# Simulation Study of the Magnetized Electron Beam\*

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## Abstract

Electron cooling of the ion beam plays an important role in electron ion colliders to obtain the required high luminosity. This cooling efficiency can be enhanced by using a magnetized electron beam, where the cooling process occurs inside a solenoid field. This paper presents detailed simulation studies performed using ASTRA and GPT programs on magnetized electron beam compared to predictions for beam-based magnetization measurements conducted from the magnetized electron beam generated from a DC high voltage photo-gun as a function of beam size and rotation angle variations along the beamline, for different solenoid currents and other parameters.

#### INTRODUCTION

Electron ion colliders must provide ultra-high collision luminosity to achieve the promised physics goals. To meet this high luminosity, transverse emittance of the ion beam must be small at the electron-ion collision point. Emittance growth that results from intra beam scattering can be controlled by electron cooling of the ion beam. The cooling efficiency can be improved by using a magnetized electron beam, where the cooling process occurs inside a solenoid field and thereby, the small helical trajectories help to increase the electron-ion interaction time while suppressing the electron-ion recombination [1-2]. But, the radial fringe magnetic field at the entrance of the solenoid creates a large additional rotational motion which adversely affects the cooling process. At the electron source, we create the electron beam inside a similar magnetic field but inducing rotational motion in the opposite direction to compensate this effect.

The generation and characterization of the magnetized electron beam was successfully conducted at Thomas Jefferson Accelerator Facility (JLab). Simultaneously, simulations were performed using ASTRA (A Space Charge Tracking Algorithm) and GPT (General Particle Tracer) programs. This paper presents details of the simulations and comparison to beam-based measurements which help to understand the theory, both qualitatively and quantitatively and to optimize the parameters for better results.

# **EXPERIMENTAL SETUP**

The beamline consists of a DC high voltage photo-gun operating at 300 kV. It is an inverted ceramic with  $K_2CsSb$  photocathode and a green 532 nm drive laser. The

transverse size of the laser at the photocathode is set by the focusing lens in the laser transport. The laser beam temporal profile is a uniform distribution with rms duration of 25 ps.

The magnetic field is provided by the cathode solenoid magnet which is designed to fit in front of the gun chamber, 0.2029 m away from the cathode. The magnet operates at a maximum of 400 A to provide 1.5 kG at cathode.

Downstream, the beam line consists of two fluorescent YAG screens slit combinations (viewer) at 1.5 m, 2.0 m and one YAG screen at 3.75 m to measure the beam's transverse density profile at those locations, trace the beam rotation angles and measure the transverse emittance. Additionally, in order to focus and steer the beam four focusing solenoids and several correctors are included.

A schematic diagram of the beamline is shown in Figure 1.



Figure 1: The beam line.

### MEASUREMENTS

For a cylindrically symmetric laminar beam with transverse rms beam sizes  $\sigma_l$  at  $z_1$  location and  $\sigma_2$  at  $z_2$  location along the beam line, the averaged mechanical angular momentum is given by [3].

$$= 2 p_z \frac{\sigma_1 \sigma_2 \sin \theta}{D}$$
 (1)

Where  $p_z$  is the longitudinal component of the electron's momentum,  $\theta$  is rotation angle of the beam due to the magnetization and  $D = z_2 - z_1$ . Thus, in order to identify the mechanical angular momentum variation with the magnetic field strength at the cathode, transverse rms beam sizes ( $\sigma_1$ ,  $\sigma_2$ ,  $\sigma_3$ ) at three screen locations and rotation angles at second and third screen locations were measured by varying the magnetic field strength from 0 A to 400 A. The rotation angle was obtained by inserting a slit at first screen and measuring the corresponding angles

<sup>\*</sup> This work is supported by the Department of Energy, Laboratory Directed Research and Development funding, under contract DE-AC05-06OR23177

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at second and third screen and inserting a slit at second screen and measuring the angle at third screen. For more accurate results the data table (.SDDS file) for each case was saved and angles were calculated using MATLAB curve fitting tool. All these measurements were taken at 300 kV, with the laser spot size setup to 0.3 mm with 0.5 mm vertical offset and no horizontal offset and with no focusing solenoids on.

### MODELLING

The beam line was modelled using ASTRA and GPT programs separately and post processing was carried out using MATLAB.

The common input parameters used for ASTRA and GPT simulations are shown in the following table.

Parameter	Value
Gun voltage	300 kV
Max magnetic field, Bz at the cathode	0.1511 T
Mean Transverse Energy	0.130 eV
Longitudinal beam size, Uniform	~24 ps
Horizontal offset of the laser	0 mm
Vertical offset of the laser	0.5 mm
Number of macro particles	100000

Table 1: Input parameters used in simulations.

In order to account the effect of the electric field of the gun and the magnetic field of the cathode solenoid, field maps were used. Electrostatic field maps were generated using POISSON for 1D, 2D and COMSOL for 3D cases. Magnetic field map was generated using Opera, and it is shown in Figure 2. It was found that the magnetic field was distorted from the steel field clamps of the focusing solenoids.



Figure 2: The magnetic field map of the cathode solenoid.

## ASTRA Simulations

ASTRA is used here as 1D modelling tool considering its less computation time, high accuracy, user friendliness etc.

Initial particle distribution was created using the program *generator* which comes as part of ASTRA suite where the electron bunch emitted from the cathode is defined in terms of number of macro particles, transverse distributions, etc. (see Table 1) In addition, transverse beam size 0.301 mm (Gaussian) and initial emittance 0.56 mm mrad/mm are used. In input file three screens were included as in the beam line.

Considering the field maps, for rotationally symmetric fields, an on-axis field map is used where we define as a table with the longitudinal position and longitudinal field of both electric (z,  $E_z$ ) and magnetic (z,  $B_z$ ) fields. Thus, radial electric and magnetic field components are deduced from the 1<sup>st</sup> to 3<sup>rd</sup> derivatives of the on-axis field[4].

ASTRA does not include any effect from beam pipe walls, we included circular apertures along the beam line to confine the pipe size as in the experiment setup in order to track the beam getting off axis and thus to predict the pipe size for higher bunch charge simulations [4].

In order to visualize the beam profile at each screen location, beam propagation along the beam line, calculate the beam rms sizes and rotation angles at each screen locations, the output is post processed using MATLAB. Beam's x\_rms and y\_rms sizes are calculated using the standard deviation of the x coordinates and y coordinates of each particle respectively. In order to calculate the rotation angles a virtual slit is created at the 1<sup>st</sup> screen and the particles are numerically tracked to the 2<sup>nd</sup> screen as px and py are constants for each particle after they exit electromagnetic fields as there are no additional forces acting on them afterwards. From the gradients of the linear fits of the two screen images the rotation angle is calculated.

#### **GPT** Simulations

GPT is used as a 2D modelling tool with simulation parameters shown in table 1 and transverse beam size 0.35 mm (Gaussian). In addition, minimum calculation accuracy is set to  $10^{-6}$ , beam pipe radius is taken as 6 mm and three screens were included as in the beam line.

The 2D electric and 1D magnetic field maps generated from POISSON and Opera are converted to General Datafile Format (GDF) before use in GPT kernel. GPT reads the 1D table of  $B_z$  on axis and extrapolates to a cylindrical symmetric field map with 1<sup>st</sup> derivative of the on-axis field. Thus, beam near the z-axis gives reliable results. For our 2D cylindrically symmetric electric field map with r and z coordinates, GPT reads as it is [5].

GPT provides both time and position output where the time output write all particles coordinates at user defined times and position output writes all particle coordinates passing any plane in 3D space. GPT post processing tools GPTwin, GDFA and GDF2A are used to visualize the beam profiles at various simulation times, extract the beam parameters (stdx, stdy, avgz) and get Ascii output file respectively. MATLAB is used to get the beam profiles at each screen location and calculate the rotation angles. With GPT, in order to calculate the rotation angles a virtual slit is creates at the 1<sup>st</sup> screen and tracked the

particles within the slit through the data set to the 2<sup>nd</sup> screen and rotation angle is calculating from the gradient of linear fit of two screen images.

# SIMULATION RESULTS ANALYSIS

Following plots show the comparison between measurements, ASTRA and GPT simulations on beam size variations and rotation angle variation as a function of cathode solenoid current.



Figure 3: Beam rms size variation with the cathode solenoid current (up), rotation angle variation with the cathode solenoid current (down) for slit 1-viewer 2 combination. Colour code: green measured values, red GPT and blue ASTRA.

According to the above plots measurements and simulations show good agreement with each other. The first plots (up) shows few oscillations in the beam sizes, converging and diverging with the current which is known as mismatch oscillations in the accelerator field. This occurs due to our non-uniform magnetic field which is shown in figure 2. Magnetic force from the cathode solenoid does not match with the initial emittance force caused imbalanced forces inside the solenoid thus they end up showing oscillations in the beam size.

The second plot which is the rotation angle variation with the solenoid current shows the opposite pattern to the first one which is reasonable. When beam size decreases which means beam is converging and the rotation angle should increase and vice-versa. But few cathode solenoid currents result to unexpected negative angles (large angles). This occurs when a converging beam at the slit is being examined by the viewer downstream of the focal point of the converging beam. According to this concept a general form for the rotation angle  $\theta$  in equation (1) is formulated as follows

$$\theta_{rot} = \tan^{-1} \frac{\dot{\theta} D/v_z}{1 - D/f}$$
(2)

where  $\dot{\theta}$  indicates the rotation due to the magnetization,  $v_z$  is the velocity in z direction and f is the focal length due to the convergence. Thus, when focusing is achieved before the viewer (D>f), the denominator is negative thus it is possible for the observed rotation angle to be in the second quadrant and when beam is diverging (f<0) or beam at the slit is at waist the observed rotation angle should be in first quadrant.

The measured beam size value for first few current values (0 A-20 A) are significantly higher than the simulated values. It might be the electric field maps we used, a 3D electric field map with high accuracy would give us a better agreement. Beam sizes are measured by focusing a camera in to the YAG screens. Since beam sizes are significantly small the camera resolution also affects the measurement. In addition, accuracy of the measured laser spot size at the cathode and horizontal and vertical beam offset at the cathode also cause the small disagreements.

### CONCLUSION

In summary the magnetized beam generated at JLab is successfully modelled using ASTRA and GPT software and they are in good agreement with the measurements. But more accurate field maps and input parameters will lead us to a better agreement with the measurements.

Simulations helped to understand the physics in mismatch oscillations and rotation angles with large angles. Nonetheless a general formula is presented to calculate the rotation angle for both converging and diverging beams.

#### ACKNOWLEDGMENTS

This work is supported by the Department of Energy, Laboratory Directed Research and Development funding, under contract DE-AC05-06OR23177.

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