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MAGNETIZED ELECTRON SOURCE FOR JLEIC COOLER*

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Abstract

Magnetized bunched-beam electron cooling is a critical part of the Jefferson Lab Electron Ion Collider (JLEIC). Strong cooling of ion beams will be accomplished inside a cooling solenoid where the ions co-propagate with an electron beam generated from a source immersed in a magnetic field. This contribution describes the production and characterization of magnetized electron beam using a compact 300 kV DC high voltage photogun and bi-alkali antimonide photocathodes. Beam magnetization was studied using a diagnostic beamline that includes viewer screens for measuring the shearing angle of the electron beamlet passing through a narrow upstream slit. Correlated beam emittance with magnetic field (0-1.5 kG) at the photocathode was measured for various laser spot sizes. Measurements of photocathode lifetime were carried out at different magnetized electron beam currents up to 28 mA and high bunch charge up to 0.7 nano-Coulomb was demonstrated.

INTRODUCTION

To achieve the required luminosity, ion beams at JLEIC must be cooled. In general, this is accomplished when an electron beam co-propagates with the ion beam. The cooling rate can be improved by about two orders of magnitude if the process occurs inside a solenoidal field that forces the electrons to follow small helical trajectories thereby increasing the interaction time with ions and improving the cooling efficiency [1]. This cyclotron motion also suppresses electron-ion recombination, a serious problem, especially for heavy ions. Cooling rates of a magnetized electron beam are ultimately determined by electron longitudinal energy spread rather than the transverse emittance as the transverse motion of the electrons is quenched by the strong magnetic field.

The envisioned JLEIC magnetized cooler is part of the ion collider ring and aims to counteract emittance degradation induced by intra-beam scattering, to maintain emittance during electron-ion collisions and extend the luminosity lifetime. To implement cooling at relatively high energy, the electron beam must be bunched and accelerated in an SRF Linac. The required electron beam parameters from the magnetized electron source are difficult to achieve due to both the very high charge (3.2 nC) and high average current (140 mA) [2].

To implement cooling inside a solenoid, the electron beam must be generated inside a magnetic field. Otherwise, the electron beam will have mechanical angular momentum inside the cooling solenoid per Busch's theorem [3] induced by the radial fringe field as the electron beam enters the solenoid. This paper reports on generation and characterization of magnetized electron beams from a 300 kV DC high voltage magnetized electron source.

MAGNETIZED ELECTRON SOURCE

This prototype magnetized electron source consists of drive laser system, bi-alkali antimonide photocathode preparation chamber, photogun HV chamber, cathode solenoid, and diagnostic beamline (see Fig. 1), as described in details in the following subsections.

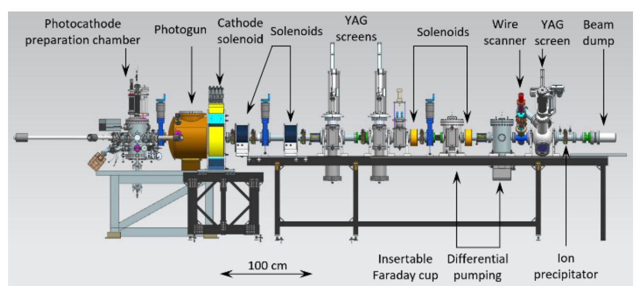

Figure 1: Schematics of main components of the magnetized electron source.

Drive Lasers

There were two different drive lasers used to generate magnetized beam. For high beam currents, a master-oscillator-power-amplifier system, composed of a 1066 nm gain-switched diode laser and multi-stage Yb-fiber amplifier chain followed by a harmonic converter, was constructed to provide Watts of power with picosecond light pulses at 533 nm. Good harmonic conversion efficiency up to 30% was achieved using a PPLN crystal. For high bunch charge, a commercial ultrafast laser with pulse duration less than 0.5 ps, 20 μJ pulse energy, operating at 50 kHz pulse repetition and 1030 nm wavelength was used. The IR beam was converted to 515 nm using a BBO crystal.

Photocathode Preparation Chamber

Bi-alkali antimonide photocathodes were grown inside a preparation chamber using co-evaporation of Cs and K from an effusion source onto a thin Sb layer deposited on

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a diamond-paste polished molybdenum substrate. The substrate was heat cleaned at about 700°C for 20 hours prior to activation. The technical details of key components of the deposition system and process are similar to [4]. During chemical deposition the substrate temperature was maintained at 120°C and the substrate was kept at 3.2 cm distance from the evaporation sources. The photocurrent was continuously monitored during alkali deposition by applying a low voltage bias (-280 V) and using low power green laser. The Sb source was resistively heated and the Sb was deposited for 10 minutes to get a translucent Sb layer. A mask with 5 mm aperture was used to limit the photocathode active area within the 13 mm diameter molybdenum substrate. Alkali deposition was discontinued when the photoemission current reached a maximum showing a QE of 5% or higher. Upon activation, the photocathode was transferred to the photogun cathode electrode.

High Voltage DC Photogun

The photogun is based on a conical inverted geometry insulator designed for operation at -350 kV with maximum field strength of 10 MV/m. This design provides a small volume resulting in better vacuum since there is less surface area contributing gas load and the insulator serves as the electrode support structure leaving less metal biased at high voltage contributing to field emission. The high voltage is applied to the cathode electrode using a commercial high voltage cable with a termination designed to mate with the inverted geometry insulator. Rather than illuminating the photocathode at nearly normal incidence which is typical of most photogun systems, the drive laser beam passes through entrance and exit holes in the anode electrode at 25° angle of incidence thereby eliminating the need for in-vacuum laser mirrors which can restrict the effective aperture of the beamline. The anode positioned 9 cm from the photocathode is also electrically isolated from ground potential to enable measurement of field emission from the cathode electrode and to enable biasing as a means to repel downstream ions created by the beam [5]. The photogun internal components were UHV cleaned, assembled and baked at 200°C for 100 hours.

A -500 kV DC and 5 mA Cockcroft-Walton SF_6 gas–insulated high voltage power supply with a 300 MOhms conditioning resistor in series was employed to energize the photogun. The photogun was high voltage conditioned to -360 kV using krypton gas to eliminate field emitters [6] and then the conditioning resistor was removed for beam operation. For high current delivery, a Spellman high voltage power supply (-225 kV and 30 mA with a power limit of 3 kW) was used.

Cathode Solenoid and Diagnostic Beamline

The cathode magnetizing solenoid provides magnetic field at the photocathode. It was positioned at the front of the gun chamber, 21 cm away from the photocathode. The solenoid was energized with a power supply (400 A, 80 V) and can provide magnetic field up to 1.5 kG at the photocathode and 3.3 kG at the center of the magnet. A magnetic model was developed that includes the gun solenoid and other magnetic components along the beamline. First trials of energizing cathode solenoid with photogun at high voltage resulted in new field emission and vacuum activity. Later a procedure was developed and followed to energize cathode solenoid without exciting new field emitters.

The diagnostic beamline extends 4.6 m from the gun and consists of: i) three YAG screens and two slits, ii) seven steering magnets, iii) four focusing solenoids, iv) ion-clearing electrodes, and v) differential pumps, ion pumps and NEG pumps to maintain good vacuum.

RESULTS AND DISCUSSION

Beam Sizes and Shearing Angles

Beam sizes and shearing angles were measured for various magnetic fields at the photocathode. The shearing angle is a manifestation of the mechanical angular momentum of the magnetized beam.

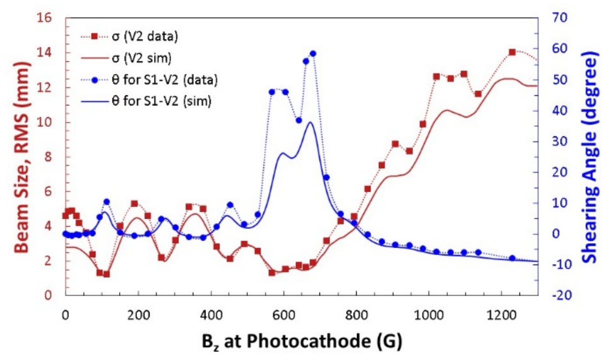

Figure 2: Measured beam sizes and shearing angles as a function of the magnetic field at the photocathode with high voltage of -300 kV and laser RMS spot size of 0.30 mm. Solid lines show the results of GPT simulation.

Figure 2 summarizes the measurements at the second YAG screen for beamlet passing through the first slit, showing beam sizes and corresponding beamlet shearing angles versus magnetic field at the photocathode. The strong magnetic field of the cathode solenoid causes mismatch oscillations, resulting in repeated focusing inside the solenoid which affects the beam size at the exit of the solenoid field. These mismatch oscillations introduce varying beam profile expansion rates and shearing angles in the field free region.

Drift (Correlated) Emittance

According to Busch's theorem [3], electrons born inside a magnetic field will acquire mechanical angular momentum (L) in the field free region which increases the emittance of the electron beam. This new emittance is referred to as the drift or correlated emittance and is given by:

$$\varepsilon_d = \frac{eB_z a_0^2}{2m_e c} = \frac{\langle L \rangle}{2m_e c}$$

where B_z is the longitudinal magnetic field at the photocathode and a_0 is the laser RMS spot size.

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The drift emittance of the magnetized beam with low bunch charge was characterized by measurement and simulation for two different laser RMS spot sizes (0.44 and 0.90 mm) as a function of varying longitudinal magnetic field (0-1.5 kG) at the photocathode. The emittance was measured by scanning one of the beamline solenoids and measuring the beam size on a downsteam YAG screen. The measured drift emittance results are shown in Fig. 3 for 20 femto-Coulomb bunches with the photogun at -200 kV showed good agreement with GPT [7] simulations. With the larger laser spot size, beam loss was observed (increase in beamline vacuum level) at the highest magnetic fields due to the difficulty of transporting the electron beam with very large drift emittance and thus very large transverse size. The thermal (uncorrelated) emittance of the bi-alkali antimonide photocathode was measured to be 0.5 µm/mm (laser RMS).

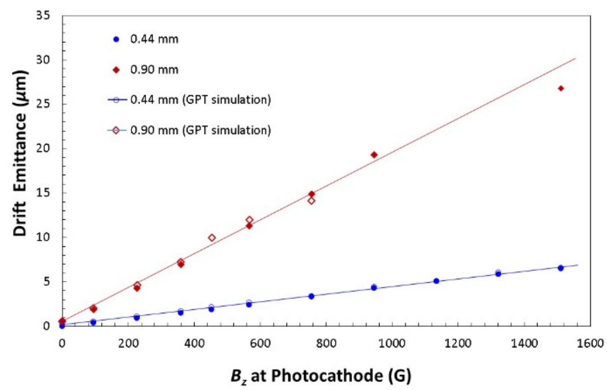

Figure 3: Measured drift emittance compared to GPT simulation as a function of cathode solenoid field for two laser RMS spot sizes (0.44 and 0.90 mm).

High Current Magnetized Beam

Sustained high current beam delivery was achieved only by applying a positive bias (+1000 VDC) to the anode of the photogun. Beamline ion-clearing electrodes were employed to preserve photocathode QE, but alone, these clearing electrodes did not prevent rapid photocathode damage. When the anode is grounded, photocathodes are quickly damaged by "micro-arc discharges" manifested by high voltage power supply current spikes, vacuum bursts and subsequent visible damage sites on the photocathode.

Figure 4 shows the highest beam current produced, 28 mA with a cumulative extracted charge of 5 kC and an estimated 1/e charge lifetime of 9.4 kC. For this run, a 1.4 mm (RMS) laser spot was used with 50 ps (FWHM) pulse width and 374.25 MHz repetition rate. The cathode magnetic field was set at 568 G. The bunch charge of the beam was 75 pC at the dump. The superior thermal conductivity of the molybdenum substrate improved charge lifetime over the same photocathode grown on GaAs wafer substrate. The drop in photocurrent after 24 hours is likely a result of photocathode heating and associated bandgap shift, chemical changes (such as dissociation), or enhanced ion bombardment which indicates the need for photocathode cooling for higher average current delivery.

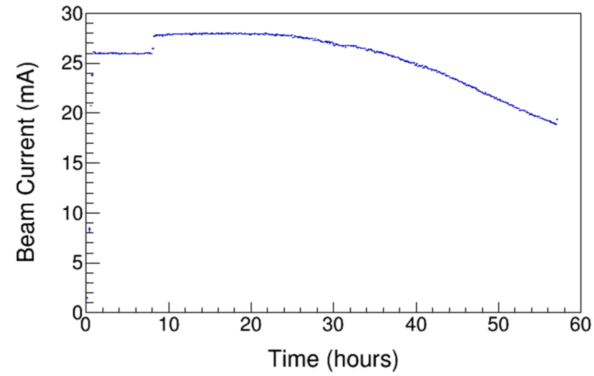

Figure 4: Magnetized beam current measured over 2 days at high voltage of -100 kV and an initial 28 mA average current. The magnetic field at the cathode was 568 G with the cathode solenoid powered at 150 A. The gun high voltage was set to -100 kV for this extended run due to power limit (3 kW) of the high voltage power supply.

CONCLUSION

A high current, high charge magnetized electron source was developed as a prototype for JLEIC magnetized electron cooler. Magnetized beam was characterized for various magnetic fields at the photocathode, laser spot sizes, and gun high voltages. Shearing angle and drift emittance were measured and compared to GPT simulations. Sustained high average current magnetized beam up to 28 mA was demonstrated. High bunch charge magnetized beams up to 0.7 nC at 50 kHz repetition rate were also successfully generated [8]. A new green gain-switched laser showed high degree of stability and reliability. Bi-alkali antimonide photocathode deposited on molybdenum substrate provided good QE and longer charge lifetime compared to similar photocathodes grown on GaAs substrates. The new photogun operated reliably at -300 kV. The application of positive bias on anode helped to effectively prevent QE loss from ion-induced micro-arcing events. The cathode solenoid provided up to 1.5 kG at photocathode and a procedure was developed to energize the solenoid without exiting new field emitters.

Recently, the photogun was replaced with a thermionic gun [9]. Magnetized electron beam delivery will start shortly using the same cathode solenoid and an improved diagnostic beamline.

To meet the ultimate requirements of the JLEIC magnetized cooler, a new DC high voltage photogun operating reliably at -400 kV or higher is under consideration. To improve operational lifetime, different photocathode compounds and substrates and photocathode cooling will be explored.

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