PROCEEDINGS OF SCIENCE

Funneling multiple bunches of high-charge polarized electrons

Erdong Wang[1]
Brookhaven National Laboratory,
Upton, NY 11973, USA
E-mail: `wange@bnl.gov`

Ilan Ben-Zvi[1,2], **David M Gassner**[1], **Wuzheng Meng**[1], **Alexander I. Pikin**[1], **Omer Habib Rahman**[2], **Triveni Rao**[1], **Eric Riehn**[1], **Brian Sheehy**[1], **John Skaritka**[1], **Qiong Wu**[1]
[1]*Brookhaven National Laboratory,*
Upton, NY 11973, USA
[2]*Stony Brook University,*
Stony Brook, New York 11794, USA

The future electron ion collider (eRHIC) at Brookhaven National Laboratory requires a polarized electron source with a high average current, short bunch length and small emittance. The state-of-the art single GaAs-based electron source is far from delivering the required 50mA current due to ion back-bombardment and the limit on surface charge. Currently, we are designing and constructing a high-average current, polarized electron-source based on the principle of the Funneling gun. Our funneling gun is designed such that the electron bunches generated from 20 photocathodes in a 220 kV DC gun, funnel to one common beam-axis. This article details our design of a high-average-current polarized electron source, encompassing its mechanical design, the preparation of the cathode, the beam's dynamics and diagnostics, and the laser system. We also discuss our recent progress in building the funneling gun.

XVth International Workshop on Polarized Sources, Targets, and Polarimetry
September 9-13, 2013
Charlottesville, Virginia, USA

PoS(PSTP 2013)041

---

[1] Erdong Wang

1. Introduction

A key technological demand in constructing a future heavy-ion collider lies in assuring a high average-current, high-bunch-charge polarized electron source [1]. To meet the requirements for luminosity and electron energy for an electron- and heavy-ion-collider, we are developing a polarized electron source with a 50 mA average current, 2.3 A peak current, and 20 µm emittance. The quantum efficiency (QE) lifetime due to ion back-bombardment limits the achievable level of the average current, and bunch charge with a single GaAs photocathode in a DC gun. One solution to the QE lifetime is to funnel the electron bunches generated from several photocathodes to a single common axis. Here, we assume that the performance of an individual photocathode is not affected by the presence of others [2]. In our design, each photocathode generates an average current of 2.5 mA, a value demonstrated by state-of-the-art photocathode polarized electron gun. Twenty GaAs photocathodes were placed along the rim of a 32 cm- diameter cathode electrode at a potential of -220 kV. A series of fixed magnetic field dipoles first bend the off-axis electron bunches that then are kicked into alignment with the main axis by a rotating magnetic field. Figure 1 is a schematic layout of the funneling gun for transporting current from the cathodes to the depressed collector that acts as a beam dump. The repetition frequency of the funneled bunches is 14 MHz; the total average current reaches 50 mA when the charge of individual bunches is 3.5 nC. The repetition frequency of a single cathode is 704 kHz, due to our multiplexing 20 cathodes.

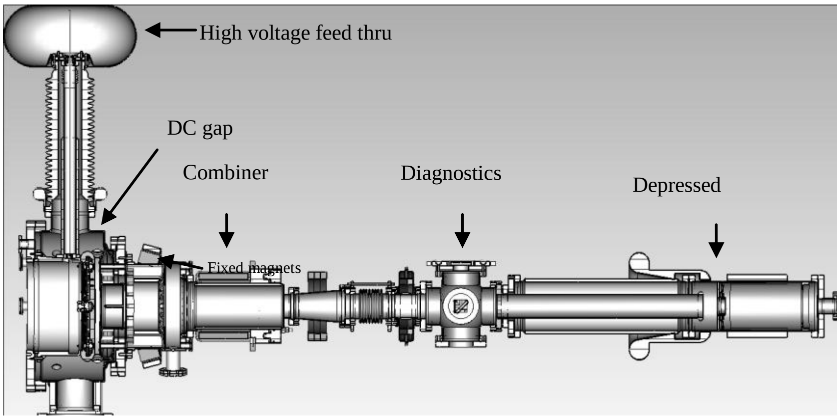

Figure 1: The schematic layout of the funneling gun.

2.DC gun’s design

We will accelerate the electrons with a Pierce-like DC gun whose gap geometry is illustrated in Figure 2. A focusing field near the cathode balances the strong space-charge field generated by the bunch. The optimized angle between the cathode surface normal and the cathode’s electrode is 67°; In designing the gun, we assumed that high-voltage breakdown would not be a problem for 220 kV across the 2.8 cm gap. Field simulations indicate that the maximum field on the cathode is 5.3MV/m. There is a small transverse field in the DC gap due to the non-axisymmetric geometry of the cathode and the anode about the beam’s axis. The geometrically optimized deflection field is less than 0.26% of the acceleration field. This small deflecting field in the DC gun’s gap did not degrade the beam’s quality. Solenoids placed after the anodes compensate for the defocusing of the space charge in the electrode gap. We minimized the beam's size downstream, especially at the entrance of the combiner, by varying the solenoid field; an integral field value of 0.22 T-cm was the optimum. The anode tube was NEG-coated to increase the pumping speed in the vicinity of the cathode and maintain the pressure in 10^{-12} torr range. The proposed cathode is Distributed Bragg Reflector (DBR)-superlattice GaAs photocathode that is expected to reduce the thermal load from the laser to generate a high-average-current polarized electron beam with long lifetime [3].

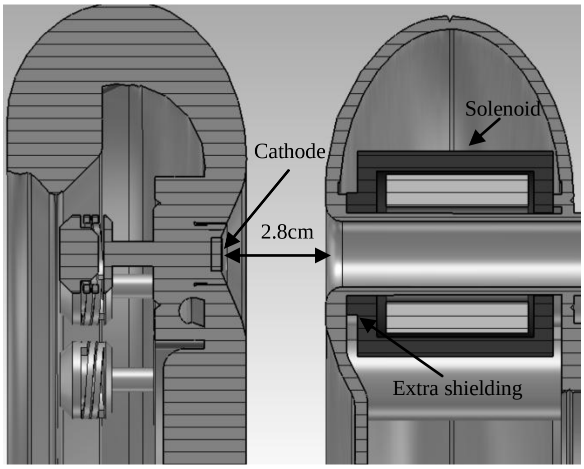

Figure 2: DC gun structure

3.Design of the bending magnet, combiner, and downstream optics

To preserve the longitudinal direction of electron spin-polarization, we designed compensated dogleg trajectories in the beam's funneling system encompassing 20 fixed bending fields, one for each cathode, generated by 20 dipole-magnets, and a single rotating bending-field generated by the magnetic combiner. A small beam is preferable in the combiner to reduce spherical aberration, and to eliminate loss of beam on the beam pipe. The funneling geometry we adopted precluded placing focusing lenses between the dipole magnets and the magnetic combiner. Increasing the bending angle reduces the drift space between two components. However, a large bending angle requires a large offset from the combiner's axis at its entrance where there is a non-linear field, resulting in increased normalized RMS emittance. The optimum deflection angle is 29°, achieved via the C dipole magnet. Space charge dominates the beam's divergence throughout the dipole. A single power supply will drive the dipoles controlling stability to < 25 ppm. The machine's tolerance will be controlled to < 25µm.

The original design of the combiner encompassed 12 dipole coils and 24 quadrupole ones [4]. However, recently, we obtained much larger linear bending and a more extensive focusing-field region by using 20 dipole coils and 40 quadrupole ones. The OPERA AC steady-state solutions confirmed the degree of rotation of the fields and that the multicathode emitted beams are in phase. The effect of the rotating time-dependent field on the beam can be ignored. In the gun simulation, we used the static field maps generated by Opera-3D/TOSCA for simulating the 3D beam in CST Particle Studio.

4.Vacuum system

The DC cathode shroud and anode assembly are made of vacuum fired 316L Stainless Steel with out-gassing rate of low 10^{-13} torr L/cm^{2}s. The anode shell that contains the solenoids is made from titanium having an potential out-gassing rate of 10^{-15} Torr L/cm^{2}s.The design baseline vacuum in the DC gun vessel is $6*10^{-13}$ torr. NEG pumps with total pumping rate of 8,000l/s were mounted in the centre of anode. After conditioning, we realized a $5*10^{-12}$ torr vacuum in the DC gun. We will employ a 10^{-13} torr resolution VatLab 3BG vacuum gauge to measure the gun vessel’s vacuum. We studied the residual gas distribution in XHV chamber using a Monte-Carlo code MolFLOW+. We found the pressure on the cathodes is about $7*10^{-13}$ torr. Additionally, a 6000L/s NEG pump will be placed close to the combiner. The beam line’s design vacuum is $1*10^{-11}$ torr. Another NEG pump is present in the depressed collector. The cathode exchange and transferring chambers can be maintained in a base pressure < 10^{-12} torr. The cathode preparation chamber can attain a 10^{-12} torr vacuum; we activated a bulk GaAs photocathode with 8% QE at 532 nm in this chamber.

5.Simulation of beam dynamics

Table I: Input parameters after optimization

Parameter	Value
Bunch charge at cathode	3.5nC
Longitudinal charge distribution at cathode	Gaussian distribution(σ=1.5ns)
Transverse charge distribution at cathode	Uniform
Bunch length at cathode	1.5ns
Bunch radius at cathode	4mm
Thermal emittance	0.5 μm/mm(rms) [5]

The main problems we encounter in the beam dynamics are the high bunch charge, the three dimensional geometry of the beam path, and the non-axisymmetricity of the field at the DC gap and at the combiner’s entrance about the beam’s axis. Therefore, we studied the beam dynamics of the gun and the design of the beam line optics using “Particle Studio”, a 3D beam-tracking code and the Particle In Cell (PIC) code developed by Computer Simulation Technology (CST). After optimizing the parameters of the optics, the round beam’s profile at the diagnostic cross was 15 mm diameter when we applied a 7.5A current on the quadrupole coils wherein the divergence angle is x’/y’=23.6 mrad/25.1 mrad. The transverse normalized RMS emittance is $\varepsilon_{n,x}$/ $\varepsilon_{n,y}$=17.0 mm-mrad/14.9 mm-mrad when we apply an optimized quadrupole current on the combiner.

Figure 3 illustrates the trajectory of entire beam line based on the parameters given in Table 1. The beam expands downstream of the diagnostic cross. Therefore, we used a third solenoid to focus the beam into the depressed collector. The diameter of the beam’s waist at the entrance to the collector is 15mm, i.e., half of the diameter of the collector’s entrance aperture. We simulated the beam’s longitudinal characteristics using the CST Particle Studio PIC code. The full beam’s energy spread at the beam diagnostic cross is 22 keV. The energy spread of 97% of the bunch particles is 8 keV, viz., an acceptably small value compared to its energy after the booster. We also explored beam loss based on the particle core model. It verified that the electrons at the bunch's edge will not strike the components' aperture.

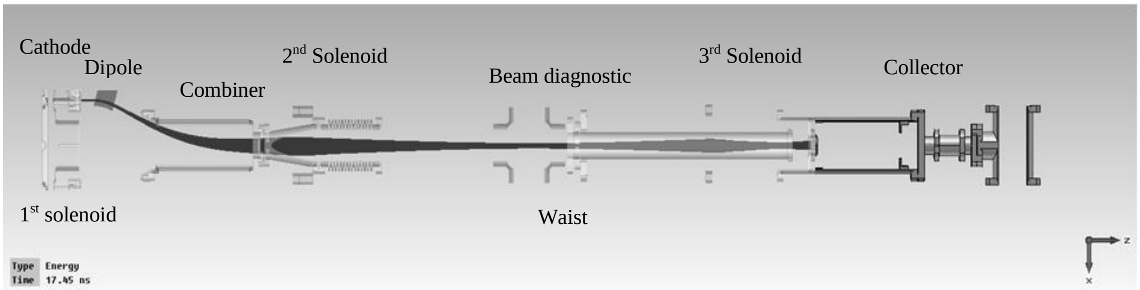

Figure 3 Tracking the entire beam line. The black curve is our simulated bundle of beam trajectories generated using the CST particle-tracking solver.

6.Laser system

The laser for the funneling Gun is a frequency-doubled erbium-doped fiber laser. The fiber laser, operating at 1560 nm, consists of a narrow-band CW laser that is electro-optically (EO) modulated, followed by a four-stage power amplifier. The EO modulation in the first stage allows for flexible tailoring of the pulse width (from 1 to 1.7 ns), shape and repetition rate. The synchronization with accelerating RF is achieved electronically without requiring any mechanical stabilization, an important consideration in extending the prototype system to illuminate 20 cathodes. The power amplifier delivers 10 kW peak power in the fundamental. The 1560 nm laser is currently undergoing final assembly and testing at the vendor (Optilab Inc). The average output power of 1560nm is 10W. The laser output will be doubled to 780 nm in periodically poled Lithium niobate, to be produced by a separate vendor. We expect doubling efficiencies of 40%, achieving average powers of 3 - 4 Watts.

7.Beam Diagnostics [6]

The beam diagnostics will measure the funneling gun beam characteristic including average current, bunch charge, beam profile, beam position, and beam loss.The transverse multi-beam profiles will be measured with a 5-cm diameter bakeable YAG:Ce screen. The bunch-by-bunch and the bunch train's charge will be measured by an integrating Current Transformer (ICT). We plan to employ a synchronized fast digitizer to measure the individual bunch charge. This information can be used to track independently the evolution of each photocathode's quantum efficiency. We will install a beam-position monitor using four 9.3mm diameter button pick-ups for nondestructive measurements. The halo beam at the entrance of the depressed collector will be measured with a halo detector. We studied a pepper pot for measuring the Funneling gun's emittance. Our findings show that we can achieve the best resolution by analyzing 5 beamlets produced by a 1 mm thick tungsten pepper-pot mask with 1mm wide slits spaced 1.5 mm apart. The beamlets will be imaged on a downstream profile monitor with a drift space of 0.1-0.3 m.

8.Depressed collector[7]

In the phase 1 project, we will replace the bunching section and energy boosting section by a simple depressed collector biased to almost same level as the cathode potential. Collecting the electron beam at low energy reduces out-gassing in vacuum chamber. Effectively trapping all the primary-, secondary-, and backscattered- electrons away from the beam line would reduce the gas load from the beam line by the returned electrons dramatically.

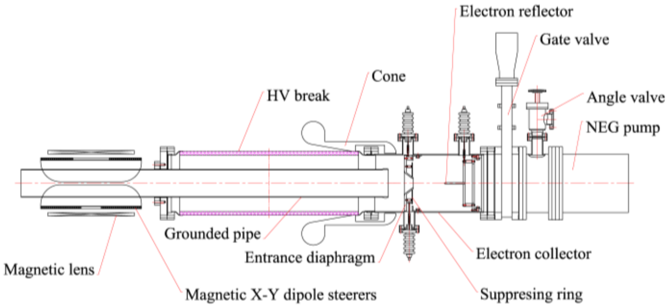

Figure 4. Structure of the depressed-electron- collector assembly for the Funneling-gun test stand.

The electron collector is mounted on a high-voltage terminal of the ceramic break. The magnetic lens and the magnetic deflectors for focusing the electron beam into the entrance are located up-stream to the high-voltage break. The region of electron deposition is restricted by the electric fields of two reflecting electrodes on both sides of the electron-deposition area. The radial component of the electric field of these electrodes pushes the secondary electrons back to the cylindrical wall and deflects the backscattered electrons, thus preventing them from escaping through the entrance diaphragm and back into the high-vacuum region. The NEG pump, mounted behind the electron reflector, is equipped with a gate valve and an angle valve for non-disruptive activation. The energy of the primary electrons hitting the surface of the electron collector is reduced to a value close to the electrons' energy spread. With the collector voltage being higher than the primary electron's energy spread, the returned primary electron current does not exceed 0.1% of the primary electron beam current. The penetration of the secondary and backscattered electrons into the beam pipe is practically eliminated.

9.Proof-of-principle test

In near future, we will schedule a proof- of -principle test for the Funneling gun. We plan to employ two super-lattice GaAs photocathodes and funnel the beams together. Table 1 presents the beam parameters from a single cathode. A DC power supply with switches will be used for driving the combiner. Combining the two beams and measuring at the depressed collector will yield a 5 mA average current. We will measure the beam's profile, its position, along with bunch charge, bunch shape, and beam loss in the beam line. We will evaluate the charge lifetime of single and double-cathode operational modes. Subsequently, we will measure the polarization of the electron beam and transverse emittance after the beam funneling.

10.Recent progress

We completed the design of the DC gun, the funneling system, and the beamline. The cathode preparation chamber is functional and 8% QE of the cathode for a photon energy of 2.32 eV and bulk GaAs was achieved. The 2D- and 3D-simulation of beam dynamics was studied, and verifies that the requirement of the eRHIC’s electron source was met. A 10^{-12} torr scale vacuum was achieved in the cathode transferring chamber that was fabricated by MDC. The DC gun is fabricated at Atlas Technology. The gun vessel and all the manipulators are fabricated by Transfer Engineering Corp. Mid-10^{-12} torr was established in gun vessel. The dipole magnets and combiner magnets have been fabricated and tested by Stangenes Industries Corp. who will be designing and fabricating the rest of the magnets also.

In the next 6 months, we will start preliminary tests at Stangenes Industries Corp wherein we will use two copper cathodes to generate two beams from opposite sides of the cathode shroud with a 100 pC bunch charge and then combine them. The beam’s position and current will be measured after beam funneling. This test will demonstrate that the combiner section can funnel the electron beams. Subsequently, we will replace copper cathodes with activated GaAs photocathodes and evaluate their lifetime at an average current of 21 μA. A chopped CW laser pointer will drive the cathodes, generating a beam with 4.2 uA of average current and 2 Hz repetition frequency. The planned beam current is set by the limited power of the laser pointer and assumed GaAs QE .

11.Summary

The design of the funneling gun was completed. Several companies are fabricating the gun’s components, tasks that will be completed by the end of this year. We have scheduled a proof-of-principle test for next year.

12.Acknowledgement

This work was carried out at Brookhaven Science associates, LLC under Contracts No.DE-AC02-98CH10886 with the U.S.DOE.

References

[1] V. Ptitsyn, in AIP Conference Proceedings (American Institute of Physics, 2012), pp. 646–648.

[2] V. N. Litvinenko, *Gatling Gun: High Average Polarized Current Injector for eRHIC* (2011). CA/AP/#417

[3] E. Riehn, E.J.K. Aulenbacher, in PSTP2011 (St. Petersburg, 2011), pp. 17–20.

[4] I. Ben-Zvi, Physical Review Special Topics - Accelerators and Beams **14**, 092001 (2011).

[5] I. V. Bazarov, Journal of Applied Physics **103**, 054901 (2008).

[6] D.M. Gassner, in International Beam Instrumentation Conference 2012 (Tsukuba, 2012).

[7] A.Pikin, *Depressed electron collector for the gatling gun test stand*, private commnicate (2012).