# Magnetized beam generated from DC gun for JLEIC Electron Cooler

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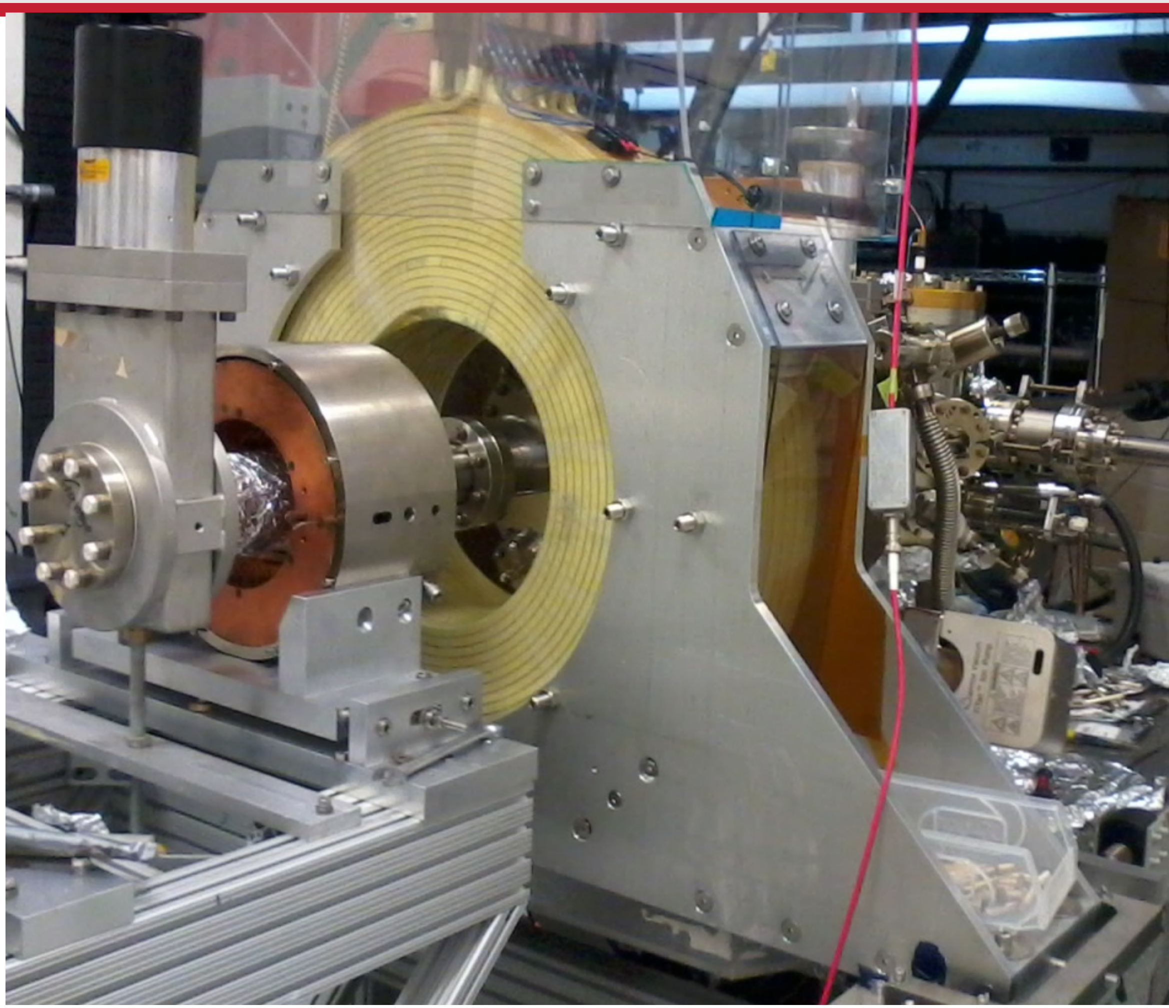
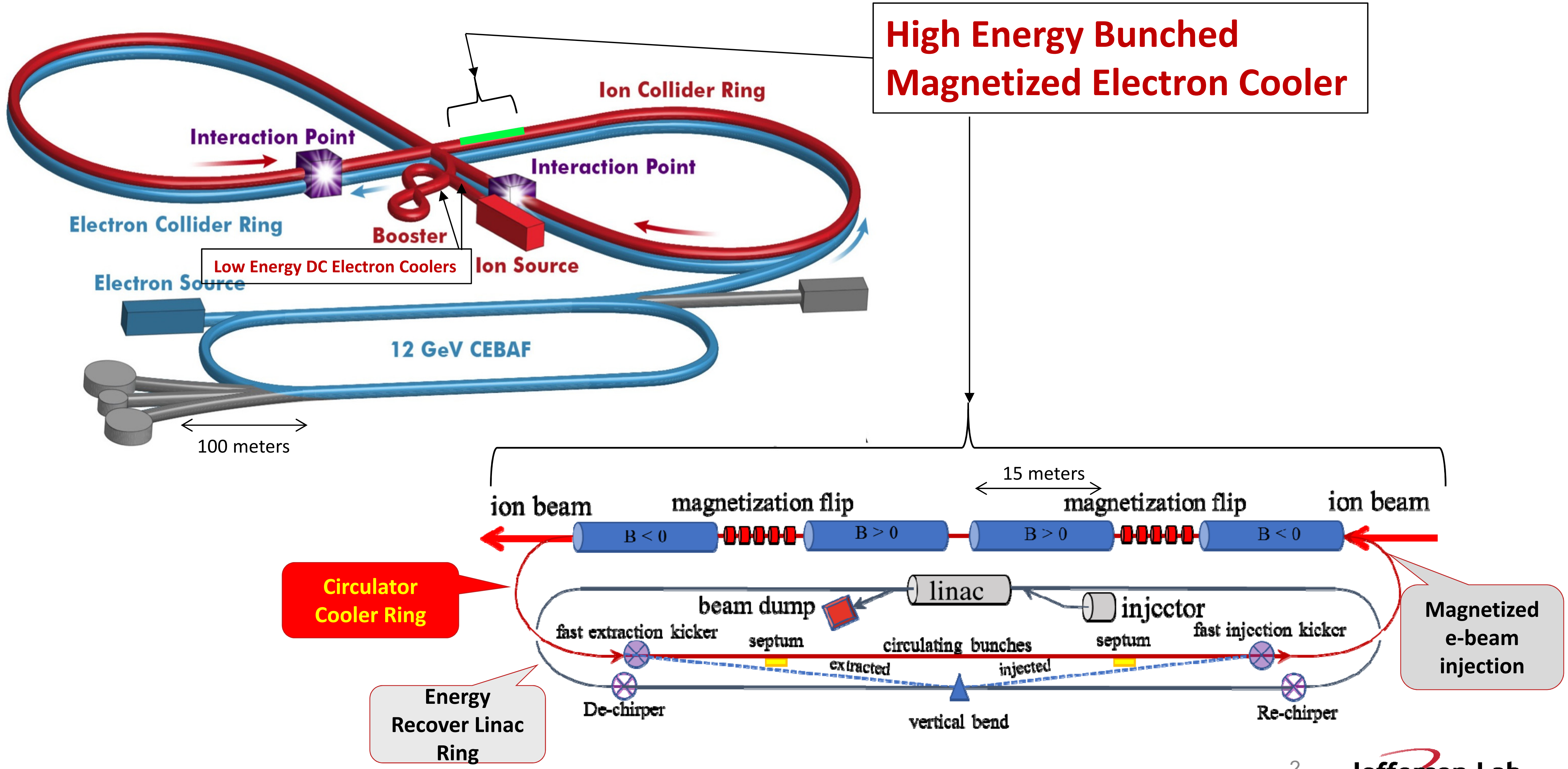


Supported in part by DoE and JLab LDRD

# The proposed JLEIC High Energy Electron Cooler is based on magnetized bunched electron beam generated in an Energy Recover Linac

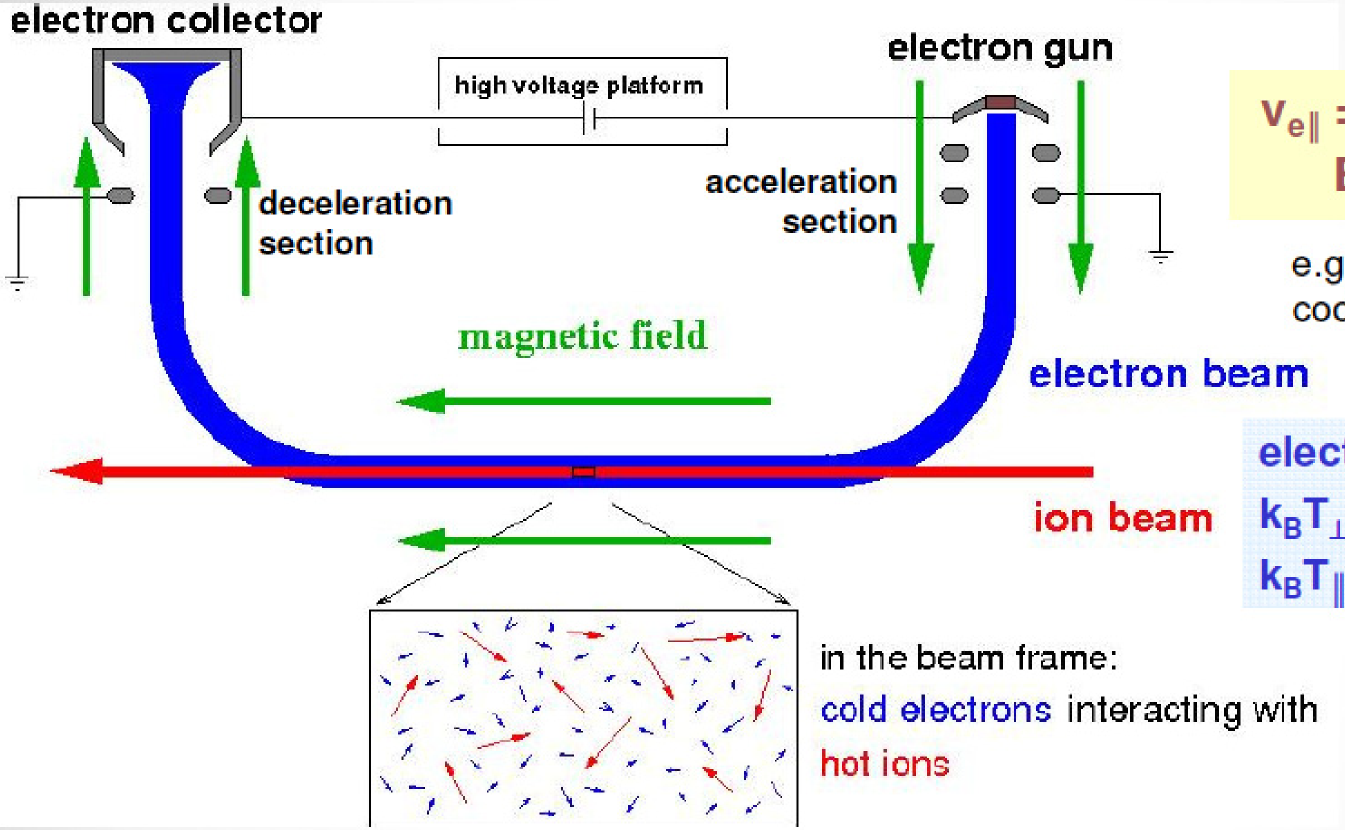


# Magnetized bunched-beam electron cooling of the ion beam

- Ion beam cooling in the presence of a solenoid 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 less sensitive to electrons transverse velocity
  - However, using an SRF linac to accelerate the electrons implies a discontinuous solenoid field.
- Long cooling solenoid provides strong hadron cooling:
  - Counteracting emittance degradation induced by intra-beam scattering
  - Maintaining ion beam emittance during collisions and extending luminosity lifetime
  - The spin effects of the solenoid must be compensated.

# Incoherent Electron Cooling

## 1. Electron Cooling




$v_{e\parallel} = \beta_e c = \beta_i c = v_{i\parallel}$

$E_e = m_e/M_i \cdot E_i$

e.g.: 220 keV electrons cool 400 MeV protons

electron temperature

$k_B T_\perp \approx 0.1$ eV

$k_B T_\parallel \approx 0.1 - 1$ meV

superposition of a cold intense electron beam with the same velocity

momentum transfer by Coulomb collisions

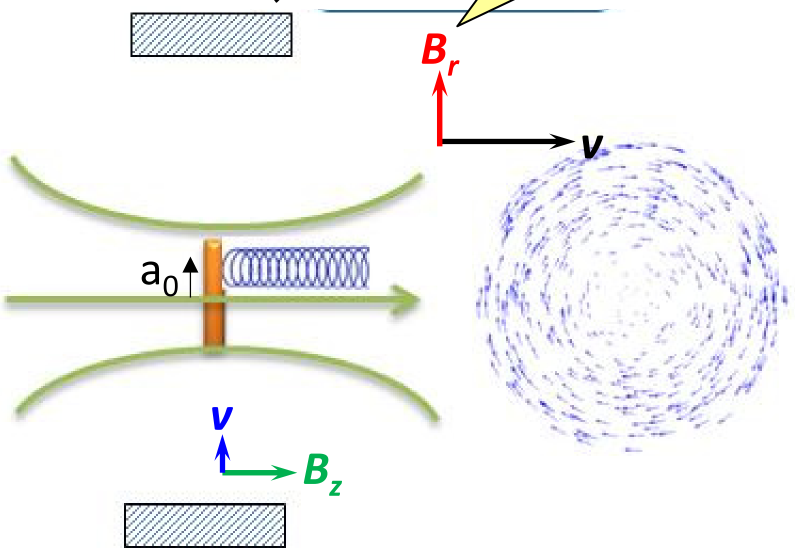
cooling force results from energy loss in the co-moving gas of free electrons

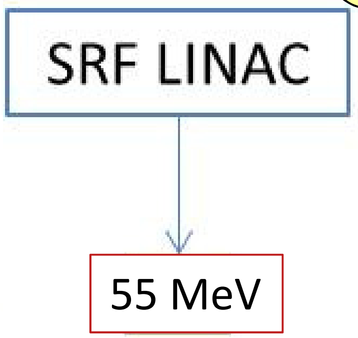
# Magnetized cooling schematics

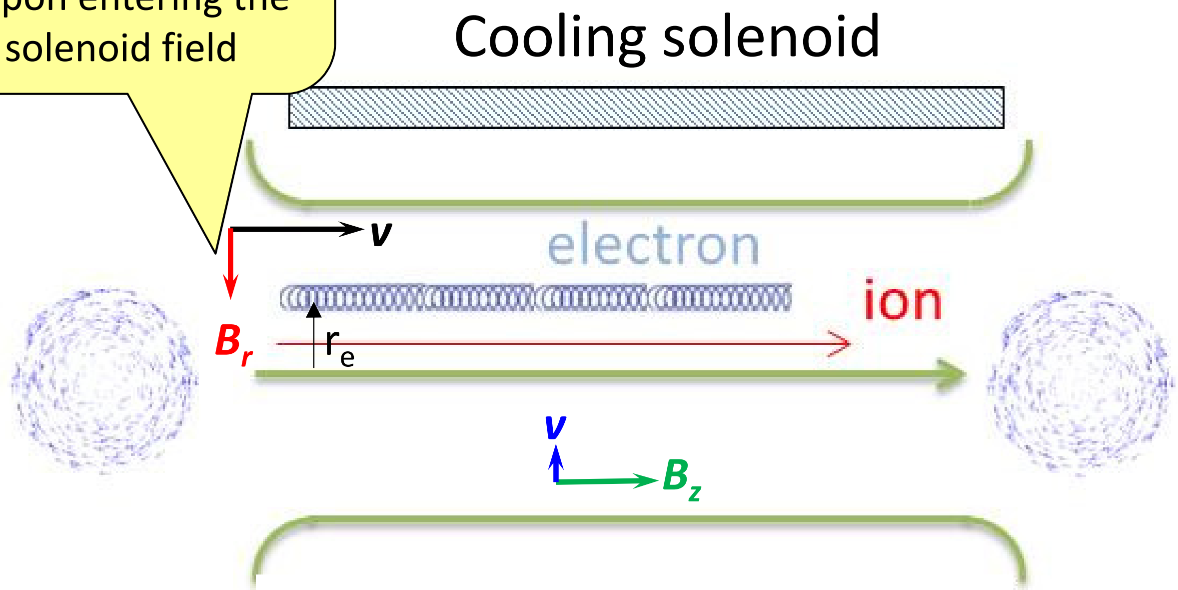
Electrons are generated in the strong uniform $B_z$ of the cathode solenoid

Mechanical angular momentum <L> is imparted to the e-beam when leaving the cathode solenoid field

Mechanical angular momentum <L> is removed from the e-beam upon entering the cooling solenoid field




Initial electron cyclotron motion is preserved in the cooling solenoid

Intrinsic transverse momentum of electrons at photocathode translates into cyclotron motion

$$\langle L \rangle = \frac{eB_z a_o^2}{4} \rightarrow \boxed{\frac{B_{cool}}{B_z} = \frac{a_0^2}{r_e^2}} \leftarrow \langle L \rangle = \frac{eB_{cool} r_e^2}{4}$$

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# JLEIC magnetized source beam requirements

| Parameter | Magnetized Source Parameters |
|---|---|
| Electron bunch length | 100 ps (3 cm) Flat-top at cooler injection |
| Repetition rate | 43.3 MHz |
| Bunch charge | 3.2 nC |
| Peak current | 32 A |
| Average current | 140 mA |
| Transverse normalized (Larmor) emittance | <10 microns |
| Normalized drift emittance | 36 microns (@ 3.2 nC) |
| Cathode spot radius – Flat-top ($a_0$) | 3.14 mm |
| Solenoid field at cathode ($B_z$) | 0.50 kG |

**World record is 65 mA CW, non-magnetized (Dunham et al., Appl. Phys. Lett. 102 (2013) 034105)**



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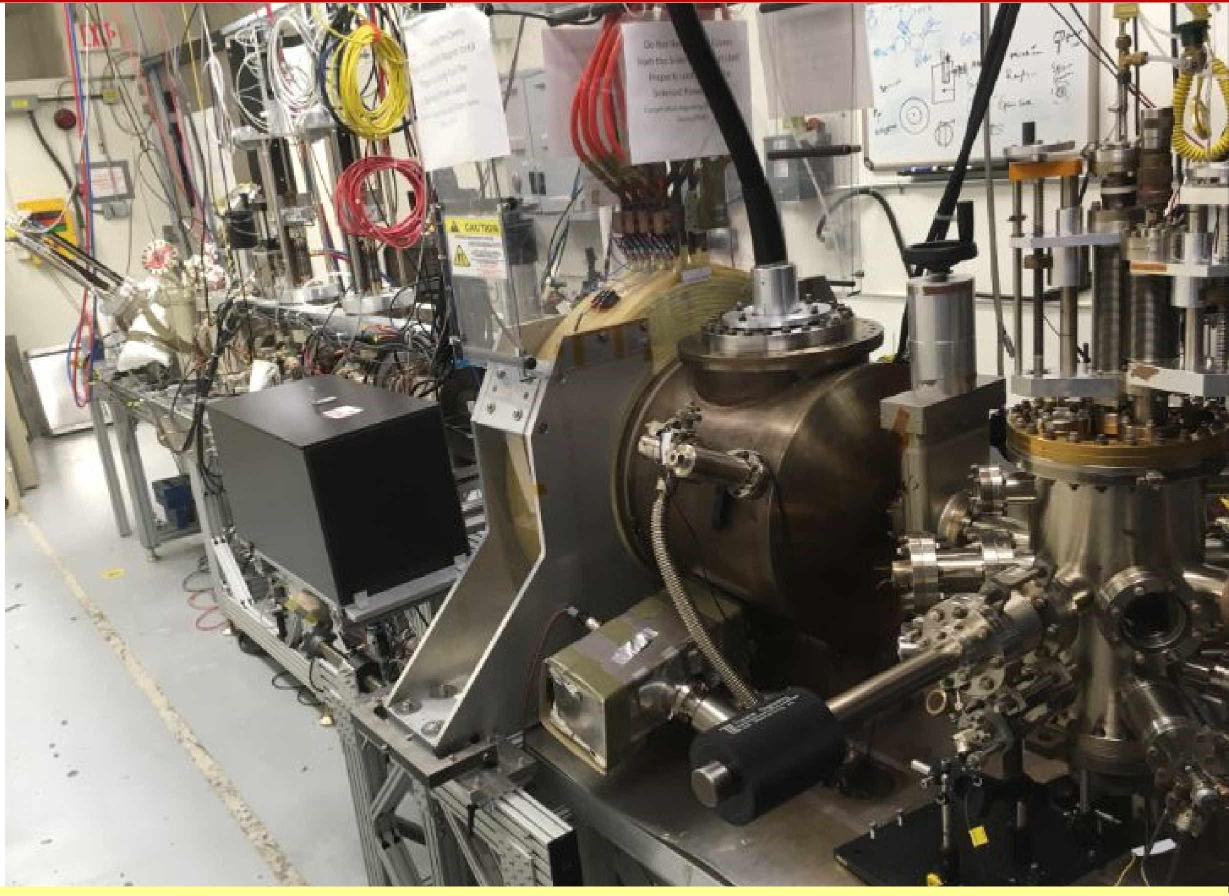
# The JLab magnetized source test stand is utilized to develop the technology for achieving the JLEC magnetized source requirements

- 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 2018
- Goals of the project:
  - Generate magnetized bunched electron beam from dc high voltage photogun and measure its properties
  - Explore impact of cathode solenoid on photogun operation
  - Perform simulations and measurements to provide insights on ways to optimize JLEIC electron cooler and help design appropriate source
  - Provide JLab with direct experience on magnetizing electron beams at high current

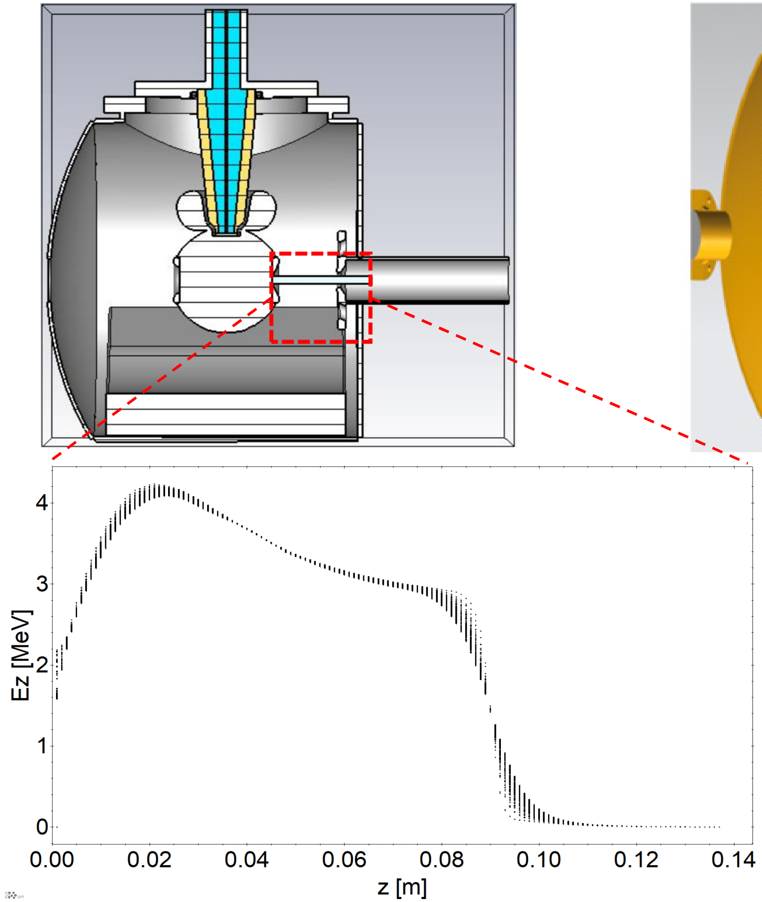


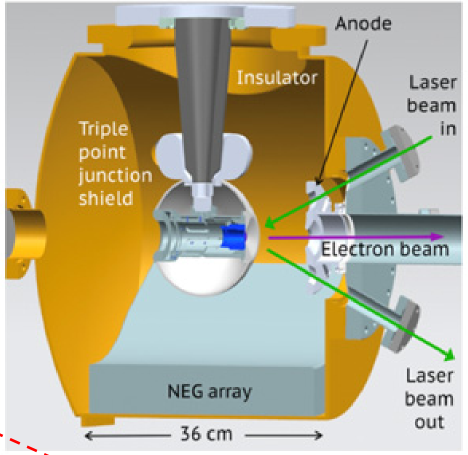
- Gun high voltage: 100 – 300 kV
- Average beam currents up to 30 mA CW
- Laser spot size at cathode $a_0$ = 0.1 - 1.0 mm (rms)
- Laser pulse length: 50 ps FWHM
- Laser wavelength 532 nm
- Laser operating frequency: 1-15 Hz , or 100-500 MHz
- Longitudinal magnetic field at cathode $B_z$ = 0 - 1.5 kG
- Target Bunch charge: 3 nC

# The magnetized source consists of a 300 kV inverted electron gun with $K_xCs_ySb$ photocathode and a cathode solenoid magnetization coil

## Gun high voltage chamber:

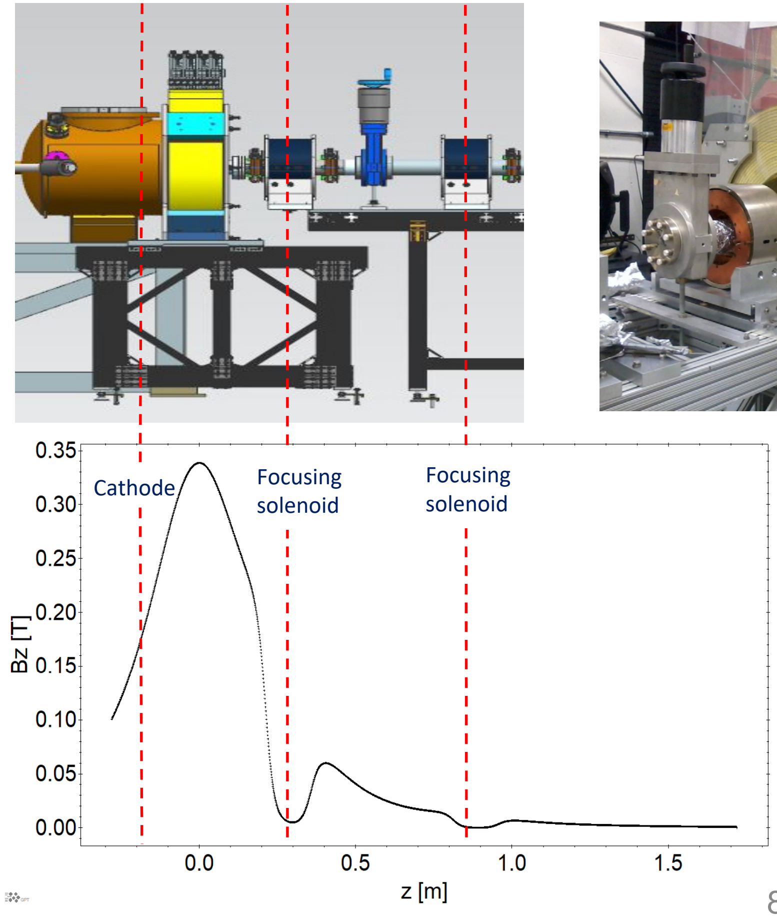
- Based on alumina inverted insulator and triple junction shield for max gradient of 10 MV/m at 350 kV
- High voltage conditioned to 360 kV in 70 hours
- Nominal vacuum levels ~5x10$^{-12}$ Torr after vacuum bake and high voltage conditioning for 300 kV operation

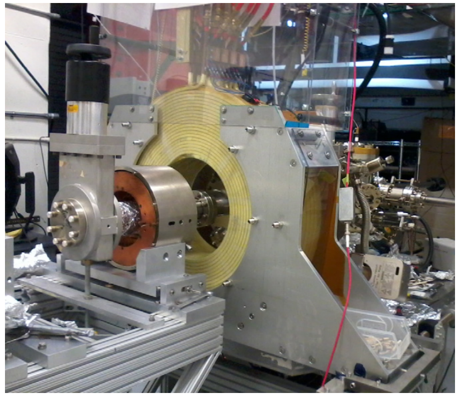


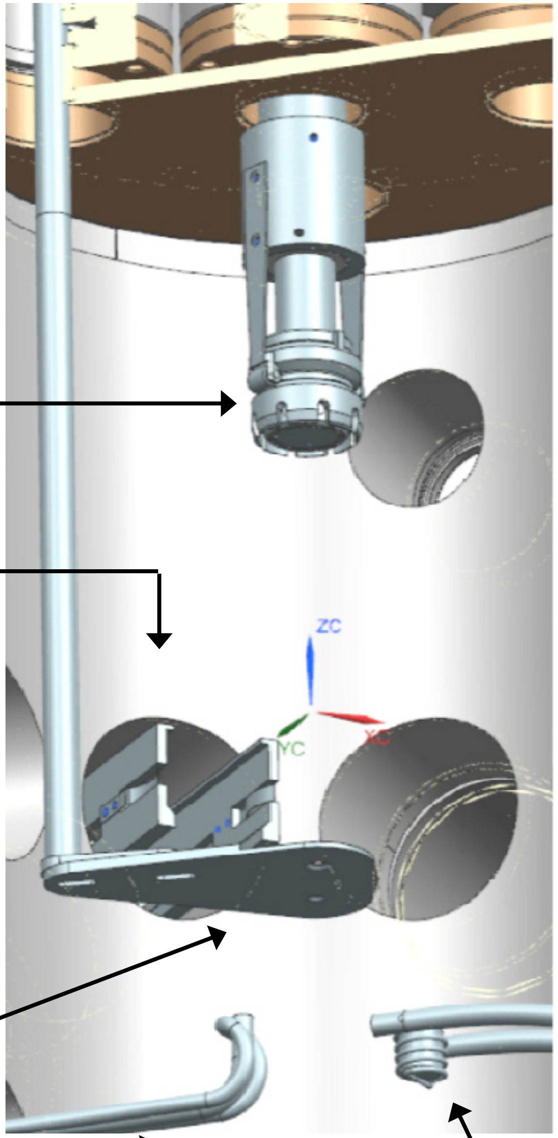

## Cathode Solenoid:

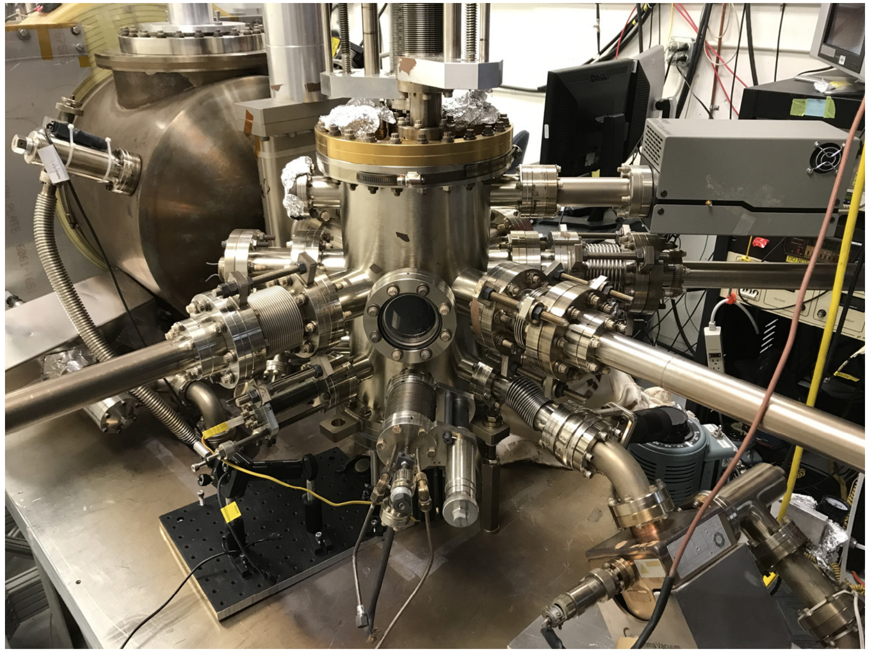
- Located 0.2 m away from the cathode.
- Provides 1.5 kG to the cathode for a maximum of 400 A.
- Field map is distorted due to the shield covers of the neighboring focusing solenoids.

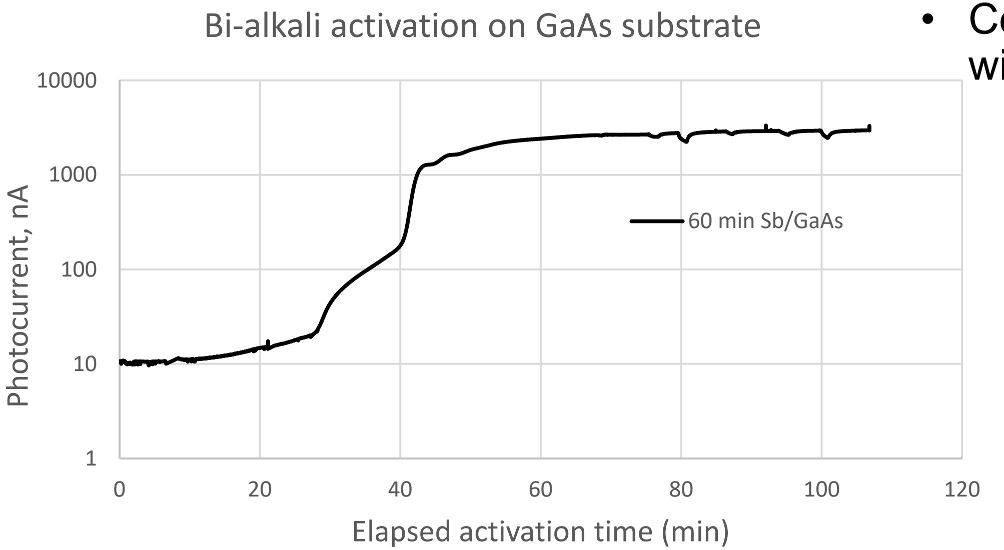


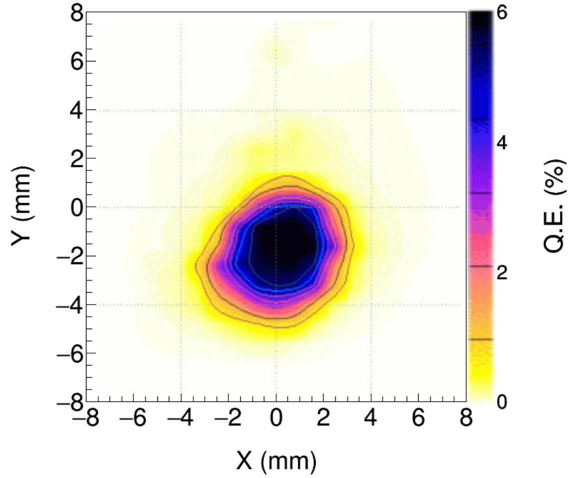
# $K_xCs_ySb$ photocathode films are grown on substrates in a vacuum chamber connected to the photogun






- $K_xCs_ySb$ grown with a mask – limit photocathode active area (3 and 5 mm diameter) to reduce beam halo and prolong quantum efficiency 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
- **Moly substrate** to reduce laser induced thermal desorption of chemicals during high current run
- Consistently fabricated photocathodes with ~5% QE

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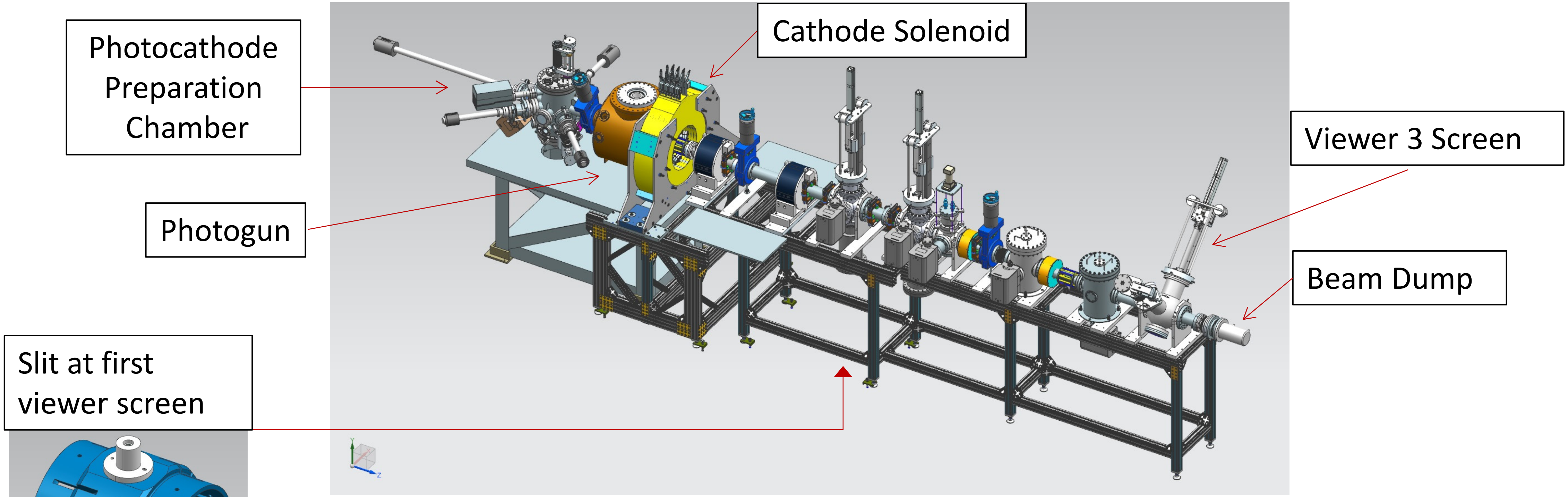
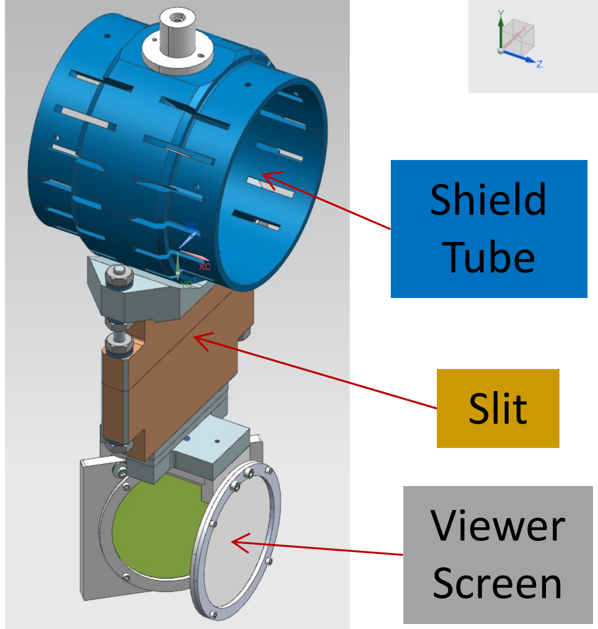
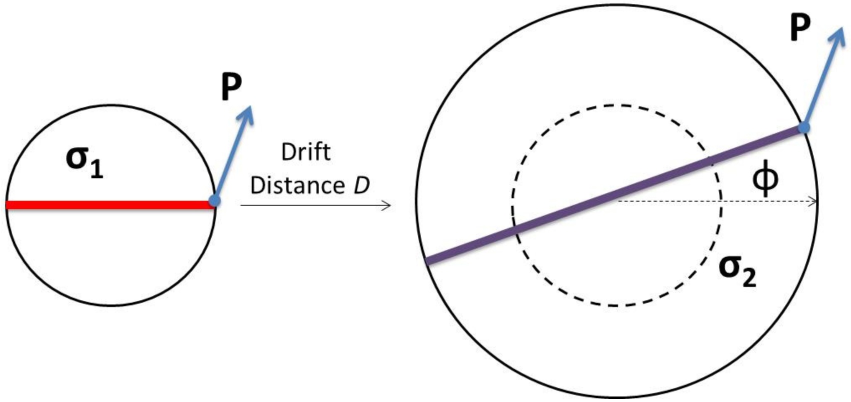
# A diagnostic beamline for magnetized electron beam source characterization



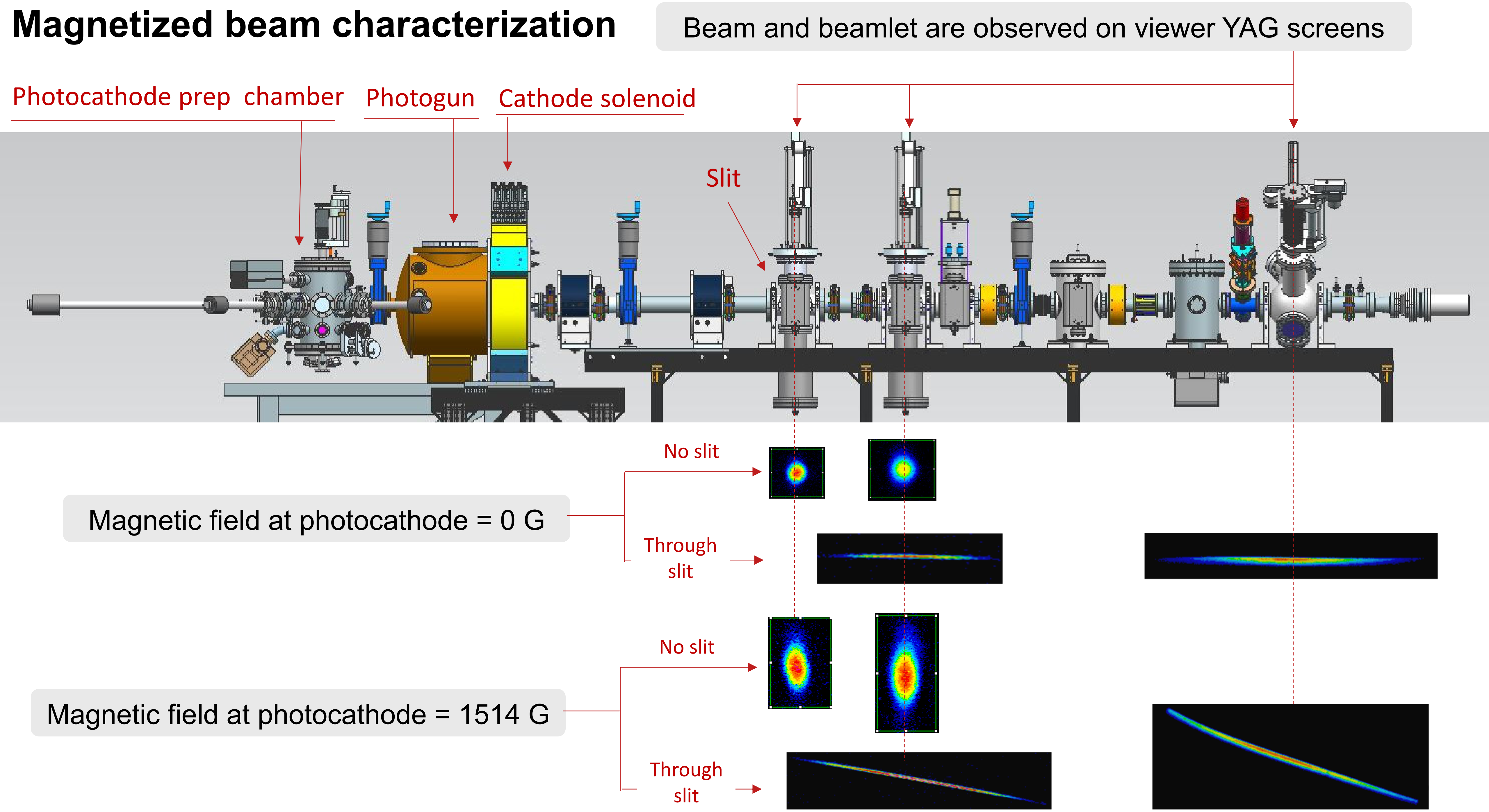




**The slit crops the magnetized beam into a beamlette that appears rotated when imaged in a downstream viewer screen**




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

# Magnetized beam characterization

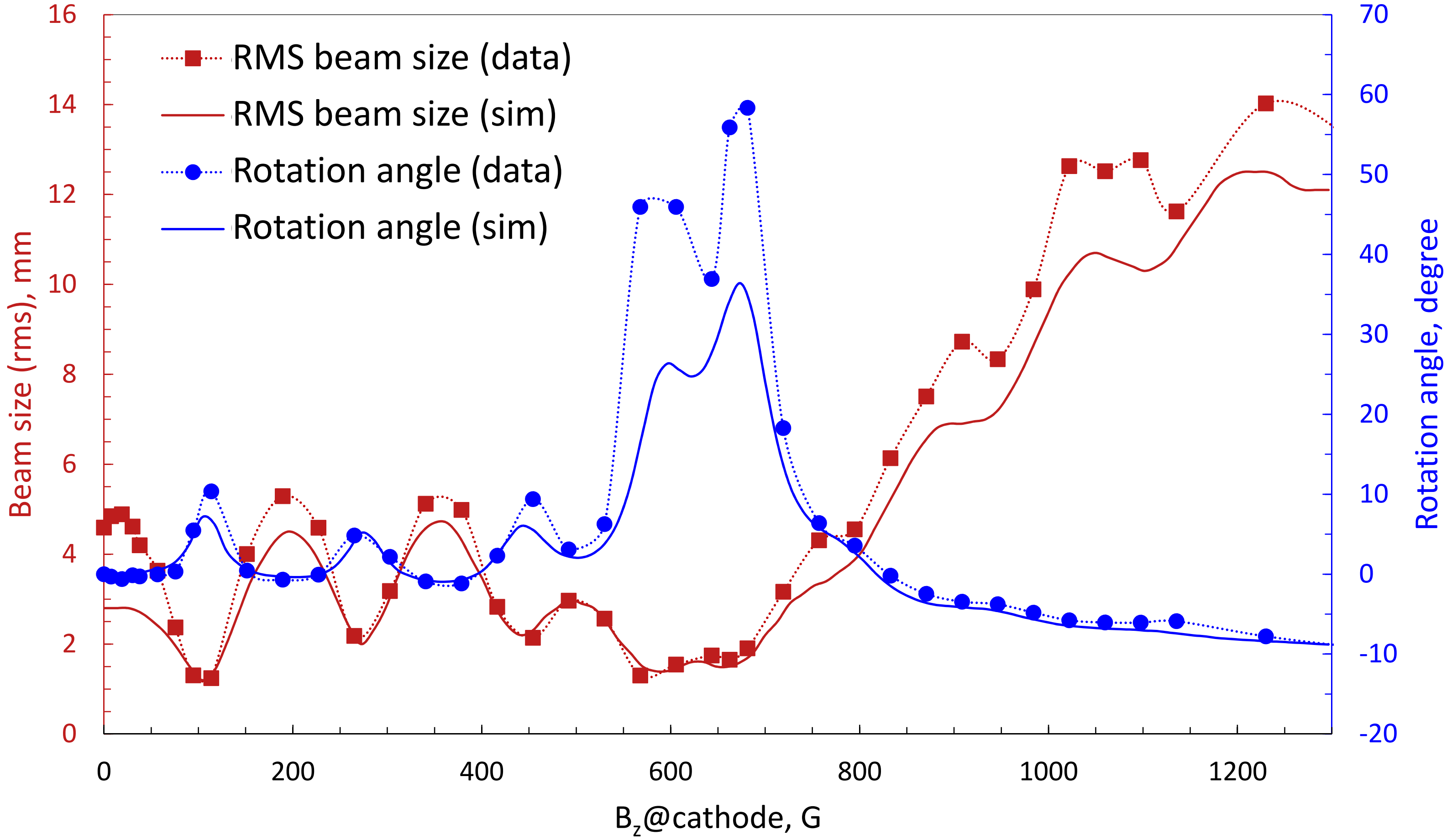


# Characterizing beam magnetization

Beam size and Rotation: Experiment vs ASTRA simulation

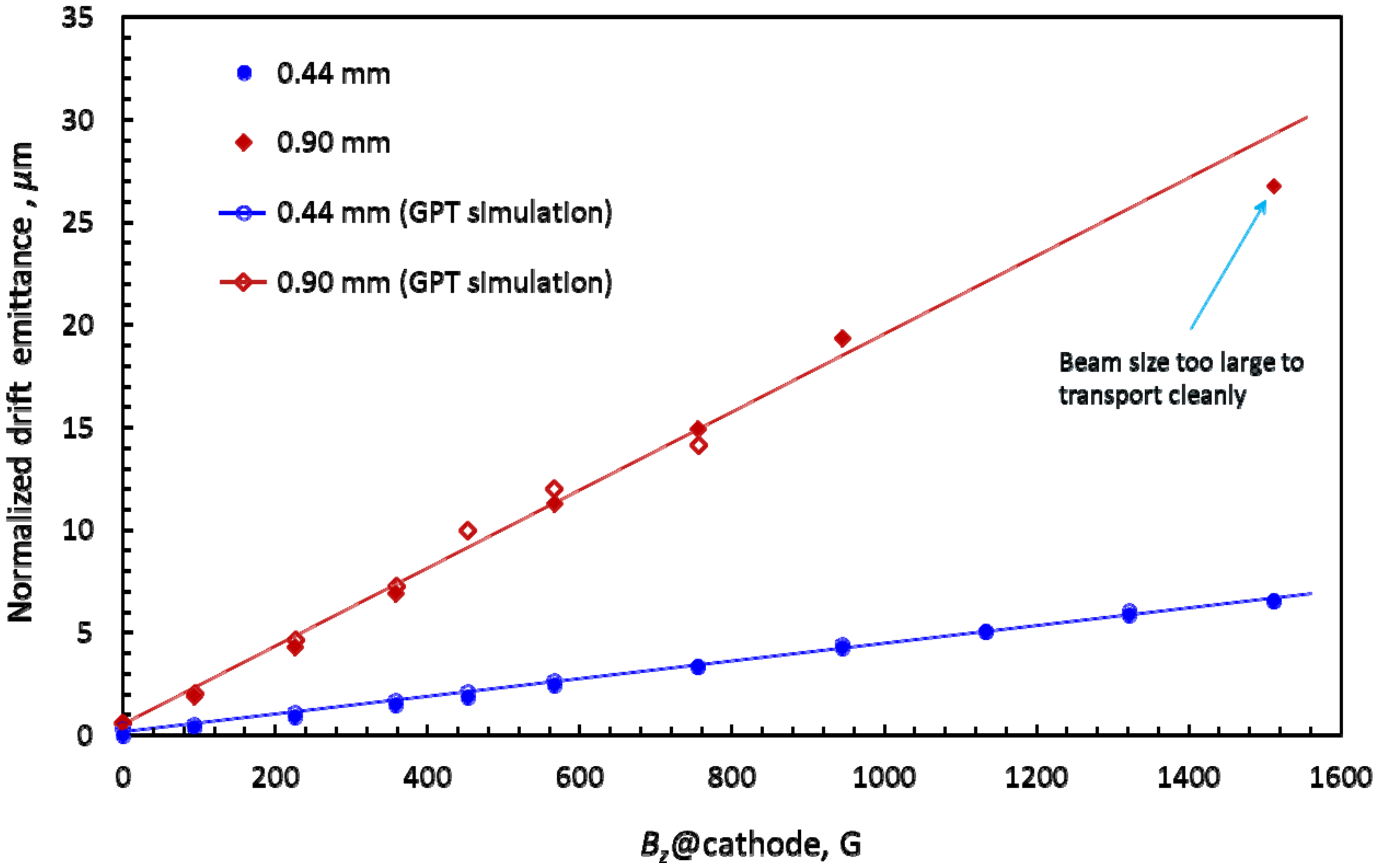
- A non-uniform cathode magnetic field causes mismatch oscillations
- repeated focusing inside the solenoid field affects the beam size at the exit of the solenoid field
- resulting in varying beam expansion rate in the field free region.

Gun voltage 300 kV and laser spot size 0.2 mm rms on photocathode center




Observed and simulated oscillating beam profiles and corresponding beam rotation

# Magnetized beam emittance measurements for two laser spot sizes at 200kV



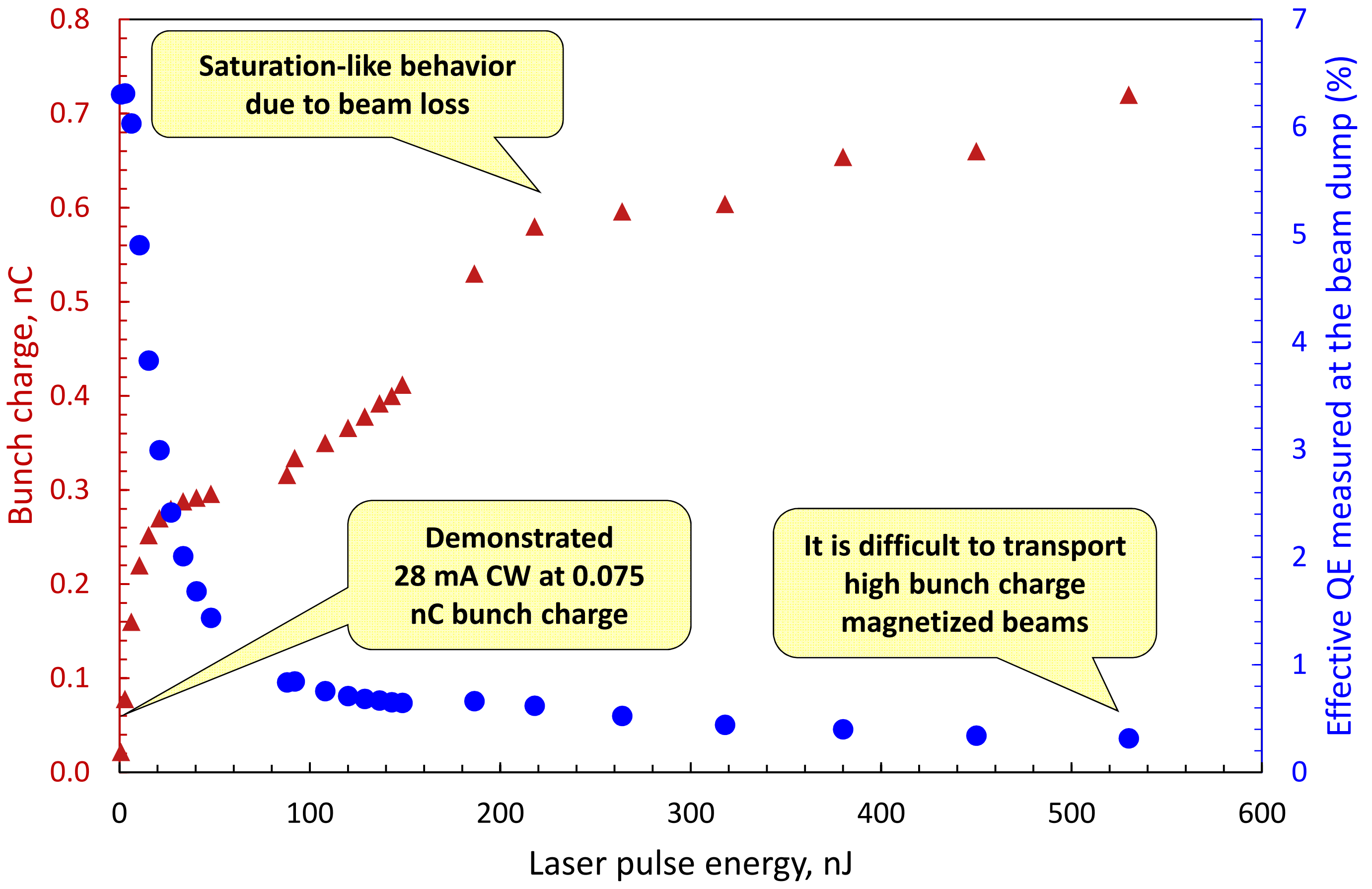

20 femto-Coulomb bunch charge

GPT simulations and experimental results with 20 femto-Coulomb bunch charge show encouraging agreement between the laser spot size and magnetic field at the photocathode

# Magnetized beam bunch charge measurements vs. laser pulse energy

- A maximum of ~ 14 nC extractable charge at the photocathode for available laser power (QE%=6.3, P=2.65 × $10^{-2}$ W, f = 50 kHz)
- Observed an exponential decay in effective QE% with the measured charge at the beam dump
- We encountered space-charge-limited regime within 0.3 nC for different magnetized conditions
- Beam scraping due to limited beamline aperture and insufficient strength of focusing solenoids restricted clean beam transport to the dump for pulse energy >70 nJ
- Need longer laser pulses, higher gun voltage and better beamline optics to get nC bunches

Gun voltage 225 kV, Magnetic field at cathode 757 G, Laser pulse width 75ps (FWHM)



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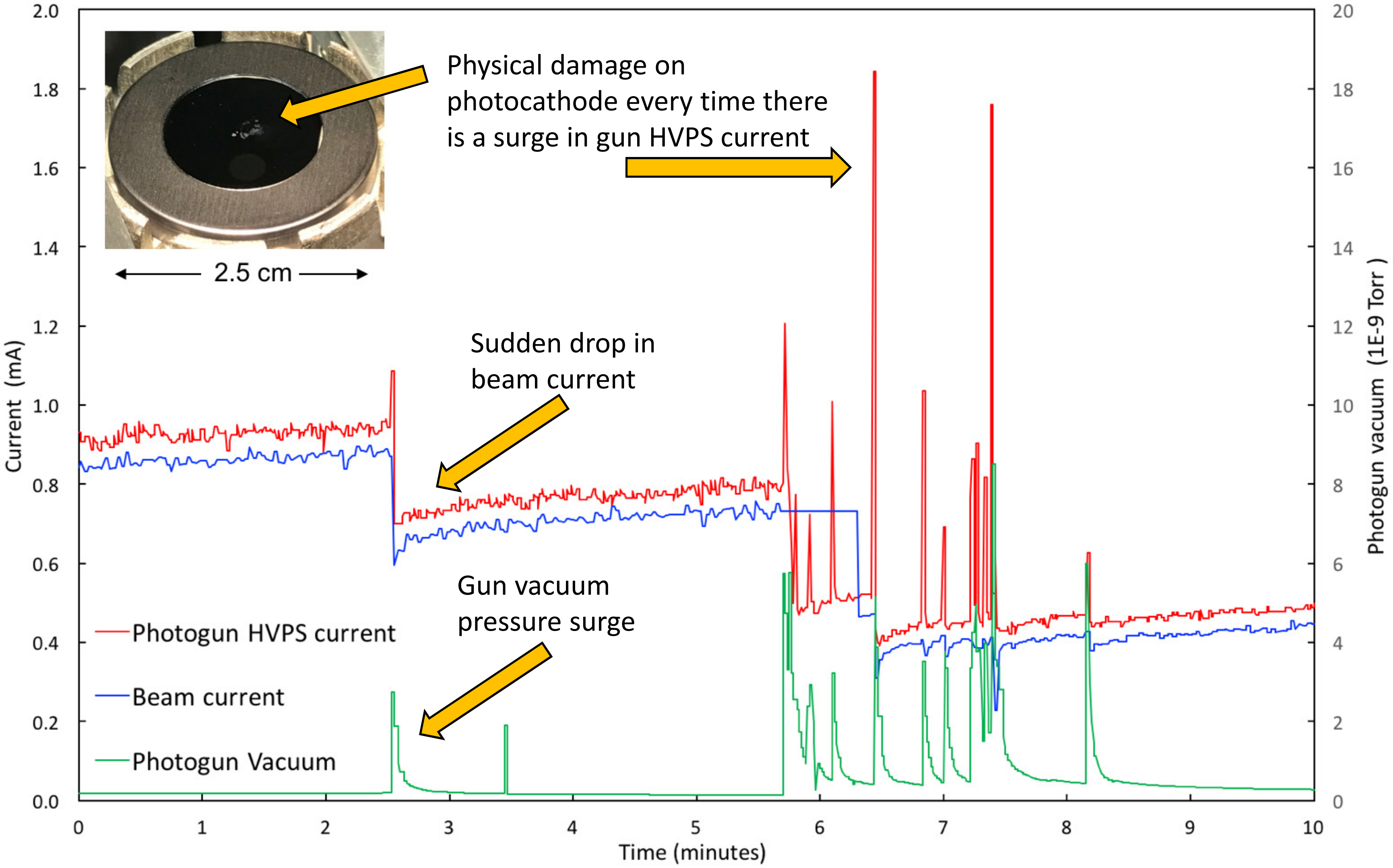
# Initial attempts to run high current magnetized beam were limited by gun current surges tripping off the high voltage power supply damaging the photocathode at 1 mA CW



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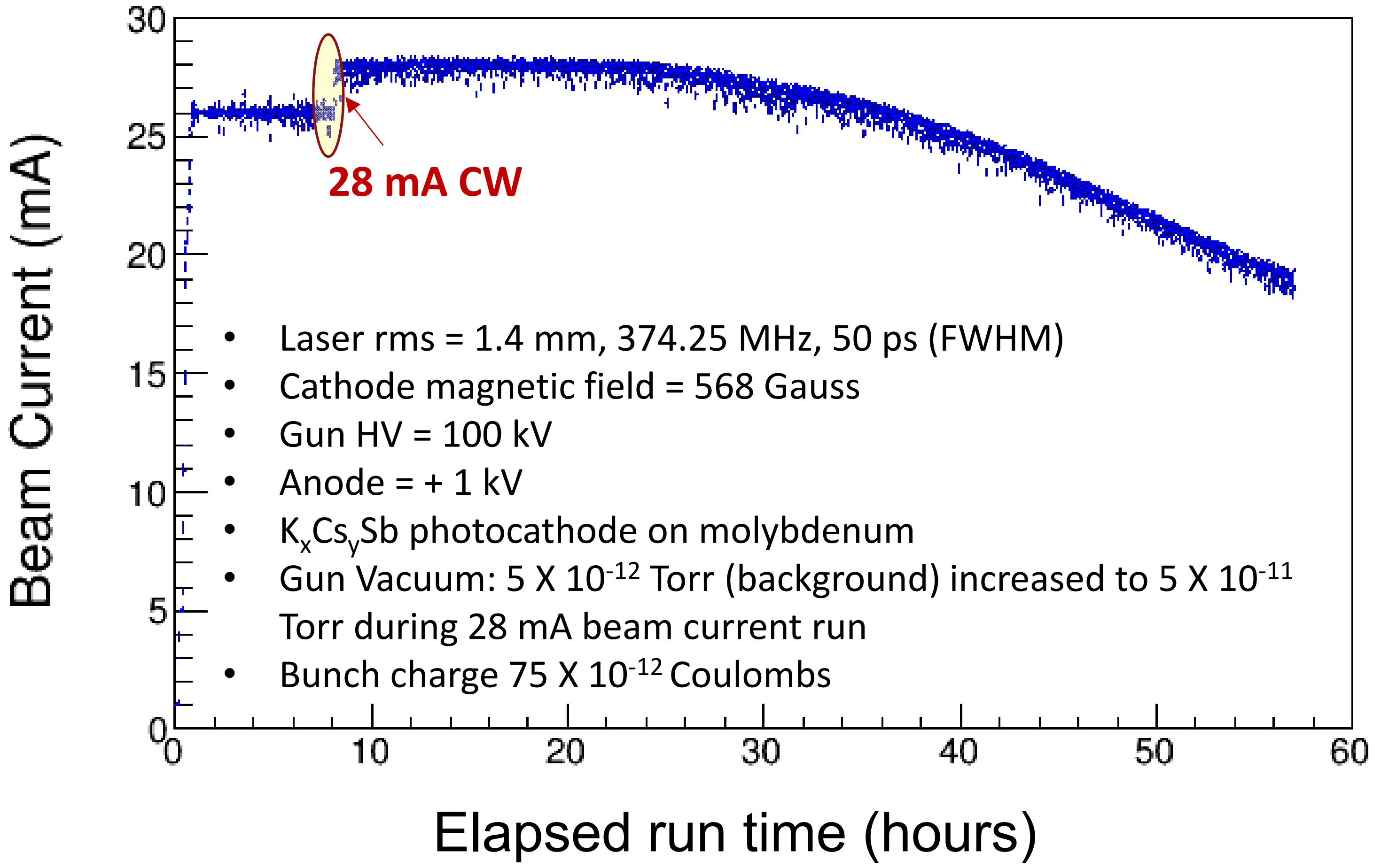
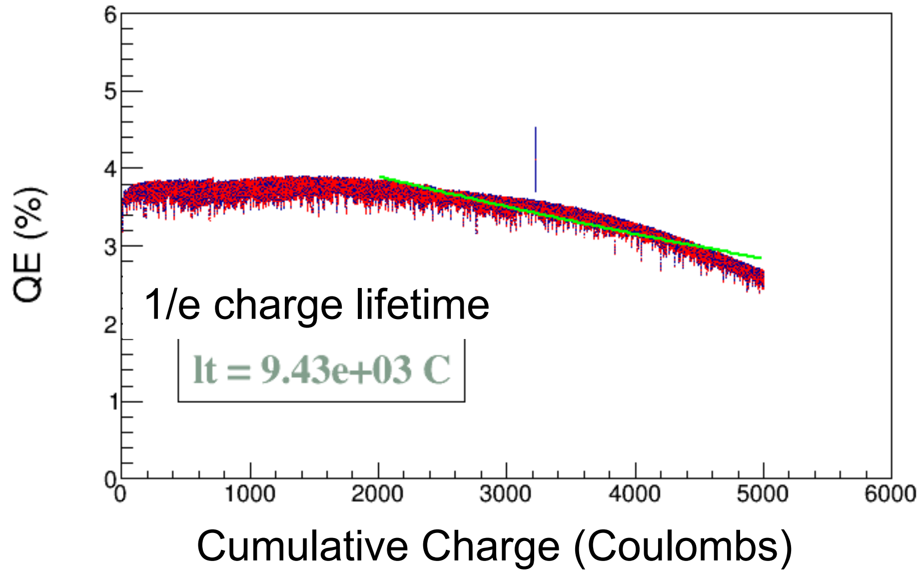
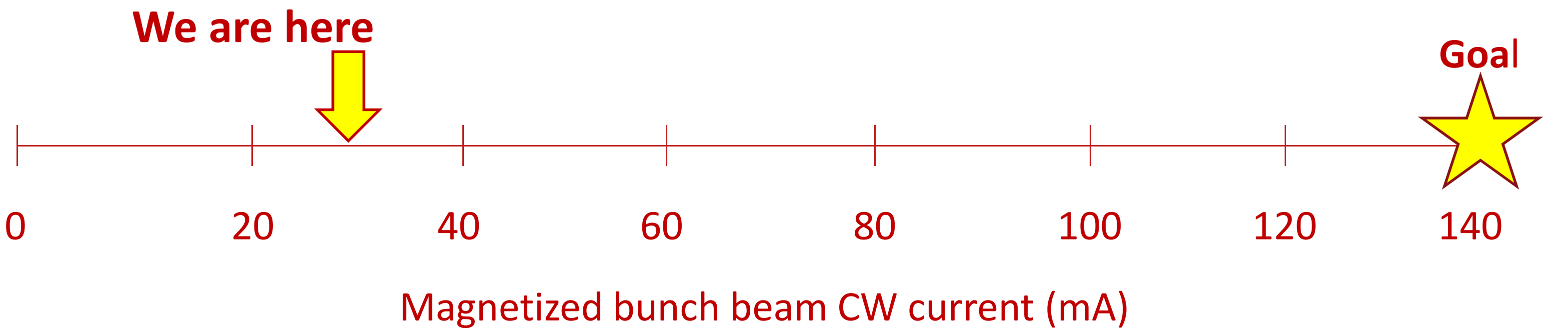
# Biasing the gun anode to +1 kVDC was essential to achieve high current magnetized beam for extended periods of time without photocathode arcing




Limited lifetime might be a result of photocathode heating and associated bandgap shift, or ion back bombardment

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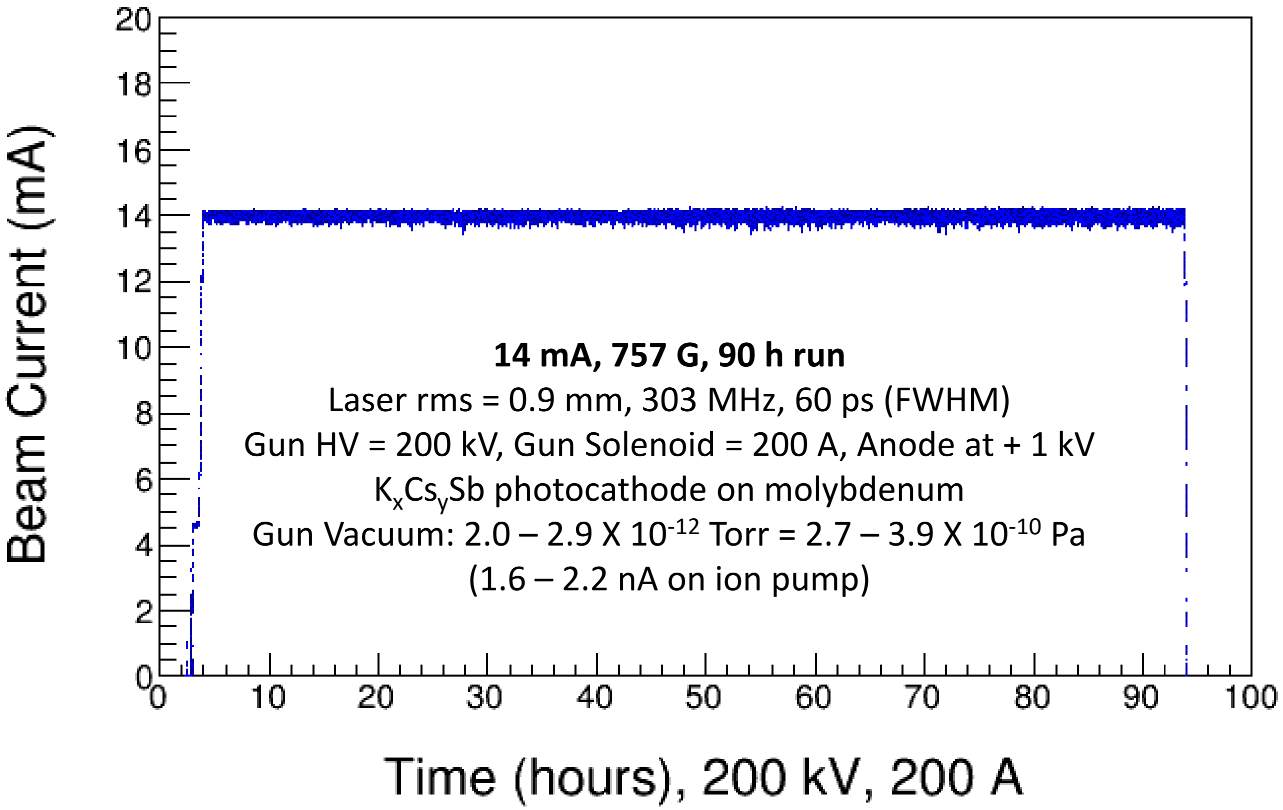
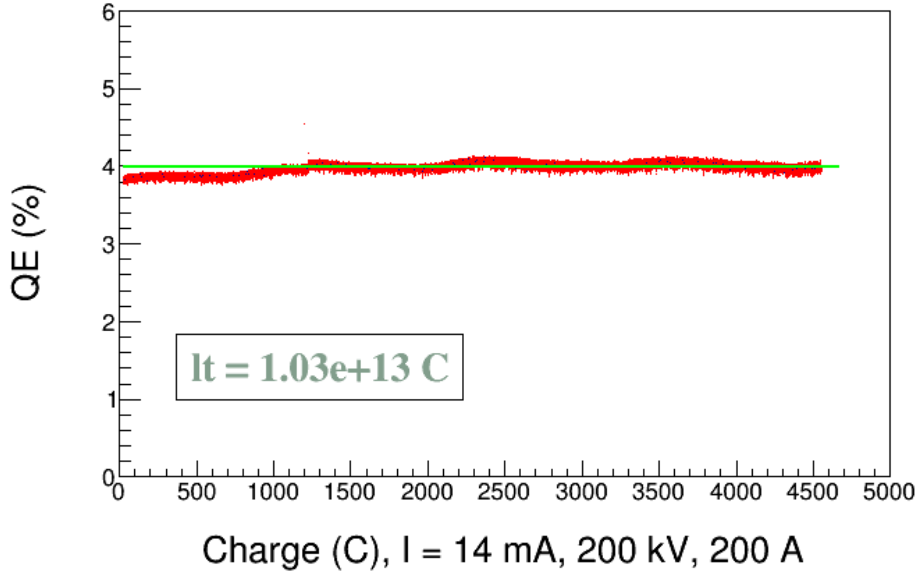
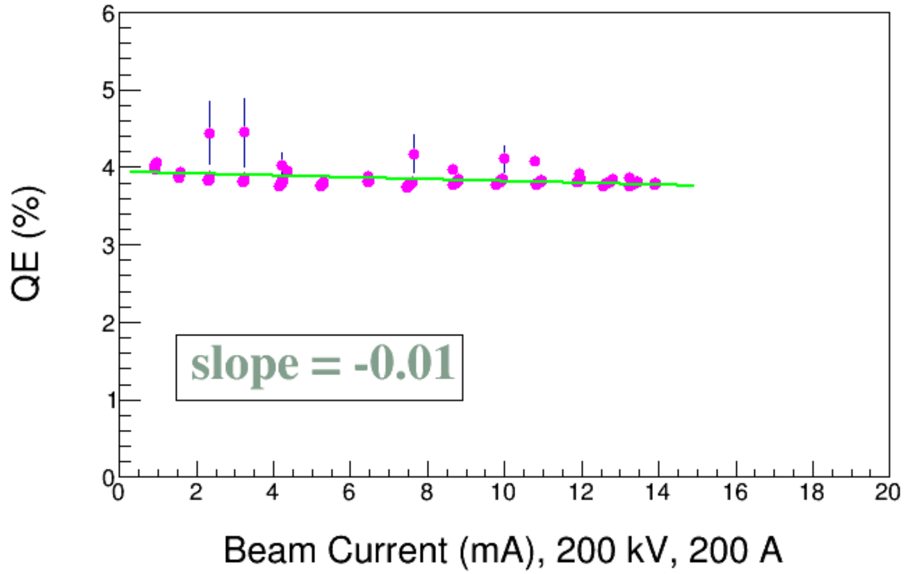
# High Current Magnetized Beam: 14 mA at 757 G for 90 h




- 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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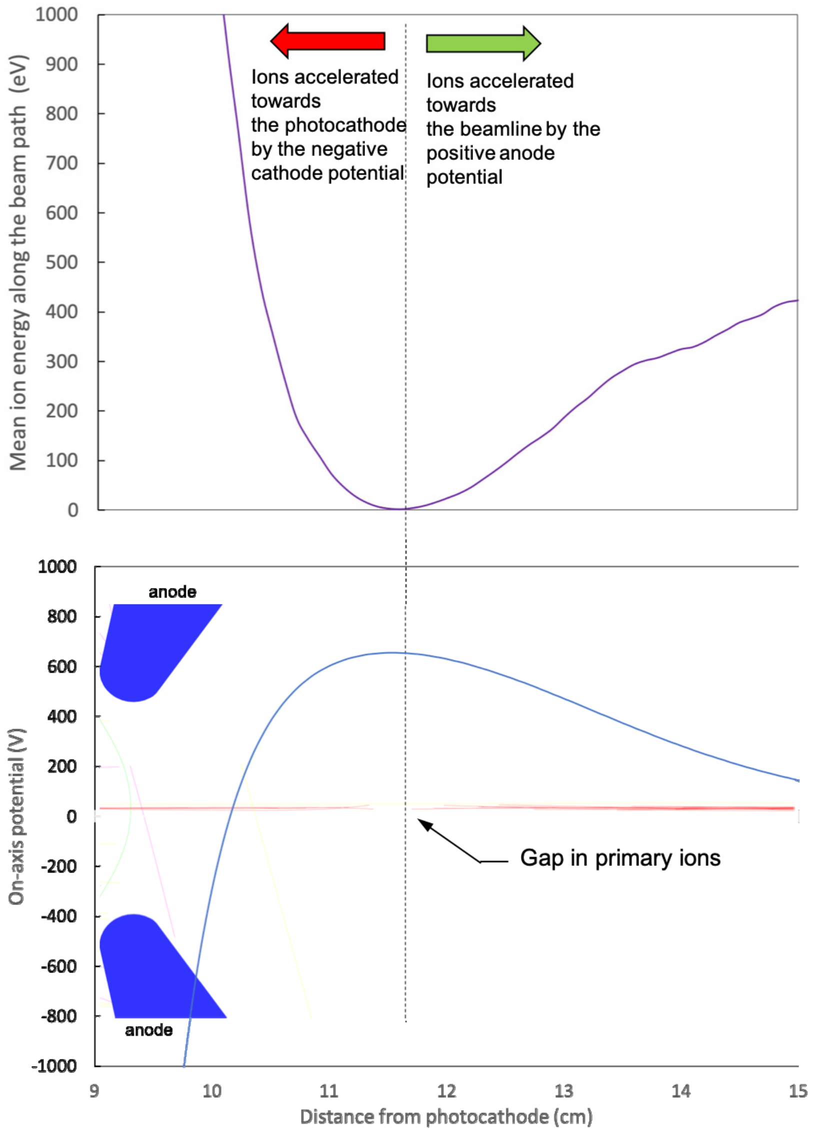
# Anode-cathode potential when anode is biased to +1kVDC



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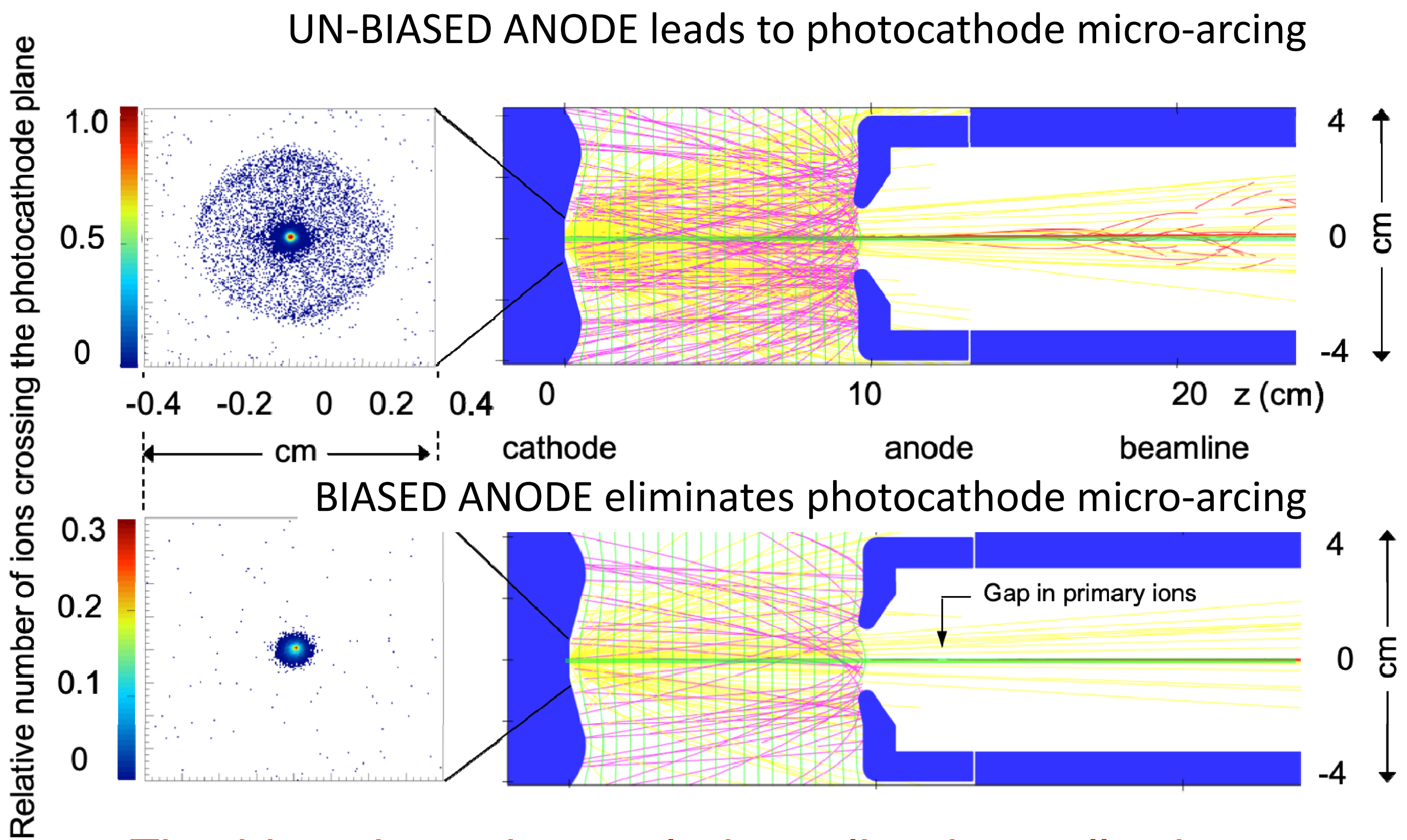
# Simulations of ions generated by the high current electron beam suggest that:




The biased anode repels beamline ions allowing to run high current without photocathode arcing

- Ions in the beamline (**red**) are attracted to the potential well formed by the electron beam (**green**)
- These trapped ions are then accelerated towards the negatively biased photocathode where they generate secondary electrons (**yellow**) upon impact which in turn strike the anode and generate secondary ions (**pink**).
- High density 'channels' could form in the anode-cathode gap leading to ***arcing*** between the ***photocathode*** and the anode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# JLEIC magnetized source beam requirements compared to parameters achieved in this work

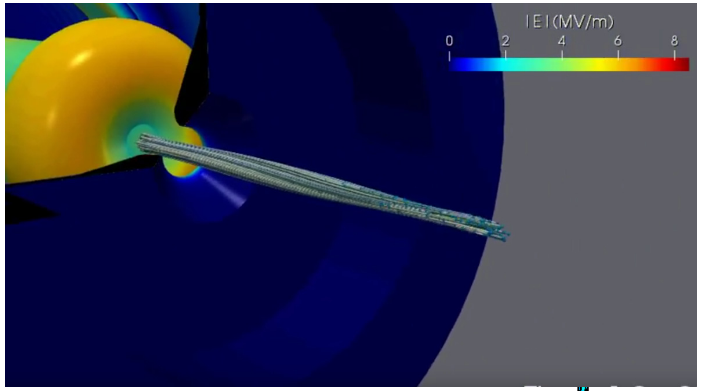
| Parameter | JLEIC | Gun Test Stand Demonstrated |
|---|---|---|
| Electron bunch length 60 ps (2 cm)<br>Flat-top at cooler injection | 60 ps (2 cm) | Gaussian **laser pulse 25 – 75 ps** FWHM |
| Repetition rate | 43.3 MHz | 100 Hz – 374.3 MHz |
| Bunch charge | 3.2 nC | 0.7 nC (75 ps FWHM, 25 kHz, 225 kV, 0.76 kG) |
| Peak current | 53.9 A | 9.3 A |
| Average current | 140 mA (**400 kV**) | 28 mA (50 ps FWHM, 74.8 pC, 374.25 MHz, **100 kV**, 0.57 kG) |
| Transverse normalized emittance | <10 microns | <2 microns |
| Normalized drift emittance | 36 microns (@3.2 nC) | 26 microns (@ 20 femto-Coulomb bunch charge) |
| Cathode laser spot radius | 3.14 mm Flat-top ($a_0$) | 0.9 mm rms (Gaussian) |
| Solenoid field at cathode ($B_z$) | 0.50 kG | 1.51 kG |

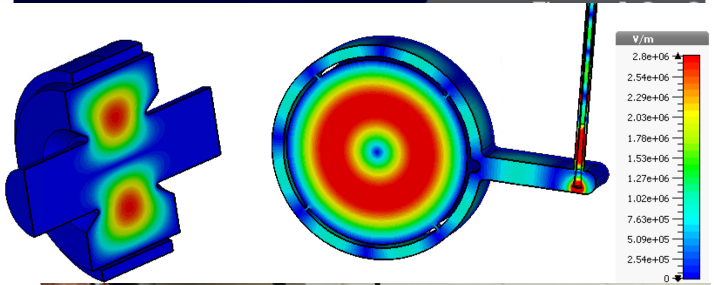
The beam current was limited by the high voltage power supply
(30 mA/225 kV with 3 kW max power)

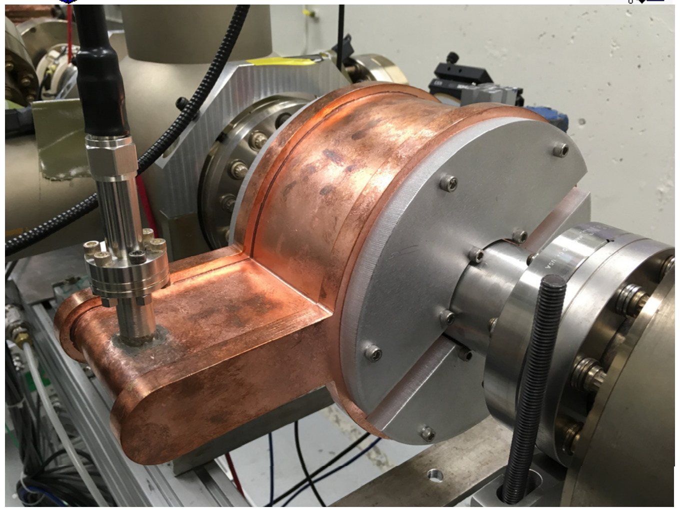
**Higher gun voltage and longer laser pulse are being explored to achieve required MAGNETIZED bunch charge**

# Future Plans

- Recently, the photogun has been replaced with 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
- Measure beam magnetization and electron bunch-length for high bunch charge beam with the installed non-invasive magnetometers - $TE_{011}$ Cavity and “Brock” Cavity from Electrodynamic: another SBIR II funded project
- Reinstall photogun, now with Xelera’s power supply and BNL laser (10 MHz), the setup will enable high average current AND high bunch charge, **simultaneously** (30 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



# THANK YOU

On behalf of the JLab magnetized source team!