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ROTATING DIPOLE AND QUADRUPOLE FIELD FOR A MULTIPLE CATHODE SYSTEM*

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Abstract

A multiple cathode system has been designed to provide the high average current polarized electron bunches for the future electron-ion collider eRHIC [1]. One of the key research topics in this design is the technique to generate a combined dipole and quadrupole rotating field at high frequency (700 kHz). This type of field is necessary for combining bunches from different cathodes to the same axis with minimum emittance growth. Our simulations and the prototype test results to achieve this will be presented.

INTRODUCTION

The future eRHIC project, next upgrade of RHIC, will be the first electron-heavy ion collider in the world. For polarized-electron and polarized proton collisions, it requires a polarized electron source with 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 [2], but much less than 50 mA. The current is limited by the quantum efficiency, lifetime, 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 combine the multiple bunched beams from cathodes to the same axis [1]. We name it as "Gatling gun" because its operations bear similarity to a multi-barrel Gatling gun.

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 after the solenoid and the rotating bending field in combiner must be either a pair of electric bendings or a pair of magnetic bendings. We choose the scheme with a pair of magnetic bendings because it is much easier than the scheme with a pair of electric bendings at our 200 keV electron energy level.

As the beam bunches from the cathodes reach the combiner in a rotational pattern, with a revolution frequency of $f=700$ kHz, a rotating magnetic bending field is required to align all the beams to the combiner axis. This is one of the key components in this Gatling gun project.

To preserve the extreme vacuum quality, the magnetic combiner is isolated from the ultra-high vacuum chamber by a ceramic tube. The ceramic tube must be metal-coated to prevent charge build up on the tube and generate strong static space charge force. However, to allow the rotating magnetic field to penetrate the ceramic tube, the metal coating must be thin enough, such that the surface

resistance is sufficiently high. This coating technique has been demonstrated in many applications.

As the beam bunches follow axial symmetry, we use a ferrite tube to generate the rotating field which keeps the same field pattern at all orientation angles.

Due to the strong space charge force and limited focusing components, the spot size of the beam bunches becomes very big, maximum radius of about 1.2 cm, when they arrive the combiner. Besides, as the entering angle of the beam is 30° , the beam must be offset a lot from the combiner axis at entrance. This requires a large aperture combiner.

There is another important issue needs be considered: Due to the geometry of the combining scheme, the beam trajectory at the combiner entrance is quite different from its trajectory at the combiner exit; the injection path is offset from the field axis and is inclined to the gun axis, while the offset and angle vanish at the combiner exit. This leads to unbalanced focusing in the two transverse directions for a pure dipole field. Even if we add a rotational quadrupole field downstream of the rotating dipole field, the effective emittance is increased due to the bunch-to-bunch transverse shape change. The best way to solve this problem is to generate a combined rotational dipole and rotational quadrupole magnetic field at the same location with the same magnetic core, such that the beam keeps round during bending.

SIMULATION

We know a continuous $\cos(\theta)$ current distribution on a tube generates a perfect dipole field. In fact, limited coils with $\cos(\theta)$ current distribution can approach a good dipole field with large good field region. Similarly, a continuous $\cos(2\theta)$ current distribution generates a perfect quadrupole field and limited $\cos(2\theta)$ current distribution coils can approach a good quadrupole field. They are all eigenmodes of the field and therefore are independent.

Fig.1 illustrates our combiner with 12 dipole coils. The currents on the dipole coils are:

$$I_D(\Phi_D) = I_{0D} \cos(\omega t + \Phi_D) \quad (1)$$

where I_{0D} is the dipole coil peak current, $\omega = 2\pi f$ is the angular frequency of the rotation, Φ_D is the orientation angle of the dipole coil.

Fig.1 also shows the magnetic field distribution calculated by a 2D simulation code (OPERA-2D [3]). One can see that the dipole field is uniform over a large area. It is found that the radius of the good field region (Sextupole component less than 5×10^{-4}) with the 12 dipole coils design is bigger than 6cm.

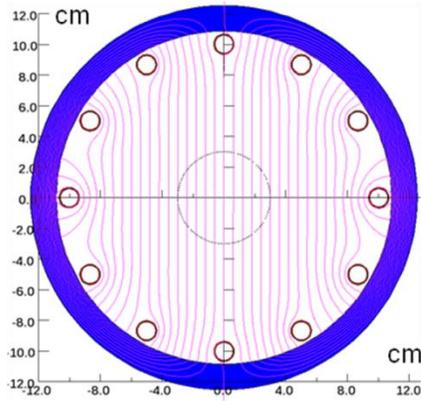


Figure 1. Flux plot from 12 dipole coils with a ferrite core

The peak dipole current on each dipole coil is $I_{0D} = 135.5$ A to bend the 200 kV beam by 30° . The total power loss in dipole coils is about 600 W. A water cooled coil can easily handle this power density.

We choose MN8CX to be the material of the ferrite core, which can operate into the MHz range frequency [4]. The peak field in the core is 619 G and the power loss is 648 W. As the ferrite size is very big, this power can be dissipated by air cooling.

We observed the non-equal focusing of the beam in 2 transverse directions after bending by the combiner without the quadrupole field. The difference is about 1° at radius of 1.5 cm. This corresponds to an integrated emittance increase of about 3 mm.mrad.

To equalize the focusing of the beam in 2 transverse directions during bending, quadrupole coils are wound on the same ferrite. The currents on the quadrupole coils are:

$$I_Q(\Phi_Q) = I_{0Q} \cos 2(\omega t + \Phi_Q) \quad (2)$$

where I_{0Q} is the quadrupole coil peak current, Φ_Q is the orientation angle of the dipole coil. Fig.2 illustrates the ferrite with 12 dipole coils and 24 quadrupole coils.

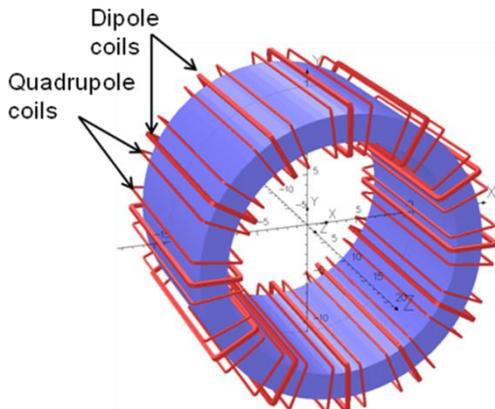


Figure 2. Combiner with combined dipole and quadrupole field. The ferrite has a length of 20 cm and inner radius of 10cm.

Fig.3 illustrates the electron (200 keV) trajectories in the dipole and quadrupole fields calculated by a 3D code (OPERA-3D [3]). The peak quadrupole coil current which makes equal focusing in 2 transverse directions is only I_{0Q}

= 2.4 A by simulation. The power loss on the quadrupole coils is negligible.

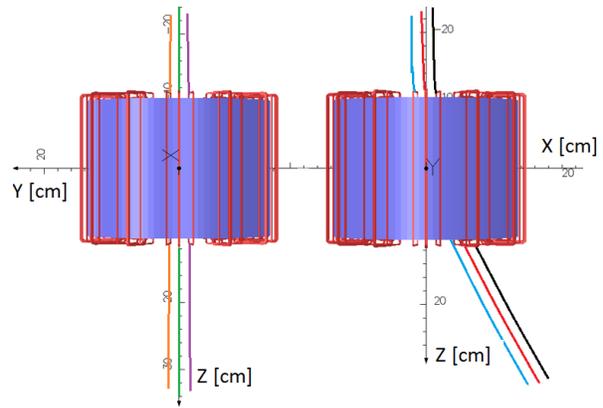


Figure 3. Electron (200 keV) trajectories in the combined dipole and quadrupole fields.

We have assumed the ideally wound coils in the above simulations. Each coil is independent of the others. It's important to find a way to approach the ideal current distribution in practice with the minimum expenses, such as the high frequency power supplies.

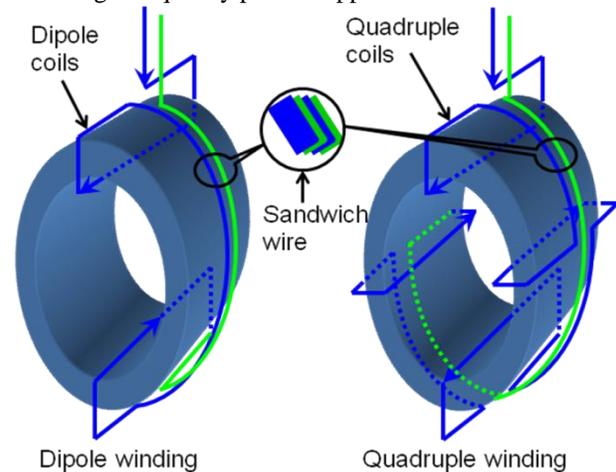


Figure 4. Dipole windings and quadrupole windings.

As shown in fig.4, each dipole coil and the dipole coil on its opposite side on the ferrite have the same amplitude current at all time during operation. We can connect them in serial to form one pair of dipole coils. Similarly, every 4 quadrupole coils with the same amplitude current, with separation of 90° s, can be connected in serial to form a set of quadrupole coils.

The connection of the coils is through the multiple layer sandwich like wire shown in fig.4. The sandwich wires are located near the field free region in the middle part outside the ferrite. As the net current of the sandwich wire is always zero due to the current cancellation, the sandwich wires are independent. Another important benefit of the sandwich wire is that it can reduce the wire resistance at high frequency dramatically. The skin depth of a copper wire at our 700 kHz frequency is about 75 μm . If we use single wires, only a small portion of the wire is effective. While a sandwich wire with multiple thin layer conductors can utilize most of the conductors.

The power leads for each coil employ similar technique. With these techniques, we can construct the required current distribution as approximating well the model that has been simulated.

The phase shift between the dipole coil pairs is within 180° . For example if there are 6 pairs of dipole coils, the phase difference between adjacent pairs is 30° and the maximum phase difference is 150° . A possible scheme powering all the 6 pairs dipole coils with one high frequency source is by using a transformer. First, split the source signal to 6 signals by a transformer with 6 secondary windings. Then adjust each secondary winding turns and the capacitor of each coil's LC circuit to achieve desired phase shift and amplitude. This method is easy to cover a phase shift range of $\pm 45^\circ$ but hard to cover $\pm 90^\circ$. But if we use 2 stage of above circuit, the first stage transformer generates 2 signals with 90° phase difference, the secondary 2 transformers generate 6 signals which cover the required 150° phase difference.

To verify our analysis, a simple combiner prototype has been made and tested. Fig.5 is our prototype with 4 pairs of dipole coil windings and 4 sets of quadrupole coil windings. The connection wires are twisted wires instead of the sandwich wire.

We first measured the coupling between the dipole field and the quadrupole field. We generated the rotating dipole field by applying to the dipole coils with signals of 500 kHz, 2 V amplitude and 45° phase shift between signals. The pickup signal amplitudes on the quadrupole coils were all less than 3 mV. Then we generated the rotating quadrupole field similarly and measured the pickup signal on the dipole coils. We got the similar results. This proved our assumption that the dipole and quadrupole fields are independent.

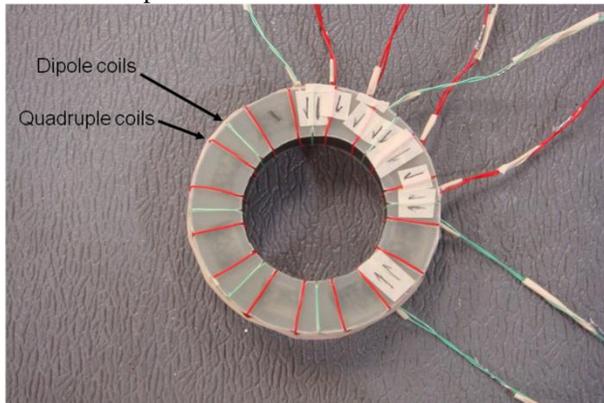


Figure 5. A combiner prototype with 4 pairs of dipole coil windings and 4 sets of quadrupole coil windings.

We also measured the quality of the rotating dipole and quadrupole fields in the prototype. They are consistent with the analysis within the error.

CONCLUSIONS

We have designed in detail a possible magnetic combiner, one of the key components of the gatling gun project for eRHIC. This combiner generates the combined

dipole and quadrupole magnetic field with field rotating frequency of 700 kHz, rotational symmetric, enough to bend 200 keV beam 30° . The simulations show that the radius of good field region is more than 6 cm. The total coil power loss is about 600 W and the ferrite core power loss is about 650 W. They can be easily dissipated with water cooling, even possible by air cooling. The simple prototype has proven that the dipole field and the quadrupole field generated in the same ferrite core are independent. This combiner design is quite feasible for the Gatling gun project.

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