SPACE CHARGE EFFECTS IN LOW ENERGY MAGNETIZED ELECTRON BEAMS

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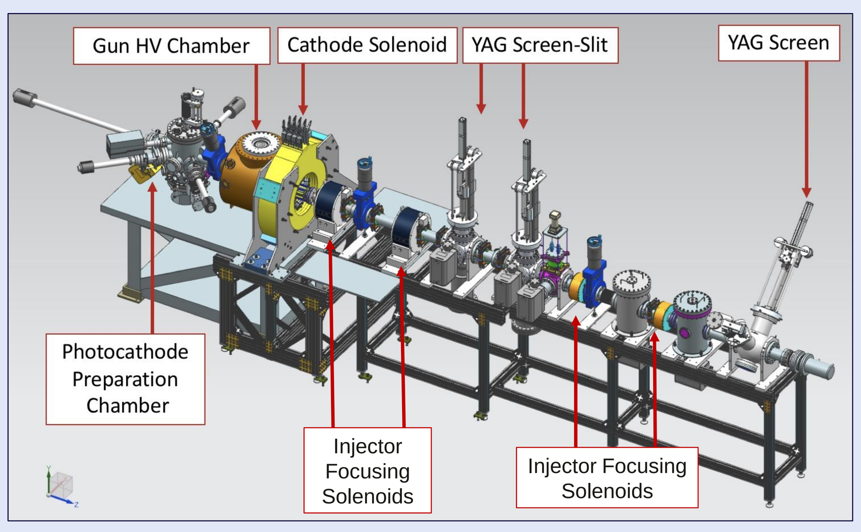
INTRODUCTION

Magnetized electron cooling is one of the major approaches towards obtaining the required high luminosity in the proposed Electron-Ion Collider (EIC). In order to increase the cooling efficiency, a bunched electron beam with a high bunch charge and high repetition rate is required. At Jefferson Lab, we generated magnetized electron beams with high bunch charge using a new compact DC high voltage photo-gun biased at -300 kV with bialkali-antimonide photocathode and a commercial ultra-fast laser. This contribution discusses how magnetization affects space charge dominated beam as a function of magnetic field strength, gun high voltage, and laser pulse width, and spot size in comparison with simulations performed using General Particle Tracer.

Beam Line



Beamline consists of:

- DC high voltage photo-gun operates at or below 300 kV
- K_2CsSb photocathode preparation chamber
- Cathode solenoid operates at a maximum current of 400 A to provide up to 0.1514 T at the photocathode
- Commercial ultrafast laser (<0.5 ps, 20 µJ, 50 kHz, 515 nm) Four focusing solenoids

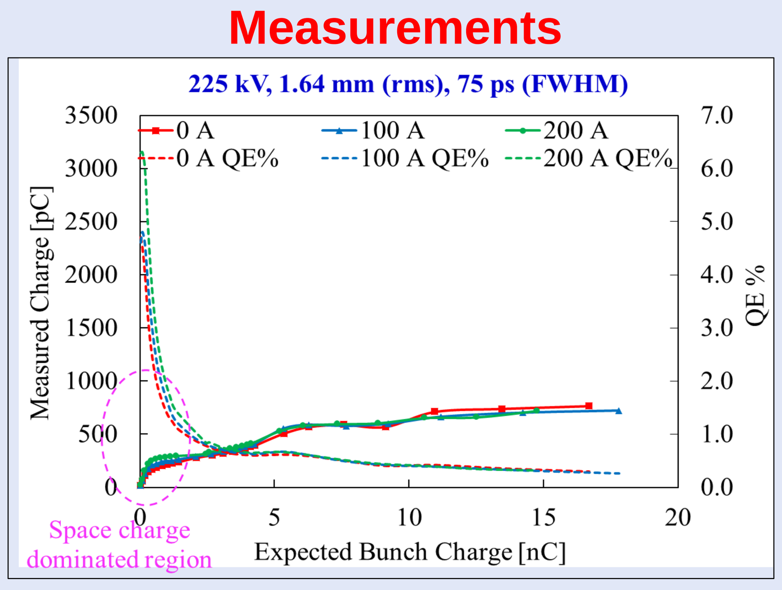
Results Analysis

- Varied the laser power and measured the average current at the dump
- Calculated the charge using
- Beam line is modeled using **GPT** (**G**eneral **P**article **T**racer)

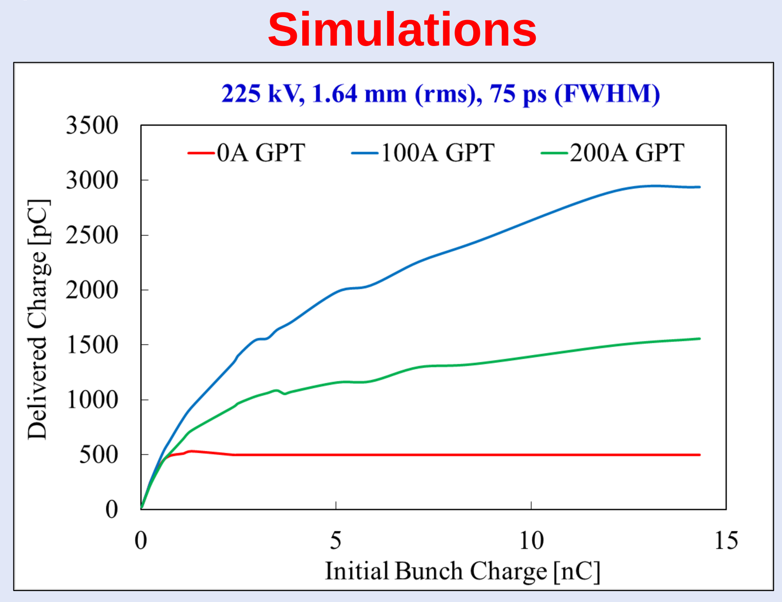
$$QE = \frac{hc\, I}{\lambda e\, P} \times 100\%$$

$$I_{avg} = Q_{extracted}\, f$$

Measurements



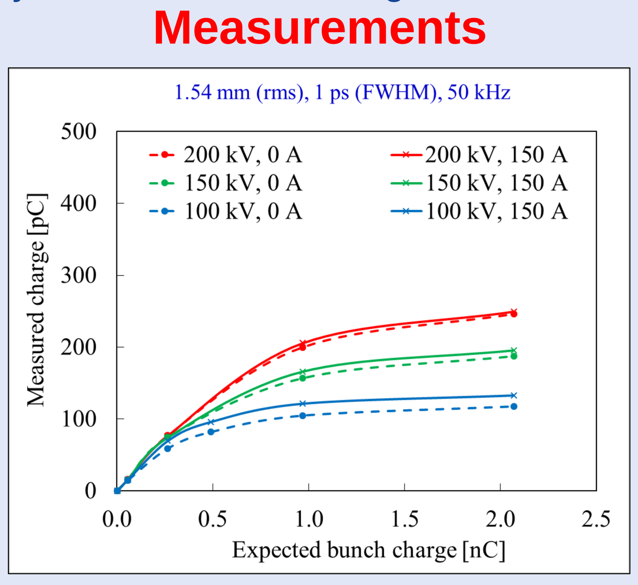
Simulations

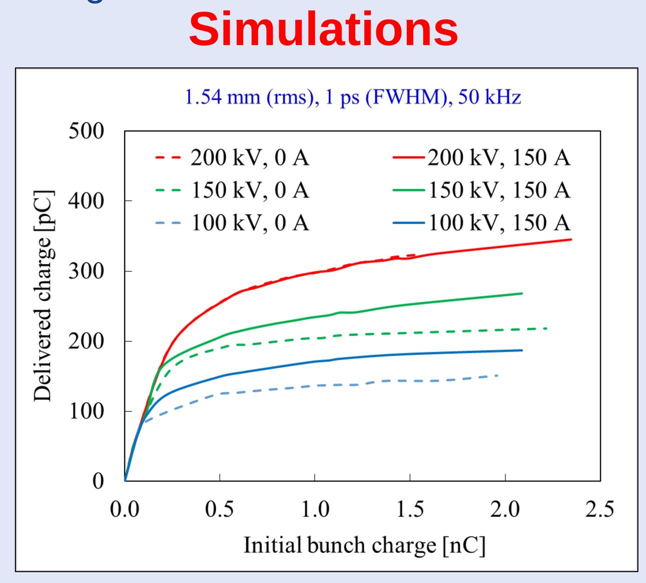


- QE falls rapidly with increasing laser power, implying that we have reached the space charge limitations immediately
- The space charge limit is reached at ~0.3 nC and increased for a maximum extracted charge of 0.7 nC
- There is a less notable effect of magnetization on the space charge current limitation at small initial bunch charges
- The charge beyond ~0.3 nC is likely to originate from the edge of the Gaussian laser profile
- The oscillatory behavior seen at higher pulse energies likely stems from beam loss
- The limited beamline aperture and insufficient strength of the focusing solenoids prevent clean transportation of the beam to the dump
- GPT simulations show some agreement at 0 A, but a large discrepancy at 100 A and 200 A
- GPT does not show any notable effect of magnetization on the space charge current limitation

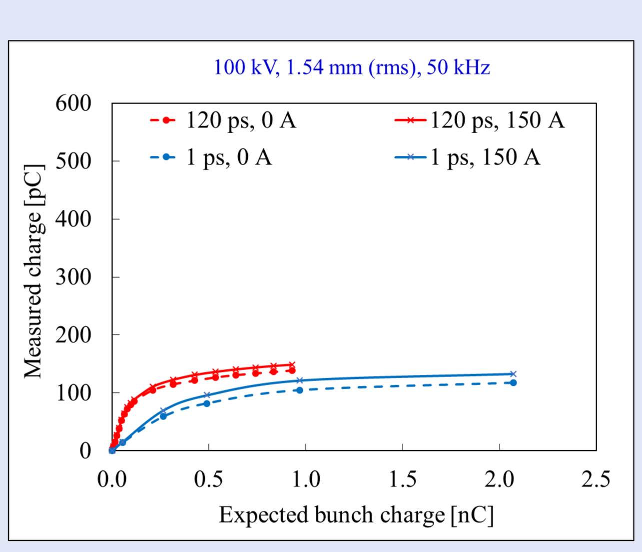
Measurements / Simulations

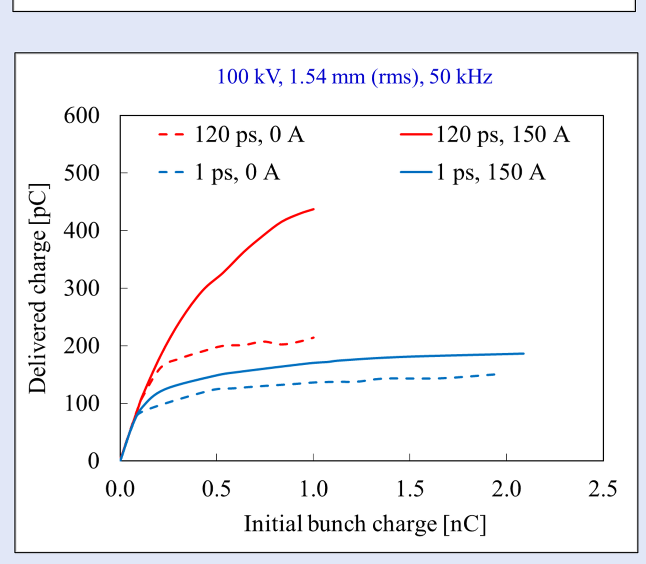
Gun high voltage dependence on space charge current limitations



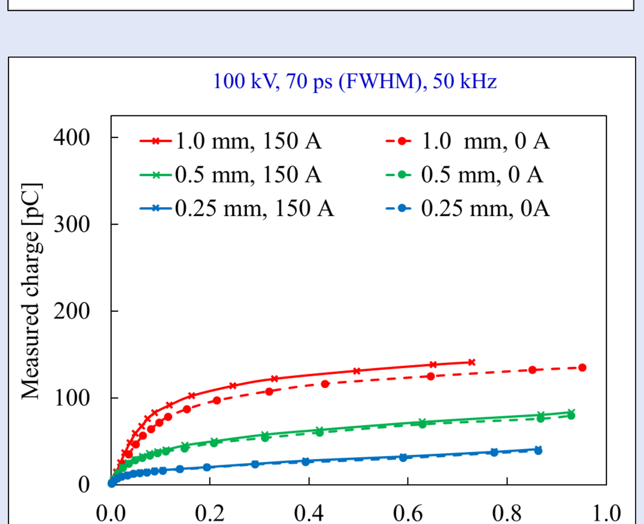


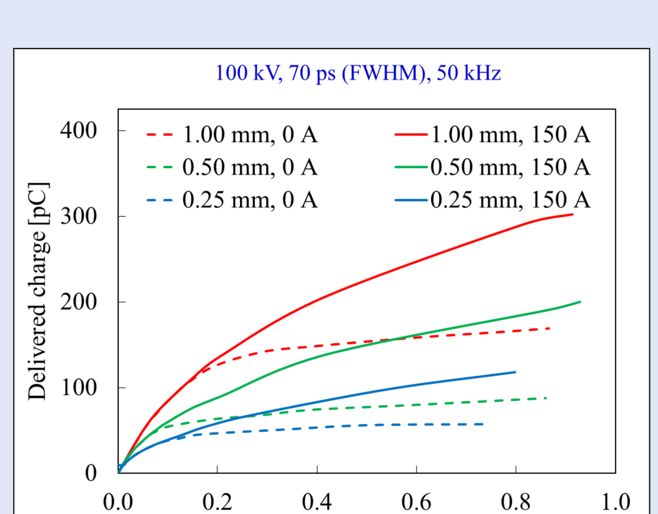
Pulse width dependence on space charge current limitations





Laser spot size dependence on space charge current limitations





- Measured charge at the dump increased with the higher gun voltage, longer pulse width and larger laser spot size in the clean beam transport regime
- GPT also shows the same trend, but for magnetized beam, higher beam extraction than non magnetized beam
- Less notable dependence of the space charge current limitations on magnetization

Theoretical Background

Emittance The transverse emittance associated with the magnetized beam is given by,

$$\varepsilon_{tot} = \sqrt{{\varepsilon_u}^2 + {\varepsilon_d}^2}$$

ε_u - uncorrelated emittance – thermal - small.
ε_d - correlated emittance – magnetization - large.

$$\varepsilon_d = \frac{eB_z {r_0}^2}{8m_e c}$$

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

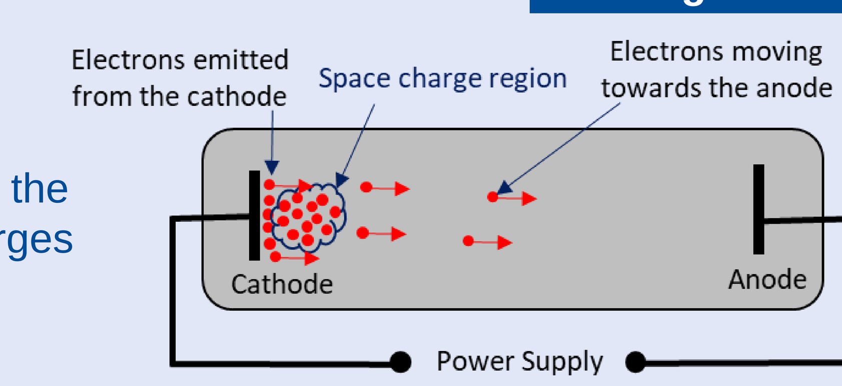
- Space charge : Accumulation of charges in a particular region
- Space charge forces : Coulomb forces inside the region of charge accumulation
- Space charge effect : Degrade the beam quality, cause instabilities, energy spread, halo formation, particle losses etc.

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

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

Larger correlated emittance ➡ **Larger beam size** ➡ **Decrease space charge forces**

- Space charge current limitation: Accumulation of space charge next to the cathode limits further emission of charges from the surface.

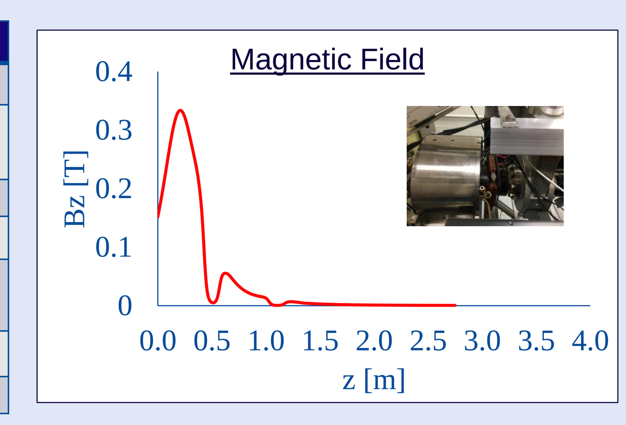


Simulation Analysis

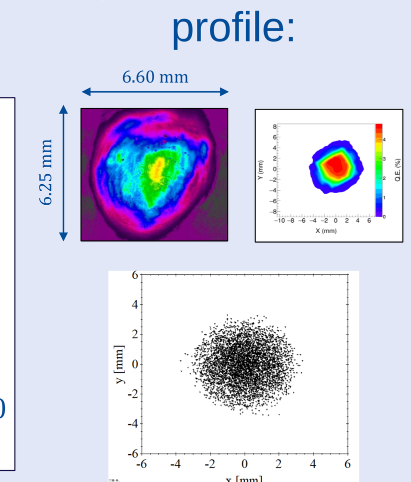
Why GPT shows higher beam extraction?

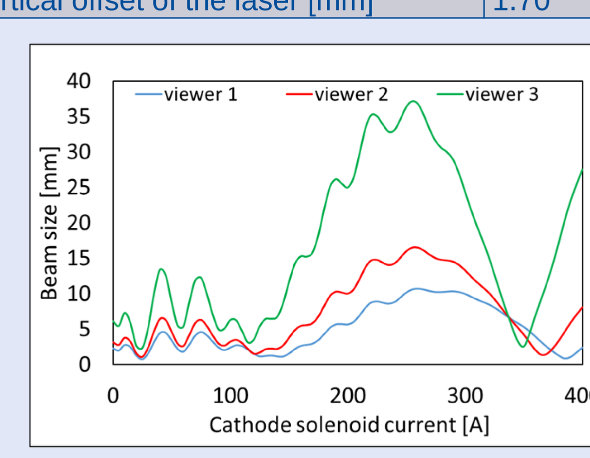
- Simulation parameters:

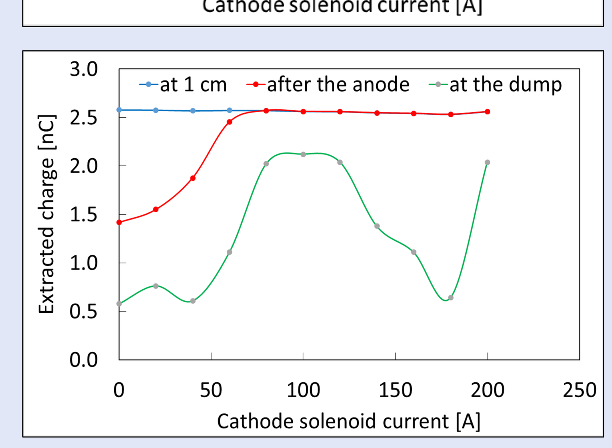
Parameter	Value
Gun high voltage [kV]	225
Magnetic field, B_z at the cathode [T] (0, 100, 200 A)	0, 0.038, 0.076
Mean Transverse Energy [eV]	0.075
Pulse width, Gaussian (FWHM) [ps]	75
Transverse laser spot size, Gaussian (rms) [mm]	1.64
Bunch charge [nC]	0.01 to 14
Vertical offset of the laser [mm]	1.70



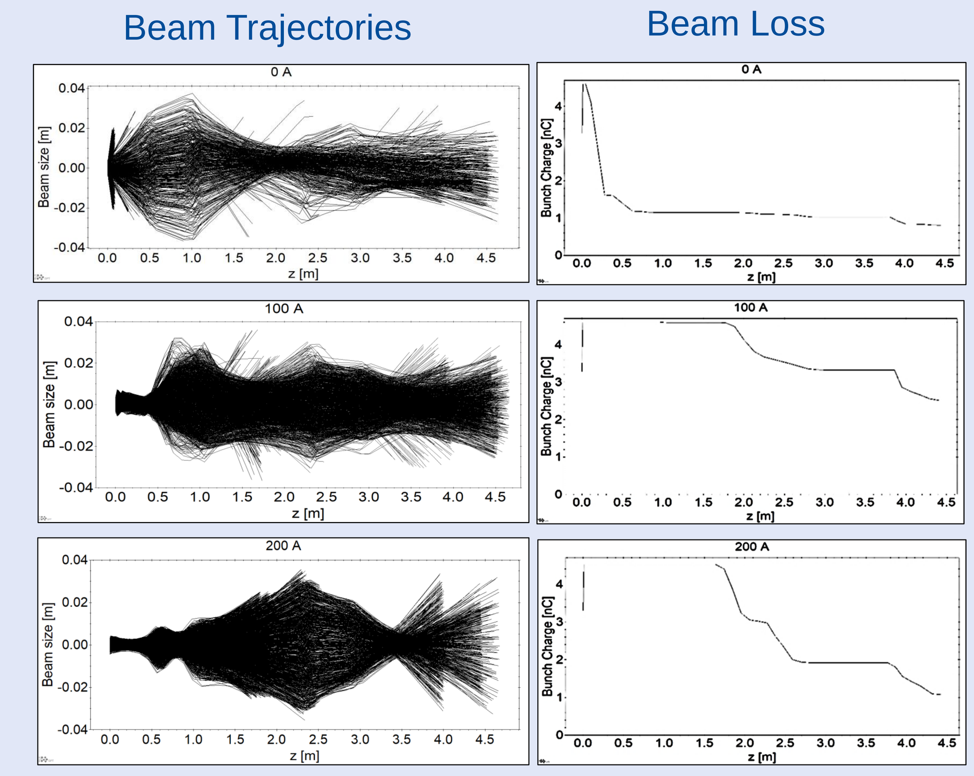
Digitized laser *QE profile:







Beam Trajectories / Beam Loss



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

Summary

- Observations from measurement:
  - Less notable effect of magnetization on space charge current limitation
  - 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 effect of magnetization on space charge current limitation
  - Beam loss also depends on the cathode solenoid current

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