Magnetized Beam LDRD

Abdullah Mamun
On behalf of JLab Injector Group

JLEIC Collaboration Meeting Spring 2018, March 26-28,, Jefferson Lab

Outline

- Magnetized Bunched-Beam Electron Cooling
- LDRD Magnetized Electron Source
  I. K_xCs_ySb Photocathode and HV Chambers
  II. Gun Solenoid
  III. Beamline
- Generation of Magnetized Electron Beam
- Measuring Electron Beam Magnetization
  – Slit and View-screens
  – TE_{011} Cavity: new non-invasive method
- Measuring Transverse Emittance of Non-magnetized Beam
- Measuring Charge Lifetime from High Current Beams
- Outlook
- Summary

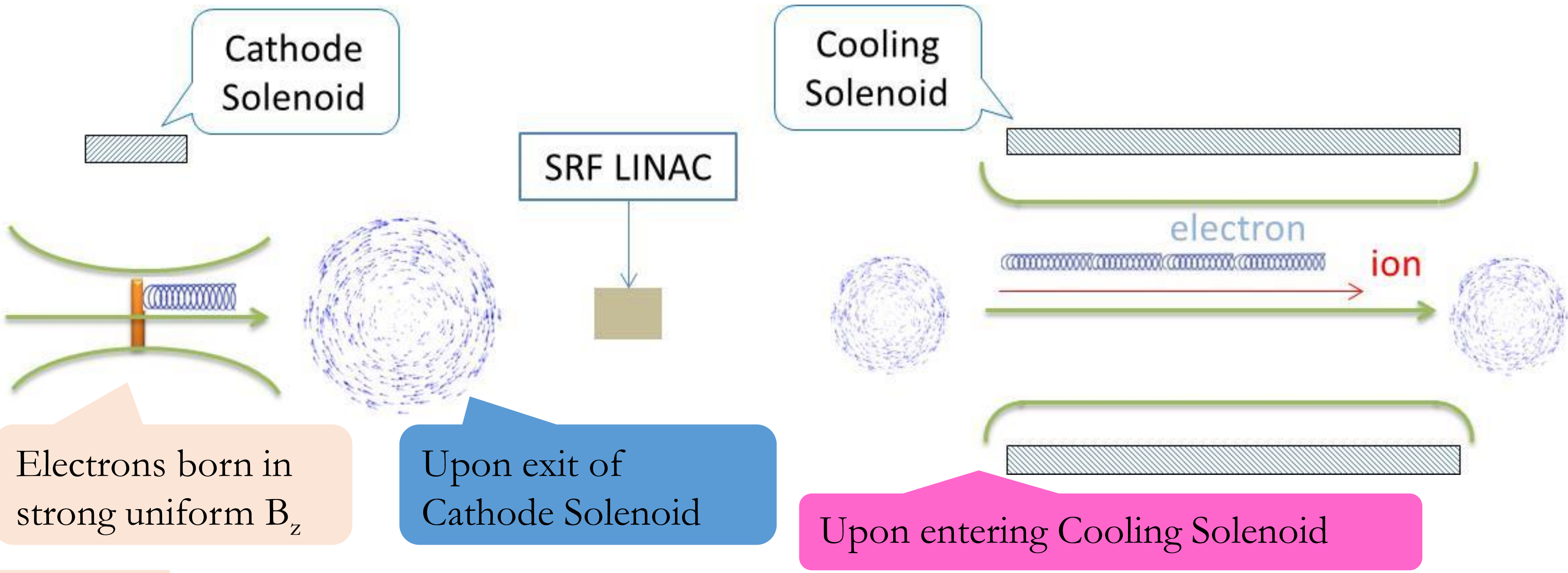
Magnetized Bunched-Beam Electron Cooling

- 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

but 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



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

a_0 = R$_{laser}$ = 3.14 mm
B$_z$ = 0.5 kG

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

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

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

r$_e$ = 0.7 mm
B$_{cool}$ = 1 T

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

JLEIC Magnetized Source Requirements

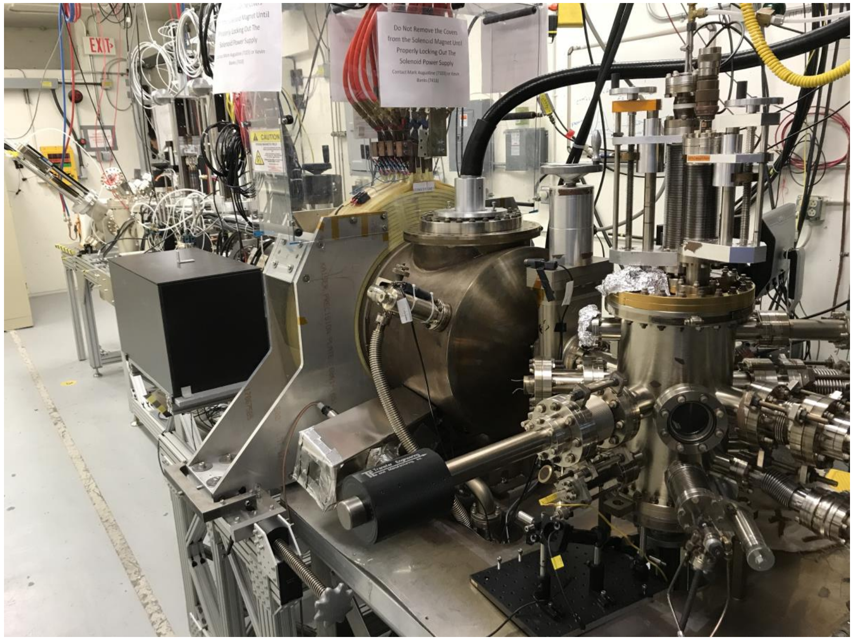
Bunch length	60 ps (2 cm)
Repetition rate	43.3 MHz
Bunch charge	3.2 nC
Peak current	53.9 A
Average current	140 mA
Transverse normalized emittance	<19 microns
Cathode spot radius – Flat-top (a_0)	3.14 mm
Solenoid field at cathode (B_z)	0.5 kG

- Cornell University demonstrated 65 mA and 2 nC, but not at same time, and non-magnetized

- Fermilab Magnetized Photoinjector Laboratory:
  - Pulsed NCRF gun with Cs_2Te photocathode and UV laser (λ=263 nm)
  - Bunch charge: 0.5 nC and bunch length: 3 ps
  - 0.5% duty factor (average current: 7.5 μA)
    - Bunch frequency: 3 MHz
    - Macropulse duration: 1 ms
    - Number of bunches per macropulse: 3000
    - Macropulse frequency: 5 Hz

Magnetized Source for e-cooler at 32 mA

- A high charge (420 pC) magnetized source is funded by the Jefferson Lab LDRD program that should operate up to 32 mA average current. This project concludes in 2018.



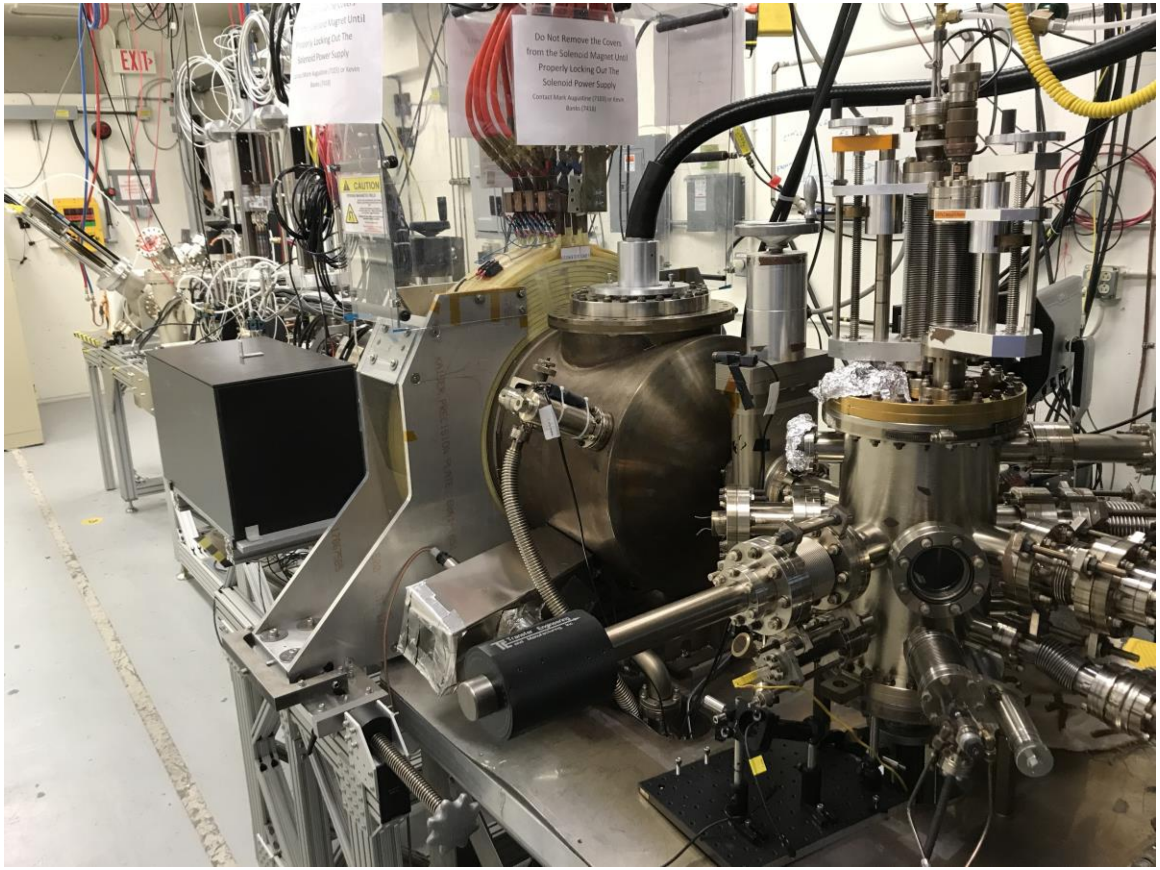
Magnetized beam parameters:
- a_0 = 0.1-1 mm, B_z = 0-1.5 kG
- Bunch charge: up to 2 nC
- Frequency: 1-15 Hz , 100-500 MHz
- Bunch length: 50 ps
- Average beam currents up to 32 mA
- Gun high voltage: 200 – 350 kV

Magnetized Beam LDRD

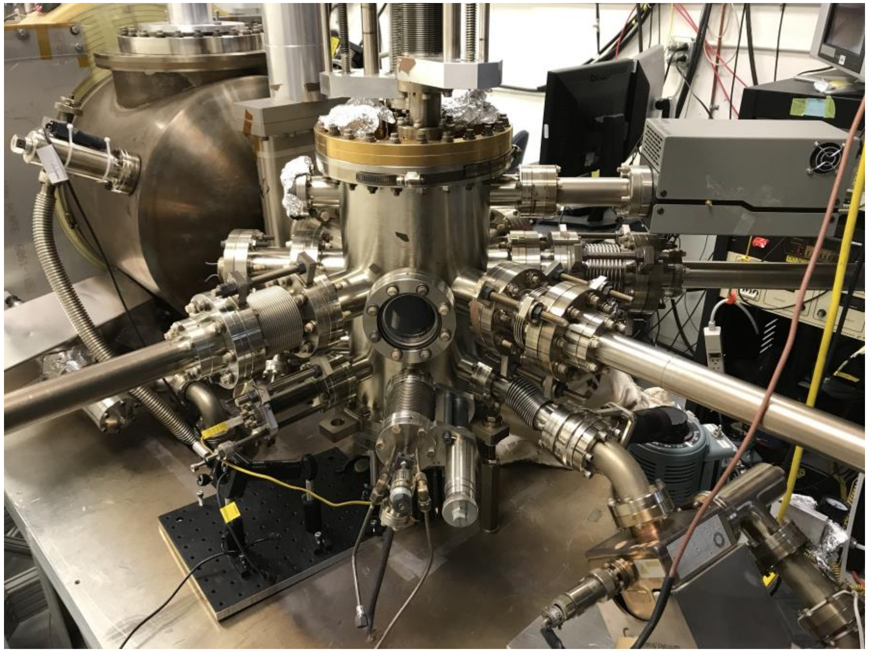
- Three-year project (FY16 – FY18):
  - Generate magnetized electron beam from dc high voltage photogun and measure its properties
  - Explore impact of cathode solenoid on photogun operation
  - Simulations and measurements will provide insights on ways to optimize JLEIC electron cooler and help design appropriate source
  - JLab will have direct experience magnetizing electron beams at high current

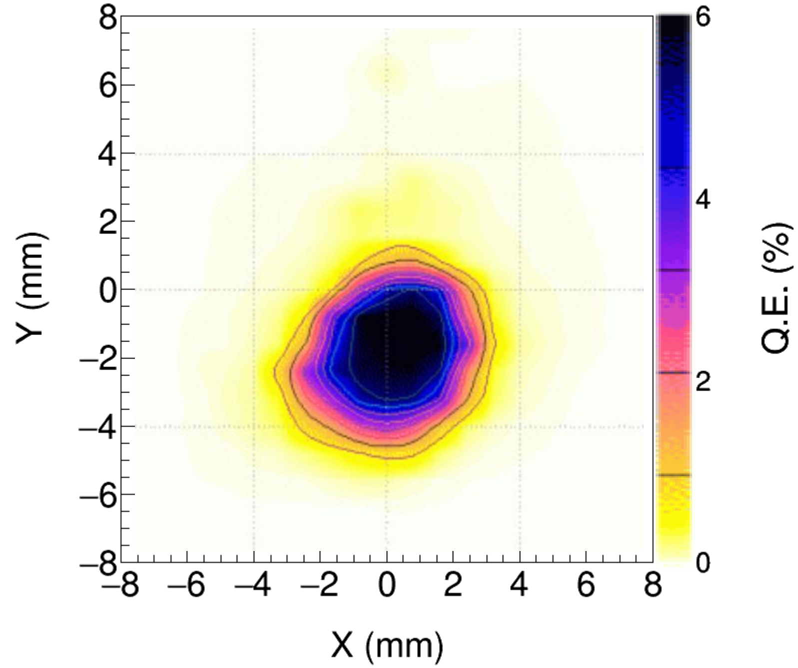
LDRD Magnetized Electron Source

- Bialkali Antimonide Photocathode Preparation Chamber, Gun, Solenoid and Beamline are all operational



Photocathode Preparation Chamber



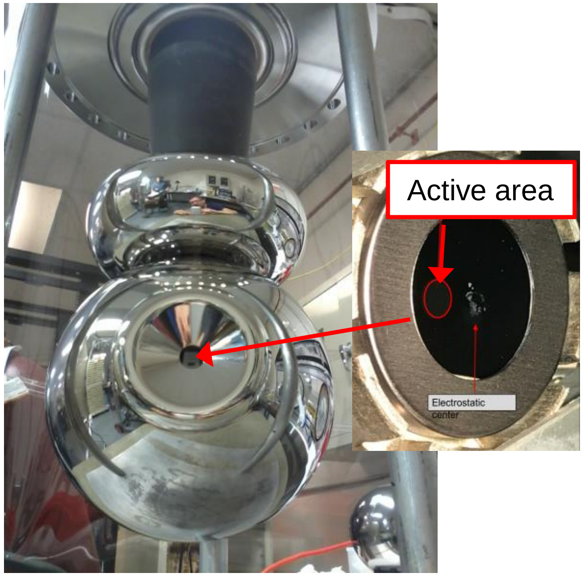


- K_xCs_ySb grown with a mask – limit photocathode active area (3 and 5 mm dia.) to reduce beam halo, minimize vacuum excursions and high voltage arcing, prolong photogun operating lifetime
- Active area can be offset from electrostatic center
- 3 and 5 mm dia. active area available; entire photocathode can be activated too
- Consistently growing photocathodes with 5-7% QE

Photocathode Preparation

- Co-deposition of alkalis (K and Cs) on Sb layer using an effusion alkali source to grow bialkali 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.
- 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, > 1x10^{-6}Pa and post-deposition to ~10^{-7}-10^{-8}Pa quickly.
- H_2O partial pressure < 2x10^{-9} Pa.

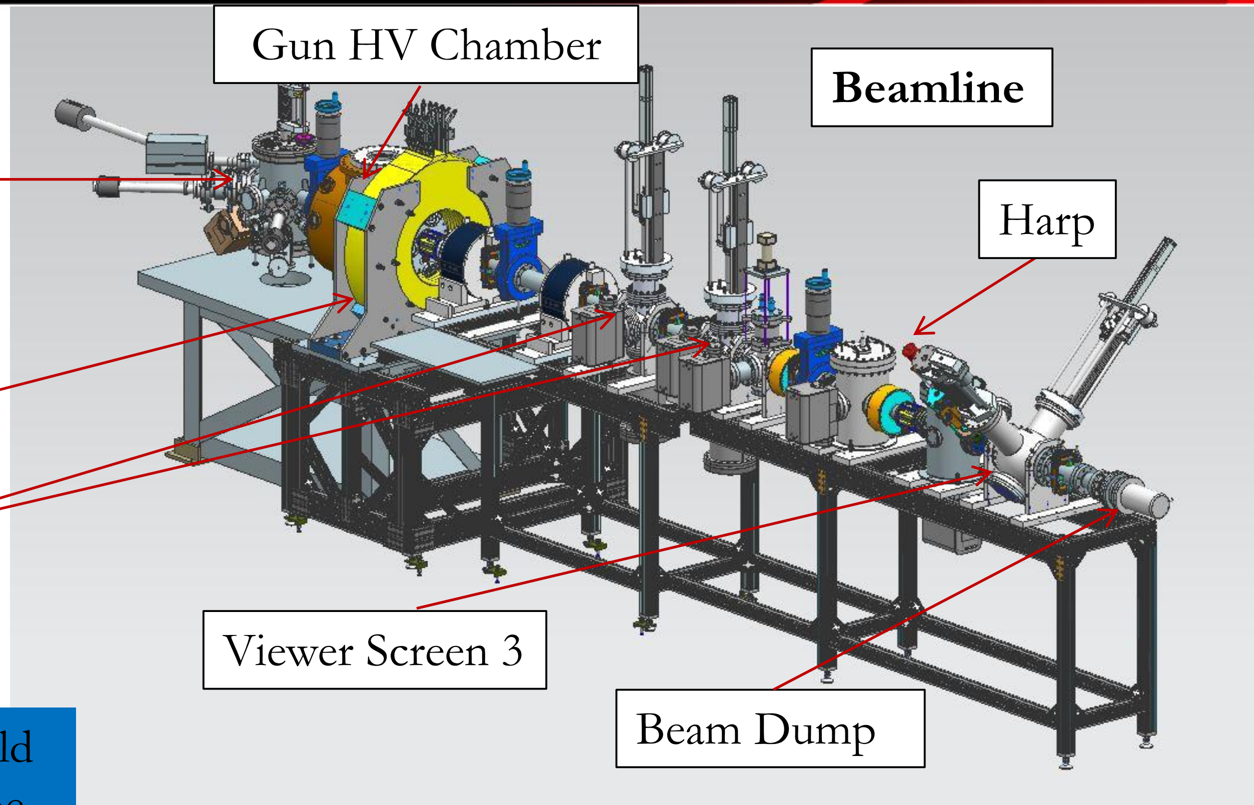
Gun HV Chamber

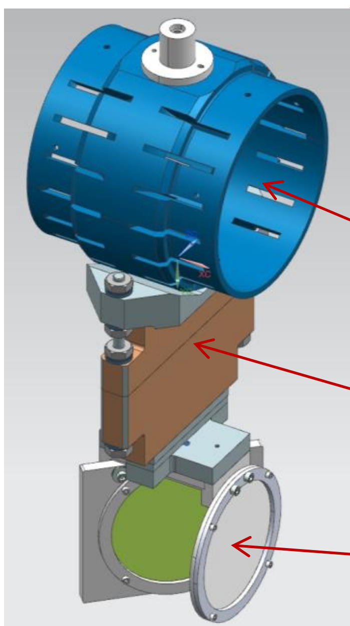


- Upgraded HV Chamber with new doped-alumina inverted insulator and newly designed screening electrode (triple point junction shield) to lower gradient from 12 MV/m to 10 MV/m at 350 kV
- Photogun operates at 300 kV with gun solenoid at 400 A

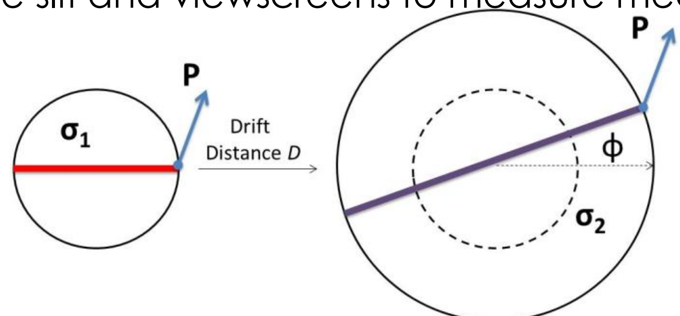
- Two weeks ago we got a setback from ceramic breakdown.
- Under process of replacing with a new ceramic, afterward baking and conditioning the gun for making it operational again.

Magnetized Source Schematics





Use slit and viewscreens to measure mechanical angular momentum:



$$\langle L \rangle = 2 p_z \frac{\sigma_1 \sigma_2 \sin\varphi}{D} = e B_z a_o^2$$

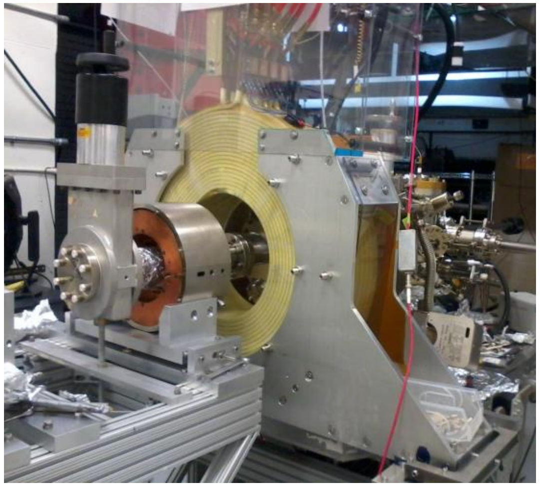
B_z: solenoid field at photocathode

a_0: laser rms size

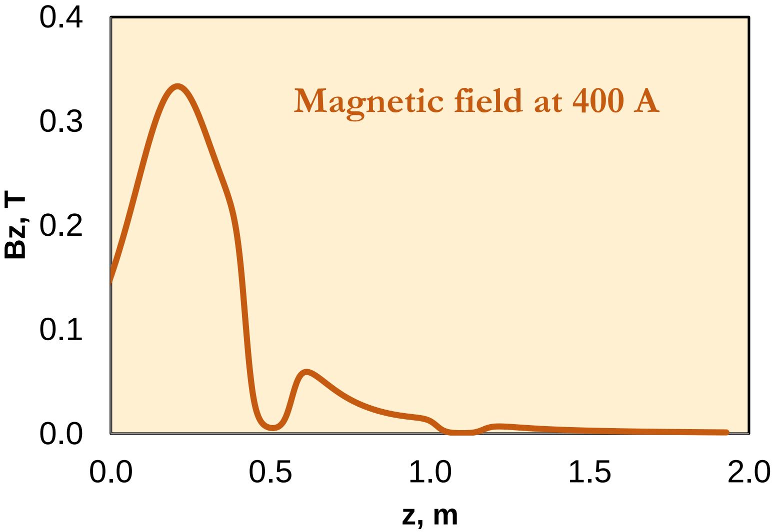
φ: rotation (sheering) angle

Gun Solenoid

Size	11.811" ID, 27.559" OD, 6.242" Z
Conductor	L=500 m, A=0.53 cm^2 16 layers by 20 turns
Coil Weight	254 kg (560 lbs)
Resistance	0.198 Ω
Field at Photocathode	1.5 kG
Voltage	79 V
Current	400 A

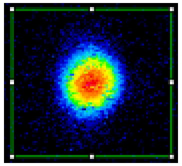


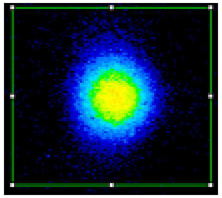
- Using spare CEBAF Dogleg magnet power supply (500 A, 80 V)
- Learned that gun solenoid **can** influence field emission
- First trials with gun at high voltage and solenoid **ON** resulted in new field emission and vacuum activity
- Procedure to energize solenoid without exciting new field emitters



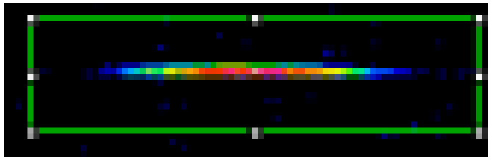
Slit and Viewscreen Measurement

0 G at photocathode

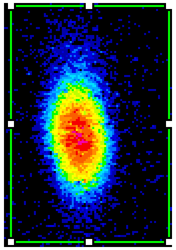


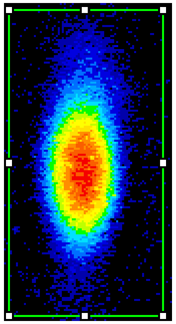


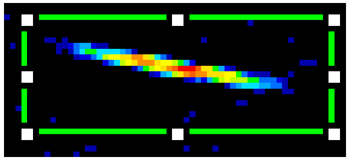
Beamlette observed on downstream viewer



1511 G at photocathode



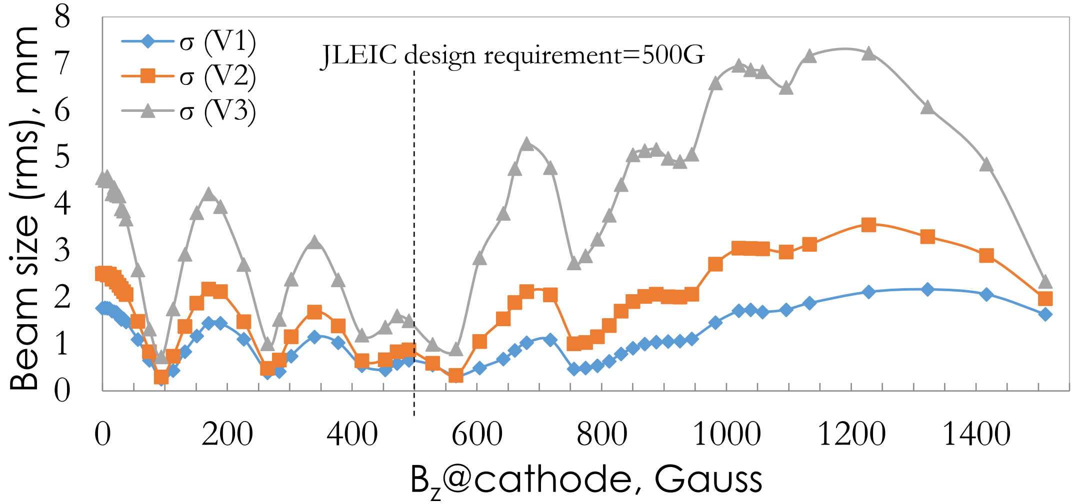




Beam Size and Rotation Angle

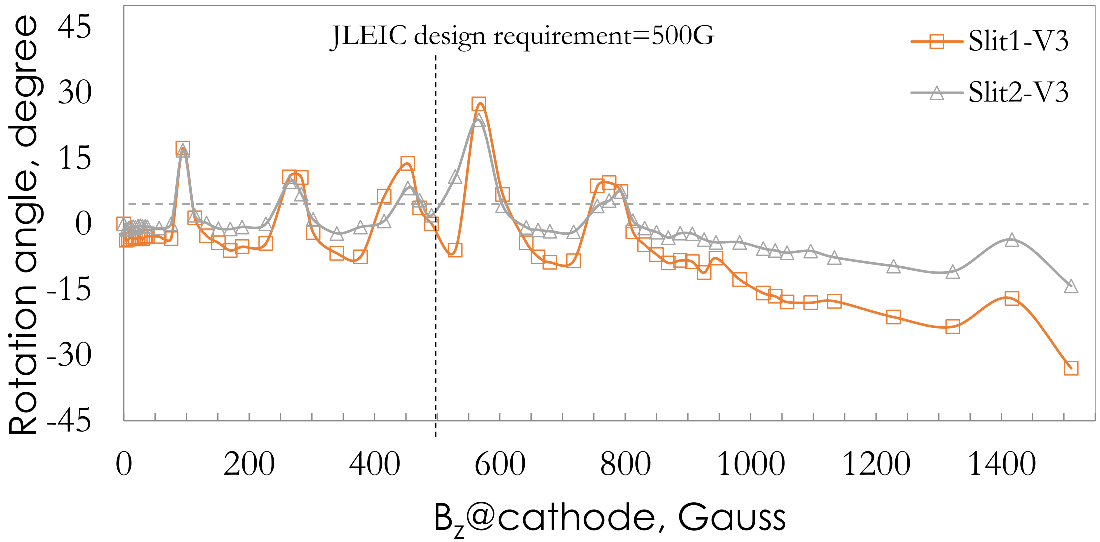
Gun HV=300 kV, Laser spot size = 0.1 mm rms, Illumination position: 5 mm off centric on photocathode

Gun solenoid magnetizes beam but also focuses beam

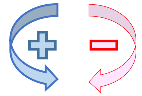


Three curves correspond to measurements at three beamline viewers

Rotation angle influenced by Larmor oscillation in gun solenoid

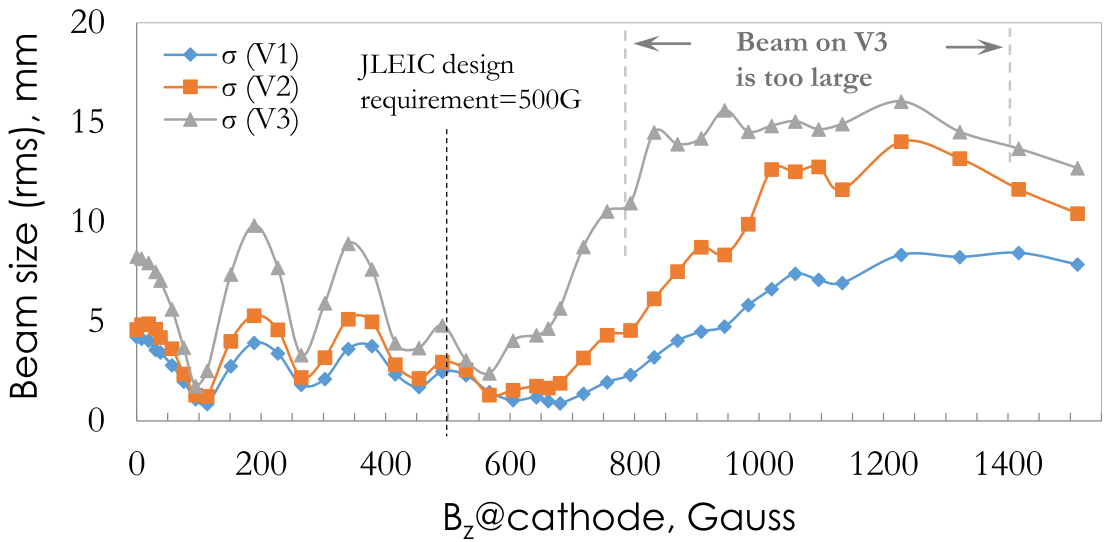


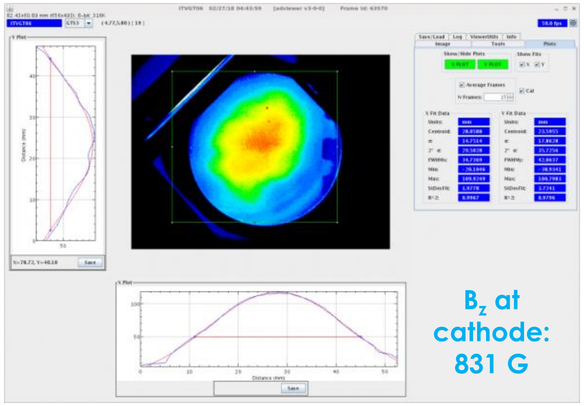
Sign convention followed

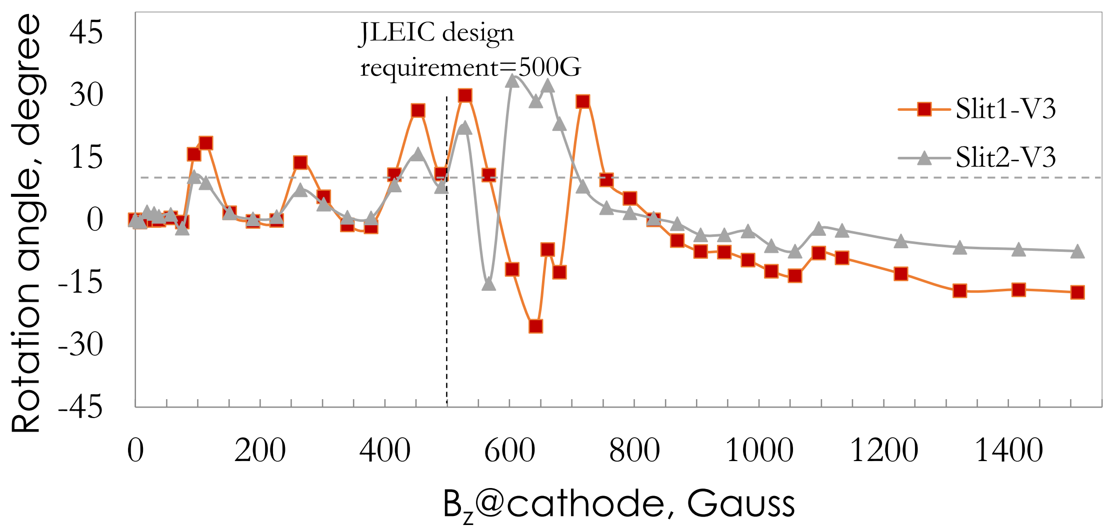


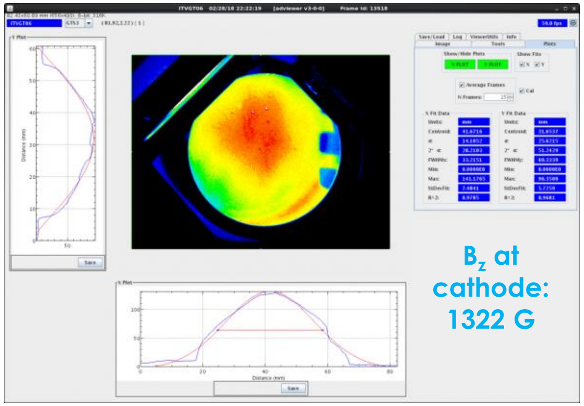
Beam Size and Rotation Angle

Gun HV=300 kV, Laser spot size = 0.3 mm rms, Illumination position: center on photocathode



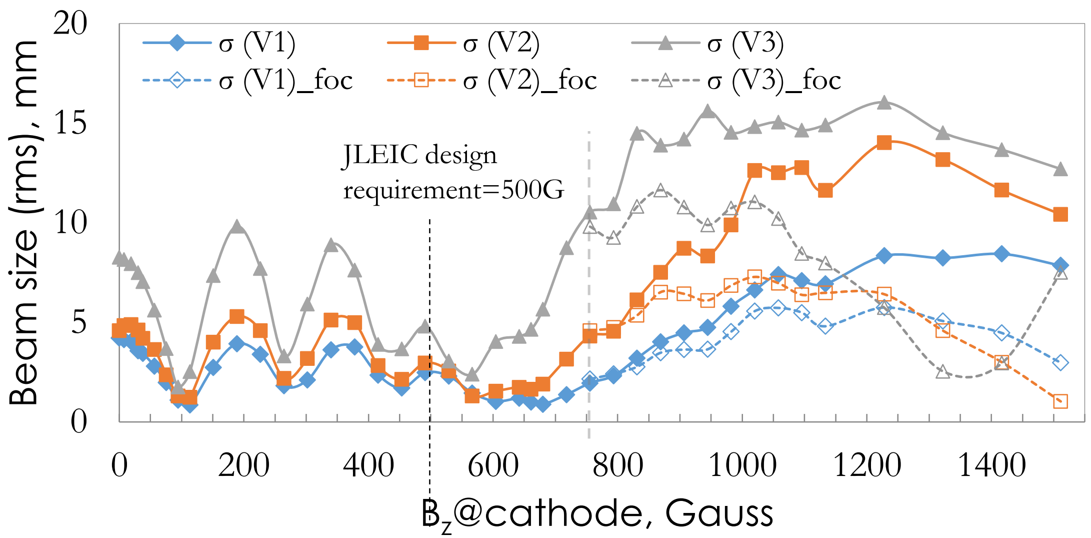


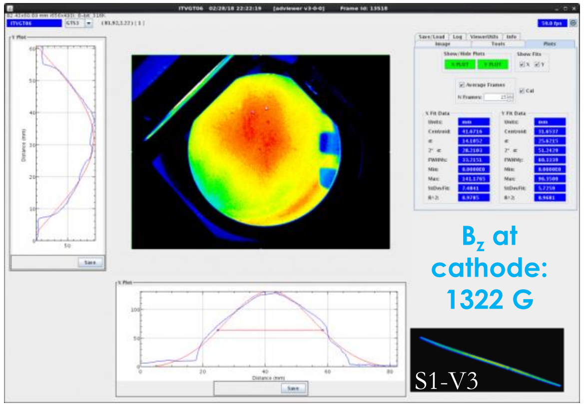




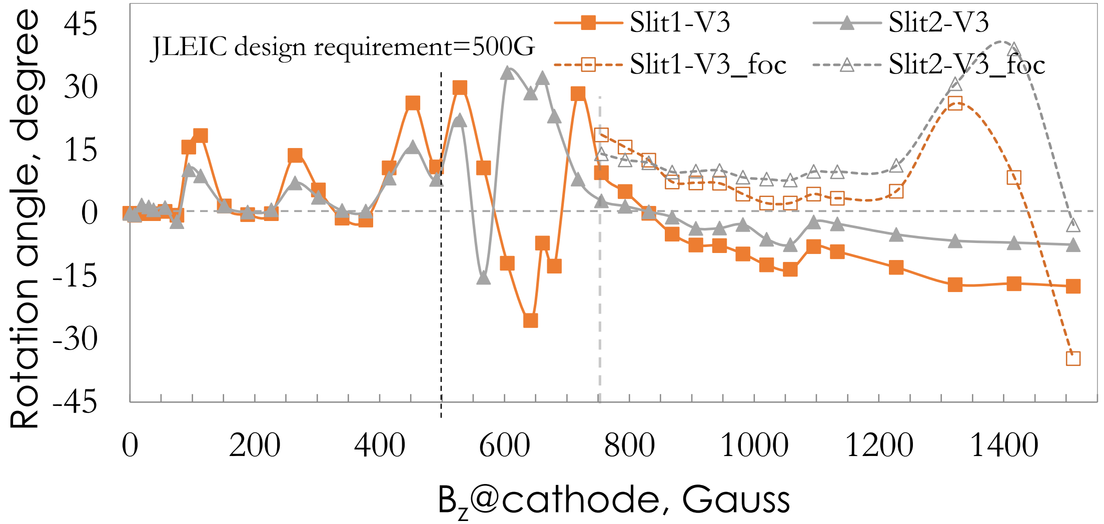
With/out Focusing with Beamline Lenses

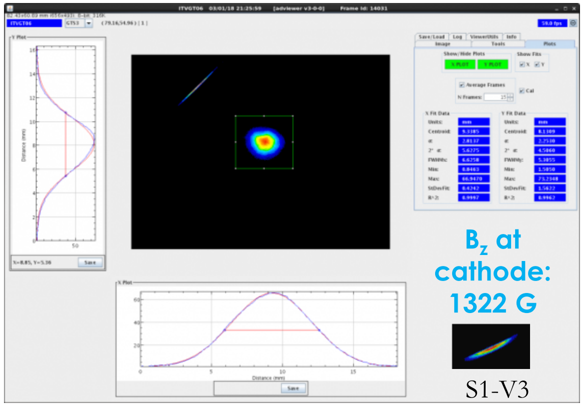
Gun HV=300 kV, Laser spot size = 0.3 mm rms, Illumination position: center on photocathode





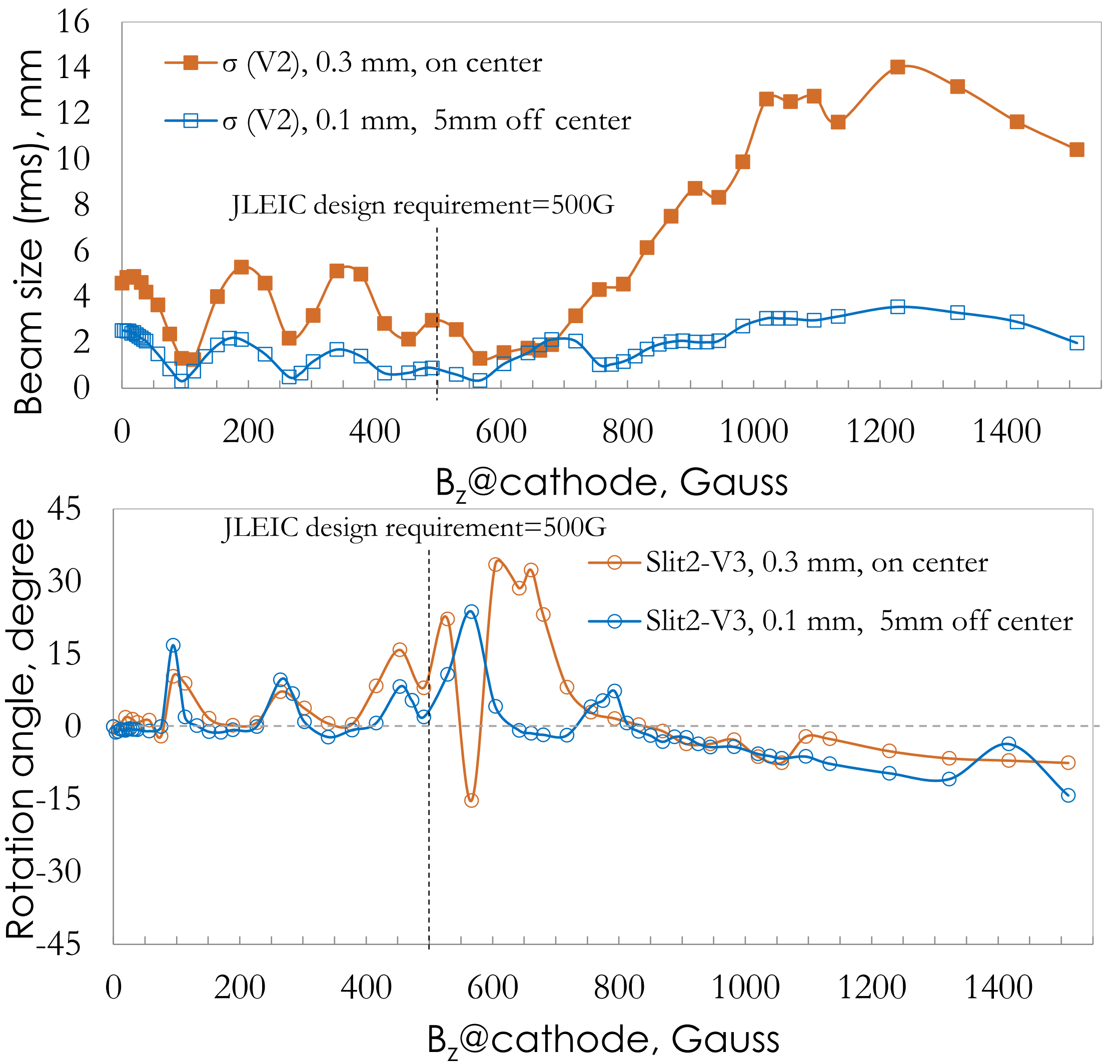
Focusing field used at 2nd lens (MFGGT03)~ 2400 G-cm (2.206 Amps) and at 3rd lens(MFHGT05) ~700 G-cm (0.736 A)





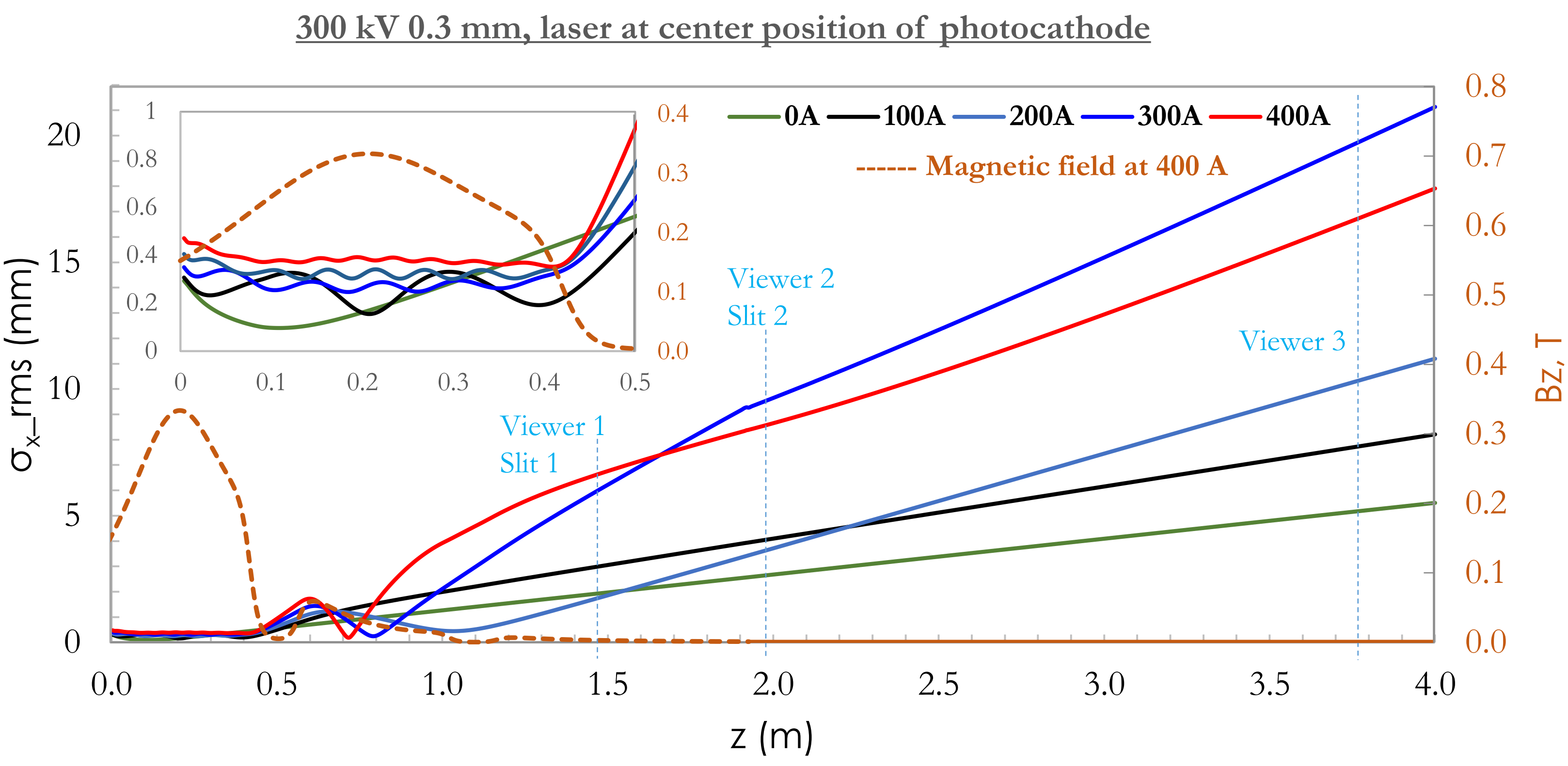
On Ceneter vs Off Center Illumination

Gun HV=300 kV



Modeling Magnetized Beam

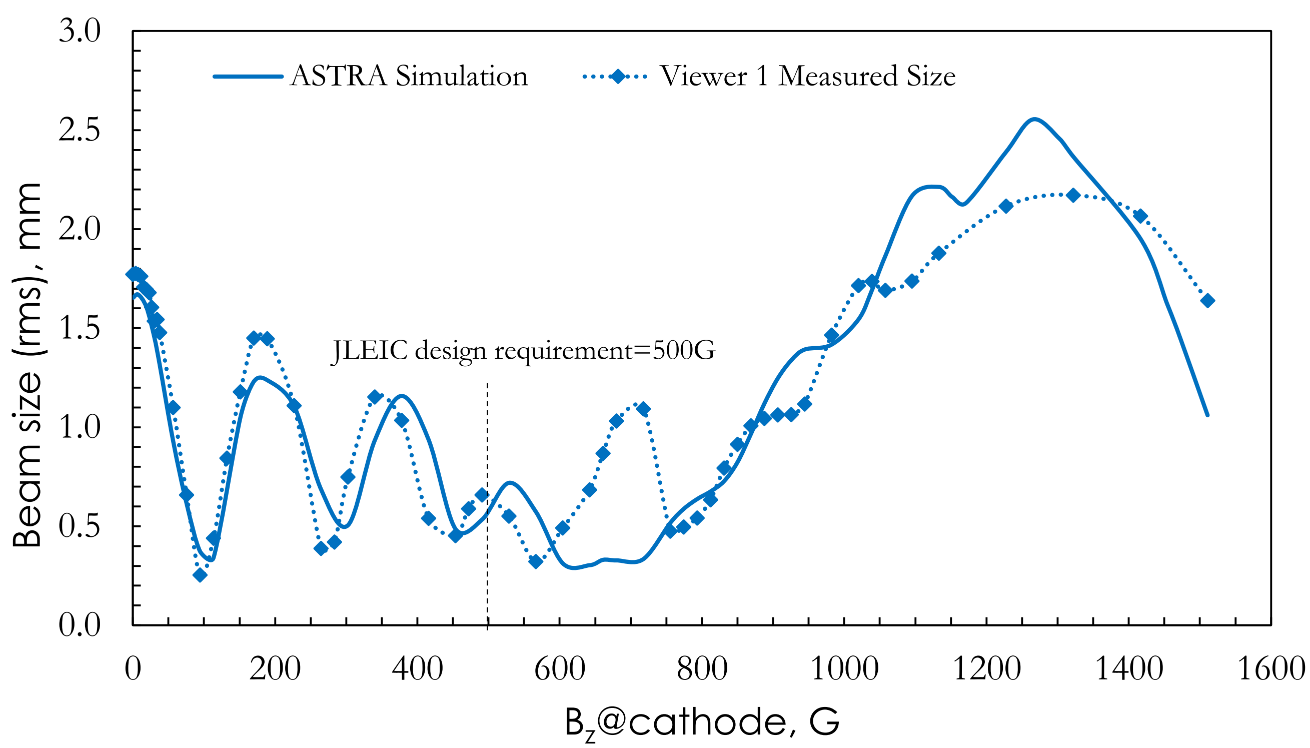
ASTRA simulation of beam size



Simulation vs Experimental

Encouraging progress in modeling our apparatus and beam magnetization

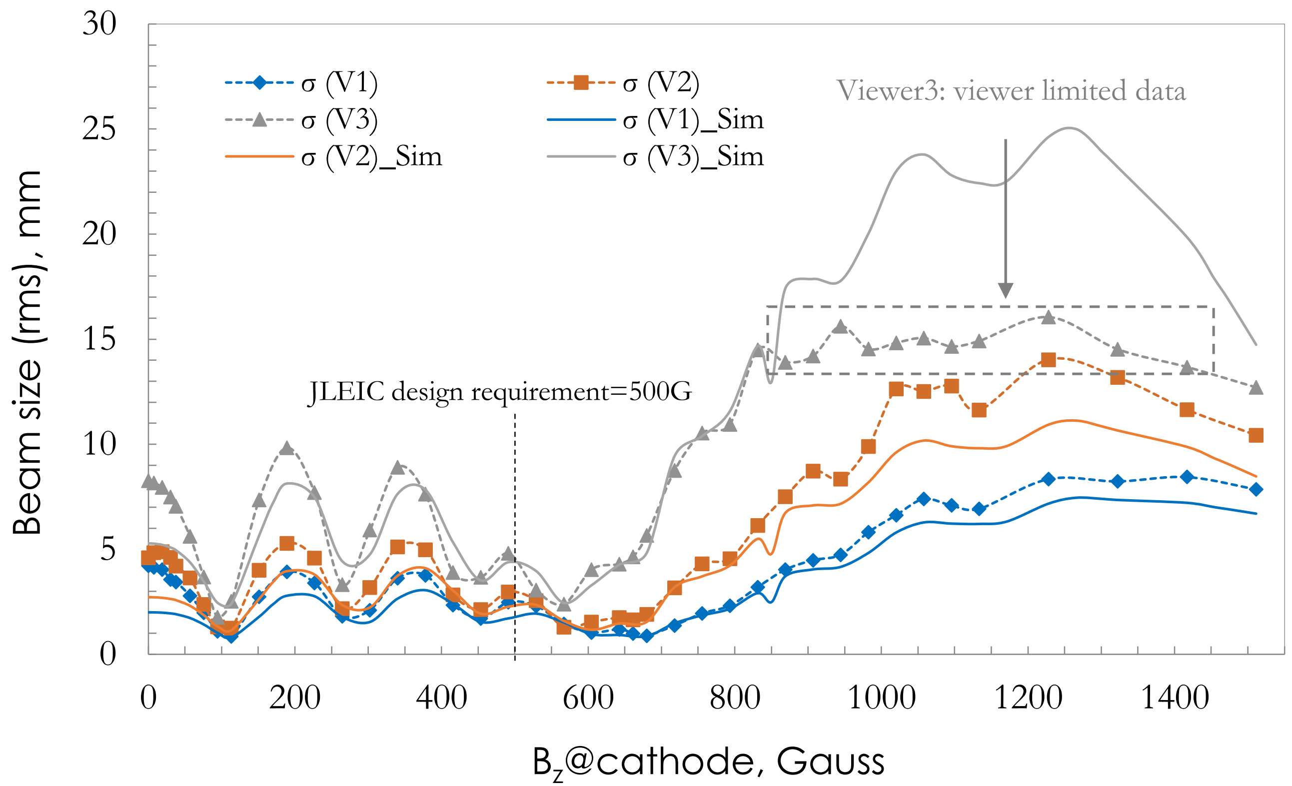
Gun HV=300 kV, Laser spot size = 0.1 mm rms, position: 5 mm off center on photocathode



Simulation vs Experimental

In progress of optimizing our simulation

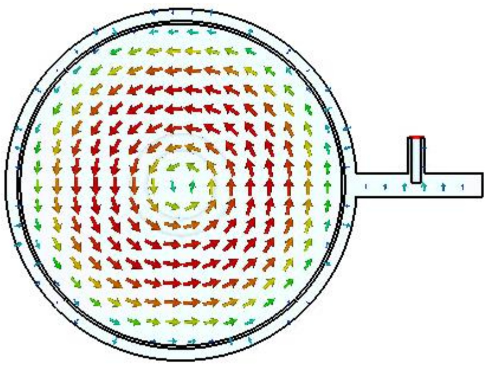
Gun HV=300 kV, Laser spot size = 0.3 mm rms, position: on center on photocathode

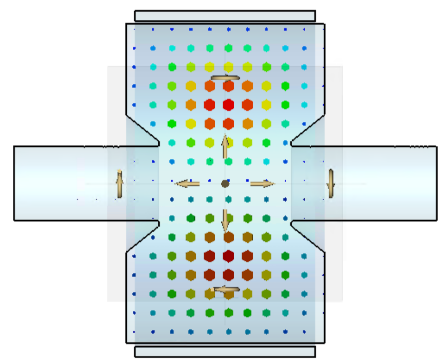


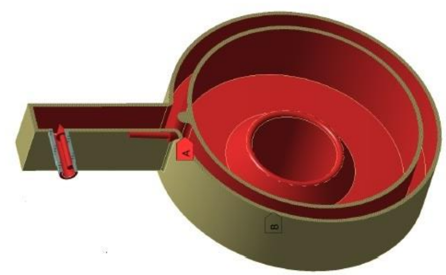
TE_{011} Cavity: Non-invasive Technique

- New non-invasive technique to measure electron beam magnetization
- Filed inventor disclosure entitled "Non-invasive RF Cavity to Measure Beam Magnetization"
- Mechanical design and vacuum pressure analysis are completed
- *Copper blocks are on-site and fabrication is in process*

E-field: only in azimuthal direction

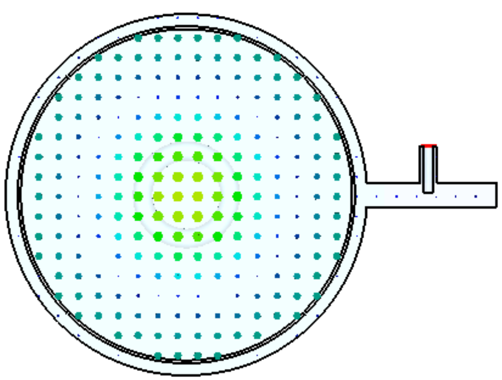


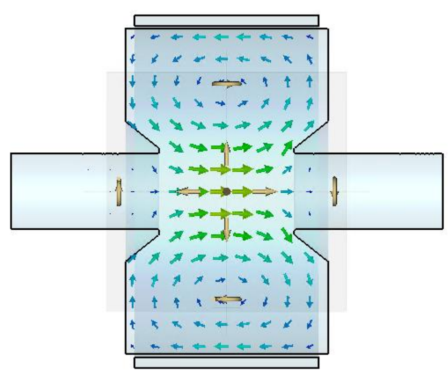


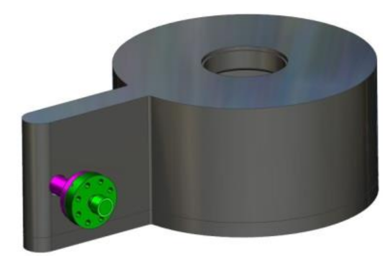


Copper cavity in progress

H-field: only in longitudinal and radial direction

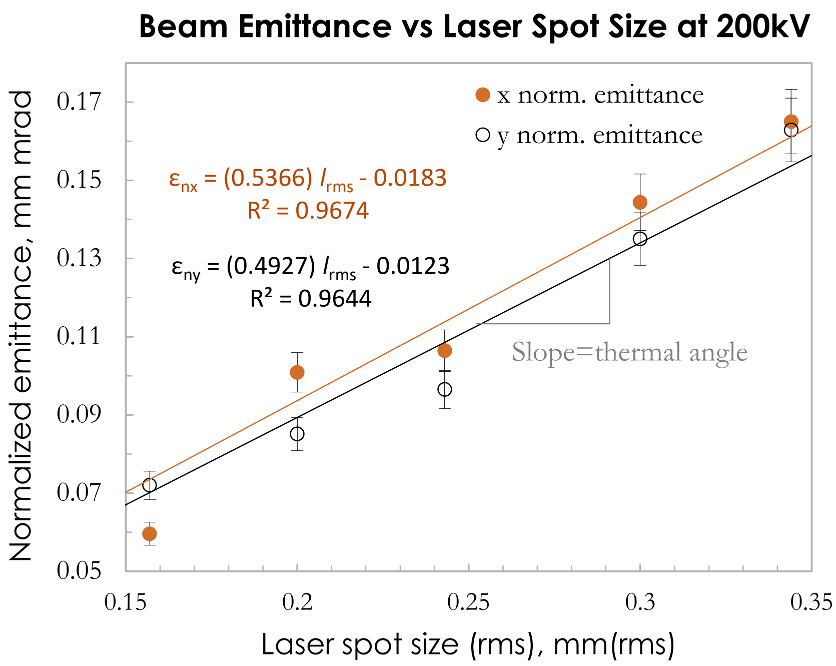


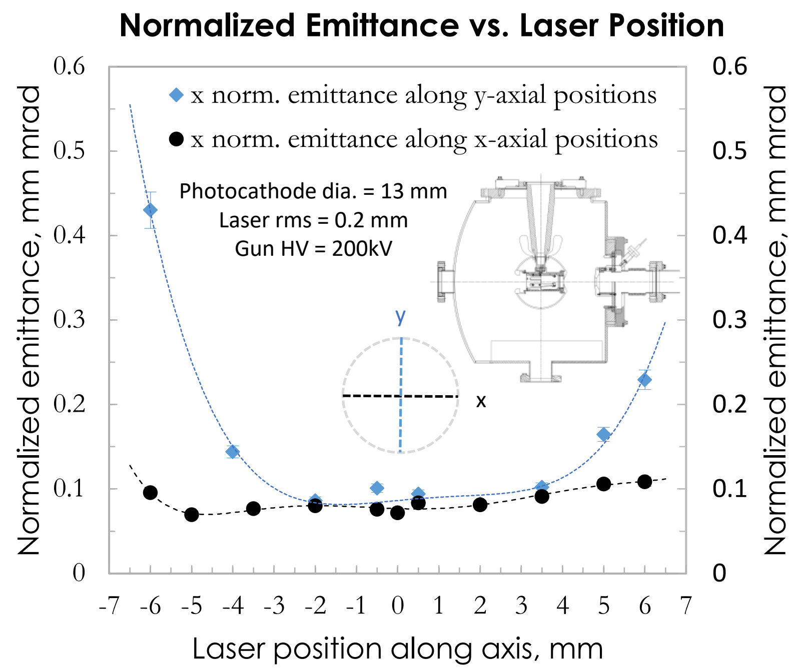




Waveguide-coax out-coupler

Non-magnetized Beam Emittance



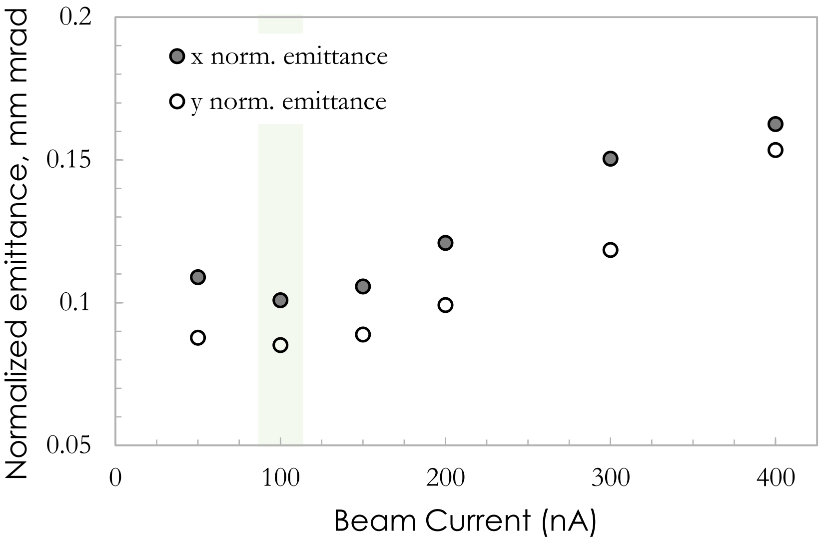


- Measured beam emittance, typical thermal angle value of 0.6 mm mrad/mm(rms), consistent with published data
- Beam current used ~100 nA

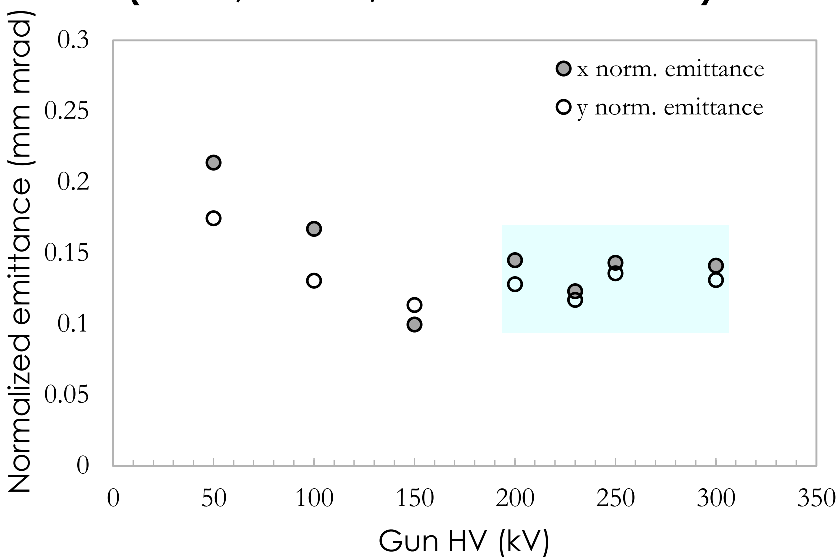
- Electrostatic field asymmetry in gun chamber significantly influences emittance growth
- Beam current used ~100 nA

Space Charge and Emittance Growth

Normalized Emittance vs Beam Current
(Gun HV = 200kV, Laser rms = 0.2 mm)



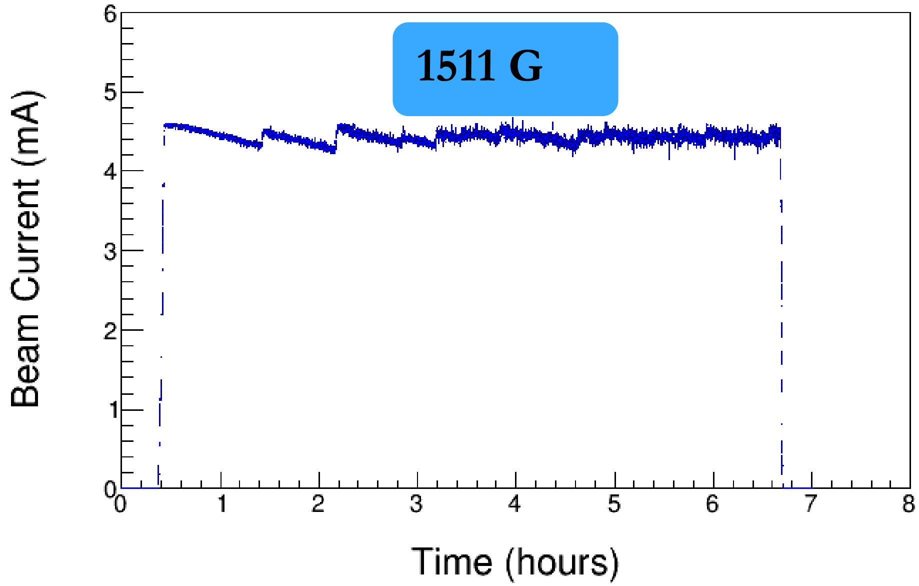
Normalized Emittance vs Gun HV
(Lens 1, RF laser, Laser rms = 0.31 mm)

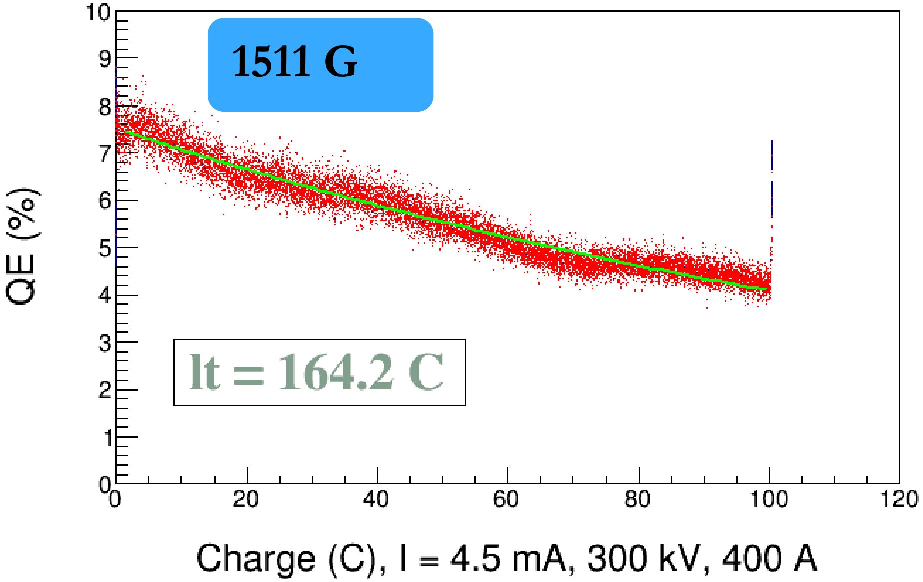


- Increasing space charge effect causes in increased beam emittance as beam current increases
- Beam current used for other measurements ~ 100 nA

- Increasing beam emittance realized at lower gun HV due to increasing space charge effect
- Operating gun HV at 200-300 kV

High Current Magnetized Beam





- Delivered 4.5 mA DC magnetized beam for ~7 h.
- Investigated charge lifetime from twenty two 1 h long runs of 3 - 4.5 mA beams at 200-300 kV gun HV, and 0-400 A gun solenoid current conditions. No apparent Lifetime dependency on gun HV, magnetization effect, or run sequence.
- Only 3 times QE dropped due to arcing and happened only with non-magnetized beam. Strong focusing due to gun solenoid might have helped keeping ions stay away from e-beam.
- For same laser spot size (0.38 mm rms)and gun HV, observed better lifetime at lower beam current, or Increased lifetime at lesser laser power
- Investigating the efficacy and necessity of installed dc ion-clearing electrodes to stop ions in beamline from reaching gun and causing HV arcs.
- To improve lifetime we will investigate metal substrate(Mo) and use different K_2CsSb photocathode recipes with increasing Sb layer thickness.

Outlook

- Continue to characterize magnetized beam and cross check measurements with simulation
- Measure and simulate space charge effect on magnetized beam
- To study space charge effect with nano-coulombs bunch charge (1-2 nC), we will get a new laser 1-15 Hz, 50 ps.
- Build and install TE_{011} cavity to measure beam magnetization in collaboration with JLab SRF Institute and Brock Roberts (Electrodynamics LLC)
- Demonstrate 32 mA magnetized beam. Need to install a new power supply (225 kV, 32 mA)
- We will study charge lifetime for different photocathode recipes and substrates

<u>Next:</u>

- Funded Phase-II SBIR with Xelera, to develop rf-pulsed dc high voltage thermionic gun to be installed at Gun Test Stand (GTS) in FY19 – will use LDRD beamline

- I will be submitting an early career proposal for FY2020 on magnetized injector (if regularized)

Summary

- K_xCs_ySb Photocathode Preparation Chamber, Gun, Solenoid and Beamline are all operational; photogun operates reliably at 300 kV
- Installed wire scanner and measured emittance
- Have successfully magnetized electron beam and measured rotation angle
- Demonstrated 4.5 mA magnetized beam and measured lifetime
- Installed RF pulsed laser, completed installation of Gain switched diode laser (1064 nm, 50 ps Gaussian pulses, doubling efficiency > 30%, 1.8W output, 1497/4=374.25 MHz)
- Then switch to 32 mA 225 kV HV power supply….

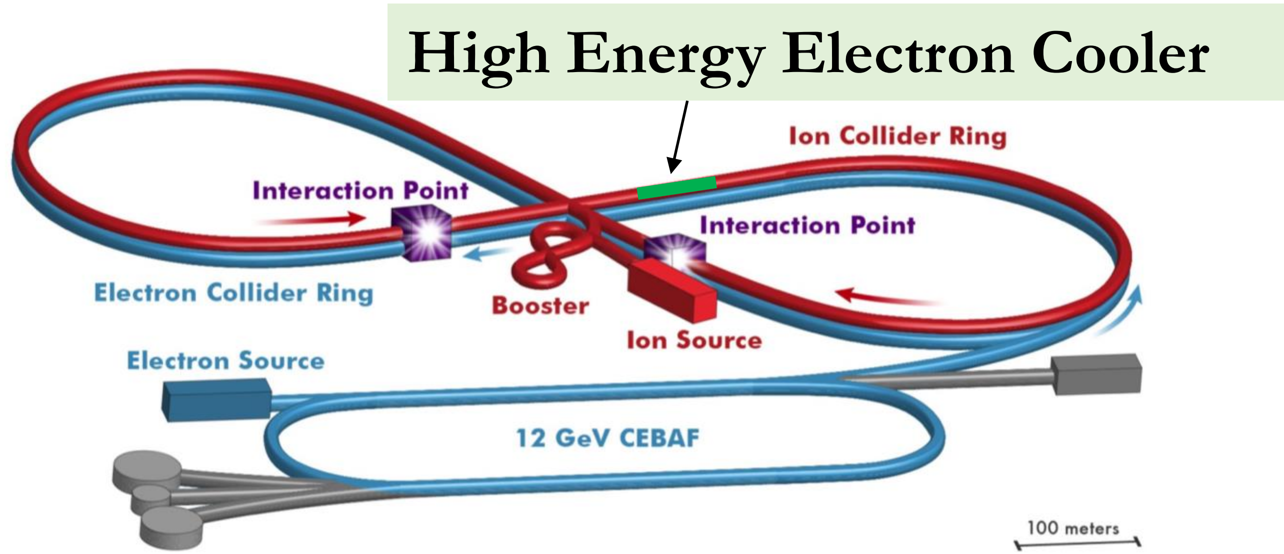
Thanks to the people involved in this team work:

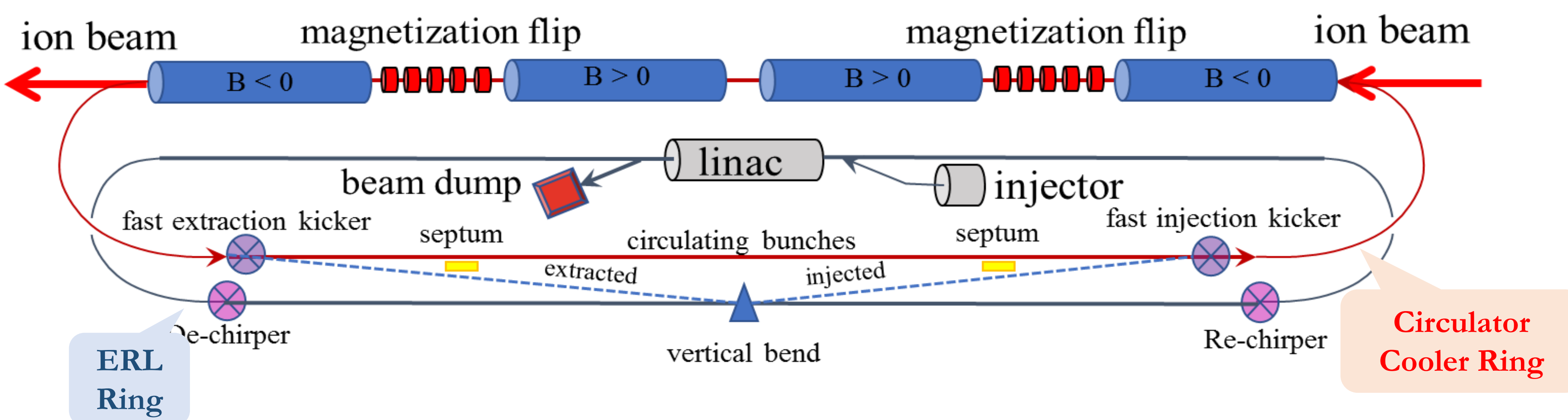
P. Adderley, J. Benesch, B. Bullard, J. Grames, J. Guo, F. Hannon, J. Hansknecht, C. Hernandez-Garcia, R. Kazimi, G. Krafft, M. Poelker, R. Suleiman, M. Tiefenback, Y. Wang, S. Wijiethunga, J. Yoskovitz, S. Zhang.

ODU Graduate Students

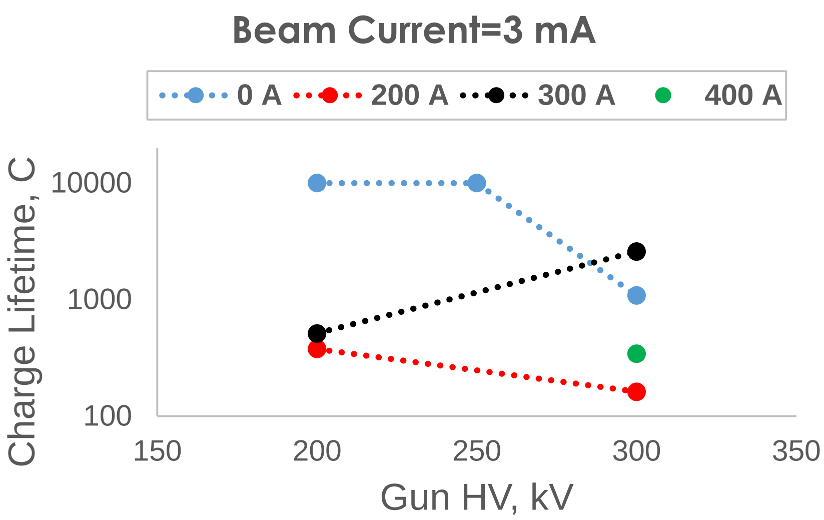
Backup Slides

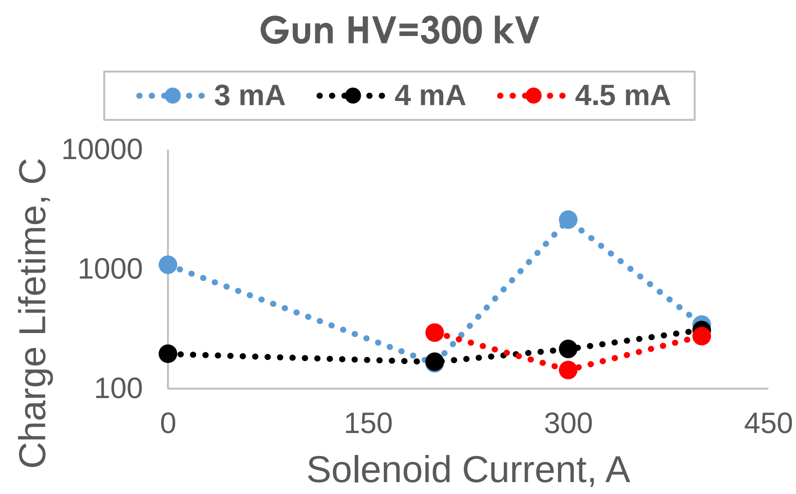
JLEIC High Energy Electron Cooler



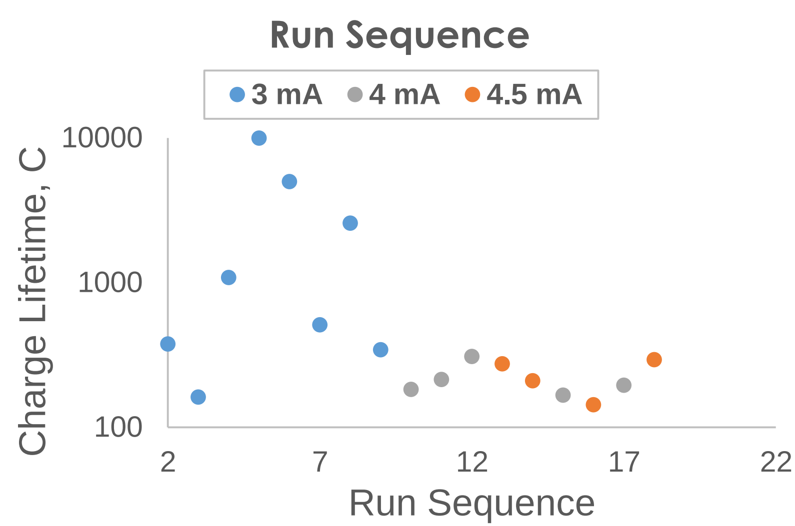


Charge Lifetime of High Current Beam

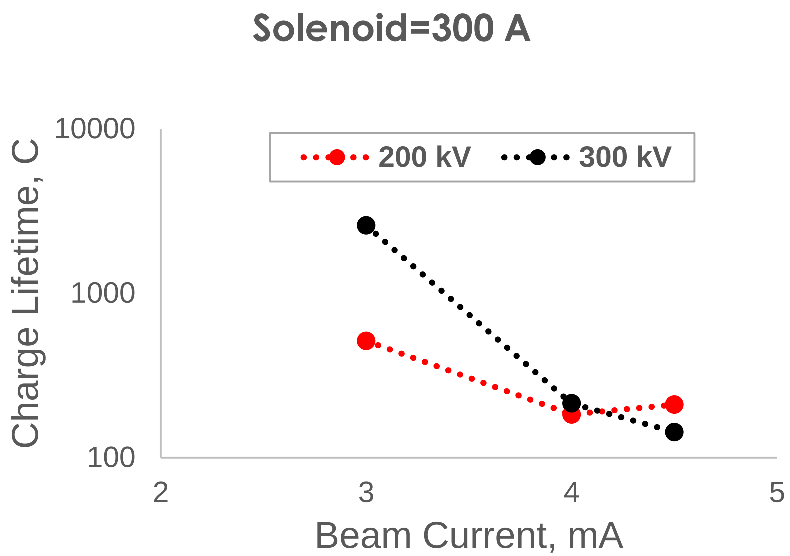


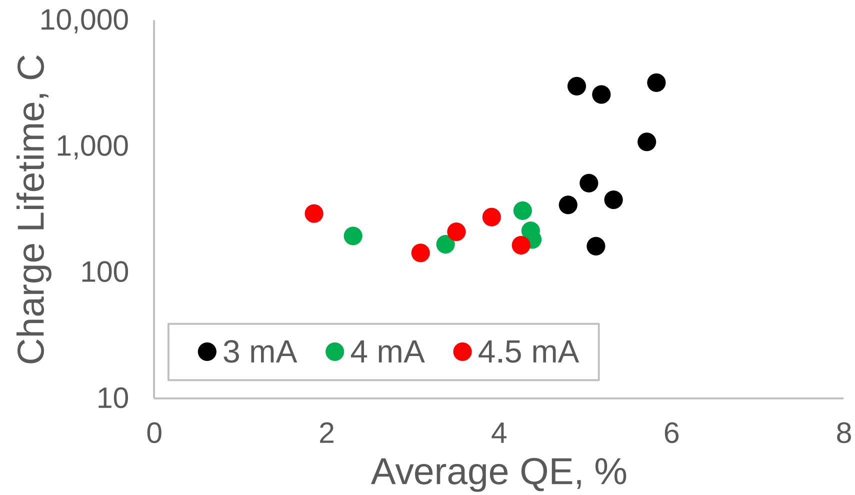


- ➢ No apparent Lifetime dependency on gun HV, magnetization effect, or run sequence
- ➢ Only 3 times QE dropped due to arcing and happened only with non-magnetized beam
- ➢ Strong focusing due to gun solenoid might have helped keeping ions stay away from e-beam

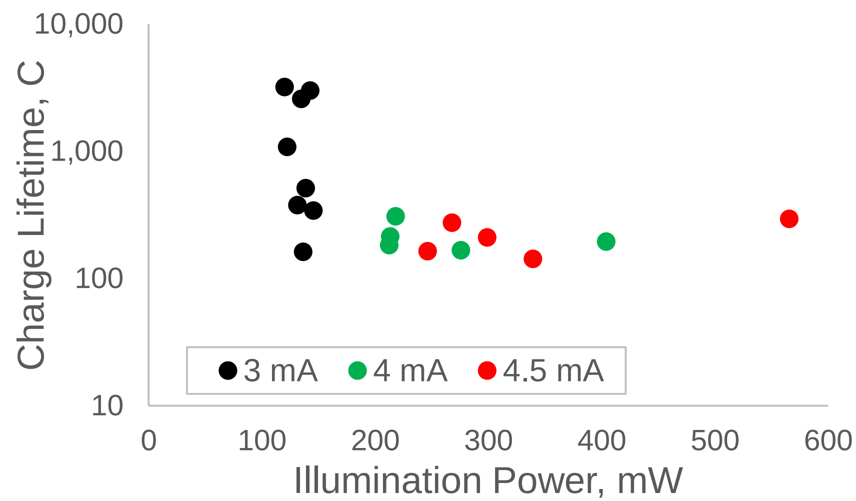


Charge Lifetime of High Current Beam





- Same laser spot size (0.38 mm rms)and gun HV
  - Better lifetime at lower beam current, or
  - Increased lifetime at lesser laser power
  - Good beam alignment is important
- With HV off: No QE drop from 22 h illumination at 0.8 W (required for 4.5 mA runs), not even at 2 W for 2 h.
- Laser spot size↑ and QE↑, good beam alignment ═ Photocathode Lifetime↑



Slit and Viewer Distance

for=>	S1-V2	S1-V3	S2-V3	S1-V2	S1-V3	S2-V3
Distance, m:	0.5	2.2965	1.7965	0.5	2.25666	1.75666
		Old			New	