Magnetized Electron Source for JLEIC Cooler

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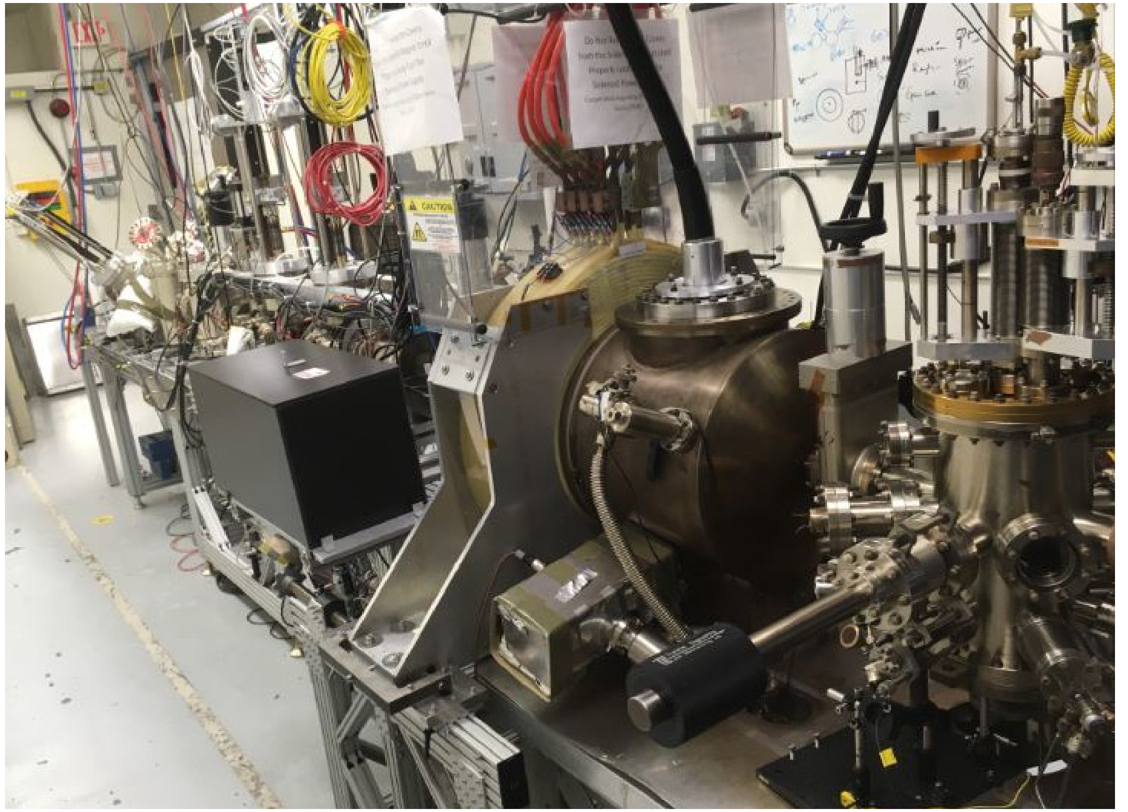

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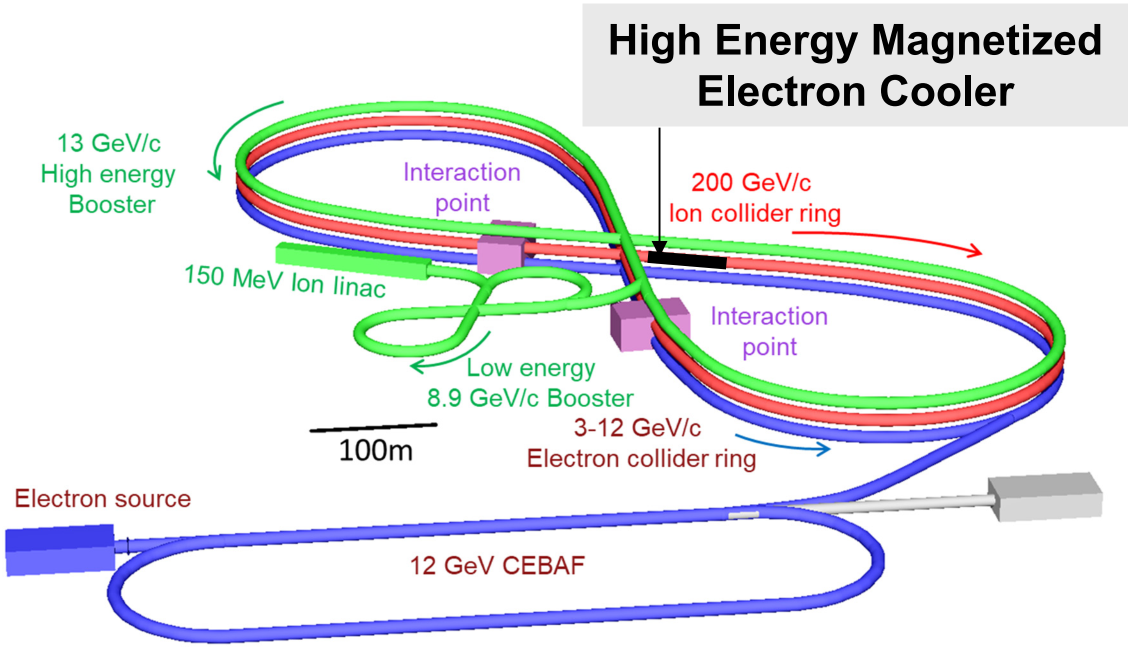
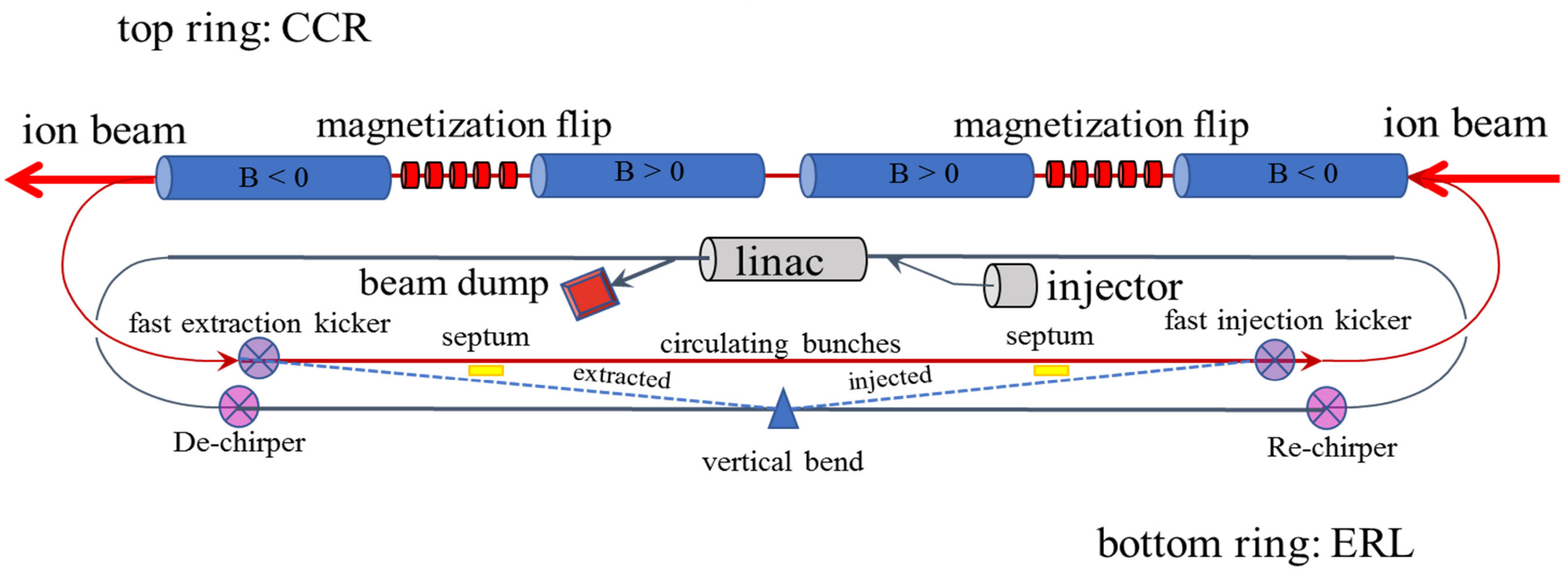
NAPAC2019 North American Particle Accelerator Conference: 1-6 September 2019

Outline

- Magnetized Bunched-Beam Electron Cooling at Jefferson Lab Electron Ion Collider (JLEIC)
- Magnetized Electron Source:
  - Photocathode Preparation Chamber
  - 300 kV Inverted Gun and Cathode Solenoid
  - Diagnostic Beamline
- Characterization of Magnetized Beam:
  - Beam Sizes and Shearing Angles
  - Drift (Correlated) Emittance
  - High Bunch Charge – see S. Wijhetunga's talk TUZBB4
  - High Average Current and Operational Lifetime
- Summary and Future Plans

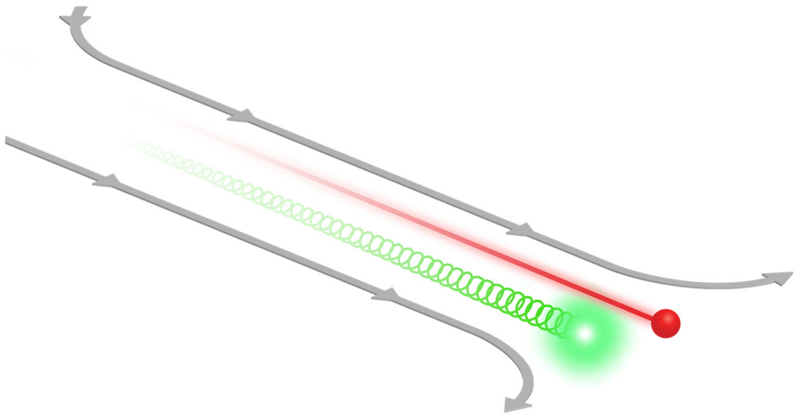
JLEIC High Energy Magnetized Electron Cooler

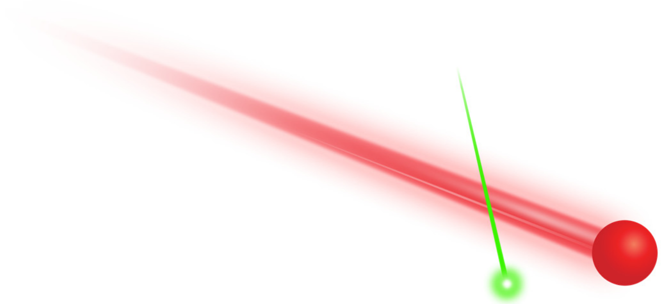




Magnetized Electron Cooling

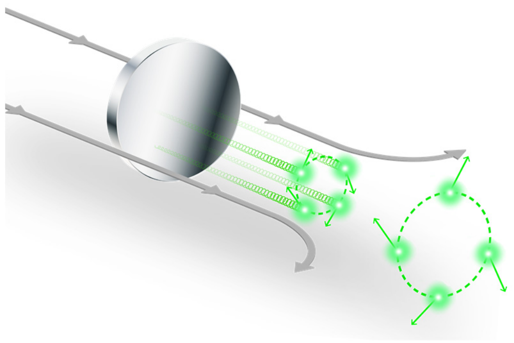
- Ion beam cooling in presence of magnetic field is much more efficient than cooling in a drift (no magnetic field):
  - Electron beam helical motion in strong magnetic field increases electron-ion interaction time, thereby significantly improving cooling efficiency
  - Electron-ion collisions that occur over many cyclotron oscillations and at distances larger than cyclotron radius are insensitive to electrons transverse velocity
  - Magnetic field suppresses electron-ion recombination – serious problem especially for heavy ions

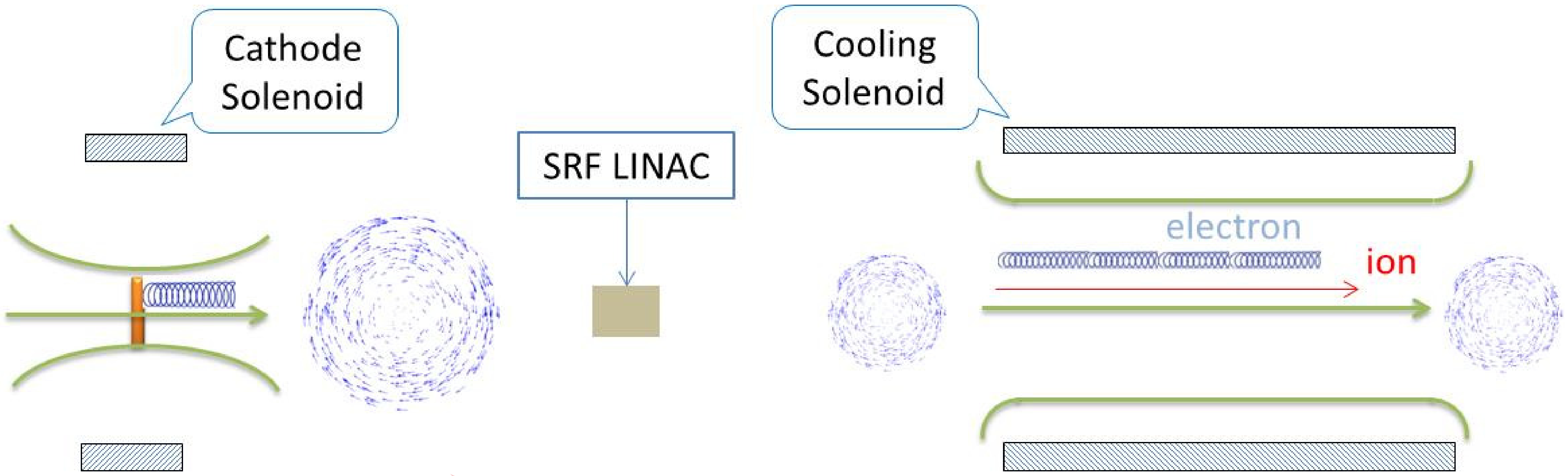




- Magnetized cooling is a critical part of JLEIC and aims to:
  - Counteract emittance degradation induced by intra-beam scattering
  - Maintain ion beam emittance during collisions and extend luminosity lifetime

Magnetized Electron Cooling Schematics





To implement cooling inside a solenoid, electron beam must be generated inside a magnetic field. Otherwise, electron beam will have mechanical angular momentum inside cooling solenoid per Busch's theorem, induced by radial fringe field as electron beam enters solenoid.

Electrons born in strong uniform B_z

$$\langle L \rangle = \frac{eB_z a_o^2}{4}$$

$a_0 = R_{laser} = 3.1$ mm
$B_z = 0.50$ kG

Upon exit of Cathode Solenoid

$$\langle L \rangle = \gamma m_e \langle r^2 \rangle \dot{\phi}$$

$$\varepsilon_d = \frac{eB_z a_o^2}{8 m_e c} = 36\ \mu\text{m}$$

Upon entering Cooling Solenoid

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

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

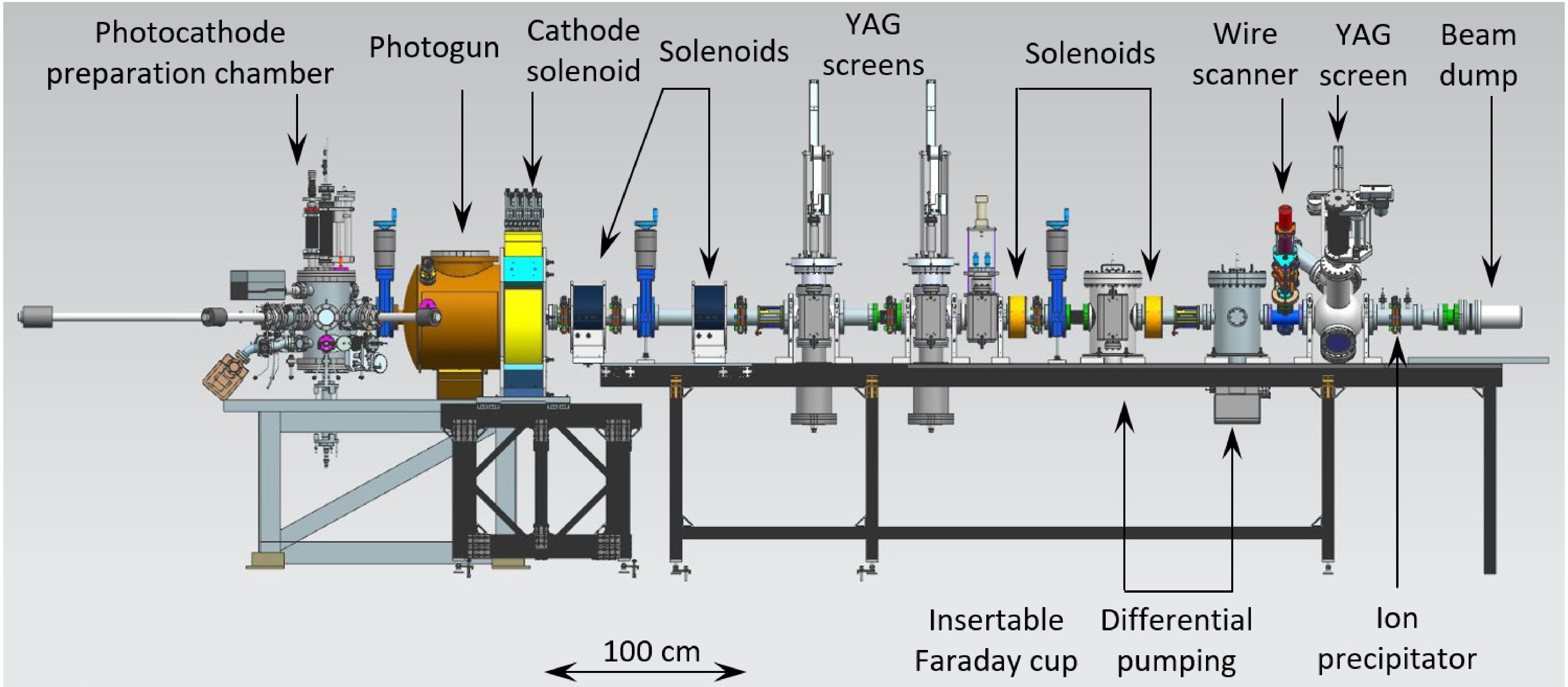
$r_e = 2.2$ mm
$B_{cool} = 1$ T

JLEIC Magnetized Electron Source Requirements

Parameter	JLEIC Requirements	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, 74.8 pC, 374.25 MHz, 100 kV, 0.57 kG)
Transverse normalized emittance	<19 µm	<2 µm
Normalized drift emittance	36 µm	26 µm
Cathode spot radius – Flat-top (a_0)	3.1 mm	1.4 mm (Gaussian RMS)
Solenoid field at cathode (B_z)	0.50 kG	1.5 kG

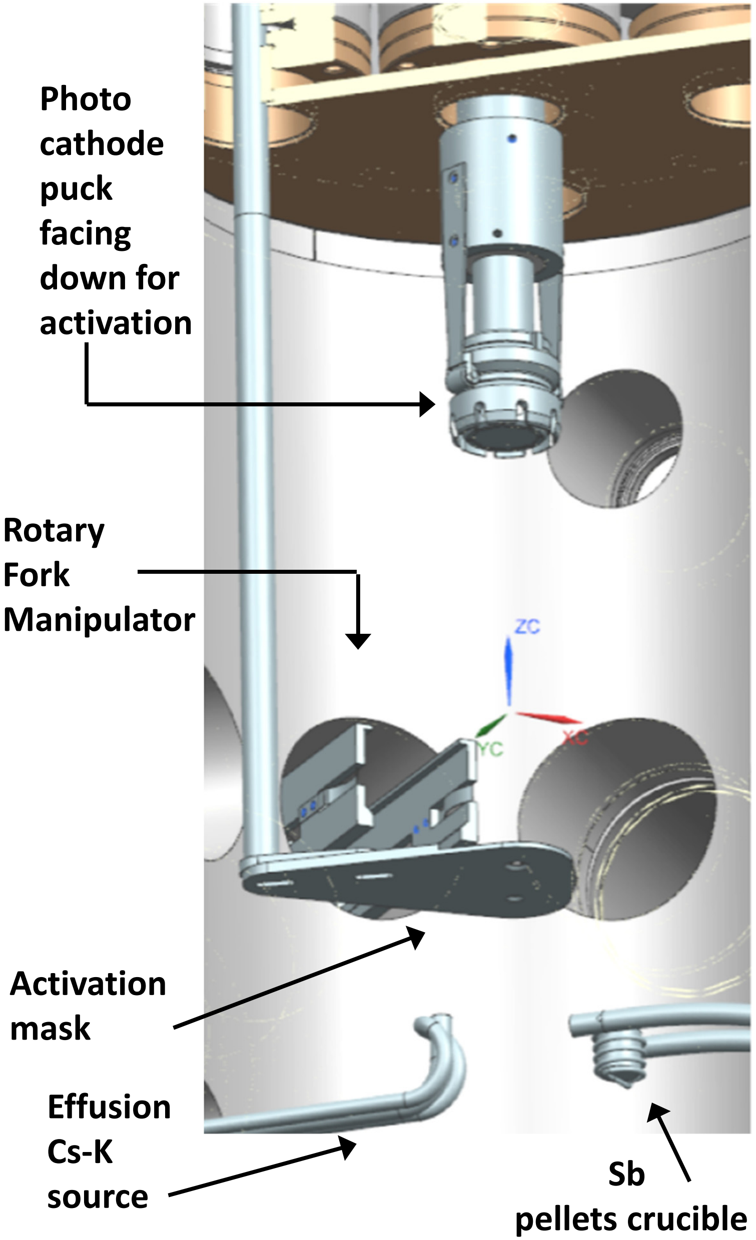
- Beam current was limited by high voltage power supply (30 mA, 225 kV with 3 kW power limit)
- World record is 65 mA CW, non-magnetized (Dunham *et al.*, Appl. Phys. Lett., vol. 102, p. 034105, 2013)

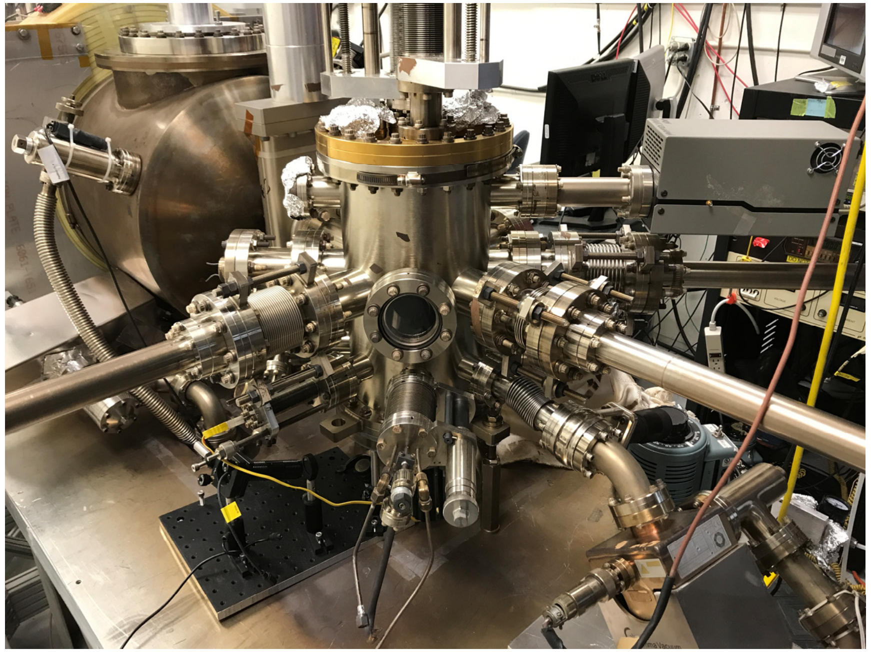
Magnetized Electron Source at Gun Test Stand

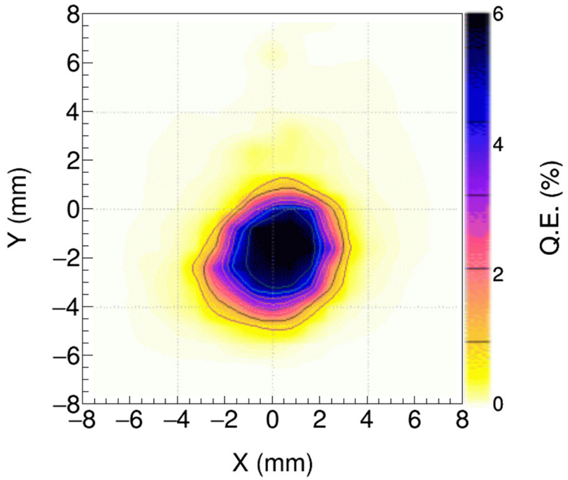


Photocathode Preparation Chamber

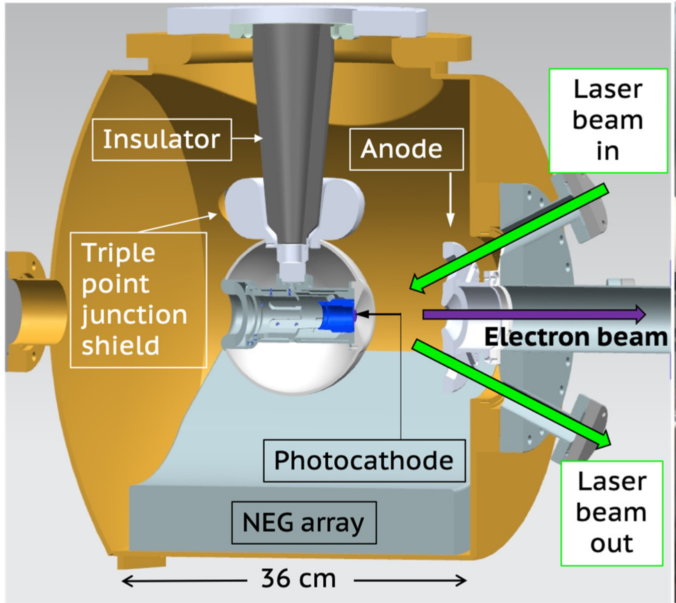
- K_xCs_ySb grown with a mask – limit photocathode active area (3 and 5 mm diameter) to reduce beam halo and prolong charge lifetime
- Active area can be offset from electrostatic center to minimize damaging of emission area from ion back bombardment and micro-arcing events during high current run
- Moly substrate to reduce laser induced thermal desorption of chemicals during high current run
- Consistently fabricated photocathodes with >5% QE

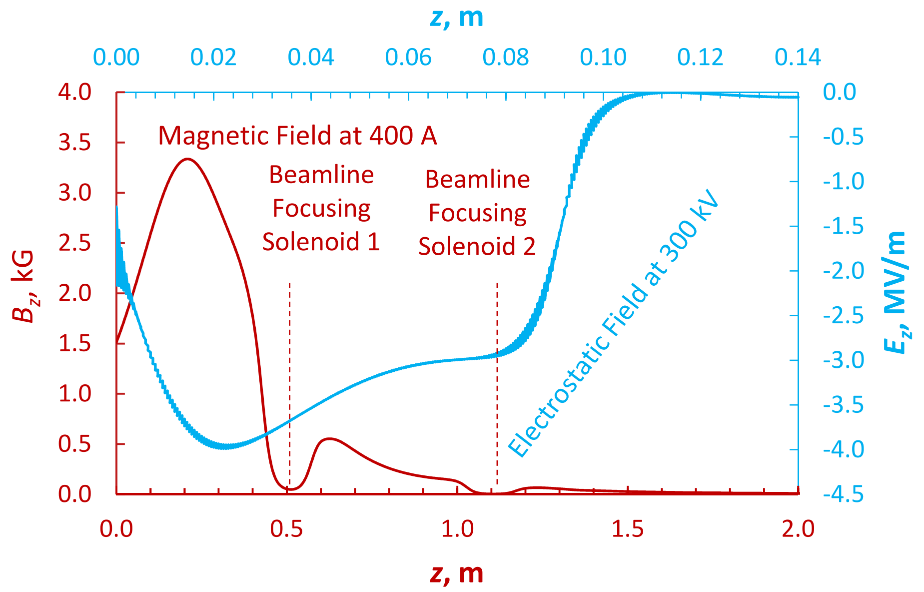


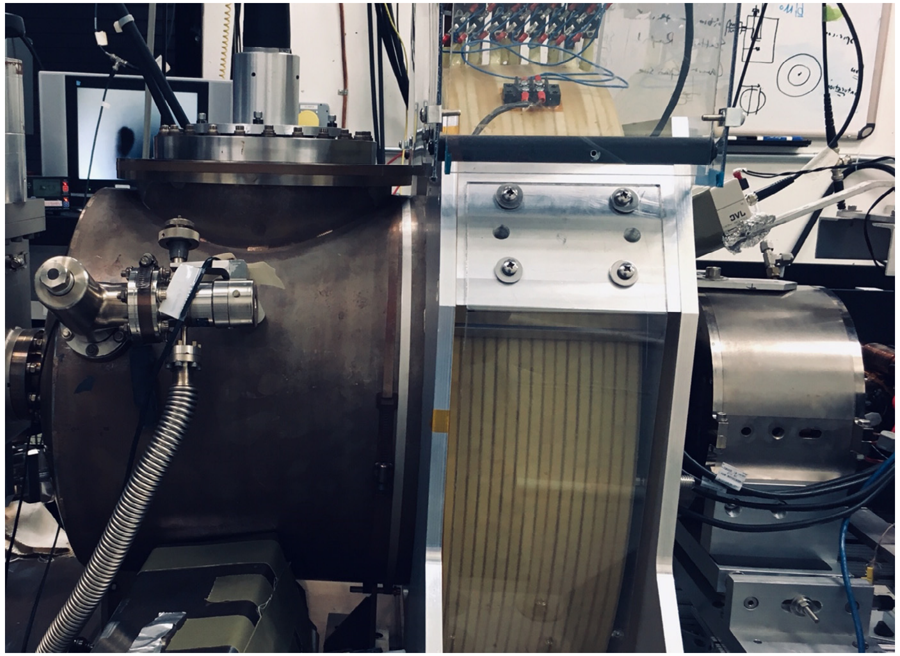




300 kV Inverted Gun and Cathode Solenoid





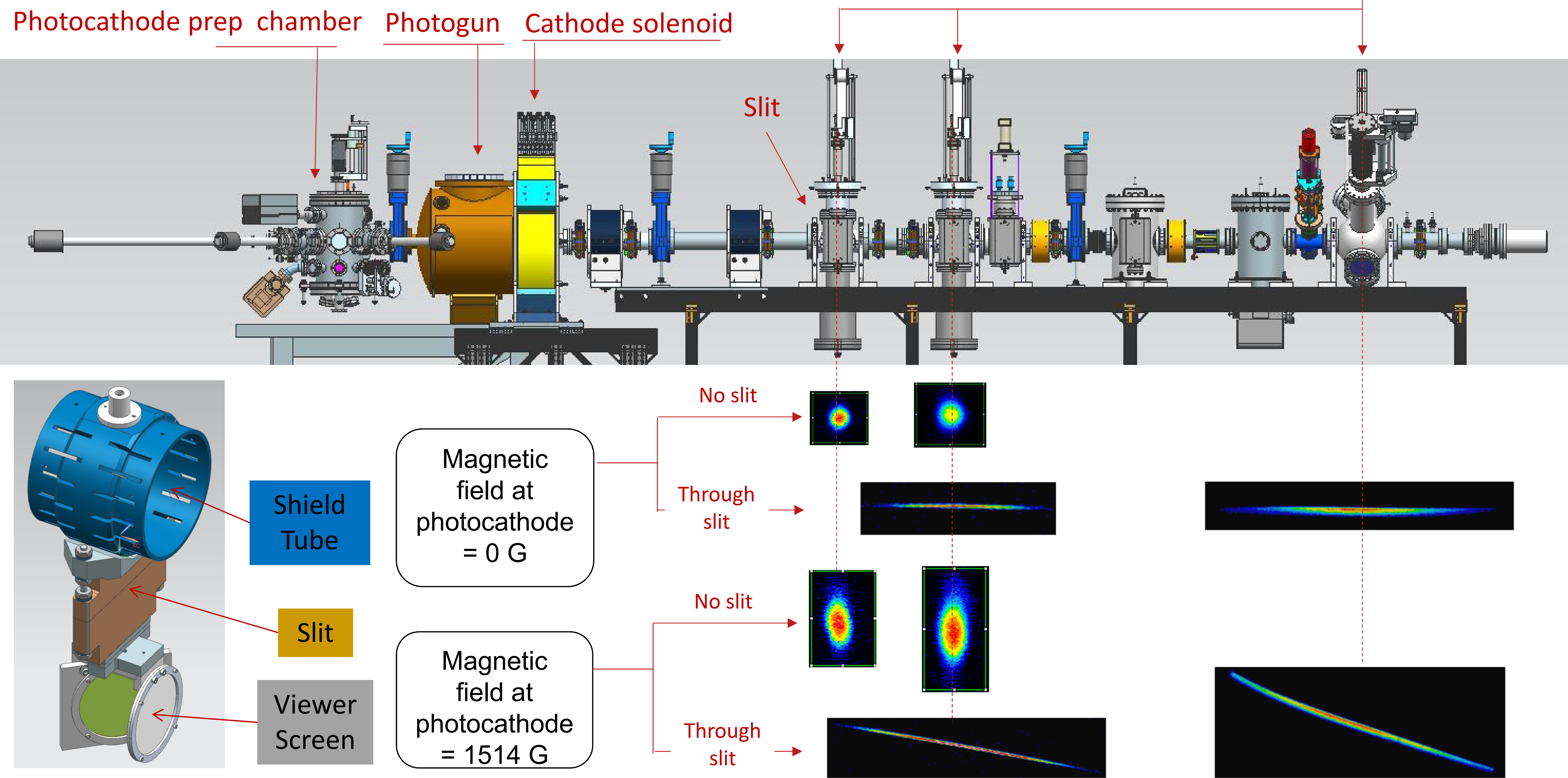


- Based on alumina inverted insulator and triple junction shield for max gradient of 10 MV/m at 350 kV
- Has been high voltage conditioned to 360 kV in 70 hours
- Nominal vacuum levels ~5x10^{-12} Torr after vacuum bake and high voltage conditioning

- Cathode solenoid provides magnetic field up to 1.51 kG at photocathode using a 400 A, 80 V supply
- Learned how to energize solenoid without exciting new field emitters
- Photogun operated at 300 kV with gun solenoid at 400 A

Characterization of Magnetized Beam

Beam and beamlet are observed on viewer YAG screens

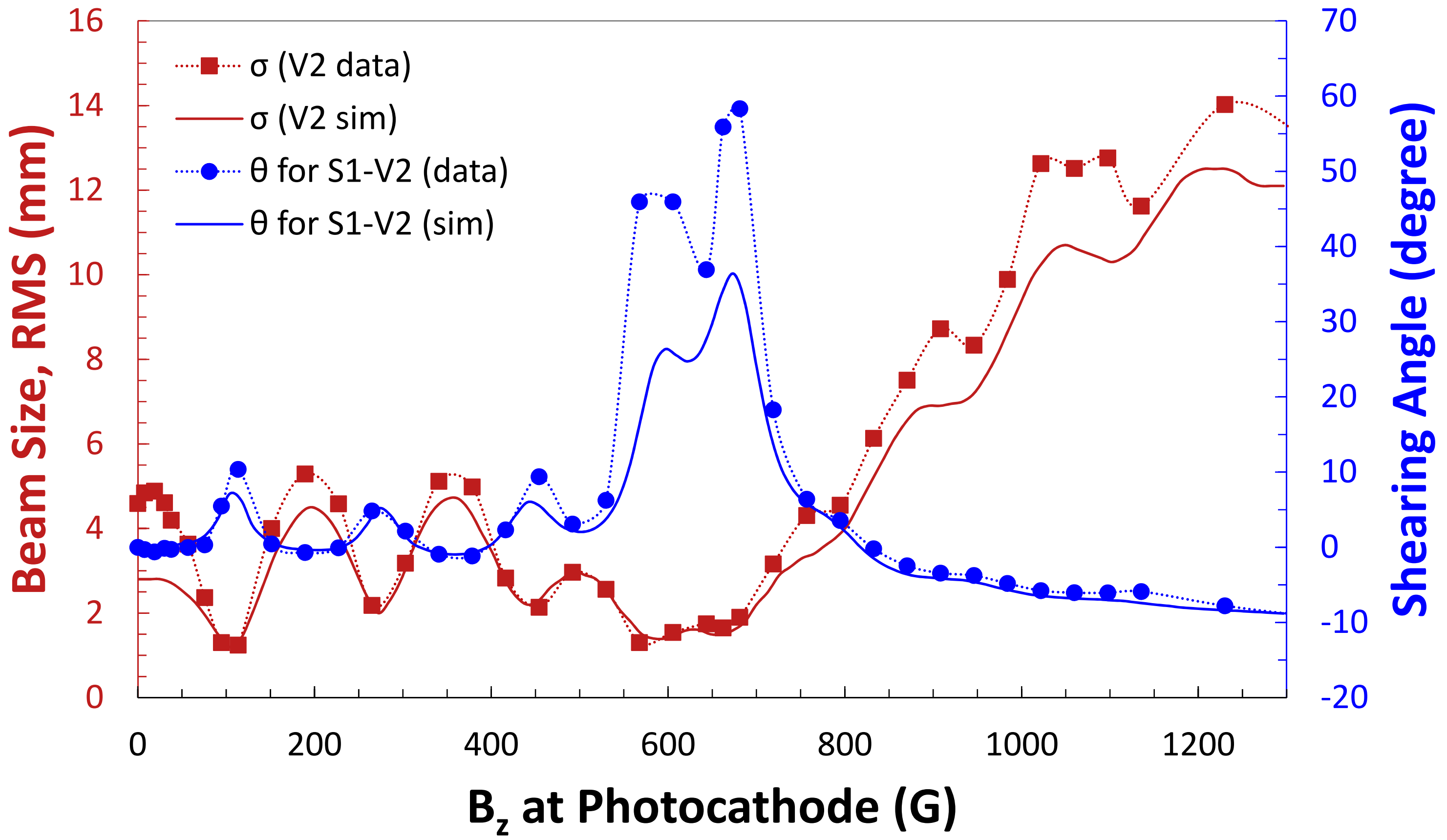


Magnetized Beam Sizes and Shearing Angles

- Strong magnetic field of cathode solenoid causes mismatch oscillations, resulting in repeated focusing inside solenoid which affects beam size at exit of solenoid. These mismatch oscillations introduce varying beam profile expansion rates and shearing angles in field free region.

- Modelled apparatus using ASTRA and GPT

Gun HV: 300 kV, laser RMS = 0.3 mm

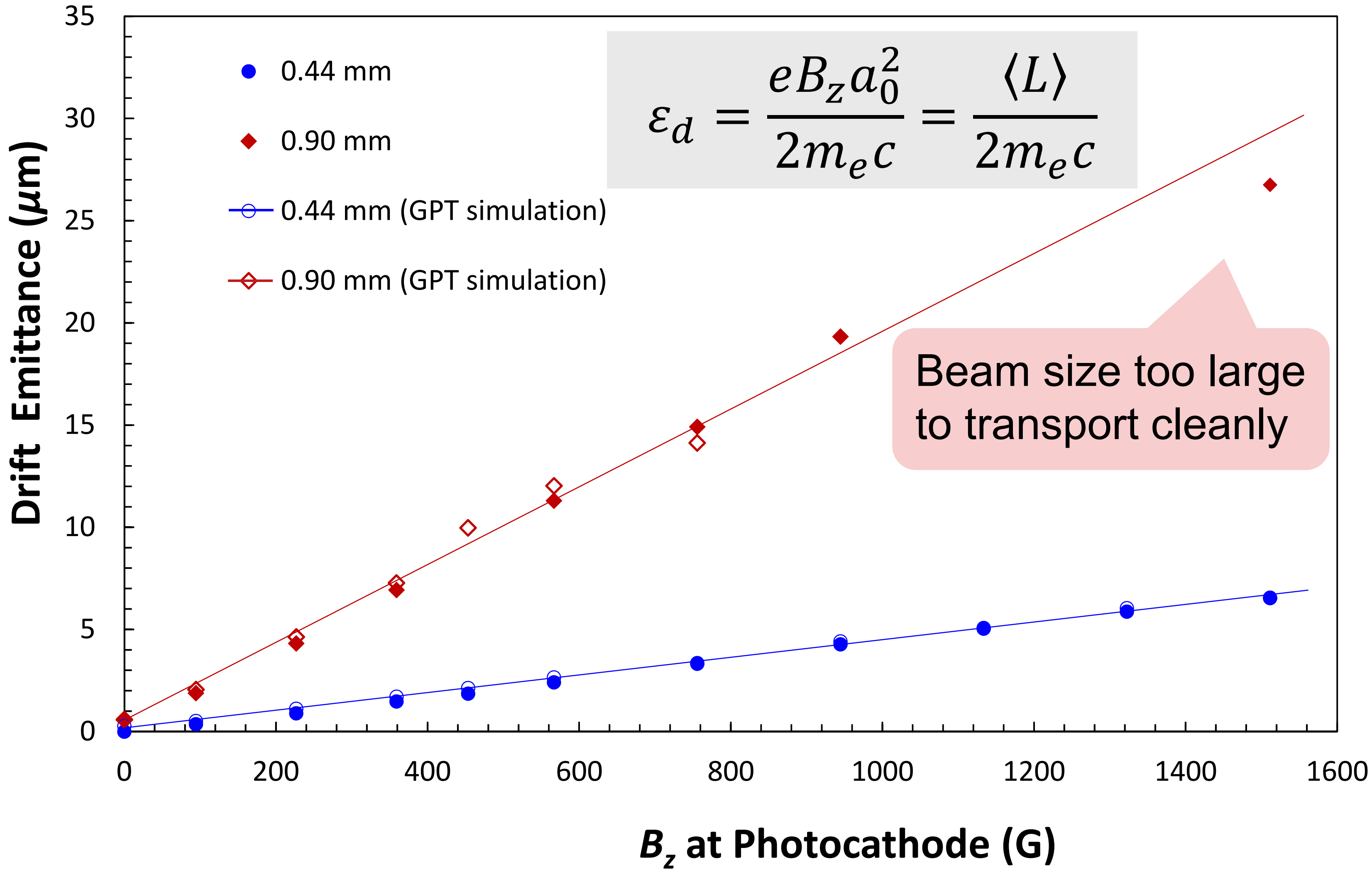


Drift (Correlated) Emittance

- Used beamline solenoid and viewer screen to measure correlated or drift emittance of magnetized beam for different laser sizes at 200 kV

- Thermal (uncorrelated) emittance of bi-alkali antimonide photocathode was measured to be 0.5 µm/mm (laser RMS)

- GPT simulation and experimental results show good agreement



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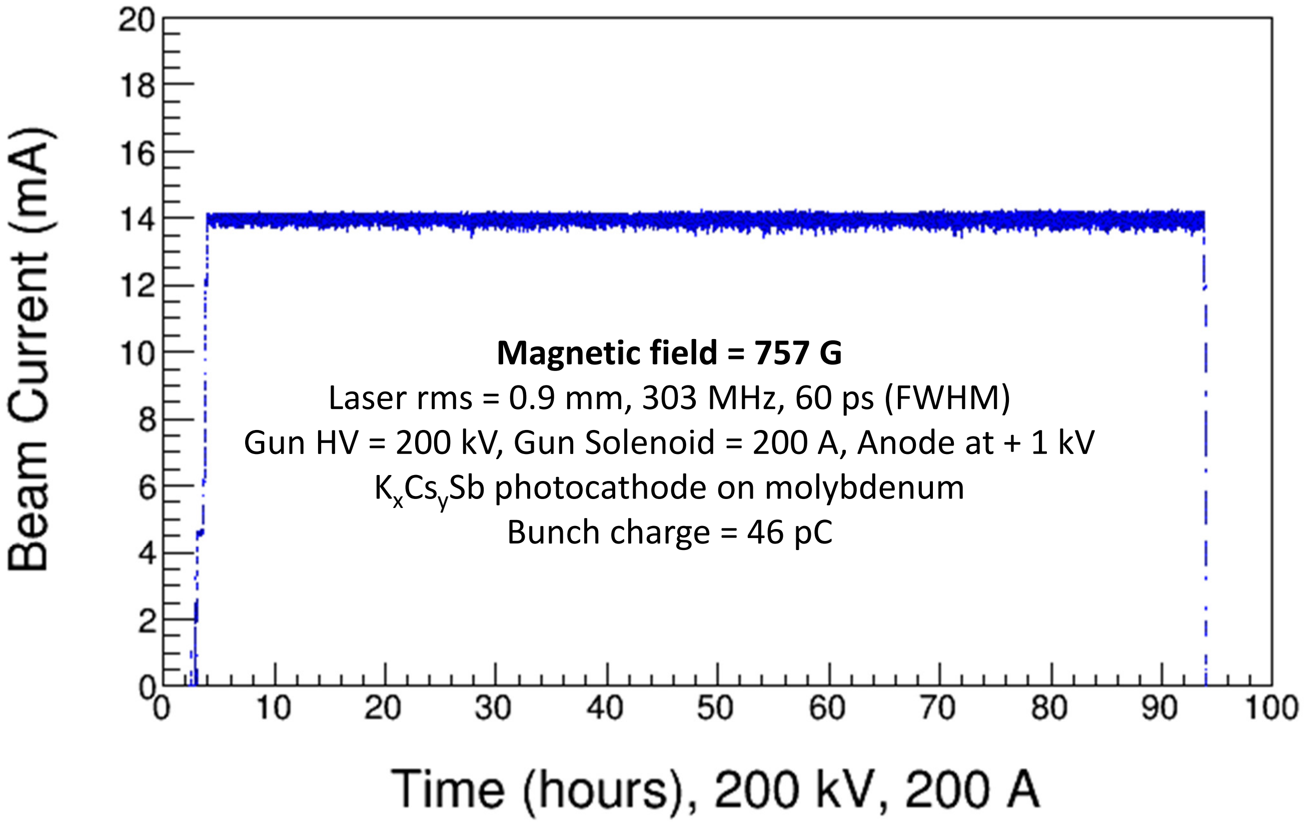
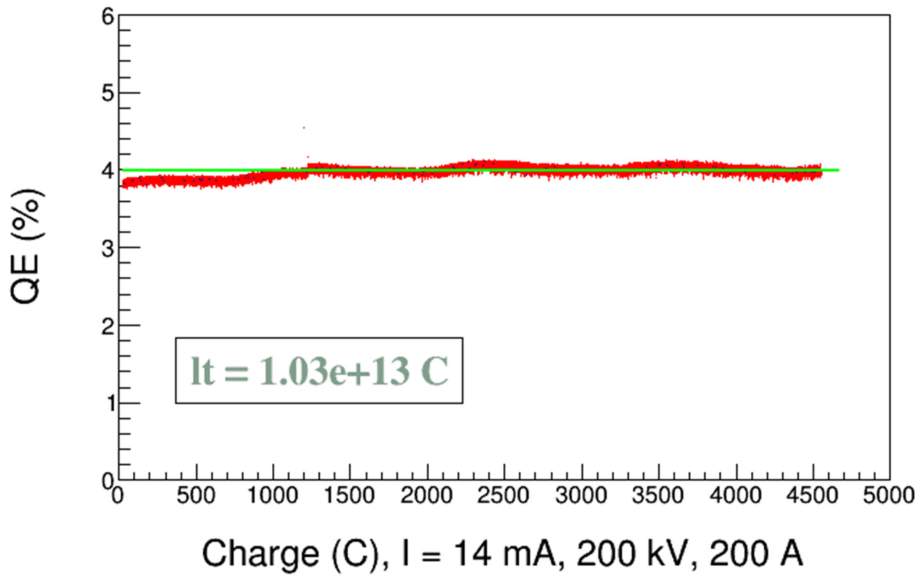
High Average Current: 14 mA





- No quantum efficiency (QE) reduction over 90 hour run
- Positive anode bias (+1 kV) effectively prevented ions in beamline from reaching gun and stopped micro-arcs and sudden QE loss (problem we struggled with)

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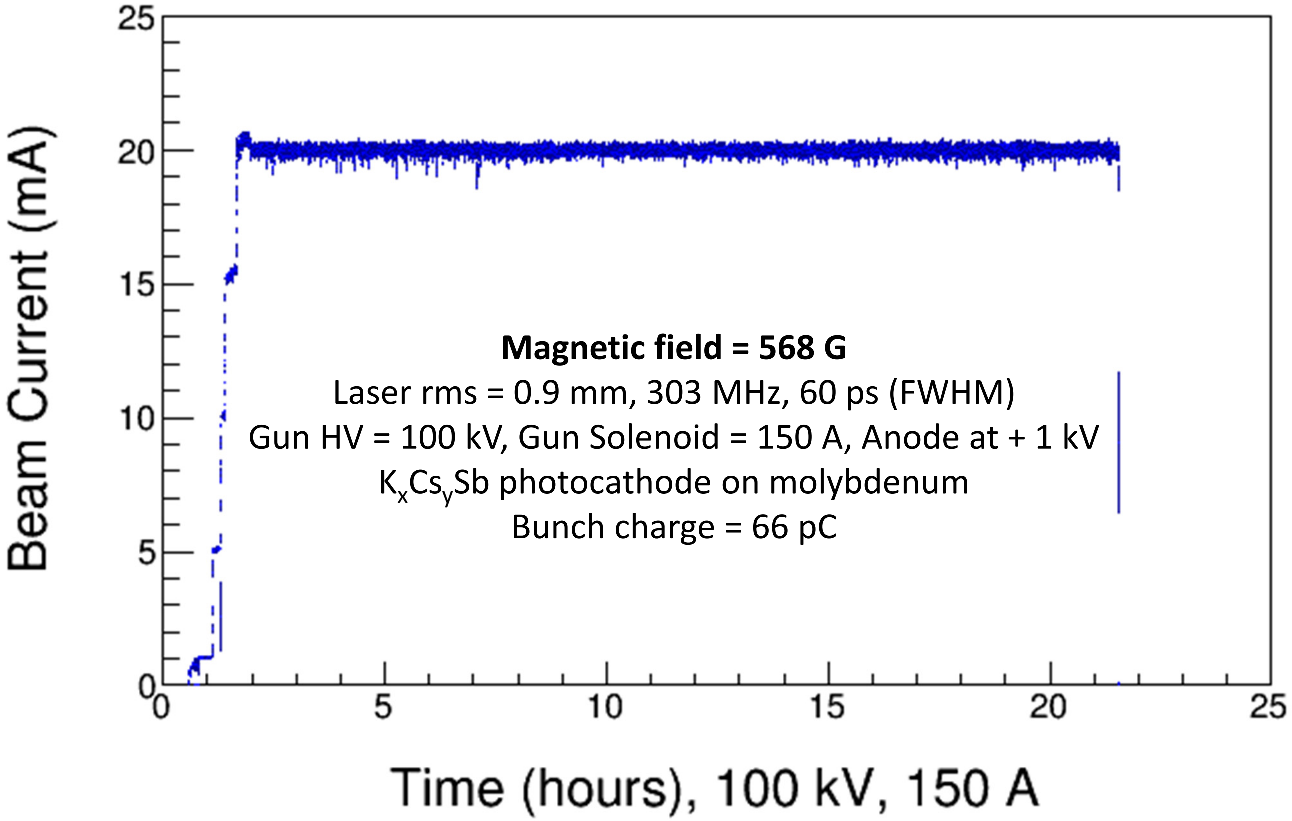
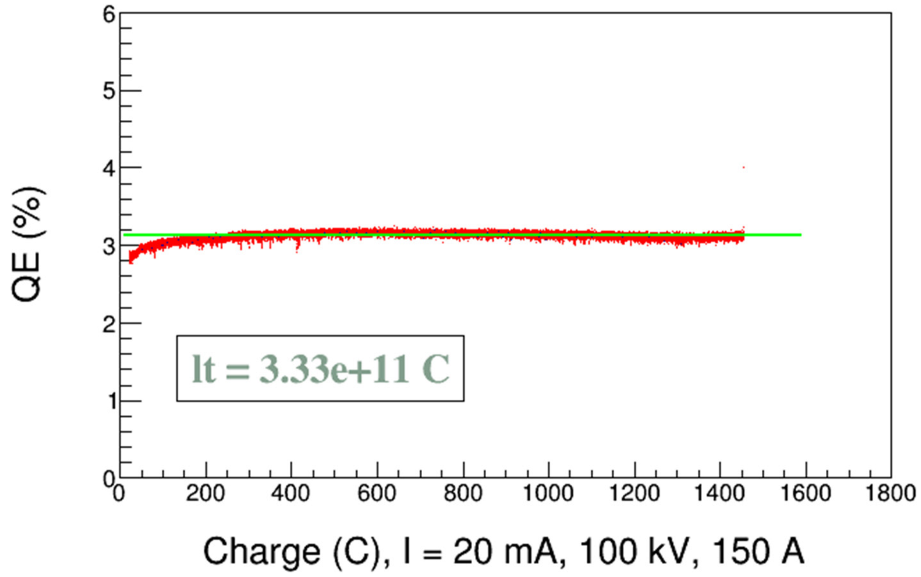
High Average Current: 20 mA





- No QE loss over 20 hours

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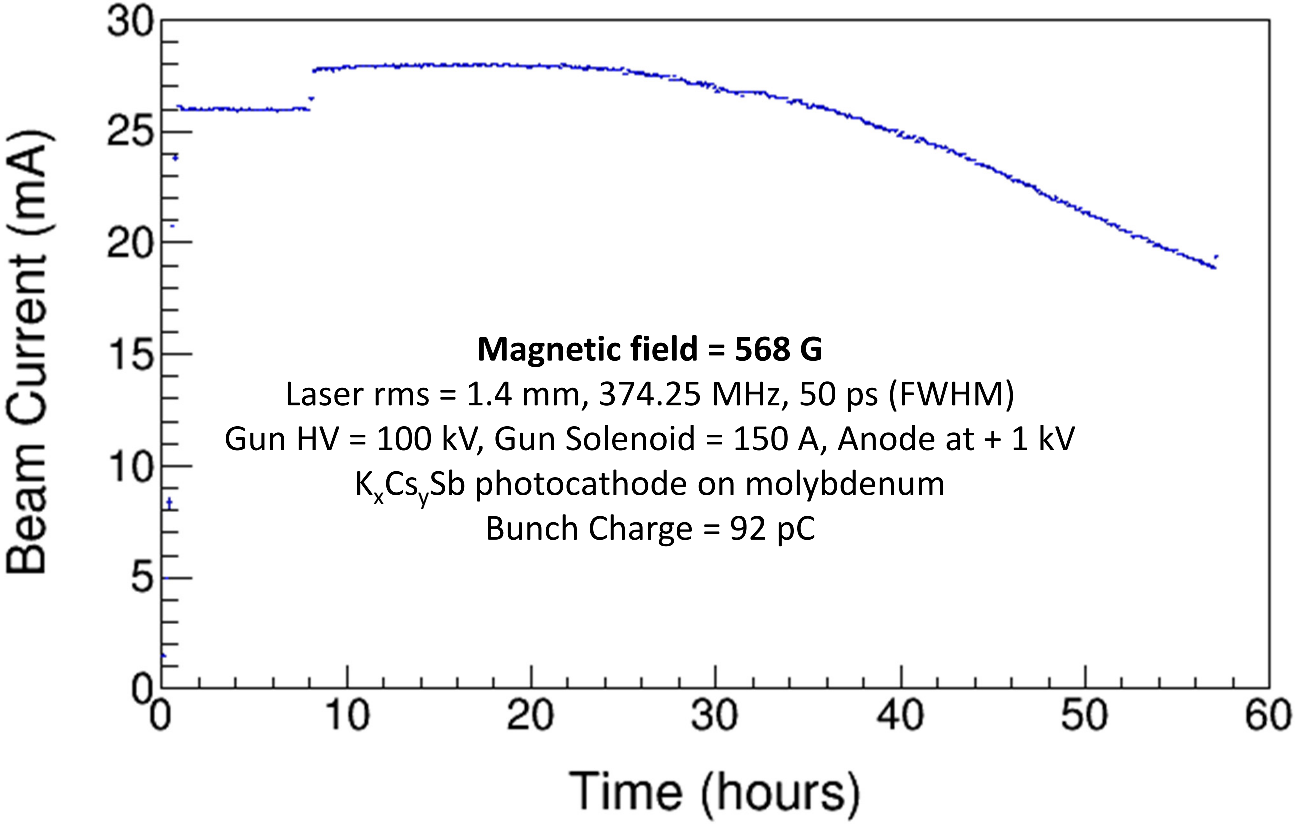
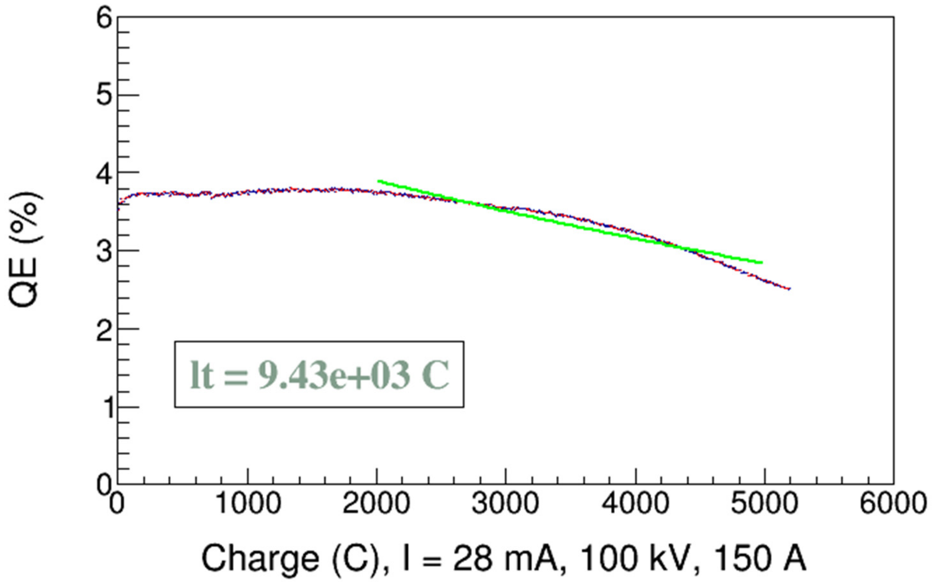
High Average Current: 28 mA





- Limited lifetime might be a result of heating and associated bandgap shift or chemical changes (such as dissociation), or enhanced ion bombardment
- To improve operational lifetime, will explore different photocathode compounds and substrates and photocathode cooling
- Will increase anode bias voltage beyond +1kV

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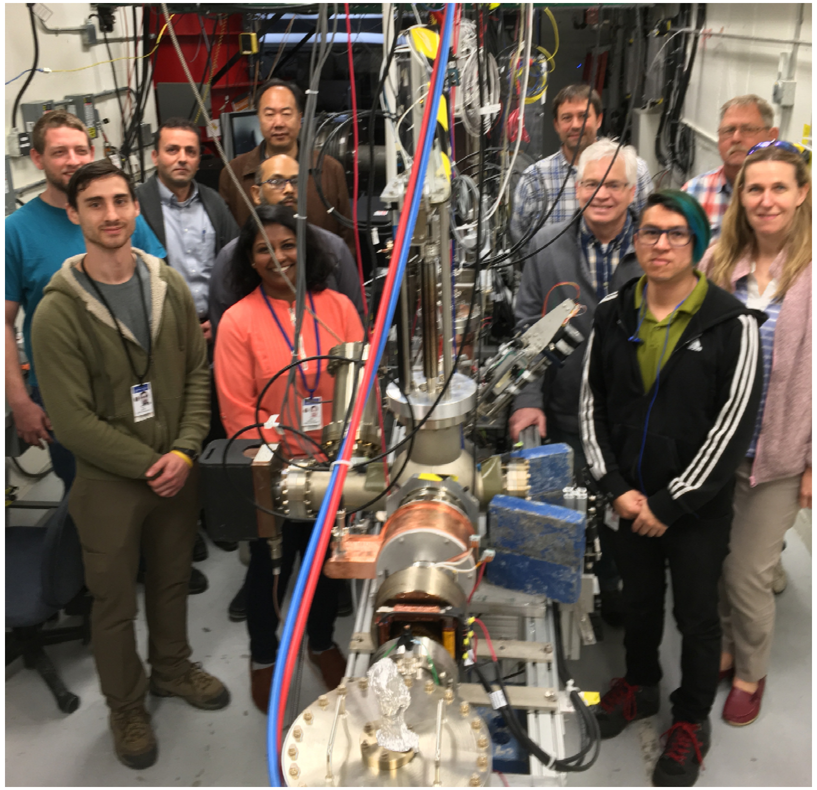
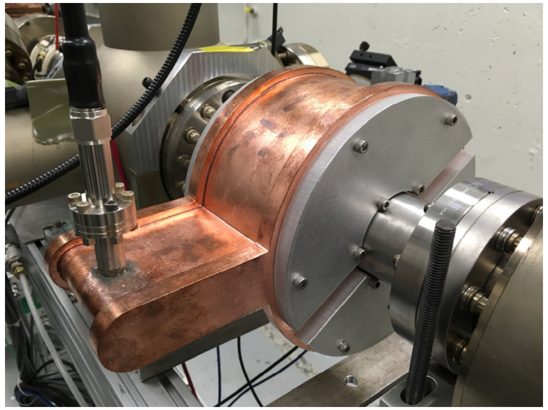
Summary and Future Plans

- K_xCs_ySb photocathode preparation chamber, photogun, cathode solenoid and beamline - all operational
- Photogun operated reliably up to 300 kV for >1000 hours
- Demonstrated high bunch charge up to 0.7 nC – see S. Wijhetunga’s talk TUZBB4
- Delivered 28 mA magnetized beam
- Positive bias on anode helps to prevent sudden QE loss from ion-induced micro-arcing events



- Replaced photogun with RF-pulsed thermionic gun to demonstrate magnetized beam at 65 mA and 125 kV – see F. Hannon’s talk THYBA4
- Envisioned new non-invasive device to measure beam magnetization (TE_{011} cavity). Cavity was designed, built and installed – to be commissioned this fall



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