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A MULTIPLE CATHODE GUN DESIGN FOR THE eRHIC POLARIZED ELECTRON SOURCE*

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Abstract

The future electron-ion collider eRHIC requires a high average current (~50 mA), short bunch (~3 mm), low emittance (~20 μm) polarized electron source. The maximum average current of a polarized electron source so far is more than 1 mA, but much less than 50 mA, from a GaAs:Cs cathode [1]. One possible approach to overcome the average current limit and to achieve the required 50 mA beam for eRHIC, is to combine beamlets from multiple cathodes to one beam. In this paper, we present the feasibility studies of this technique.

INTRODUCTION

The future eRHIC project, next upgrade of RHIC, will be the first electron-heavy ion collider in the world. It requires polarized electron source with a high average current (~50 mA), short bunch (~3 mm), emittance of about 20 μm and energy spread of ~1% at 10 MeV. The state-of-art polarized electron cathode can generate average current of about more than 1 mA [1], but much less than 50 mA. The current is limited by the low quantum efficiency, space charge and ultra-high vacuum requirement of the polarized cathode. A possible approach to achieve the 50 mA beam is to employ multiple cathodes, such as 20 cathodes, and funnel the multiple bunched beams from cathodes to the same axis. Fig.1 illustrates schematically the concept of combining the multiple beams. We name it as "Gatling gun" because it bears functional similarity to a Gatling gun.

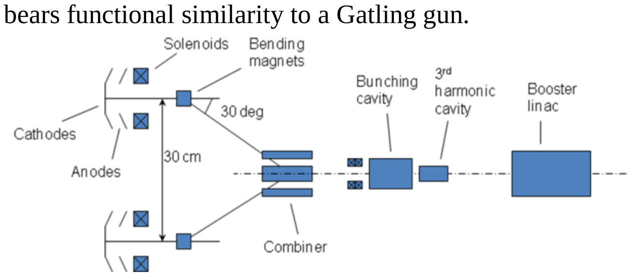

Figure 1. 20 cathodes are evenly located on a ring with diameter of 30 cm and are charged to -200 kV. Laser beams strike the cathodes sequentially with revolution frequency of 700 kHz. Each beam bunch is focused by a solenoid and is bent toward the combiner. The combiner with rotating bending field bends all bunches arriving the combiner with a rotational pattern to the same axis. The energy of each bunch is modified by a bunching cavity (112MHz) and a 3rd harmonic cavity (336MHz). The bunch length is compressed ballistically in the drift space and is frozen after energy has been boosted to 10 MeV by the Booster linac.

Each beam bunch contains 3.5 nC charge. The space charge is very strong at energy of 200 keV. A long bunch, σ of 250 ps, is adopted to reduce the space charge on cathode. To compress the beam to final length of 3 mm (10 ps) can be achieved by ballistic compression with a 3rd harmonic cavity.

THE COMPONENTS

The cathode geometry is shown in fig.2. Due to the strong space charge near the cathode, a strong focusing field near the cathode is desired to prevent fast expansion of the beam. Unfortunately, the focusing design is limited by the limited size of the individual cathode. The optimized geometry is shown in fig.2. 200 kV across the 3 cm gap is considered safe for HV breakdown.

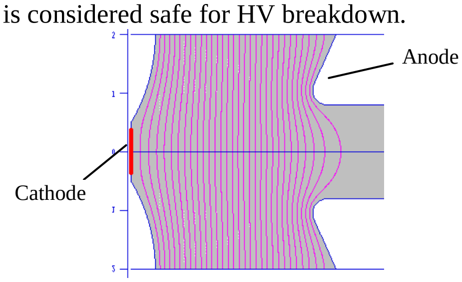

Figure 2. Individual cathode. The gap between cathode and anode is 3 cm.

The solenoids after each anode are used to compensate the less focusing in gun. They are isolated from the vacuum and can be finely adjusted individually. The strength is a practical 500 G × 4 cm.

The electron spin direction is not affected by electric field but will follow to the direction of the magnetic bending. This requires that, to preserve the spin polarization from cathode, the fixed bending field following the solenoid and the rotating bending field in the combiner must be either a pair of electric bends or a pair of magnetic bends. We choose the scheme with a pair of magnetic bends because it is much easier than the electric scheme bends at our 200 keV electron energy level. The fixed bending magnets and their coils are also located outside the chamber and can be finely adjusted individually. The fixed magnets are chevron magnets to focus the beam evenly in both transverse directions.

When an individual bunch approaches the combiner, it must be bent again magnetically to the combiner's axis. As the beam bunches from the cathodes reach the combiner in a rotational pattern, with a revolution frequency of 700 kHz, a rotational bending field is required to combine all the beams to the same axis. Due to the geometry of the combining scheme, the combining dipole magnetic field cannot provide a balanced focusing on both transverse directions for all the beams. This will result in an effective emittance increase to the combined

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beam. Even if we add a rotational quadrupole field after the rotational dipole field, it can still introduce emittance increase due to the change in the transverse shape of the beams. The best way to solve this problem is to generate a combined rotating dipole and rotatingl quadrupole magnetic field at the same location with the same magnetic core, such that the beam has the same focusing on both transverse directions during bending. This is one of the key techniques in the Gatling gun project. We have proven the feasibility of this rotating combined field technique [2].

A smaller beam spot size is preferred in the combiner to reduce the non-linear field of the combiner at large radius. Unfortunately, as all the bunches from cathodes converge at the combiner, there is no space to insert any focusing component for each individual bunch between the fixed bending and the combiner. So, if the drift space between the 2 bendings is too long, the bunch spot size at combiner becomes too big due to the strong space charge. On the other hand, to reduce the drift space between the 2 bendings, one must increase the bending angles; larger bending angles require a larger deviation of the beam from the combiner axis at combiner entrance, which can also bring in large emittance increase. Our optimized bending angle for both bendings is 30°.

After the beams are combined to one beam, it must be longitudinally compressed sufficiently small before it is frozen by energy boosting. It is impractical to compress our initial sigma of 7.5 cm long bunch to 3 mm at high energy. If we assume that a set of chicane magnets is used to compress the beam at high energy, the compression of a chicane is $\Delta Z \approx 7.5cm \approx 2L\theta^2\delta$, where L is the length between the 1^{st} and 2^{nd} magnet of the chicane, θ is the chicane bending angle, δ is the modified energy spread of a bunch. This requires a total chicane length of about 50 m with bending angle of 30° and δ of 1%. It will spoil the emittance dramatically. Also, the energy spread will not be reversible because the bunch length is too short after compression. Ballistic compression of the beam is more realistic. The emittance increase due to the compression is also small with ballistic compression because the beam is kept axially symmetric during the compression. To get the best compression of the beam, a 3^{rd} harmonic cavity is required to better manipulate the longitudinal phase space of the bunch. Fig.3 shows the optimized longitudinal phase space of the bunch after the bunching cavity and the 3^{rd} harmonic cavity.

The left figure in fig.3 is not a straight line due to the non-linear correlation of velocity and energy of the beam. As shown in right figure of fig.3, the phase space after compression and energy boosting up becomes almost a straight line. The energy difference also becomes smaller at end due to the longitudinal space charge. The final energy spread is 1.1% at 10 MeV. The booster linac is assumed to be a 112 MHz superconducting RF cavity. Although the final bunch length is 5 mm, it can be further compressed in the following energy boosting section. The final longitudinal emittance is 550 ps.keV. In principle the beam can be compressed to 1.5 mm.

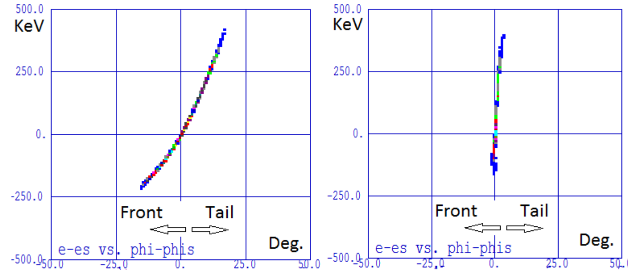

Figure 3. Optimized longitudinal phase space after bunching cavity and 3^{rd} harmonic cavity (Left, reference energy: 840 keV) and at booster linac exit (Right, reference energy: 8.5 MeV).

The energy gain in the bunching cavity is 1 MeV and the energy loss in the 3^{rd} harmonic cavity is 0.4 MeV. The low field gradient requirements for these 2 cavities make it possible to employ normal conducting cavities.

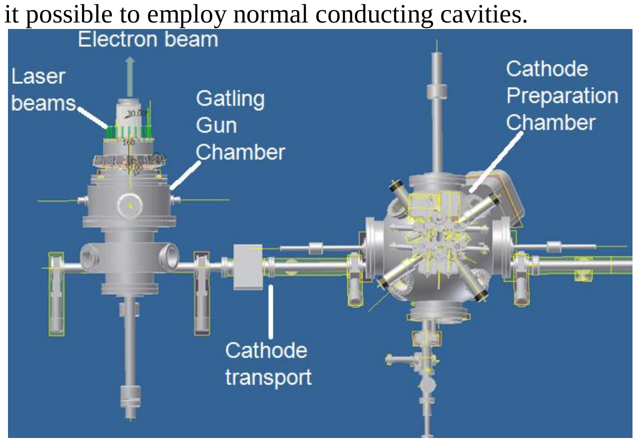

Figure 4. Cathode preparation chamber and gatling gun chamber

The polarized electron source must work in ultra-high vacuum environment, better than 10^{-11} Torr. As shown in fig.4, the cathode preparation chamber is directly connected to the Gatling gun chamber through a transport section. The cathodes are under ultra-high vacuum at all times during the preparation, transport and operation.

We have completed most of the mechanical design (fig.4) and all the critical parts, such as the preparation chamber, the Gatling gun chamber etc. are being manufactured.

SIMULATION

We have done our 2D simulations of the Gatling gun system with the codes Parmela, Superfish, Poisson, etc.

The laser distribution was assumed to be a transverse uniform with maximum radius of 4.2 mm and longitudinal Gaussian with sigma of 250 ps. Charge per bunch was assumed to be 3.5 nC.

Fig. 5 is the beam envelope vs. Z from one cathode to the booster linac exit. The beam size was made maximum in the compression section (drift space in fig.5) to reduce the strong space charge, especially near the booster linac entrance.

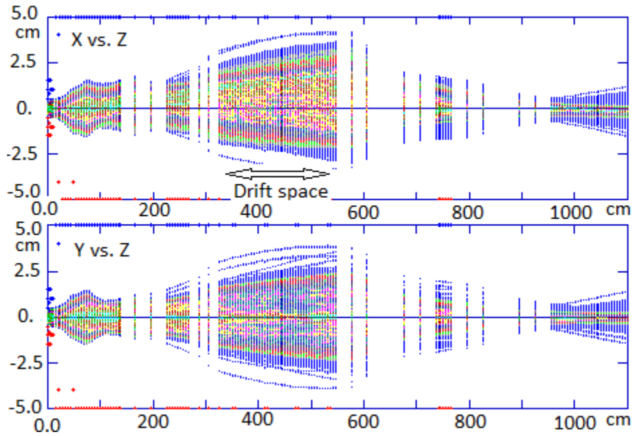

Figure 5. Beam envelope vs. Z. The drift space shown is the compression section between the 3rd harmonic cavity and booster linac.

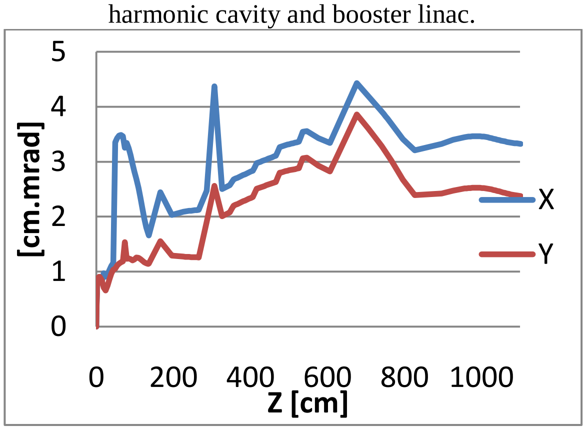

Figure 6. emittance vs. Z. The final emittance is 33 µm in X direction and 24 µm in Y direction.

The emittance in X direction (ε_X) is higher than in Y direction (ε_Y) due to the dispersion. ε_X is contributed mostly by a small portion of the "bad" particles. As an example, if we drop off 30% "bad" particles, ε_X becomes 24 µm and ε_Y decreases to 19 µm.

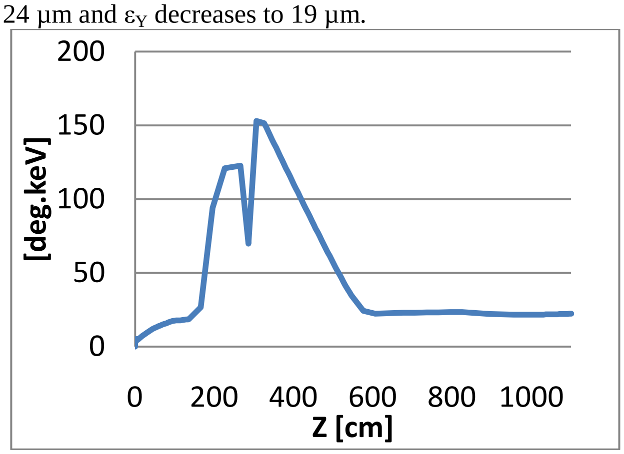

Figure 7. Longitudinal emittance vs. Z.

As shown in fig.7, the longitudinal emittance is compensated greatly in the compression section (Z from 3.3 m to 5.8 m) by the longitudinal space charge. It is found that, a longitudinal Gaussian distribution beam, due to its special longitudinal space charge force distribution, can have much better longitudinal emittance compensation than that with a longitudinal uniform distribution.

Our 3D simulation of the Gatling gun system is in progress with the code Vorpal.

CONCLUSIONS

We have designed a possible multi-cathode system to provide the 50 mA polarized electron beam as required by the future eRHIC project. With this design, the beam bunches from 20 cathodes are combined to the same axis and then be compressed ballistically before the acceleration by a booster linac. It is found from our 2D simulations that the beam can be compressed to be 1.5 mm with energy spread of 1.1% at 10 MeV energy. The final emittance (ε_X of 33 µm and ε_Y of 24 µm) is very close to the eRHIC requirements. The emittance can be further improved by sacrifising a little bit longitudinal compression. Our scheme is quite promising to be the eRHIC required polarized electron source.

REFERENCES

[1] J. Grames, et al., "Lifetime Measurements of High Polarization Strained-Superlattice Gallium Arsenide at Beam Current >1 Milliamp Using a New 100kV Load Lock Photogun", Proceedings of PAC07, Albuquerque, New Mexico, USA.

[2] X. Chang, et al., "Rotating dipole and quadrupole field for a multiple cathode system", in these proceedings.