SPACE CHARGE STUDY OF THE JEFFERSON LAB MAGNETIZED ELECTRON BEAM

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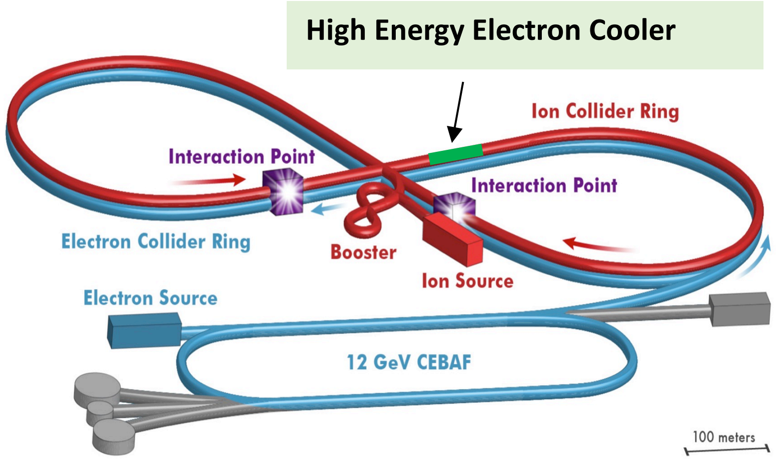
Outline

- Electron cooling
- Magnetized electron cooling
- Magnetized electron cooler dynamics
- Emittance compensation in a magnetized beam
- Space charge
- Experimental setup
- Measurements and simulations
- Summary and outlook

Electron Cooling

Luminosity: $$\mathcal{L} = \frac{N_1 N_2 f N_b}{4\pi\sigma_x\sigma_y}$$

- JLEIC requirement: $10^{34}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$
- High luminosity: high bunch charge, high repetition rate, high average current and small beam size at the colliding point
- To achieve the small beam size (small transverse emittance and less momentum spread) ion beam must be cooled



Requirements of the electron beam for efficient cooling:

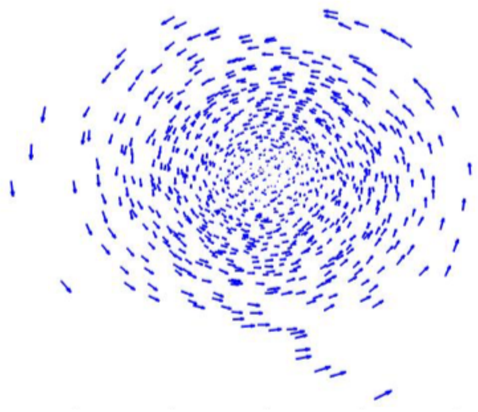
- High bunch charge
- Low beam temperature

These features combine to enhance the collective interaction, such as space charge effect which can adversely affect the cooling process.

Magnetized Electron Cooling

Ion beam cooling is much more efficient in the presence of a uniform magnetic field

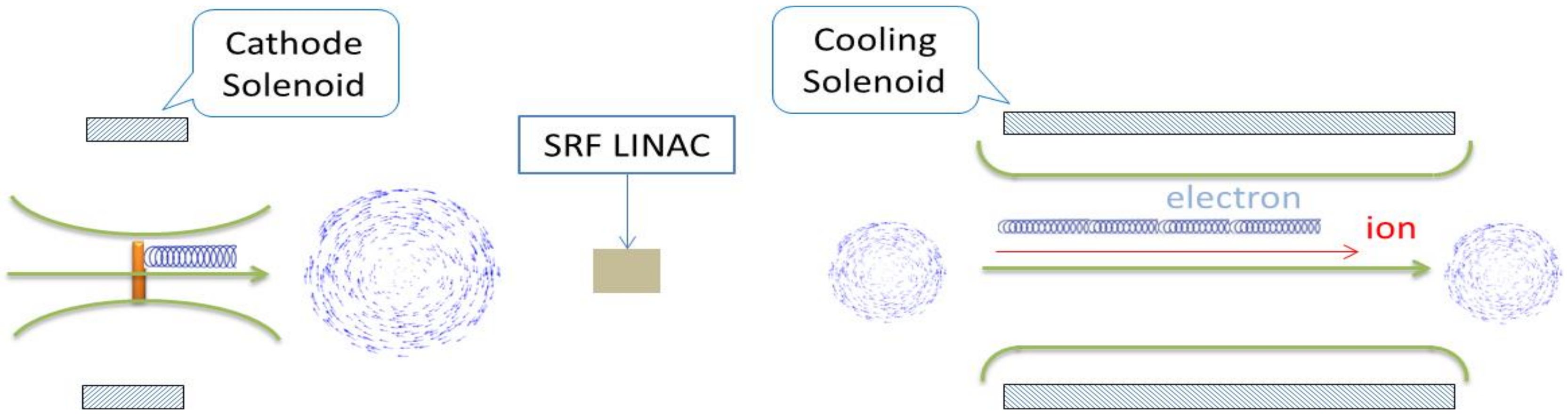
- The helical motion of an electron in a strong magnetic field increases electron-ion interaction time
- The cyclotron motion of the electrons due to the magnetic field suppresses electron-ion recombination



However, the radial fringe field at the entrance and the exit of the cooling solenoid exerts a large rotational motion on the electron beam that increases the beam size and thus the correlated emittance.

Magnetized Electron Cooler Dynamics

The magnetic field of the cathode solenoid is tuned to affect a zero net rotation of the electron beam at the cooling solenoid.



Electrons are born with transverse thermal momentum in magnetic field B_z each electron will have a helical cyclotron motion, At the photocathode, $\dot{\phi}$=0	Upon leaving the solenoid, B_z =0 But due to the torque exerted in the transition region	Upon entering the cooling solenoid	Inside the cooling solenoid

$$\langle L\rangle = \frac{eB_z a_o^2}{4} \longrightarrow \langle L\rangle = \gamma m_e \langle r\rangle^2 \dot{\phi} \longrightarrow \frac{B_{cool}}{B_z} = \frac{a_0^2}{r_e^2} \longleftarrow \langle L\rangle = \frac{eB_{cool}{r_e}^2}{4}$$

Emittance Compensation in a Magnetized Beam

Emittance of a magnetized beam

- $\epsilon_{correlated}$ - Correlated - from the magnetization – large
- ϵ_0 - Uncorrelated – thermal - small

$$\epsilon_{total} = \sqrt{{\epsilon_0}^2 + {\epsilon_{correlated}}^2}$$

Correlated emittance

Paraxial envelope equation for particle trajectory,

$$r_m'' + \frac{\gamma'}{\gamma\beta^2} r_m' + \frac{\gamma''}{2\gamma\beta^2} r_m + \left(\frac{qB}{2mc\beta\gamma}\right)^2 r_m - \underbrace{\boxed{\left(\frac{p_\theta}{mc\beta\gamma}\right)^2 \frac{1}{{r_m}^3}}}_{\text{Canonical angular momentum}} - \underbrace{\boxed{\left(\frac{\epsilon_0}{\beta\gamma}\right)^2 \frac{1}{{r_m}^3}}}_{\text{Emittance variations}} - \frac{K}{r_m} = 0$$

$$p_\theta = \gamma m r^2 \dot{\phi} + \frac{1}{2} e B_z {r_0}^2$$

Emittance term has the same r_m^{-3} dependence as the angular momentum term.

$$\left(\frac{p_\theta}{mc\beta\gamma}\right)^2 \frac{1}{{r_m}^3} = \left(\frac{\epsilon_0}{\beta\gamma}\right)^2 \frac{1}{{r_m}^3} \Rightarrow \boxed{\epsilon_{correlated} = \frac{p_\theta}{mc} = \frac{e B_z {r_0}^2}{2mc}}$$

B_z - Magnetic field at the cathode

r_0 - Beam size at the cathode

Magnetic field can generate a canonical angular momentum that increases the total emittance.

Space Charge

Space charge forces

- Space charge : Accumulation of charges in a particular region
- Space charge forces : Coulomb forces inside the region of charge accumulation
- Space charge effect : Degrade the beam quality, cause instabilities, energy spread, halo formation, particle losses etc.

Space charge force acting on a charge inside the beam:

For a Gaussian distribution (r, z),

$$\boldsymbol{F_r(r,z)} = \frac{\boldsymbol{q}}{\boldsymbol{2\pi\epsilon_0\gamma^2}}\frac{\boldsymbol{q_0}}{\boldsymbol{\sqrt{2\pi}\,\sigma_z}}\boldsymbol{e^{(-z^2/2\sigma_z{}^2)}}\left[\frac{\boldsymbol{1-e^{(-r^2/2\sigma_r{}^2)}}}{\boldsymbol{r}}\right]$$

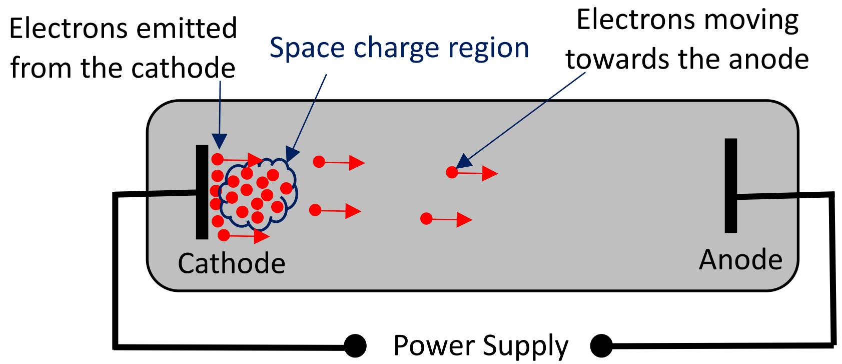
where q_0 bunch charge, σ_z and σ_r longitudinal and transverse rms beam sizes.

- For a non-magnetized electron beam: The bunch transverse dimension is small and the charge density is intense, hence the nonlinear space charge force can have huge effect during acceleration from low to higher energy and during the long drift, which would cause emittance growth beyond the specifications required for electron cooling.

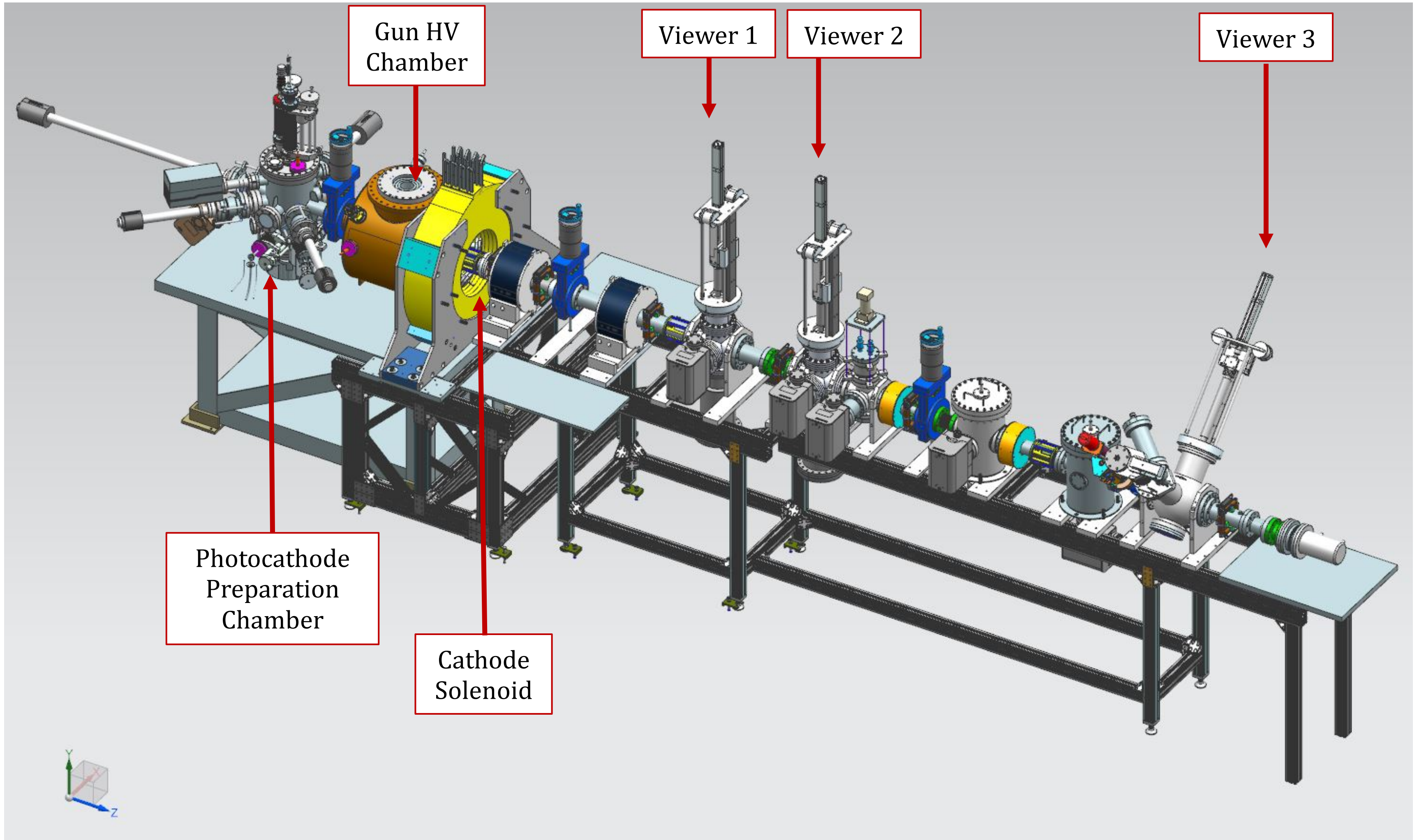
- For a magnetized electron beam- The transverse size is set by the beam's correlated emittance which is much larger and thus the space charge effect is minimal.

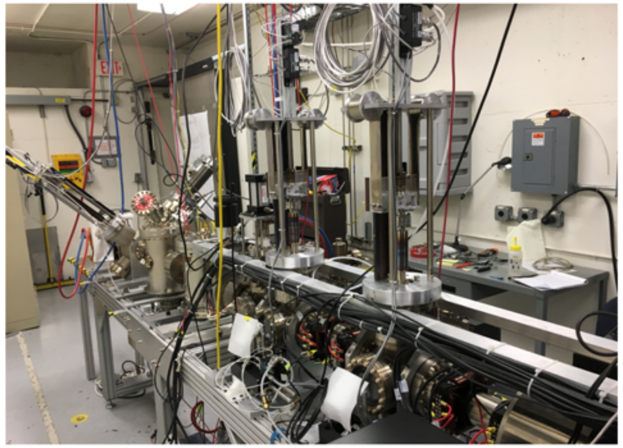
Space charge current limitation

Accumulation of space charge next to the cathode limits further emission of charges from the surface.



Experimental Setup





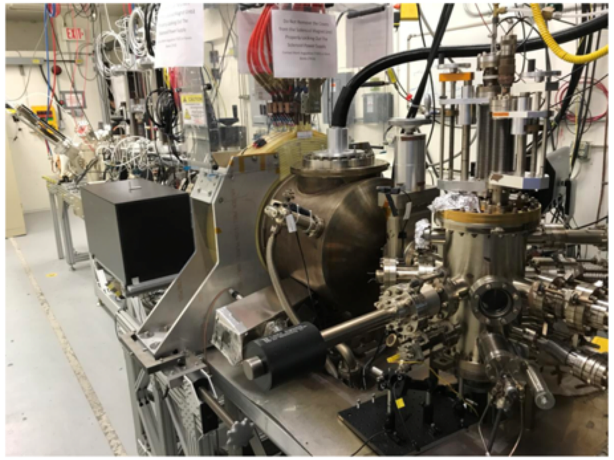
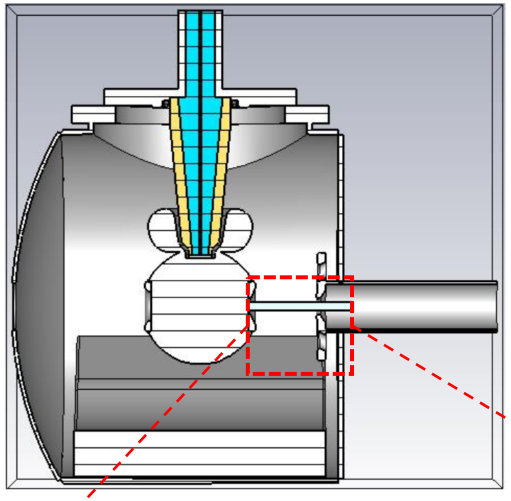
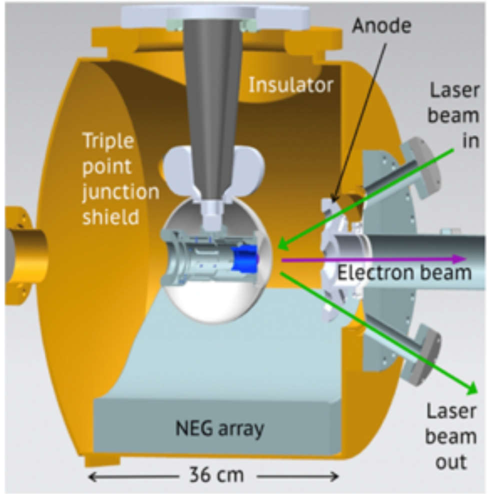


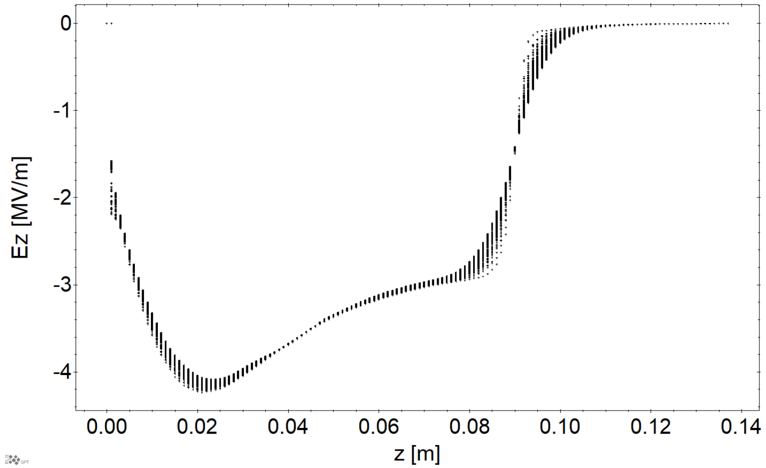
Photo-gun and Cathode Solenoid

Gun High Voltage Chamber

- Compact DC high voltage photo-gun with inverted insulator and spherical cathode electrode
- Operated at -225 kV

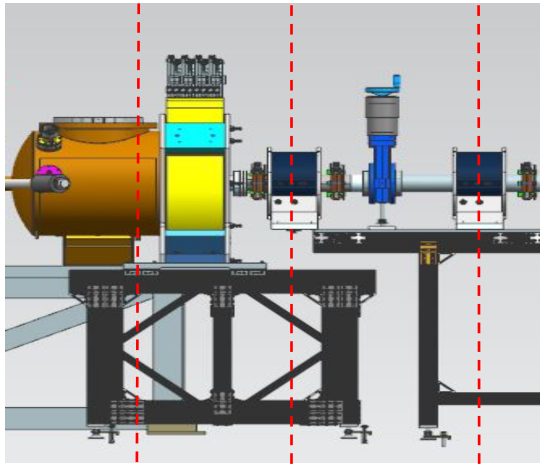


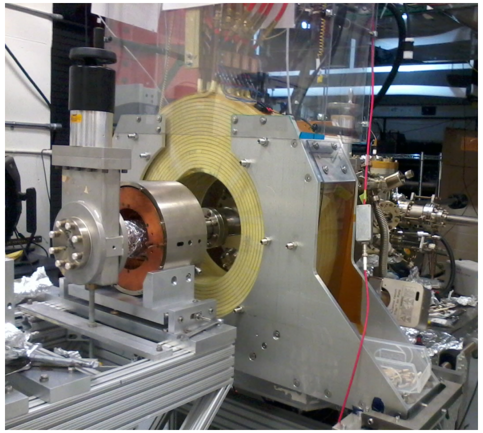


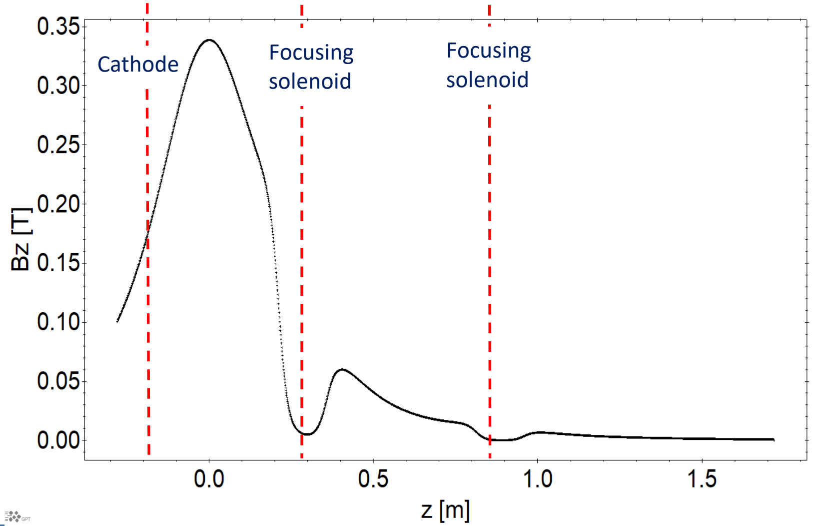


Cathode Solenoid

- 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 focusing solenoids next to it

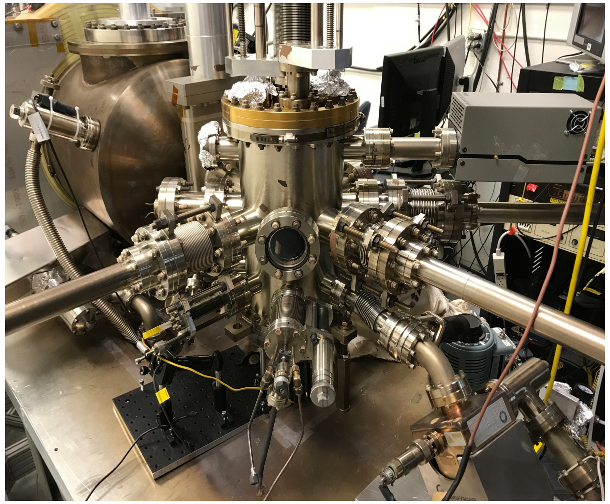


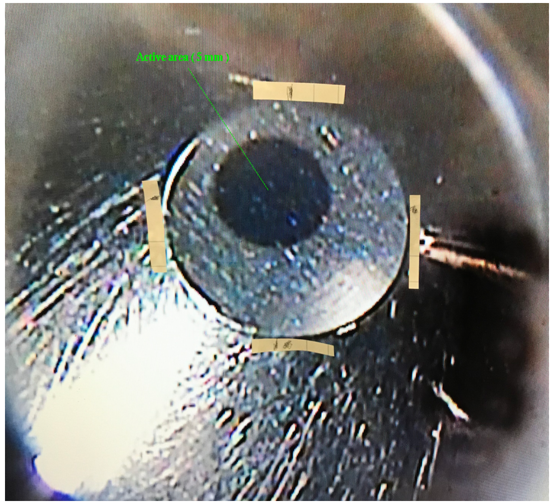




Photocathode and Laser

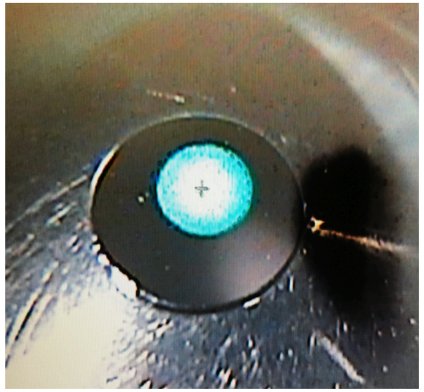
Bi-alkali Antimonide (K_2CsSb) Photocathode

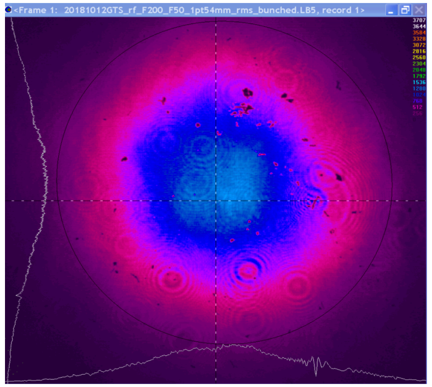




- Photocathode: GaAs substrate with 90 min deposition time of Sb layer
- Photocathode active area: 3 mm radius
- QE: 5-8% with 515 nm green laser

Laser





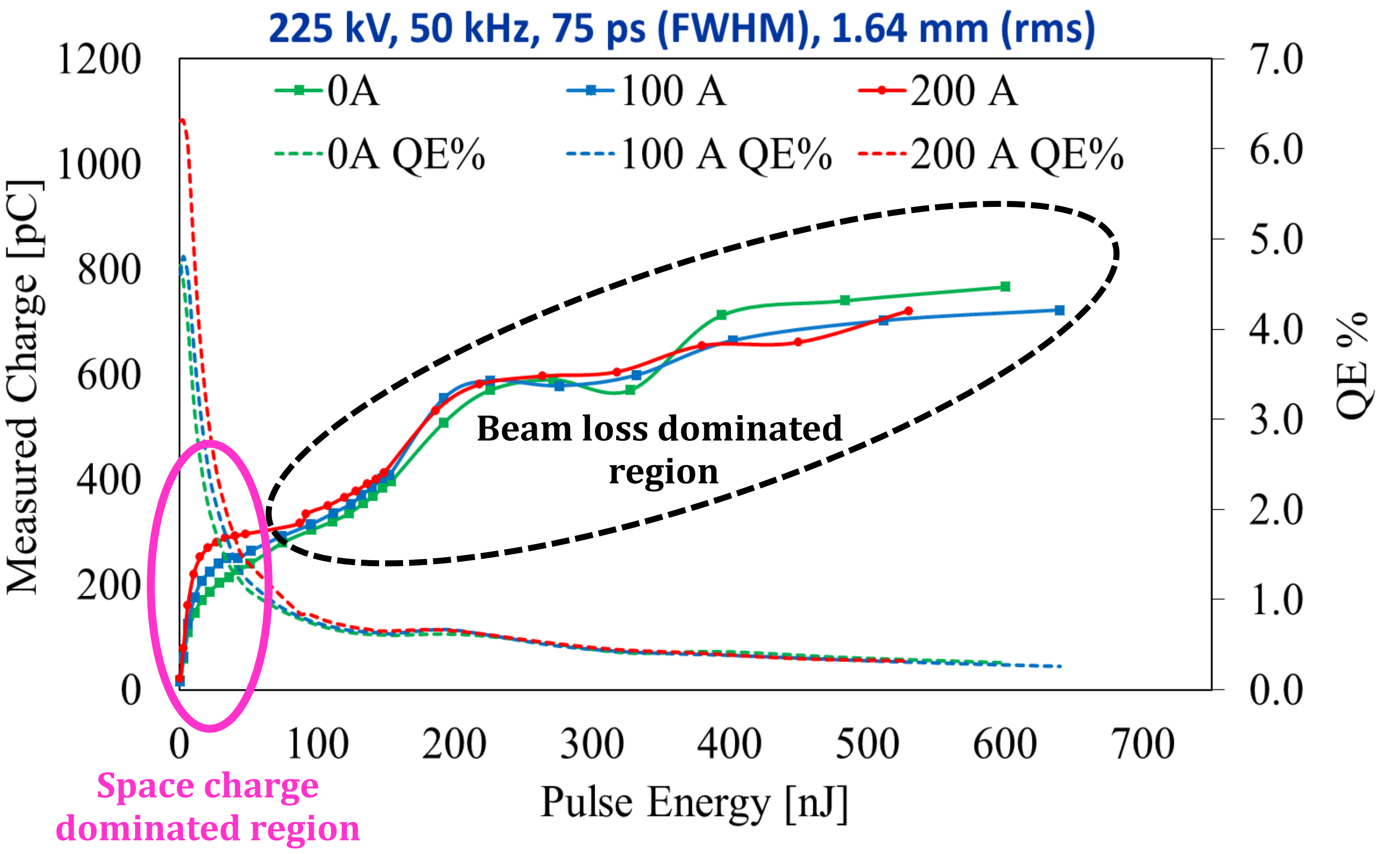
- Used a commercial ultrafast laser:

wavelength	515 nm
Pulse width	500 fs
Rep rate	Up to 50 kHz
Pulse energy	20 μJ

- Gaussian special and temporal profile
- Varied the laser size and pulse width using optical transport system with diffraction grating

Measurements

- Varied the laser power and measured the average current at the dump
- Calculated the extracted charge using $QE = \frac{hc}{\lambda e}\frac{I}{P} \times 100\%$ and $I_{avg} = Q_{extracted}\, f$



- QE falls rapidly with increasing laser power, implying that we have reached the space charge limitations immediately
- Space charge limitations were initiated as early as ~30 nJ and aperture limited beam loss increased with increasing pulse energy
- Observed an increase in measured charge with cathode solenoid current only up to ~100 nJ
- The oscillatory behavior seen at higher pulse energies likely stems from beam loss
- Beam scraping due to limited beamline aperture and insufficient strength of the focusing solenoids prevent clean transport of beam to the dump for pulse energy >100 nJ

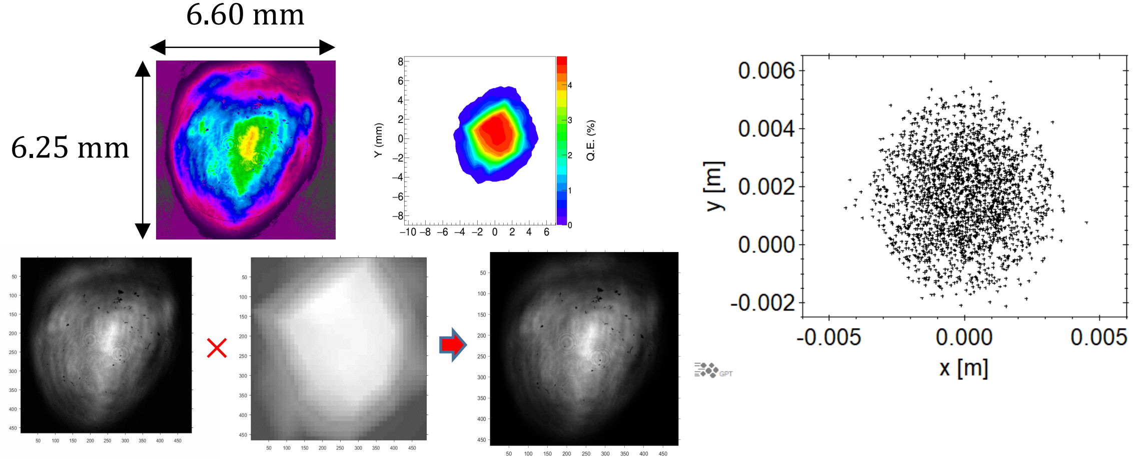
GPT Simulation vs. Measurements

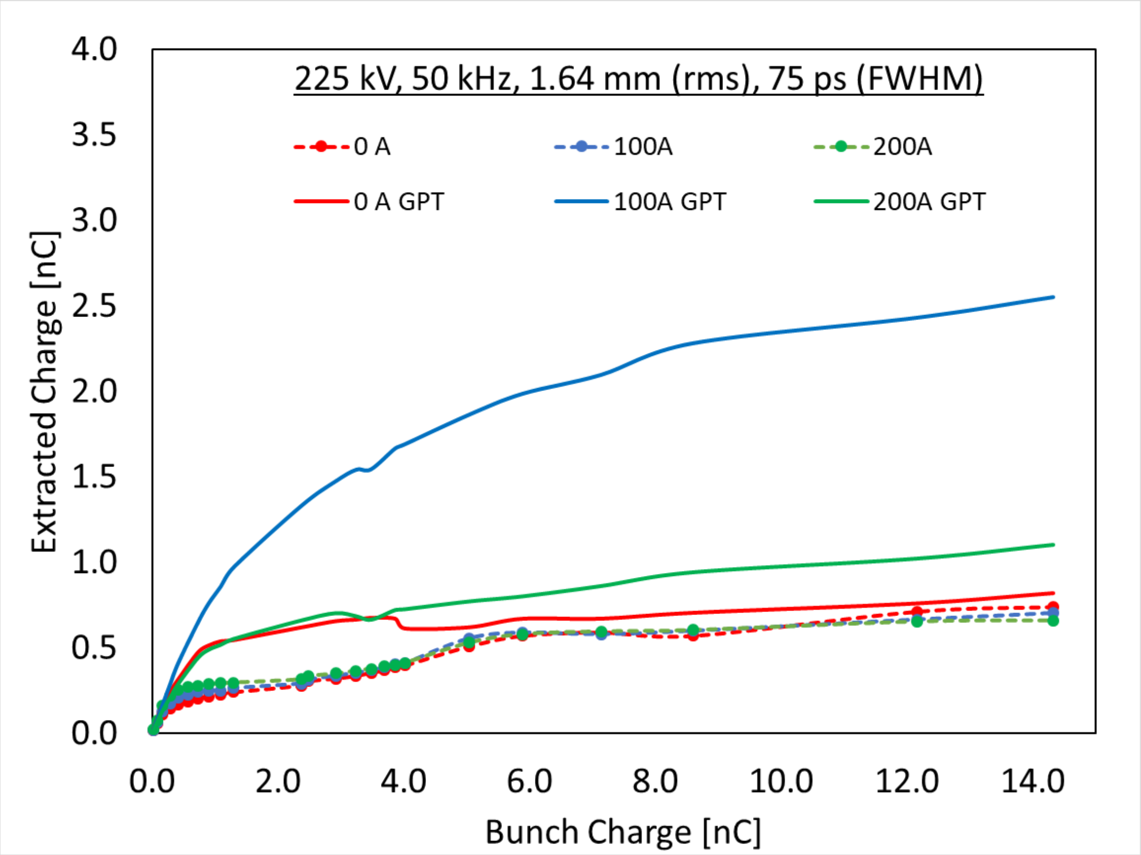
Used General Particle Tracer (GPT) to model the beamline

- Simulation parameters:

Parameter	Value
Gun high voltage [kV]	-225
Magnetic field, B_z at the cathode [T] (0, 100, 200 A)	0, 0.038, 0.076
Mean Transverse Energy [eV]	0.130
Pulse width, Gaussian (FWHM) [ps]	75
Transverse laser spot size, Gaussian (rms) [mm]	1.64
Bunch charge [nC]	0.01 to 14.00
Horizontal offset of the laser [mm]	0
Vertical offset of the laser [mm]	1.70

- Optimized the steering magnets to center the beam
- Used field maps for the focusing solenoids
- Used profile product of laser intensity and QE distribution as the initial electron emission distribution

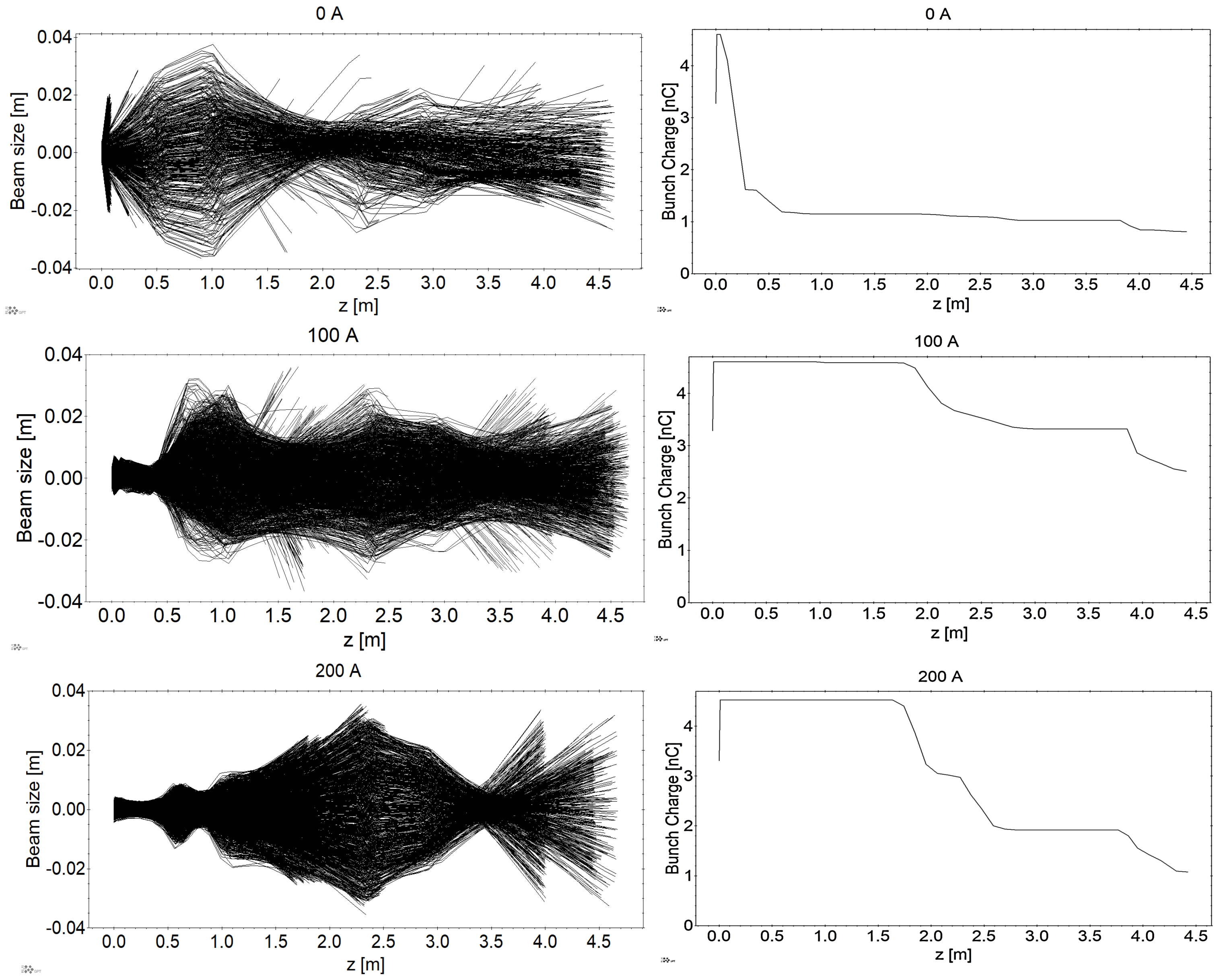




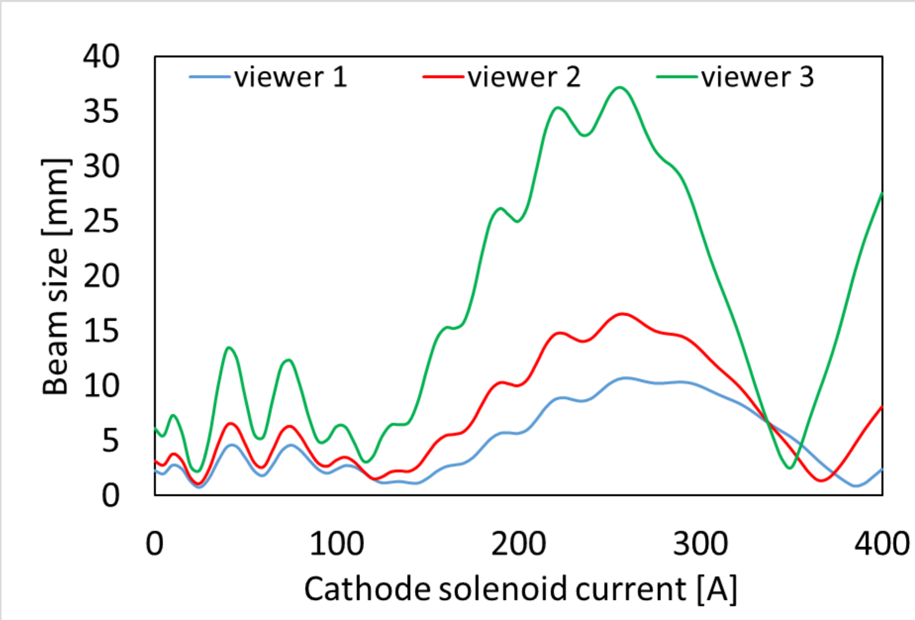
- GPT agrees fairly well with the measurements only for 0 A and 200 A cathode solenoid currents
- GPT extract more charge than measured for 100 A cathode solenoid current
- GPT shows no notable dependence of space charge limitations on magnetization

GPT Simulations Cont'd

Beam Trajectories Beam Loss

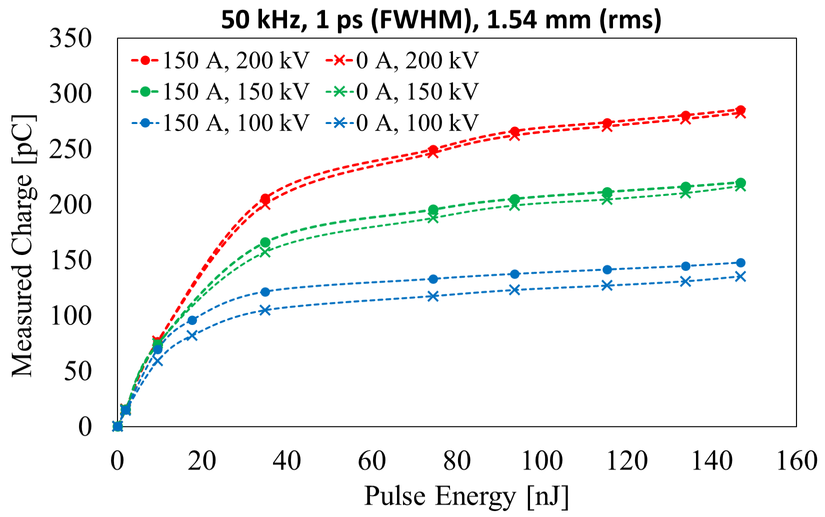


- Due to non-uniform magnetic field, beam size oscillates with the magnetic field (mismatch oscillations)
- Beam loss also depend on the cathode solenoid current

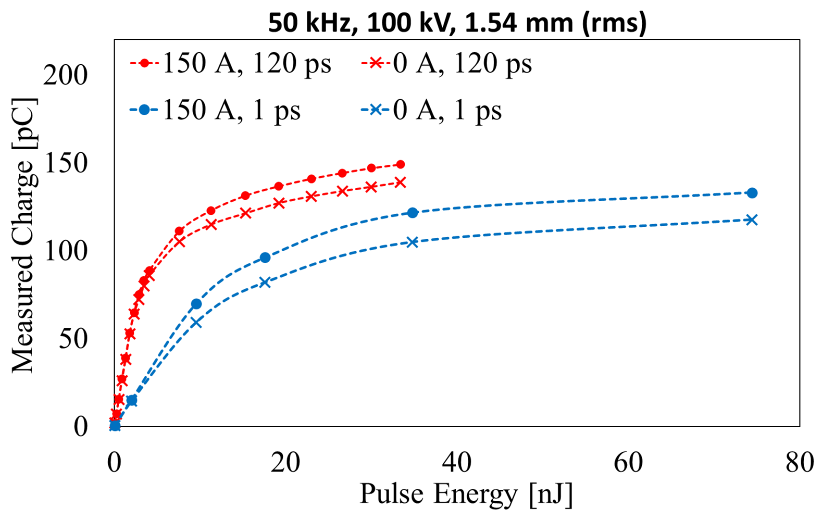


Measurements Cont'd

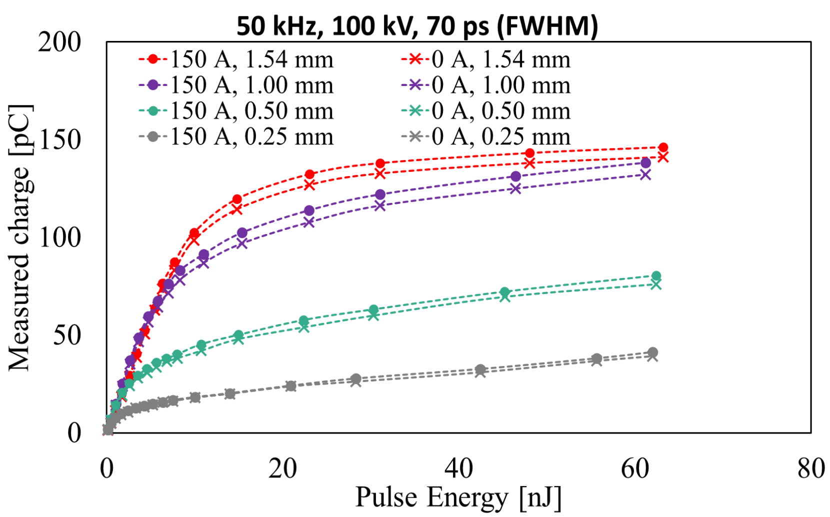
Space charge current limitation dependence on gun high voltage



Space charge current limitation dependence on pulse width



Space charge current limitation dependence on laser spot size



- Measured charge at the dump increase with the higher gun voltage, longer pulse width and larger laser spot size in the clean beam transport regime
- Less notable dependence of the space charge current limitations on magnetization

Summary and Outlook

- Used the Jefferson Lab's -300 kV photo-gun and beamline to investigate the space charge effect in magnetized electron beam.
- Measurements were taken by varying the laser power and tracking the average current at the dump for different cathode solenoid currents
- Observations from measurement:
  - Less notable dependence of the space charge current limitations on magnetization
  - The space charge current limitations can be reduced by using a higher gun voltage with larger laser spot size at the cathode and longer pulse width, regardless of the beam being magnetized
  - Beam loss due to limited beamline aperture and insufficient strength of the focusing solenoids plays a critical part in the measurements
- Observations from GPT simulation:
  - No notable dependence of the space charge current limitations on magnetization
  - Beam loss also depends on the cathode solenoid current

- More GPT simulations on optimization on the design of the gun, beam line components, and solenoid settings to ensure maximum charge extraction, clean beam transport to the dump
- More beam based measurements in January 2020 with modified beamline, higher gun voltage, new laser, new photocathode and few addition Faraday cups to track the beam loss through out the beamline

THANK YOU !