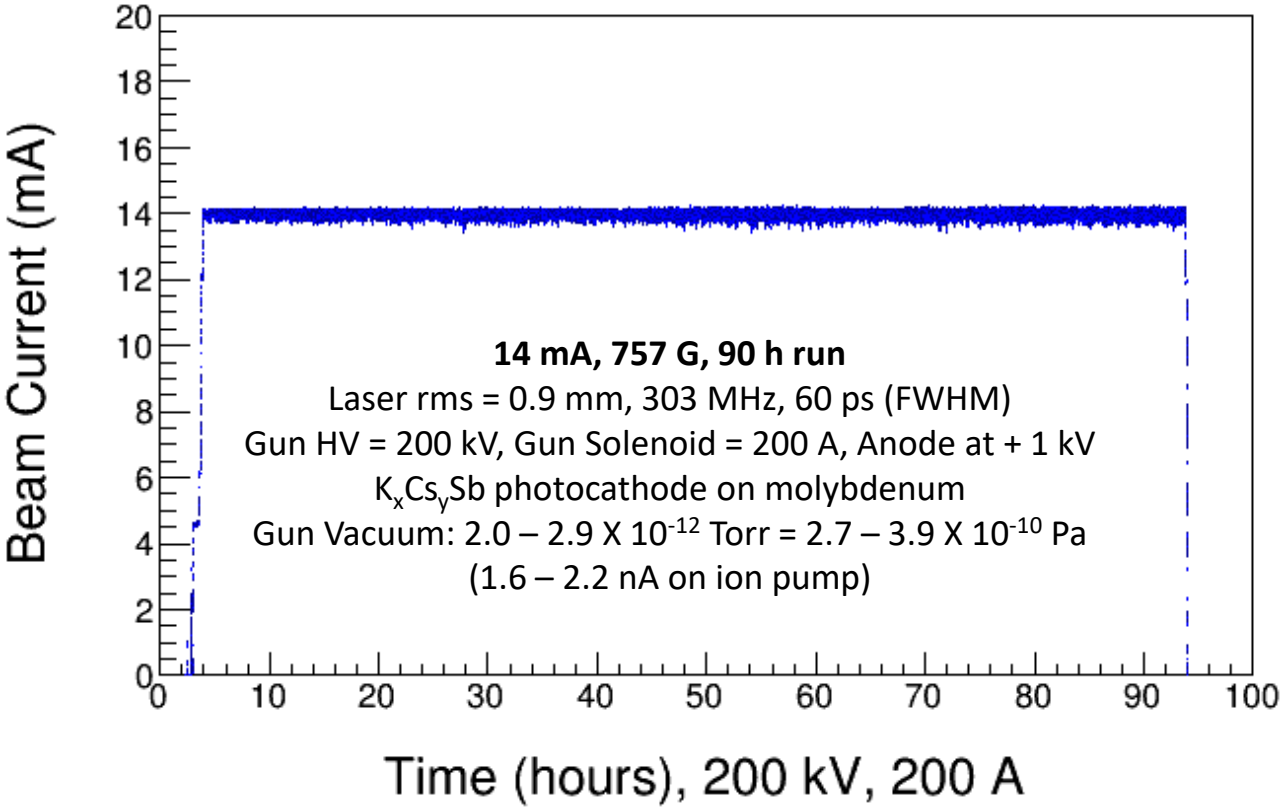


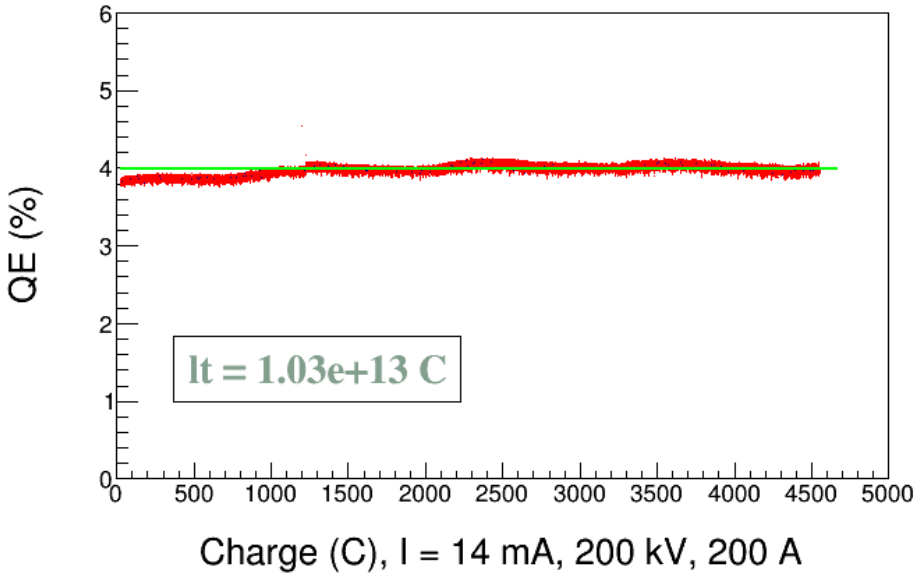



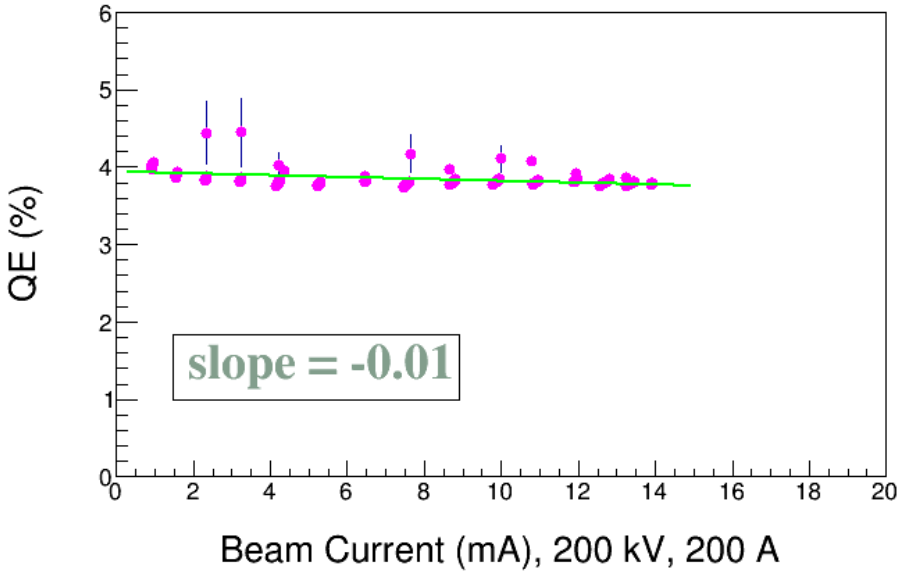

- Measured drift emittance for different spot sizes (rms) at 200 kV for 2 mm off-axis emission spot
- GPT simulation and experimental results show encouraging agreement

- We encounter space-charge-limited regime within 0.3 nC for different magnetized conditions
- Need longer laser pulses and higher gun voltage to get nC bunches

# High Current Magnetized Beam: 14 mA at 757 G for 90 h

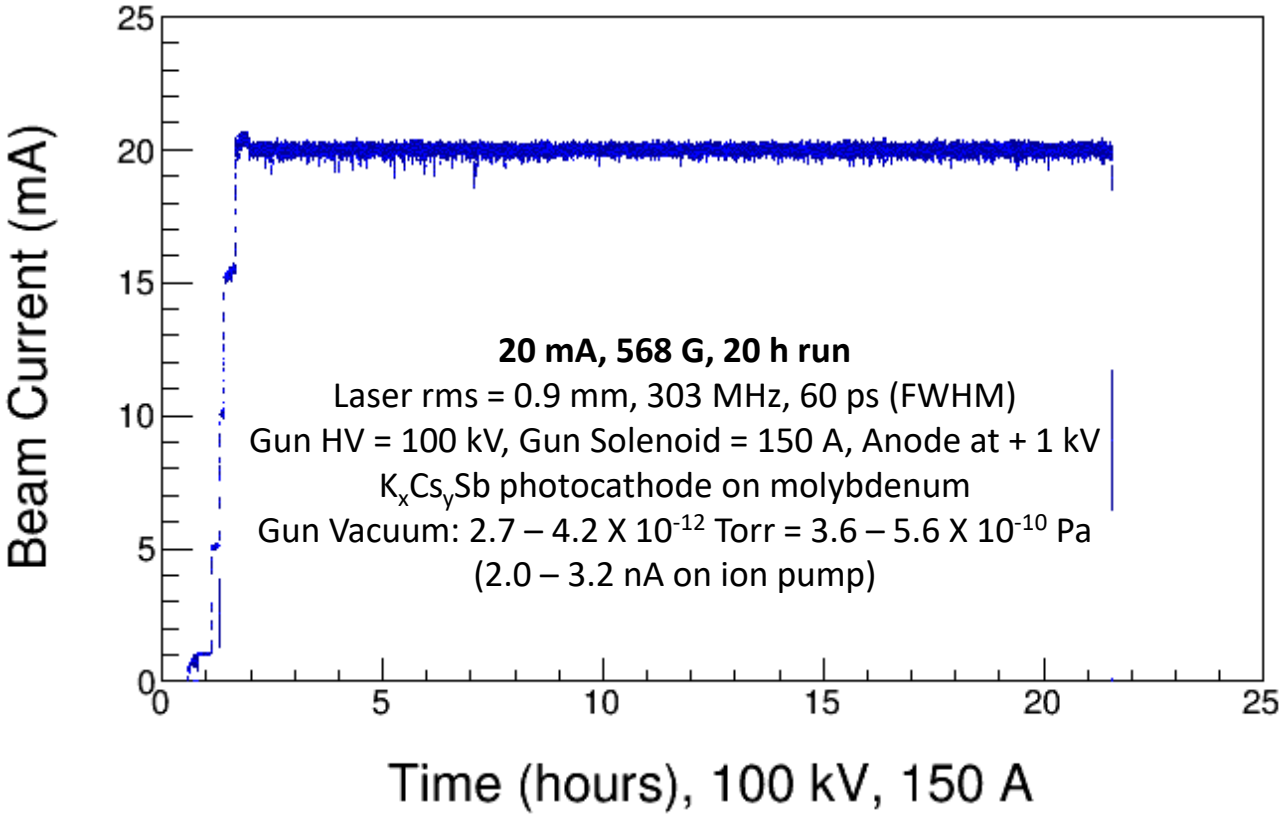


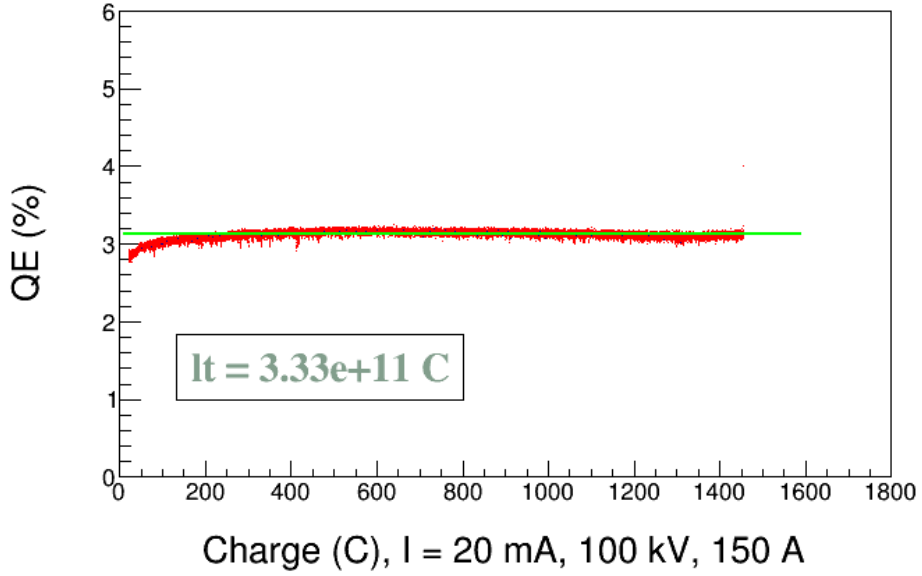



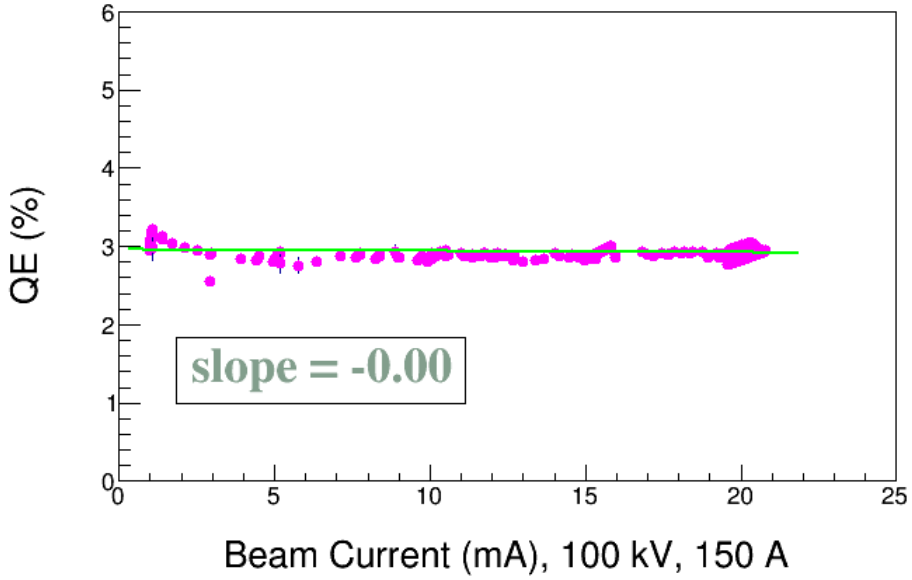




- No QE degradation over 90 hour run
- Positive anode bias (+1 kV) effectively prevented ions in beamline from reaching the gun that causes micro-arcs and sudden QE degradation

# High Current Magnetized Beam: 20 mA at 568 G for 20 h

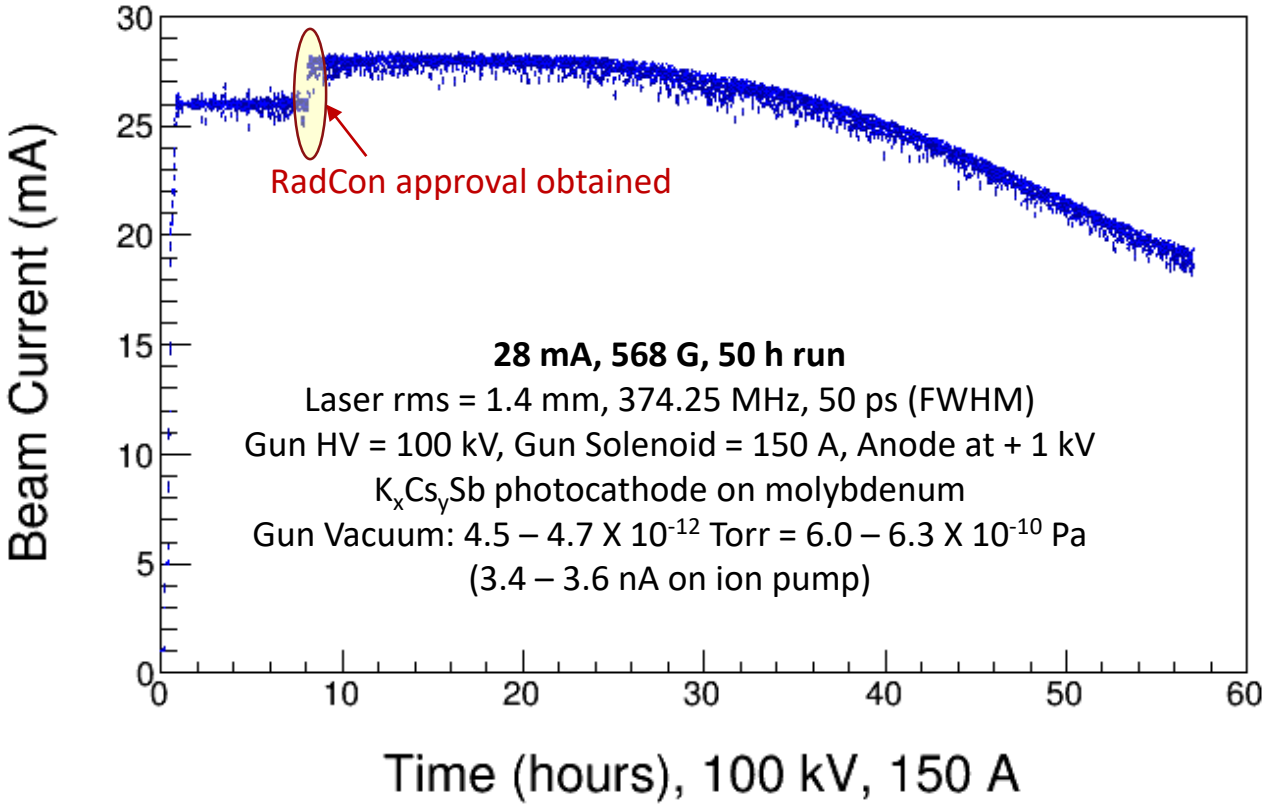


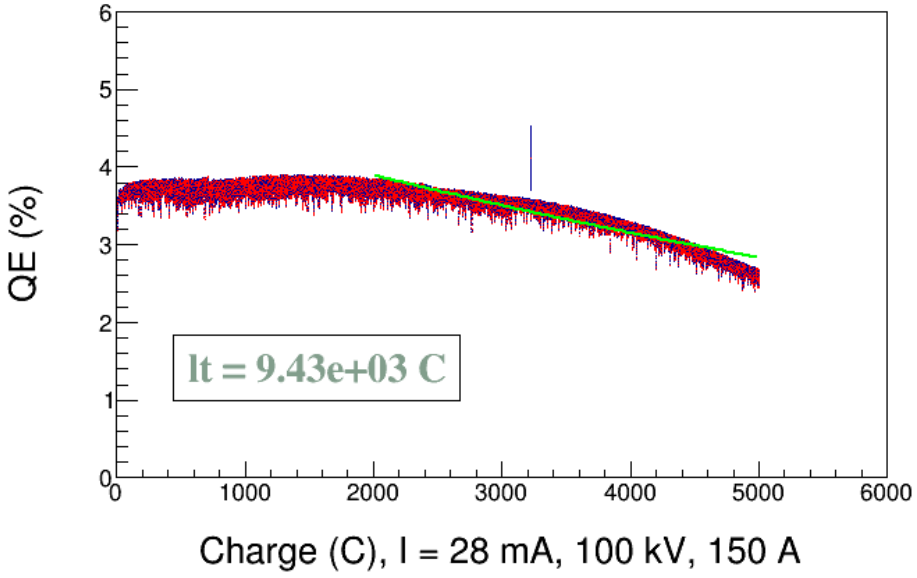



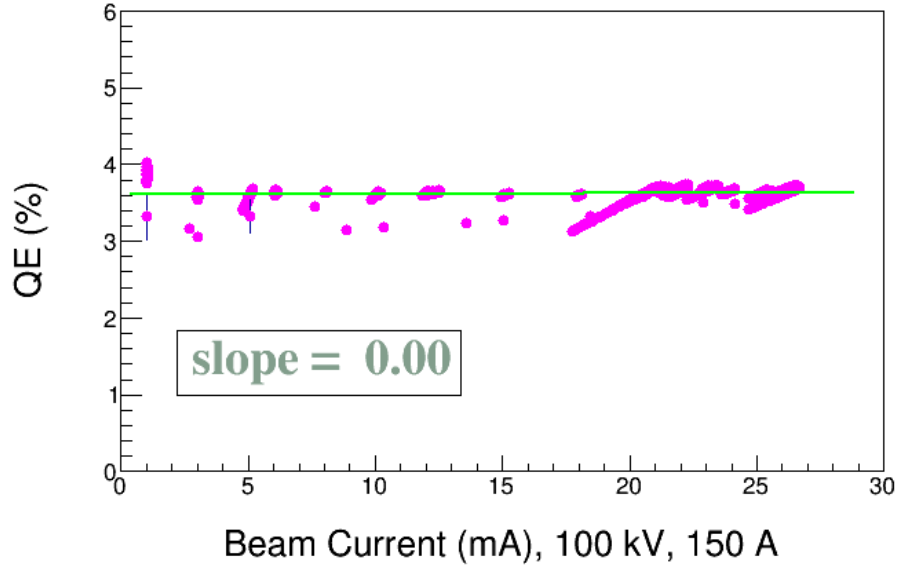




- No QE degradation over 20 hour run
- Positive anode bias (+1 kV) effectively prevented ions in beamline from reaching the gun that causes micro-arcs and sudden QE degradation

# High Current Magnetized Beam: 28mA at 568 G for 50 h



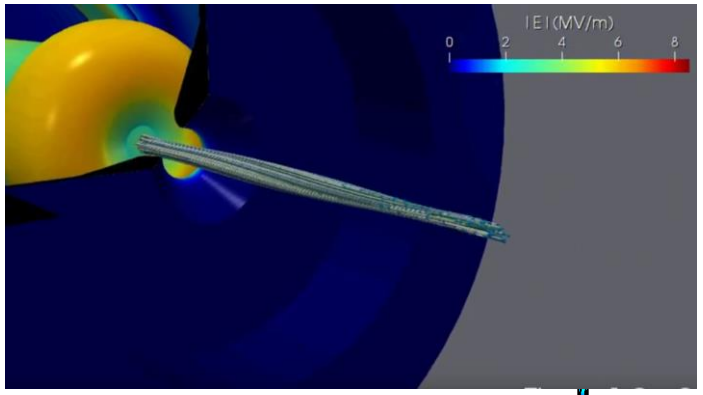



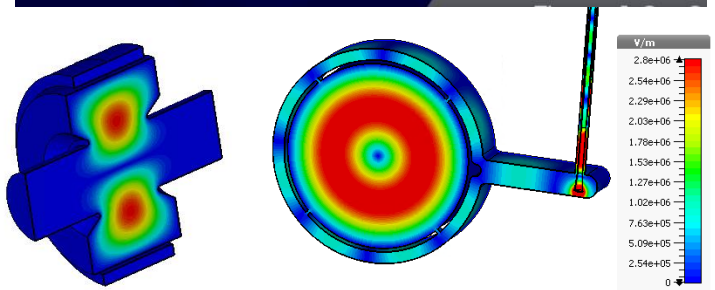



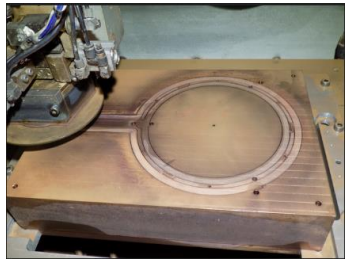

- Limited lifetime might be a result of heating and associated bandgap shift, or enhanced ion bombardment
- Will increase the anode bias voltage beyond 1kV

# Future Plans

- Swap the photogun for the RF-pulsed thermionic gun built by Xelera Research LLC to demonstrate 65 mA magnetized beam (307 G, 500 MHz, 130 pC, 90 ps rms, 125 kV): an SBIR II funded project
- Install non-invasive magnetometers - $TE_{011}$ Cavity and “Brock” Cavity from Electrodynamic to measure beam magnetization and electron bunch-length for high bunch charge beam: another SBIR II funded project
- Reinstall photogun, now with Xelera’s power supply and BNL laser, the setup will enable high average current AND high bunch charge, simultaneously (65 mA, 3 nC)
- Characterize space-charge effects of high bunch charge and high average current beam as a function of beam magnetization
- Collaborate with Xelera, Electrodynamic, BNL and others on follow-up projects



# Summary

- $K_xCs_ySb$ photocathode preparation chamber, gun, solenoid and beamline - all operational
- Photogun operated reliably up to 300 kV for >1000 h
- Cathode solenoid can trigger field emission but we have learned how to prevent this
- Have successfully magnetized electron beams and measured rotation angle and drift emittance
- Used a gain-switched drive laser (374.25 MHz, 50 ps FWHM) to generate 28 mA magnetized beam (568 G at photocathode) with RF structure at 100 kV (using 30 mA/225 kV Spellman power supply, 3 kW power limited)
- Successfully fabricated bialkali antimonide photocathode with QE ~ 9% on molybdenum substrate that provided longer charge lifetime
- Positive bias on anode helps to prevent sudden QE loss from ion-induced micro-arcing events
- Demonstrated high bunch charge up to 0.7 nC

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