The spatial distributions of chiral magnetic field in the RHIC and LHC energy regions

Yang Zhong\textsuperscript{1,2}, Chun-Bin Yang\textsuperscript{1,3}, Xu Cai\textsuperscript{1,3}, and Sheng-Qin Feng\textsuperscript{2,3}

\textsuperscript{1} Institute of Particle Physics, Central China Normal University, Wuhan 430079, China
\textsuperscript{2} Department of Physics, College of Science, China Three Gorges University, Yichang 443002, China
\textsuperscript{3} Key Laboratory of Quark and Lepton Physics (MOE), Central China Normal University, Wuhan 430079, China

Relativistic heavy-ion collisions can produce extremely strong magnetic field in the collision regions. The spatial variation features of the magnetic fields are analyzed in detail for non-central Pb - Pb collisions at LHC $\sqrt{s_{NN}} = 900$, 2760 and 7000 GeV and Au-Au collisions at RHIC $\sqrt{s_{NN}} = 62.4$, 130 and 200 GeV. The dependencies of magnetic field on proper time, collision energies and impact parameters are investigated in this paper. It is shown that a enormous with highly inhomogeneous spatial distribution magnetic field can indeed be created in off-central relativistic heavy-ion collisions in RHIC and LHC energy regions. The enormous magnetic field is quite large, especially just after the collision, and then decreases rapidly with time. We are surprised to find that the magnetic effect decreases with increasing energy from RHIC to LHC energy region. It is found that the magnitude of magnetic field in the LHC energy region is far less than that of magnetic field in the RHIC energy region.

Keywords: Spatial distribution of chiral magnetic field, Non-central collision, chiral magnetic field

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I. INTRODUCTION

The Chiral Magnetic Effect (CME) is the phenomenon of electric charge separation along the external magnetic field that is introduced by the chirality imbalance \[ 1,2 \]. It is proposed by Ref. \[ 3,7 \] that off-central relativistic heavy-ion collisions can create strong transient magnetic fields due to the fact, oppositely directed motion of two colliding nuclei. The magnetic field perpendicular to the reaction plane is aligned. Extremely strong (electromagnetic) magnetic fields are present in non-central collisions, albeit for a very short time. Thus, relativistic heavy-ion collisions provide a unique terrestrial environment to study QCD in strong magnetic field surroundings \[ 8,11 \]. This so-called chiral magnetic effect may serve as a sign of the local P and CP violation of QCD. By using relativistic heavy-ion collisions at the Relativistic Heavy-Ion Collider (RHIC) and the Large Hadron Collider (LHC), one can investigate the behavior of QCD at extremely high-energy densities.

In non-central collisions opposite charge quarks would tend to be emitted in opposite directions relative to the system angular momentum \[ 8,12,14 \]. This asymmetry in the emission of quarks would be reflected in an analogous asymmetry between positive- and negative-pion emission directions. This phenomenon is introduced by the large (electro-) magnetic field produced in non-central heavy-ion collisions. The same phenomenon can also be depicted in terms of induction of electric field by the (quasi) static magnetic field, which happens in the occurrence of these topologically nontrivial vacuum solutions. The induced electric field is parallel to the magnetic field and leads to the charge separation in that direction. Thus, the charge separation can be viewed as a nonzero electric dipole moment of the system.

Experimentally, RHIC \[ 15,19 \] and LHC \[ 20 \] have published the measurements of CME by the two-particle or three-particle correlations of charged particles with respect to the reaction plane, which are qualitatively consistent with the CME. A clear signal compatible with a charge dependent separation relative to the reaction plane is observed, which shows little or no collision energy dependence when compared to measurements at RHIC energies. This provides a new insight for understanding the nature of the charge-dependent azimuthal correlations observed at RHIC and LHC energies.

Recent years, lots of attentions \[ 21,25 \] have been paid to the chiral magnetic effect (CME). It is shown that this effect originates from the existence of nontrivial topological configurations of gauge fields and their interplay with the chiral anomaly which results in an asymmetry between left- and right-handed quarks. The created strong magnetic field coupled to a chiral asymmetry can induce an electric charge current along the direction of a magnetic field. The strong magnetic field will separate particles of opposite charges with respect to the reaction plane. Recently, possible CME and topological charge fluctuations have been recognized by QCD lattice calculations in gauge theory \[ 26,27 \] and in QCD + QED with dynamical $2 + 1$ quark flavors \[ 28 \]. Thus, such topological and CME effects in QCD might be recognized in relativistic heavy-ion collisions directly in the presence of very intense external electromagnetic fields.

Besides the chiral magnetic effect, there are other effects caused by the strong magnetic fields including the catalysis of chiral symmetry breaking \[ 29 \], the spontaneous electromagnetic superconductivity of QCD vacuum \[ 30,31 \], the possible splitting of chiral and deconfinement phase transitions \[ 32 \], the appearance of anisotropic viscosities \[ 33,34 \], the possible enhancement...
of elliptic flow of charged particles \[35, 36\], the emergence of the electric quadrupole moment of the QGP \[37\], the energy loss due to the synchrotron radiation of quarks \[38\], etc.

In Ref. \[39, 40\], we used the Wood-Saxon nucleon distribution instead of uniform distribution to improve the calculation of the magnetic field of the central point for non-central collision in the RHIC and LHC energy regions. In this paper, we will use the improved magnetic field model to calculate the spatial distribution feature of the chiral magnetic field in the RHIC and LHC energy regions. The dependencies of the spatial features of magnetic fields on the collision energies, centralities, and collision time will be systematically investigated, respectively.

The paper is organized as follows. The key points of the improved model of field are described in Sec. II. The calculation results of the magnetic field are present in Sec. III. A summary is given in Sec. IV.

II. THE IMPROVED MODEL OF CHIRAL MAGNETIC FIELD

The improved model of magnetic field mainly contains three parts:

(1) As shown in Fig.1, two similar relativistic heavy nuclei with charge \(Z\) and radius \(R\) are traveling in the positive and negative \(z\) direction with rapidity \(Y_0\). At \(t = 0\) they go through a non-central collision with impact parameter \(b\) at the origin point. The center of the two nuclei are taken at \(x = \pm b/2\) at time \(t = 0\) so that the direction of \(b\) lies along the \(x\) axis. The region in which the two nuclei overlap contains the participants, the regions in which they do not overlap contain the spectators.

As the nuclei are nearly traveling with the speed of light in ultra-relativistic heavy-ion collision experiments, the Lorentz contraction factor \(\gamma\) is so large that the two included nuclei can be taken as pancake shape (as the \(z = 0\) plane). We use the Wood-Saxon nuclear distribution instead of uniform nuclear distribution \[1\]. The Wood-Saxon nuclear distribution forms is:

\[
n_A(r) = \frac{n_0}{1 + \exp(\frac{r-R}{d})},
\]

(1)

here \(d = 0.54\) fm, \(n_0 = 0.17\) fm\(^{-3}\) and the radius \(R = 1.12\) A\(^{1/3}\) fm. Considering the Lorentz contraction, the density of the two-dimensional plane can be given by:

\[
\rho_{\perp}(\vec{x}_\perp) = N \cdot \int_{-\infty}^{\infty} d\vec{z} \frac{n_0}{1 + \exp(\frac{\sqrt{(x^2 + b^2)} + \sqrt{y^2 + z^2} - R}{d})},
\]

(2)

where \(N\) is the normalization constant. The number densities of the colliding nuclei can be normalized as

\[
\int d\vec{x}_\perp \rho_{\perp}(\vec{x}_\perp) = 1.
\]

(3)

![FIG. 1: Cross-sectional view of a non-central relativistic heavy-ion collision along the \(z\) axis. The two nuclei have same radii \(R\), move in opposite directions, and collide with impact parameter \(b\). The angle \(\phi\) is an azimuthal angle with respect to the reaction plane. The plane \(y = 0\) is called the reaction plane. The two nuclei overlap region contains the participants, and they do not overlap regions contain the spectators.](image)

(2) Secondly, in order to study the strength of the magnetic field caused by the two relativistic traveling nuclei, we can split the contribution of particles to the magnetic field in the following way

\[
\vec{B} = \vec{B}_s^+ + \vec{B}_s^- + \vec{B}_p^+ + \vec{B}_p^-
\]

(4)

where \(\vec{B}_s^\pm\) and \(\vec{B}_p^\pm\) are the the contributions of the spectators and the participants moving in the positive or negative \(z\) direction, respectively. For spectators, we assume that they do not scatter at all and that they keep traveling with the beam rapidity \(Y_0\). Combining with Eq. (2), we use the density above and give

\[
e\vec{B}_s^\pm(\tau, \eta, \vec{x}_\perp) = \pm Z e_{EM} \sinh(Y_0 \mp \eta) \int d^2\vec{x}_\perp \rho_{\perp}(\vec{x}_\perp) \times \left[ 1 - \theta_+(\vec{x}_\perp) \right] \frac{(\vec{x}_\perp - \vec{e}_z) \times \vec{e}_z}{[(\vec{x}_\perp - \vec{e}_z)^2 + \tau^2 \sinh(Y_0 \mp \eta)^2]^{3/2}},
\]

(5)

where \(\tau = (t^2 - z^2)^{1/2}\) is the proper time, \(\eta = \frac{1}{2} \ln[(t + z)/(t - z)]\) is the space-time rapidity, and

\[
\theta_+(\vec{x}_\perp) = \theta[R^2 - (\vec{x}_\perp + \vec{b}/2)^2].
\]

(6)

In the other hand, the distribution of participants that remain traveling along the beam axis is given by

\[
f(Y) = \frac{a}{2 \sinh(aY_0)} e^{aY}, \quad -Y_0 \leq Y \leq Y_0.
\]

(7)
Experimental data gives $a \approx 1/2$, which is consistent with the baryon junction stopping mechanism. The contribution of the participants to the magnetic field can be given by

$$eB_p^\pm(\tau, \eta, \vec{x}_\perp) = \pm Z \alpha_{EM} \int d^2x_\perp \int dY f(Y) \sinh(Y \mp \eta) \times \rho_\pm(x_\perp) \theta_{\mp}(x_\perp) \frac{(x' - x)}{[(x'_\perp - x_\perp)^2 + \tau^2 \sinh(Y \mp \eta)^2]^{3/2}}$$  (8)

(3) In the third part, in order to study the spatial distribution of the magnetic field, we will calculate the $eB_x$ and $eB_y$ components of the chiral magnetic field from spectator and participant nuclei. The specific forms of the contribution of $eB_x$ and $eB_y$ components from the spectator and participant nuclei are given as follows:

$$eB_{sy}^\pm(\tau, \eta, \vec{x}_\perp) = \pm Z \alpha_{EM} \sinh(Y_0 \mp \eta) \int d^2x_\perp \rho_\pm(x_\perp) \times [1 - \theta_{\mp}(x_\perp)] \frac{(y' - y)}{[(x'_\perp - x_\perp)^2 + \tau^2 \sinh(Y_0 \mp \eta)^2]^{3/2}}$$  (9)

where $eB_{sy}$ is the $y$ component of magnetic field from spectators, and the $x$ component of magnetic field from spectators is given by:

$$eB_{sx}^\pm(\tau, \eta, \vec{x}_\perp) = \pm Z \alpha_{EM} \sinh(Y_0 \mp \eta) \int d^2x_\perp \rho_\pm(x_\perp) \times [1 - \theta_{\mp}(x_\perp)] \frac{(y' - y)}{[(x'_\perp - x_\perp)^2 + \tau^2 \sinh(Y_0 \mp \eta)^2]^{3/2}}$$  (10)

In the other hand, the $y$ component of magnetic field from participants is given by:

$$eB_{py}^\pm(\tau, \eta, \vec{x}_\perp) = \pm Z \alpha_{EM} \int d^2x_\perp \int dY f(Y) \sinh(Y \mp \eta) \times \rho_\pm(x_\perp) \theta_{\mp}(x_\perp) \frac{(x' - x)}{[(x'_\perp - x_\perp)^2 + \tau^2 \sinh(Y \mp \eta)^2]^{3/2}}$$  (11)

and the $x$ component of magnetic field from participants is given by:

$$eB_{px}^\pm(\tau, \eta, \vec{x}_\perp) = \pm Z \alpha_{EM} \int d^2x_\perp \int dY f(Y) \sinh(Y \mp \eta) \times \rho_\pm(x_\perp) \theta_{\mp}(x_\perp) \frac{(y' - y)}{[(x'_\perp - x_\perp)^2 + \tau^2 \sinh(Y \mp \eta)^2]^{3/2}}$$  (12)

III. THE CALCULATION RESULTS

A. The energy relation

For consistency with the experimental results, we take Au-Au collision with RHIC energy region and Pb-Pb collision with LHC energy region. When studying the spatial distribution characteristics of magnetic field, we choose the spatial regions of $-10.0 \text{ fm} \leq x \leq 10.0 \text{ fm}$ and $-10.0 \text{ fm} \leq y \leq 10.0 \text{ fm}$.

Figure 2 shows the magnetic field spatial distributions of $eB_y$ with different collision energies $\sqrt{s_{NN}} = 62.4 \text{ GeV}$, $130 \text{ GeV}$ and $200 \text{ GeV}$. The collision energies shown in Fig.2 are in RHIC energy region. The spatial distributions of $eB_y$ show obviously axis symmetry characteristics along $x = 0$ and $y = 0$ axes. On both sides of $y = 0$ line, there are two symmetrical peaks. Two peaks are almost connected when $\sqrt{s_{NN}} = 62.4 \text{ GeV}$. As the collision energy increases, the two peaks start to separate and expose the valley between the two peaks when $\sqrt{s_{NN}} = 130 \text{ GeV}$ and $200 \text{ GeV}$. The maximum of magnetic field $eB_y$ in RHIC energy region reaches $1.2 \times 10^4 \text{ MeV}^2$.

Compared with Fig.2, Fig.3 shows the magnetic field spatial distributions of $eB_y$ in the LHC energy region. When the collision energy rises up to $900 \text{ GeV}$ in LHC
energy region, the distribution features of magnetic field are obviously different from that of the RHIC energy region. For example there are not peaks in the vicinity of $x=0$ and $y=0$. The valley of the spatial distributions of $eB_y$ are located along $y=0$, and the magnetic field begins to increase with $y$ gradually away from the $y=0$ line. The maximum of magnetic field $eB_y$ in LHC energy region reaches $7.0 \times 10^3$ MeV$^2$, which is smaller than that of RHIC energy region.

The magnetic field spatial distributions of $eB_x$ with different collision energies $\sqrt{s_{NN}} = 62.4$ GeV, 130 GeV and 200 GeV in the RHIC energy region are presented in Fig.4. It is shown that the magnetic field of $eB_x$ is also highly inhomogeneous, has a minimum value along the $x=0$ axis. The $x=0$ is the symmetry axis and also the minimum. The magnetic field of $eB_x$ begins to increase rapidly with $x$ gradually away from the center position ($x=0$). The maximum of magnetic field $eB_x$ in RHIC energy region reaches $3.0 \times 10^3$ MeV$^2$.

Figure 5 shows the magnetic field spatial distributions of $eB_x$ with different collision energies $\sqrt{s_{NN}} = 900$ GeV(a), 130 GeV(b) and 200 GeV(c), respectively in the LHC energy region. The maximum of magnetic field $eB_x$ in LHC energy region reaches $1.5 \times 10^3$ MeV$^2$ at $\sqrt{s_{NN}} = 900$ GeV. The magnetic field of $eB_x$ begins to decrease rapidly with the collision energies increase. When $\sqrt{s_{NN}} = 7000$ GeV, the maximum of magnetic field $eB_x$ is only about $50$ MeV$^2$ which is far less than $1.5 \times 10^3$ MeV$^2$ at $\sqrt{s_{NN}} = 900$ GeV.

Figure 6 shows the dependencies of the magnetic field ($eB_y$ and $eB_x$) on coordinate $y$ at $\sqrt{s_{NN}} = 130$ GeV, 200 GeV, 2760 GeV and 7000 GeV, respectively in the LHC energy region. From Fig.6 we can find that the difference of $eB_y$ or $eB_x$ between $\sqrt{s_{NN}} = 130$ GeV and $\sqrt{s_{NN}} = 200$ GeV is very small, but the magnitudes of $eB_y$ (or $eB_x$) distribution in the RHIC energy region are much large than that of LHC energy region. Please also note that the curve shape of $eB_y$ is different from that of
$eB_x$, the maximum of $eB_y$ is located at $y = 0$, but the minimum of $eB_x$ is located at $y = 0$.

Figure 7 shows the dependencies of the magnetic field ($eB_y$ and $eB_x$) on $x$ at $\sqrt{s_{NN}} = 130$ GeV, 200 GeV, 2760 GeV and 7000 GeV, respectively. The magnitude of magnetic field on $x$ at 200GeV nearly equals to that of the magnitude of magnetic field at 130GeV in the RHIC energy region. But the magnitudes of magnetic field in the RHIC are much larger than that of LHC energy region.

Figure 7 shows that $eB_y$ has a dip locating at $x = 0$, and $eB_y$ begins to decrease with collision energy increase. The $eB_x$ is nearly zero at $y = 0$. The maximum of $eB_x$ is located at $x = 0$ and then decrease with $|x|$ increase when $y = 5$ and 10 fm along with $\sqrt{s_{NN}} = 130$ GeV and 200 GeV. But for $\sqrt{s_{NN}} = 2760$ GeV and 7000 GeV, the magnitudes of $eB_x$ are much more low and almost constant.

From Fig.2 to Fig.7, we argue that the magnetic field spatial distributions of $eB_x$ and $eB_y$ are highly inhomogeneous, and $eB_x$ and $eB_y$ distributions are completely different. The distribution features in the RHIC energy region is different from that of the LHC energy region. The magnitudes of magnetic field ($eB_y$ and $eB_x$) change with the collision energy is not obvious in the RHIC energy region, but in the LHC energy region the magnitudes of $eB_y$ and $eB_x$ on collision energies decline sharply. Generally speaking, the magnitudes of magnetic field in the RHIC energy region are much larger than that of LHC energy region.

**B. Impact parameter dependence**

We calculate the spatial distributions of $eB_y$ on impact parameters at $\sqrt{s_{NN}} = 2760$ GeV with Pb-Pb interactions in the LHC energy region. The lowest points are located on the line of $y = 0$, and the magnetic field begins to increase with the $|y|$ gradually increase. The three dimensional view are given in Fig.8.

The spatial distributions of $eB_y$ on different impact parameters at $\sqrt{s_{NN}} = 2760$ GeV are shown in Fig.9. It is shown that the magnetic field spatial distribution characterizes of $eB_x$ at $b = 4$ fm, $b = 8$ fm and $b = 12$ fm are nearly similar. Compared with $eB_y$ distribution shown in Fig.8, the minimum of $eB_x$ distribution are along the symmetrical axis $x = 0$. The magnetic field increases rapidly with the increase of $|x|$.
In order to study the detailed feature of magnetic field with impact parameter, we also discuss the dependencies of the magnetic field spatial distribution at different impact parameters \( b = 4 \text{ fm}, b = 8 \text{ fm}, b = 12 \text{ fm}, \) respectively. Figure 10(a, c and e) shows that \( eB_x \) has a dip locating at \( x = 0 \), and \( eB_y \) begins to increase with \( |x| \) increase. When \( y = 0 \), \( eB_x \) approaches zero. When \( y \neq 0 \), \( eB_x \) increases with the increase of \( b \), but when \( b \) increases to 8, the growth rate slows down. So one can find that \( eB_x \) are nearly unchanged when \( b = 8 \text{ fm} \) and \( b = 12 \text{ fm} \).

approaches zero. keeps nearly unchanged with \( x \) changes. The \( eB_y \) distributions are completely different from that of \( eB_y \).

The dependencies of the magnetic field\((eB_y \text{ and } eB_x)\) on \( y \) at different impact parameters are presented in Fig.11. When \( b = 4 \text{ fm} \) and \( x = 0 \), \( eB_y \) is nearly a value of zero with \( y \) changes. When \( x \neq 0 \), the peaks of \( eB_y \) distribution are located at \( y = 0 \). Compared with \( eB_y \) distribution, \( eB_x \) distribution is completely different. The minimum of the \( eB_x \) distribution is located at \( y = 0 \), and then \( eB_x \) increases linearly with the increase of \( |y| \).

\[
eB = \sqrt{(eB_x)^2 + (eB_y)^2} \tag{13}\]

Figure 12 shows that when \( \tau = 0.02 \text{ fm} \), the maximum of the magnetic field can reaches \( 1.0 \times 10^5 \text{ MeV}^2 \), but when \( \tau = 2 \text{ fm} \), the maximum of the magnetic field is only about \( 0.9 \text{ MeV}^2 \) at \( \sqrt{s_{NN}} = 200 \text{ GeV} \). We can argue that as time increases, the magnetic field decreases drastically in the RHIC energy region.
sometimes, one often takes the y component $eB_y$ to approximately replace $eB$. This is the reason that $eB_y$ is usually larger than $eB_x$. In order to verify the rationality of the substitution, we need a detailed study the relation between $eB_y$ and $eB$. Figure 14 shows the dependencies of the ratio of $eB_y/eB$ on $x$ and $y$ at $\sqrt{s_{NN}} = 200$ GeV and at different proper time $\tau = 0.02$, 0.2 and 2.0 fm, respectively. The Fig.14(a, c and e) are for $eB_y/(eB)$ with $y$ at different proper time. From Fig.14(a, c and e), one can figure out that the ratio of $eB_y/(eB)$ with $y$
change is between 0.9 to 1.0. In this case, one can approximate the $eB_y$ instead of $eB$. Compared with the relation of ratio $eB_y/(eB)$ with $y$, the relationship of ratio $eB_y/(eB)$ with $x$ shown as Fig.14(b, d and f) is obviously different. The main different is the dip located at $x = 0$. The minimum value of the ratio at $x = 0$ can be decreased to 0.5.

**IV. SUMMARY AND CONCLUSION**

It is shown that an enormous magnetic field can indeed be created in off-central heavy-ion collisions. The magnetic field distributions of $eB_x$ and $eB_y$ are highly inhomogeneous, and $eB_x$ and $eB_y$ distributions are completely different. We were really surprised to find that the distribution features in the RHIC energy region is different from that of the LHC energy region, and then the magnitude of magnetic field decreases with the increase of collision energy in the LHC energy region. Generally speaking, the magnitude of magnetic field in LHC energy region is far less than that of RHIC energy region.

The dependencies of the ratio of $eB_y/(eB)$ on $x$ and $y$ at different collision energies at RHIC and LHC and at
But one should note that the ratio $eB_y/(eB)$ on $x$ and $y$ as Fig.14 but for $\sqrt{s_{NN}}= 2760$ GeV in the LHC energy region.

different proper time are analyzed in this paper. In most cases, the ratio $eB_y/(eB)$ approaches 1, so this is a good approximate by using $eB_y$ to approximately replace $eB$. But one should note that the ratio $eB_y/(eB)$ is between $0.5 \sim 1.0$ along $x = 0$ line.

We systematically study the spatial distribution features of chiral magnetic field in relativistic heavy-ion collisions at energies reached at LHC and RHIC with the improved model of chiral magnetic field in this paper. The feature of chiral magnetic fields at $\sqrt{s_{NN}}= 900, 2760$ and $7000$ GeV in the LHC energy region and $\sqrt{s_{NN}}= 62.4, 130$ and $200$ GeV in the RHIC energy region are systematically studied. The dependencies of the features of chiral magnetic fields on the collision CMS energies, centralities and collision proper time are systematically investigated, respectively.

The dependencies of the magnetic field on proper time and impact parameters for at RHIC and LHC energy regions, respectively. Comparing with that of RHIC energy region, one finds that the magnitudes of the magnetic fields with proper time fall more rapidly at LHC energy region. The variation characteristics of magnetic field with impact parameter at RHIC energy region are different from that of LHC energy region. The maximum position is located in the small proper time ($\tau \sim 0.02 fm$), more off-central collisions and $\sqrt{s_{NN}} \sim 200$ GeV. The maximum of magnetic field in our calculation is about $eB \sim 10^5$ MeV$^2$ when $\tau = 0.02, b \approx 8 fm$ and $\sqrt{s_{NN}} \sim 200$ GeV.

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