# SPACE CHARGE EFFECTS IN LOW ENERGY MAGNETIZED ELECTRON BEAMS


Sajini A. K. Wijethunga[1,2], M. A. Mamun[2], J. R. Delayen[1], G. A. Krafft[1,2], R. Suleiman[2], M. Poelker[2], J. Benesch[2], S. Zhang[2]

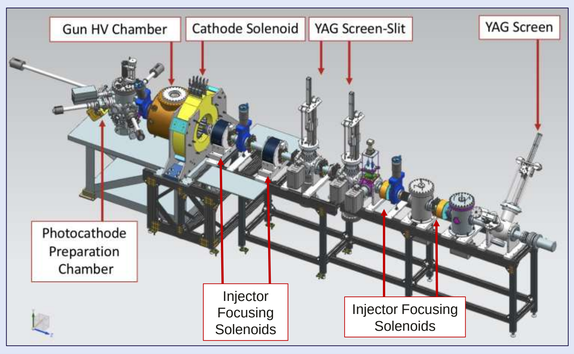
[1]Department of Physics, Old Dominion University, Norfolk, Virginia 23529, USA

[2]Thomas Jefferson National Accelerator Facility, Newport News, Virginia 23606, USA


## 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

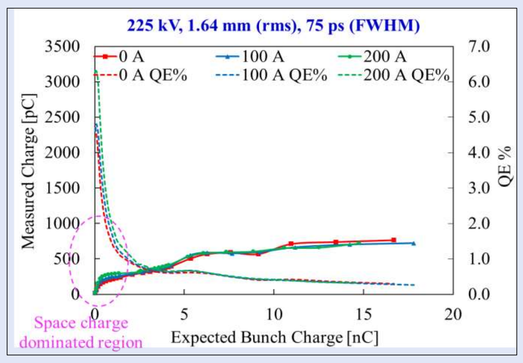
## Results Analysis

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

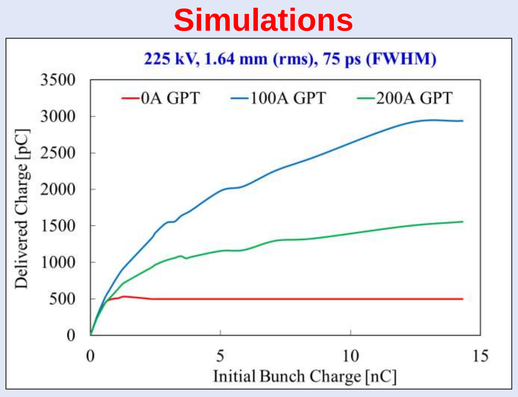
$$I_{avg} = Q_{extracted}\, f$$

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

**Measurements**



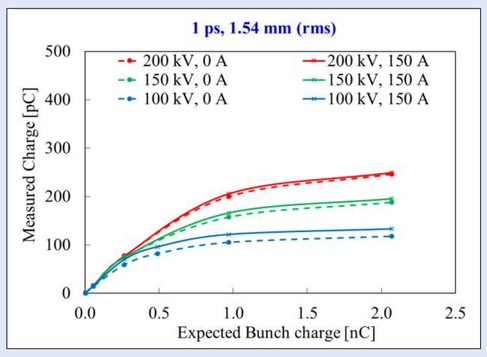

**Simulations**

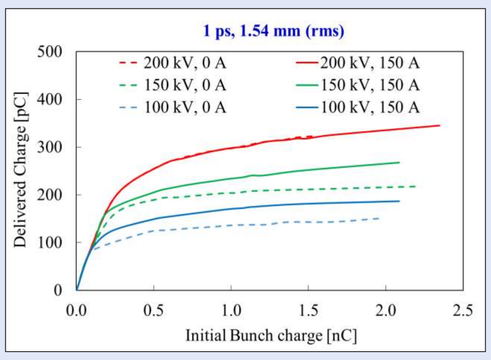



- Maximum charge extraction possible at the photocathode for available laser power ~14 nC (QE = 6.3%, P = 0.265 mW, $f$ = 50 kHz)
- Space charge limitations were initiated as early as ~30 nJ and aperture limited beam loss increased with increasing pulse energy
- Observed an increase in measured charge with cathode magnetic field only up to ~100 nC
- Beam scraping due to limited beamline aperture and insufficient strength of the focusing solenoids prohibited clean transport of beam to the dump for pulse energy >70 nC
- GPT agrees fairly well with the measurements only for 0 A cathode solenoid current but extract more charge than measured for 100 A and 200 A cathode solenoid currents
- GPT shows no notable effect of magnetization on space charge current limitation

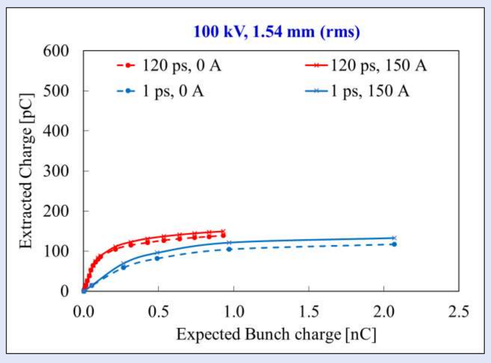
**Measurements** **Simulations**

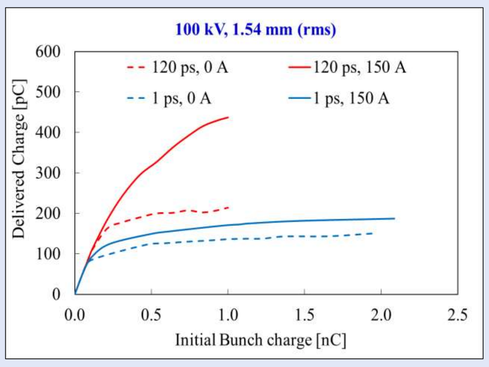
Gun high voltage dependence on space charge current limitations



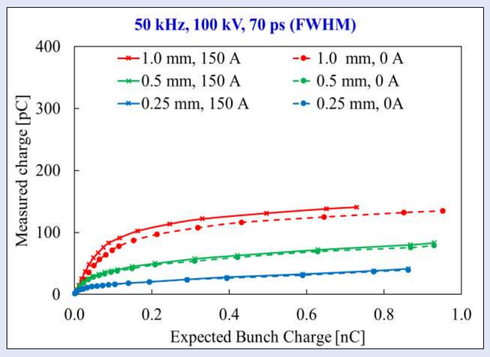



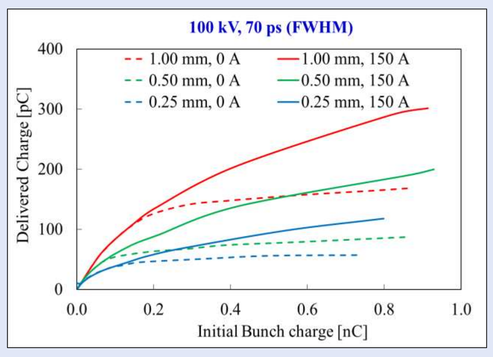

Pulse width dependence on space charge current limitations




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,

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

$\varepsilon_u$ - uncorrelated emittance – thermal - small.
$\varepsilon_d$ - 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**

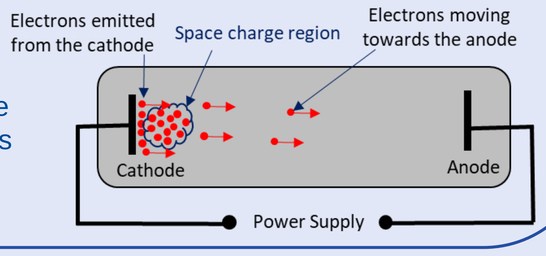
- Space charge : Accumulation of charges in a particular region
- Space charge forces : Coulomb forces inside the region of charge accumulation
- Space charge effect : Degrade the beam quality, cause instabilities, energy spread, halo formation, particle losses etc.

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

$q_0$ - bunch charge
$\sigma_z$ and $\sigma_r$ - 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.

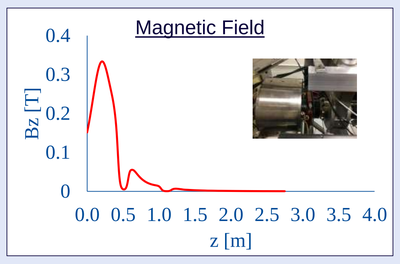



## Simulation Analysis

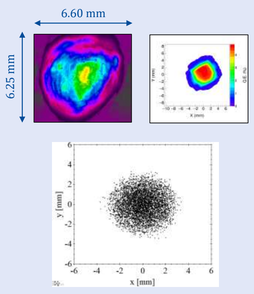
Why GPT shows higher beam extraction?

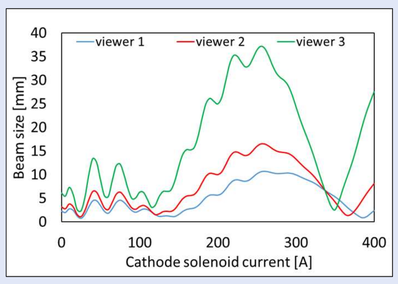
- Simulation parameters:

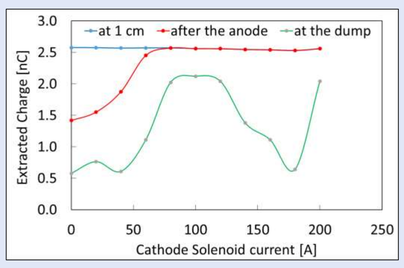
| Parameter | Value |
|---|---|
| Gun high voltage [kV] | -225 |
| Magnetic field, $B_z$ at the cathode [T] (0, 100, 200 A) | 0, 0.038, 0.076 |
| Mean Transverse Energy [eV] | 0.075 |
| Pulse width, Gaussian (FWHM) [ps] | 75 |
| Transverse laser spot size, Gaussian (rms) [mm] | 1.64 |
| Bunch charge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



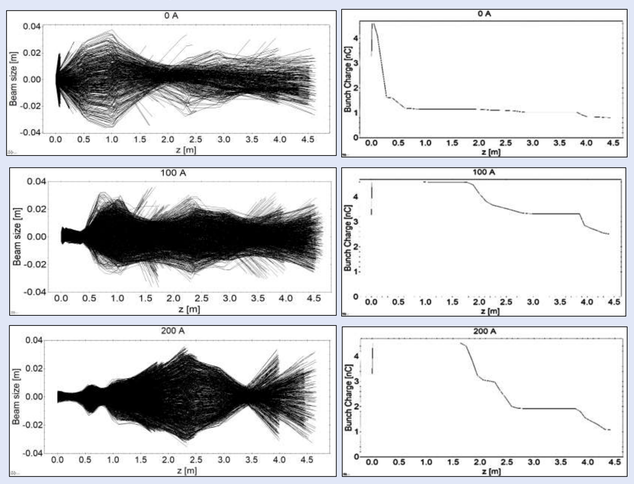

Digitized laser *QE profile:




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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wwije001@odu.edu