Centrality dependence of Electrical and Hall conductivity at RHIC and LHC energies for a Quark-Gluon Plasma Phase

Bhaswar Chatterjee, Rutuparna Rath, Golam Sarwar, and Raghunath Sahoo*

Discipline of Physics, School of Basic Sciences, Indian Institute of Technology Indore, Simrol, Indore- 453552, INDIA
(Dated: August 6, 2019)

In this work, we study electrical conductivity and Hall conductivity in the presence of electromagnetic field using Relativistic Boltzmann Transport Equation with Relaxation Time Approximation. We evaluate these transport coefficients for a quark gluon plasma phase that is possibly formed in heavy ion collisions. We explicitly include the effects of magnetic field in the calculation of relaxation time. The values of magnetic field are obtained for all the centrality classes of Au+Au collisions at \( \sqrt{s_{\mathrm{NN}}} = 200 \text{ GeV} \) and Pb+Pb collisions at \( \sqrt{s_{\mathrm{NN}}} = 2.76 \text{ TeV} \). We consider the three lightest quark flavors and their corresponding antiparticles in this study. We estimate the temperature dependence of the electrical conductivity and Hall conductivity for different strengths of magnetic field. We observe a significant dependence of temperature on electrical and Hall conductivity in the presence of magnetic field.

PACS numbers: 12.38.Mh, 24.10.Pa, 24.10.Nz, 25.75.-q, 47.75.+f

I. INTRODUCTION

Relativistic heavy ion collisions are dedicated to study the quark gluon plasma (QGP) state of nuclear matter, which is predicted according to Quantum Chromodynamics (QCD) [1, 2] and according to standard model of cosmology, the universe has gone through this phase around few microsecond after the Big Bang. Extensive study of the results of heavy ion collision experiments, by comparing the results with predictions from fluid dynamic models, strongly hints to the formation of QGP in such collisions [3–11]. These studies also conclude that for successful explanations of the experimental results using relativistic hydrodynamic models, the produced QGP requires to have very small shear viscosity to entropy ratio [12–14]. Such comparisons with models, not only confirm creation of QGP, it also gives opportunity to extract information about various thermodynamic and collective properties of QGP- like equation of state and transport properties of QGP, as they play the role of adjustable parameters in the model. Conditions created in such collisions actually help in extracting these properties, e.g., initial state geometry helps to extract viscosity of QGP, as it causes the final state momentum anisotropy, which gives measure of viscosity to entropy ratio [14–24]. Apart from the initial geometry, some other initial phenomena also significantly affects the way we need to look at it.

One such initial state phenomenon is the creation of magnetic field depending on centrality, atomic number of the nuclei and center-of-mass energy (\( \sqrt{s} \)) [25]. It has long been proposed that ultra strong (\( \sim 10^{18} \text{ Gauss} \)) magnetic field can get created in heavy ion collisions if the number of spectator nucleons are sufficiently high [26–28]. This is possible in off-central collisions and this can give rise to novel phenomena like chiral magnetic effect as well as new complexities [29]. Transport coefficients are extremely important parameters as they determine the evolution of the QGP and generate anisotropic flow velocity which can be measured. Magnetic field, if present, can be another source of added anisotropy while also affecting the phase space of the charged particles and thus the transport coefficients.

One extremely important transport coefficient is the electrical conductivity, \( \sigma_{el} \) which significantly affects the dilepton production which is a good probe to investigate QGP [30]. The presence of magnetic field can significantly affect this coefficient by affecting the phase spaces and also by generating a force perpendicular to that of the electric field. Such a choice of magnetic field can be made without losing generality. In such cases, along with regular electrical conduction, Hall conduction may also happen. However, unlike electrical conductivity, the Hall conductivity depends explicitly on the cyclotron frequency of the charged particles. This has serious implication on the outcome as QGP is different from electron-ion plasma where the mobility of oppositely charged particles are the same because of similar masses. QGP is a pair plasma where the mobility of oppositely charged particles are different because of their different masses. QGP for particular collisions, a non negligible \( \mu_B \) can be created and it would be interesting to observe the Hall conductivity and its interplay with electrical conductivity in such scenarios.

Recently, Hall conductivity has been studied in the context of heavy ion collision experiments using different methods [31–33]. It has been studied in the hadronic phase using hadron resonance gas (HRG) model also [32].
In QGP phase, quasiparticle model has been used in relaxation time approximation to investigate this [33]. In this present work, we study both the electrical and Hall conductivities in the QGP phase by using relaxation time approximation to solve the Boltzmann transport equation. In comparison to previous studies regarding Hall effect in QGP phase, we differentiate our work in the following ways:

- We explicitly incorporate the effects of magnetic field in the relaxation time itself as well as through the cyclotron frequency ($\omega_c$). This is especially important as a strong magnetic field can significantly affect the scattering processes contributing to the relaxation time. We also take a magnetic field dependent coupling instead of a temperature dependent coupling as the thermal averaged relaxation time and \(\omega_c\) is the inverse of temperature. Now, proceeding in the same manner as in [31], the solution to eq.1 can be written as

\[
\begin{align*}
    f(p) &= f_0 - q_1 F_{\mu\nu} p_\mu \left( \frac{\partial f_0(\xi,\nu)}{\partial\xi} \right) + q_2 E_{\mu} p_\mu \left( \frac{\partial f_0(\xi,\nu)}{\partial\xi} \right) + q_3 B_{\nu} \left( \frac{\partial f_0(\xi,\nu)}{\partial\xi} \right) \\
    &= f_0 - q_1 F_{\mu\nu} p_\mu \left( \frac{\partial f_0(\xi,\nu)}{\partial\xi} \right) + q_2 E_{\mu} p_\mu \left( \frac{\partial f_0(\xi,\nu)}{\partial\xi} \right) + q_3 B_{\nu} \left( \frac{\partial f_0(\xi,\nu)}{\partial\xi} \right)
\end{align*}
\]

The electric current can be written in the following form [31],

\[
    j^i = q_f \int \frac{d^3p}{(2\pi)^3} v^i \delta f = \sigma^{el} j^i + \sigma^H \epsilon^{ij} j_j,
\]

For an isotropic system, comparing eq.4 and eq.5, the electric and the Hall conductivities can respectively be expressed as:

\[
\sigma^{el} = \sum_i \frac{q_{fi}^2 \tau_i}{3T} \int \frac{d^3p}{(2\pi)^3} \frac{p^2}{c_i^2} \frac{1}{1 + (\omega_{ci}\tau_i)^2} f_0(i),
\]

\[
\sigma^H = \sum_i \frac{q_{fi}^2 \tau_i}{3T} \int \frac{d^3p}{(2\pi)^3} \frac{p^2}{c_i^2} \frac{\omega_{ci}\tau_i}{1 + (\omega_{ci}\tau_i)^2} f_0(i),
\]

where \(q_{fi}\) is the fractional electric charge, \(\tau_i\) is the relaxation time, and \(\omega_{ci} = \frac{q_i eB}{E_i}\) is the cyclotron frequency of the \(i\)th charged particle species.

B. Estimation of Relaxation Time

Relaxation time \(\tau_c\), which is the time required for the system to get back to equilibrium, is defined as the inverse of the relaxation rate [35, 36]. The relaxation rate is the rate of interaction in the system through which momentum of particles gets redistributed towards equilibrium distribution after some small disturbance makes it slightly away from equilibrium. In presence of strong magnetic field, for the hierarchy \(\alpha_s eB << T^2 \leq eB\), the dominating term for the interaction that is responsible for equilibration of quark and gluons comes from tree level processes such as quark-antiquark annihilation to gluon or vice versa [37]. With these assumptions the effective Boltzmann distribution function satisfying

\[
\frac{\partial f_0}{\partial \xi} = v^i \frac{\partial f_0}{\partial \xi} - \beta f_0, \quad f_0 = g e^{-\beta(\epsilon + \mu a)}
\]

where the single particle energy is \(\epsilon(p) = \sqrt{p^2 + m^2}\), \(g\) is the degeneracy, \(\mu_B\) is the baryon chemical potential and \(\beta = 1/T\), is the inverse of temperature. Now, proceeding in the same manner as in [31], the solution to eq.1 can be written as

\[
\begin{align*}
    f(p) &= f_0 - q_1 F_{\mu\nu} p_\mu \left( \frac{\partial f_0(\xi,\nu)}{\partial\xi} \right) + q_2 E_{\mu} p_\mu \left( \frac{\partial f_0(\xi,\nu)}{\partial\xi} \right) + q_3 B_{\nu} \left( \frac{\partial f_0(\xi,\nu)}{\partial\xi} \right) \\
    &= f_0 - q_1 F_{\mu\nu} p_\mu \left( \frac{\partial f_0(\xi,\nu)}{\partial\xi} \right) + q_2 E_{\mu} p_\mu \left( \frac{\partial f_0(\xi,\nu)}{\partial\xi} \right) + q_3 B_{\nu} \left( \frac{\partial f_0(\xi,\nu)}{\partial\xi} \right)
\end{align*}
\]

The electric current can be written in the following form [31],

\[
    j^i = q_f \int \frac{d^3p}{(2\pi)^3} v^i \delta f = \sigma^{el} j^i + \sigma^H \epsilon^{ij} j_j,
\]

For an isotropic system, comparing eq.4 and eq.5, the electric and the Hall conductivities can respectively be expressed as:

\[
\sigma^{el} = \sum_i \frac{q_{fi}^2 \tau_i}{3T} \int \frac{d^3p}{(2\pi)^3} \frac{p^2}{c_i^2} \frac{1}{1 + (\omega_{ci}\tau_i)^2} f_0(i),
\]

\[
\sigma^H = \sum_i \frac{q_{fi}^2 \tau_i}{3T} \int \frac{d^3p}{(2\pi)^3} \frac{p^2}{c_i^2} \frac{\omega_{ci}\tau_i}{1 + (\omega_{ci}\tau_i)^2} f_0(i),
\]

where \(q_{fi}\) is the fractional electric charge, \(\tau_i\) is the relaxation time, and \(\omega_{ci} = \frac{q_i eB}{E_i}\) is the cyclotron frequency of the \(i\)th charged particle species.

II. FORMULATION

A. Electrical Conductivity and Hall Conductivity

We obtain the electrical and Hall conductivities by solving the Boltzmann transport equation using relaxation time approximation in presence of an electromagnetic field as it has been done in Ref. [31, 32]. In presence of an electromagnetic field the Boltzmann transport equation is given by

\[
p^\mu \partial_\mu f(x,p) + q_f F^{\mu\nu} p_\mu \left( \frac{\partial f(x,p)}{\partial p^\nu} \right) = C[f],
\]

where \(q_f\) is the fractional electric charge of the particle, \(F^{\mu\nu}\) is the electromagnetic field strength tensor and \(C[f]\) is the collision integral [34]. In the relaxation time approximation,

\[
C[f] \simeq -\frac{p^\mu u_\mu}{\tau} (f - f_0) \equiv -\frac{p^\mu u_\mu}{\tau} \delta f,
\]

where, \(u_\mu = (1, \vec{0})\) is the fluid four velocity in the local rest frame and \(\tau\) is the relaxation time. We use the
relaxation rate becomes \([38–45]\)

\[
(\tau^{-1}_{rel}) = \frac{2\alpha_{\text{eff}} C_F m_T^2}{\omega_0 (1 - f_q^0)} \left( \frac{e^{\mu/T}}{e^{\mu/T} + 1} \right) (1 + f_g^0) \ln (T/m), \tag{8}
\]

where \(C_F\) is the Casimir factor of the processes and \(\alpha_{\text{eff}}\) is the effective coupling constant. \(f_q^0 = \frac{1}{(e^{\beta q} - 1)}\) and \(f_g^0 = \frac{1}{(e^{\beta g} - 1)}\) are respectively the distribution functions for quarks and gluons. In our case, we approximate them to be the Boltzmann distribution function. We take the coupling constant to be explicitly dependent on magnetic field \([46]\)

\[
\alpha_{\text{eff}} = \frac{g^2}{4\pi} = \frac{1}{\alpha_s^0(\mu_0)^{-1} + \frac{11N_c}{12\pi} \ln \left( \frac{\Lambda^2_{\text{QCD}} + M_B^2}{\mu_0^2} \right) + \frac{1}{3\pi} \sum f_i \frac{|q_i| B}{\sigma}}, \tag{9}
\]

where

\[
\alpha_s^0(\mu_0) = \frac{12\pi}{11N_c} \ln \left( \frac{\mu_0^2 + M_B^2}{\Lambda^2_{\text{QCD}}} \right), \tag{10}
\]

\(M_B \sim 1\) GeV is an infrared mass, \(\mu_0 = 1.1\) GeV and \(\sigma = 0.18\) GeV\(^2\) is the string tension.

The above rate is momentum dependent. Taking total relaxation rate of the system with three quark flavors along with their anti-particles, with thermal average of the relaxation rate, one gets the relevant relaxation, as

\[
\tau = \langle \tau_{rel} \rangle = \frac{1}{\sum_i \tau_{rel,i}^{-1}} \tag{11}
\]

where

\[
\sum_i \tau_{rel,i}^{-1} = \sum_i \int d^3p \tau_{rel,i}^{-1} f_0 \frac{1}{\sum_i \int d^3p f_0} \tag{12}
\]

III. RESULTS AND DISCUSSIONS

In this section, we shall discuss our findings regarding electrical conductivity \(\sigma_{el}\) and Hall conductivity \(\sigma_H\) which are obtained by solving the Boltzmann transport equation in presence of magnetic field. We show how the two coefficients vary with temperature and magnetic field for different scenarios. To make this study phenomenologically relevant, we have considered particular collision events. Because magnetic field depends on centrality of a collision event and the generation of Hall current requires a non-zero baryon chemical potential, we have considered here two particular scenarios for which both the impact parameter dependent magnetic field and the produced baryon chemical potential \((\mu_B)\) has been estimated: Pb+Pb collision at \(\sqrt{s} = 2.76\) TeV for which \(\mu_B = 2\) MeV and Au+Au collision at \(\sqrt{s} = 200\) GeV for which \(\mu_B = 25\) MeV \([47]\). We also show the interplay between the \(\sigma_{el}\) and \(\sigma_H\) for both cases for different magnetic field and temperature. We have assumed the presence of three lightest quark flavors along with their corresponding antiparticles with masses \(m_u = 3\) MeV, \(m_d = 5\) MeV and \(m_s = 100\) MeV.

In Fig. 1, we have shown the centrality dependent magnetic fields for the two experiments we have considered. Magnetic fields for different impact parameters are obtained from ref \([28]\). We can see that magnetic field strength increases as the collisions become less and less central. Centrality based impact parameter values are obtained for different collision systems using optical Glauber model \([48]\). Then, the corresponding magnetic field values in different centralities has been calculated.
After obtaining the value of magnetic fields in different centralities, it is used as an input to calculate the electrical and Hall conductivities for different centrality classes for a specific collision system. We can see in Fig. 1 that the magnetic field produced in Pb+Pb collision is much higher compared to that produced in Au+Au collision which is expected as higher center-of-mass energy should produce stronger magnetic field.

Fig. 2 and Fig. 3 shows variation of $\sigma_{el}$ with $eB$ at different temperatures of QGP for Au+Au and Pb+Pb collisions respectively. We can see that $\sigma_{el}$ decreases with increasing magnetic field but increases with temperature for both cases. Also, the fall with magnetic field becomes steeper with increasing temperature. This trend can be understood from eq.6. We can see the relaxation time $\tau_{rel}$ appears in both the numerator and denominator but with a higher power in the denominator. Since $\tau_{rel}$ increases with magnetic field, it is naturally expected for $\sigma_{el}$ to follow a decreasing trend with increasing magnetic field. Also, the cyclotron frequency $\omega_{ci}$, which appears in the denominator, increases with magnetic field and has further contribution in the decline of $\sigma_{el}$. Another reason for this can be that more and more charged particles start moving in a direction perpendicular to the electric field compared to the direction parallel to the field because of increasing Lorentz force as the magnetic field increases which consequently should reduce charge conduction along the electric field. However, this doesn’t automatically correspond to an increase in Hall conduction with increasing magnetic field as we shall see later. The increase of $\sigma_{el}$ with temperature is consistent with the findings of previous studies both with and without magnetic field and can also be understood from the eq.6. Since $\tau_{rel}$ decreases with temperature, $\sigma_{el}$ follows the reverse trend.

Fig. 4 and Fig. 5 gives a much clearer picture of the behavior of $\sigma_{el}$ where we have shown the change of $\sigma_{el}$ with temperature for different centrality classes in Au+Au and Pb+Pb collisions, respectively. Since we are considering static and homogeneous magnetic field, these two figures give us a better idea about what to expect in a particular collision event. As we have mentioned before, different centrality classes correspond to different magnetic field strengths with most central corresponding to lowest
FIG. 5: (Color online) $\sigma_{el}$ vs $T$ for different centrality class in Pb+Pb collision at $\sqrt{s}_{NN} = 2.76$ TeV.

value of $eB$ and least central corresponding to highest value of $eB$. In both cases we see rapid increase of $\sigma_{el}$ with temperature for all centrality classes with most central (hence lowest magnetic field) case giving the highest values of $\sigma_{el}$. We can see that different centrality affects $\sigma_{el}$ much more prominently in Pb+Pb collision than in Au+Au collision. This makes sense as Pb+Pb collision has a much higher center-of-mass energy ($\sqrt{s}$) compared to Au+Au collision and hence produces much stronger magnetic field for all centrality classes which in turn creates significant divergence in the values of $\sigma_{el}$ for different centralities. In all the above figures, we can also see that electrical conductivity is much higher in Au+Au collision compared to Pb+Pb collision.

So, we can conclude here that electrical conduction is higher in the early phase during the evolution of the QGP for both Au+Au and Pb+Pb collisions with magnetic field lowering the conductivity in both cases and particularly severely for Pb+Pb collision. As the system cools down, electrical conduction will become less for both cases with a steady decline for Au+Au collision and a sharper decline at higher temperature for Pb+Pb collision after which it becomes almost insignificant for all centrality classes near the phase transition. In case of Au+Au, even after the decline, $\sigma_{el}$ will have a significant value near phase transition for all centrality classes.

Next, we show the Hall conductivities for Au+Au and Pb+Pb collisions for different temperatures and magnetic field strengths. Fig. 6 and Fig. 7 shows the variation of $\sigma_{H}$ with changing temperature for different centrality classes (corresponding to different strengths of magnetic field) respectively for Au+Au and Pb+Pb collisions. First, we notice that the values for Pb+Pb collisions are around an order of magnitude smaller than those for Au+Au collisions. The main reason for this is the very small $\mu_B$ for Pb+Pb collision as the very generation of Hall conduction depends on a finite $\mu_B$ and hence for Pb+Pb collision, Hall current is very small in any situation. We must mention here that the values of $\sigma_{H}$ is smaller for Au+Au collision also compared to the values of $\sigma_{el}$. We notice that regardless of the temperature or magnetic field strength, $\sigma_{H}$ is few orders of magnitude lower compared to $\sigma_{el}$. This is because, in realistic scenarios, $\mu_B$ is always small when the magnetic
field is very strong at high collision energies. We shall see later that if we consider \( \mu_B \sim 100\ \text{MeV} \), the values of \( \sigma_H \) becomes comparable to that of \( \sigma_d \) but as of now, that scenario is not phenomenologically relevant as proposed colliders like FAIR or NICA would likely generate very small magnetic field (even in the least central events) while producing a large \( \mu_B \).

Fig. 6 and Fig. 7 show us that \( \sigma_H \) behaves differently with temperature for the two different cases. While for Pb+Pb collision, \( \sigma_H \) increases with temperature for all centrality classes, we observe a far more complex behavior for Au+Au collision. We observe reversal of two different trends with increasing temperature for Au+Au collision. First, we see that beyond a certain temperature, \( \sigma_H \) starts to decrease for all centralities and then we also observe that while \( \sigma_H \) decreases with increasing magnetic field for lower temperature, at higher temperature this trend reverses. To understand this, we need to carefully look at the integrand in eq.7 for two different cases: lower temperature range and higher temperature range. At lower temperature, because of a large relaxation time, the integrand roughly goes as inverse of \( \omega_c \) and hence decreases with magnetic field. Also, the temperature behavior is determined by the factor \( \frac{1}{T^2} \) which for lower temperature gets dominated by \( f_0 \) and hence we observe an increasing trend of \( \sigma_H \) with temperature. At higher temperature, because of a very small relaxation time, the integrand roughly varies as \( \omega_c \) and we observe \( \sigma_H \) to be increasing with magnetic field. The temperature behavior in this scenario is determined by the factor \( \frac{1}{T^2 \mu_B} \). With a very small value for \( \tau \), this term gets dominated by the \( \frac{1}{T^2} \) factor as \( f_0 \) saturates. So we see a decreasing trend of \( \sigma_H \) with temperature. We also observe that the temperature at which this reversal happens increases with magnetic field with a decreasing peak height. The decreasing peak height has also been observed in [33], though in a different model. In our case, this happens most likely because of our choice of a magnetic field dependent coupling constant which falls with increasing magnetic field.

Fig. 6 also shows that \( \sigma_H \) doesn’t always increase with magnetic field as one might expect as the Lorentz force increases with magnetic field. Magnetic field generates Hall conduction but at the same time counters it also by putting a directional constraint on the motion of charged particle. In presence of magnetic field, a charged particle goes through a confining circular motion in the plane perpendicular to the field with a radius \( r \) proportional to \( \frac{1}{B} \). So, if the velocity perpendicular to the field is low and/or magnetic field strength is very high, the radius of circular motion in the perpendicular plane can be very small. If it becomes smaller than the mean free path (\( \lambda \)) of the charged particles, then it will adversely affect Hall conduction. So increasing magnetic field can reduce Hall conduction if the velocity of the particle in the perpendicular plane is small. Here, a finite temperature can come to the rescue as it increases random motion and average velocity of the particle. So, we see that at lower temperature, increase in temperature increases \( \sigma_H \). The peak occurs when \( r \sim \lambda \), i.e, the radius of circular motion is roughly equal to the mean free path. Beyond this temperature, \( \sigma_H \) decreases as diffusion sets in. Till this region we see that lower magnetic field produces higher \( \sigma_H \) as the radius \( r \) is bigger for smaller magnetic field. However, once diffusion sets in, this behavior changes and \( \sigma_H \) starts to increase with higher magnetic field. This happens because magnetic field counters diffusion and for very high temperature, very strong magnetic field is required for this.

So, the appearance of peak in Hall conductivity at different temperatures for different strengths of magnetic field can be understood as entirely a result of competition between randomness and increase in average velocity because of temperature and the confining motion induced by magnetic field.

The absence of any change in behavior (and hence any peak) of \( \sigma_H \) with temperature in Pb-Pb collisions can also be explained by the above mentioned phenomena. The magnetic field produced in Pb+Pb collisions at \( \sqrt{s_{NN}} = 2.76 \ \text{TeV} \) is almost an order of magnitude higher than that of Au+Au at \( \sqrt{s_{NN}} = 200 \ \text{GeV} \). So the temperature range we are considering (0.15 to 0.6 GeV) is not effective at all to counter the confining effect magnetic field, resulting in absence of any peak in this temperature range, as observed for the Au+Au collision.

![FIG. 8: (Color online) Variation of \( \sigma_H \) with \( T \) and \( \mu_B \) for or different magnetic field](image)
\(\mu_B\), we can observe a clear increase in \(\sigma_H\), particularly at lower temperature. At very high \(\mu_B\), \(\sigma_H\) becomes almost comparable to \(\sigma_{el}\).

**IV. SUMMARY AND OUTLOOK**

In this work, we have tried to investigate the electrical and Hall conductivity in hot QGP matter in presence of strong magnetic field. We used the Boltzmann transport equation in presence of magnetic field to obtain the expressions for \(\sigma_{el}\) and \(\sigma_H\) using relaxation time approximation. We have incorporated the effects of magnetic field in the relaxation time itself. We have done it by changing the phase space integration in relaxation time as done in [45] as well as using a coupling constant which explicitly depends on magnetic field. We have chosen realistic magnetic field, chemical potential and temperature range to make this study relevant phenomenologically in the context of experiments at RHIC and LHC. We can summarize our findings as follows

a) The electrical conductivity increases with temperature and decreases with magnetic field. The behavior with temperature is consistent with previous studies and the values we have obtained are also in the same ballpark as previous studies. \(\sigma_{el}\) is higher in case of Au+Au collision which is also consistent with previous studies.

b) The Hall conductivity decreases with magnetic field and with temperature it shows a complex behavior. For Pb+Pb collision, it consistently increases with temperature whereas in case of Au+Au collision, it increases at lower temperature and reverses beyond a certain temperature which is dependent on magnetic field. Also, for Au+Au collision, at lower temperature, \(\sigma_H\) decreases with magnetic field and reverses the trend at higher temperature. However, the temperature at which the reversal happens is dependent on magnetic field. Also, the value of \(\sigma_H\) for a particular centrality is much higher in case of Au+Au collision.

c) \(\sigma_{el}\) is always higher compared to \(\sigma_H\). At large temperature, Hall conduction is negligible compared to electrical conduction. However, at lower temperature, it can have significant effects. Also, as we have shown in Fig. 8, at \(\mu_B \sim 100\) MeV, the value of \(\sigma_H\) can be comparable to that of \(\sigma_{el}\).

This work by no means present a complete picture as there are many features yet to be explored. First of all, we have assumed a constant and homogeneous magnetic field which is usually not the case in experiments where the change in magnetic field with time can be rapid as well as moderate depending on the conductivity of the medium. Also, one has to explore the effects of Hall conduction on the observables to create a relatable picture.

**Acknowledgements**

The authors acknowledge the financial supports from ALICE Project No. SR/MF/PS-01/2014-IITI(G) of Department of Science & Technology, Government of India. RR acknowledges the financial support by DST-INSPIRE program of Government of India. RR thanks Dr. Arvind
Khuntia for useful discussions.

[1] A. Bazavov et al. [HotQCD Collaboration], Phys. Rev. D 90, 094503 (2014).
[2] S. Borsanyi, Z. Fodor, C. Hoelbling, S. D. Katz, S. Krieg and K. K. Szabo, Phys. Lett. B 730, 99 (2014).
[3] M. Krzewicki [ALICE Collaboration], J. Phys. G 38, 124047 (2011).
[4] K. Aamodt et al. [ALICE Collaboration], Phys. Rev. Lett. 106, 032301 (2011).
[5] T. Hirano, P. Huovinen and Y. Nara, Phys. Rev. C 84, 014901 (2011).
[6] I. Arsene et al. [BRAHMS Collaboration], Nucl. Phys. A 757, 1 (2005).
[7] B. B. Back et al., Nucl. Phys. A 757, 28 (2005).
[8] J. Adams et al. [STAR Collaboration], Nucl. Phys. A 757, 102 (2005).
[9] E. V. Shuryak, Nucl. Phys. A 750, 64 (2005).
[10] M. Gyulassy and L. McLerran, Nucl. Phys. A 750, 30 (2005).
[11] B. Muller and J. L. Nagle, Ann. Rev. Nucl. Part. Sci. 56, 93 (2006).
[12] P. Kovtun, D. T. Son and A. O. Starinets, Phys. Rev. Lett. 94, 111601 (2005).
[13] P. Romatschke and U. Romatschke, Phys. Rev. Lett. 99, 172301 (2007).
[14] U. Heinz and R. Snellings, Ann. Rev. Nucl. Part. Sci. 63, 123 (2013).
[15] C. Gale, S. Jeon and B. Schenke, Int. J. Mod. Phys. A 28, 1340011 (2013).
[16] D. A. Teaney, P. Romatschke, Int. J. Mod. Phys. E 19, 1 (2010).
[17] M. Luzum and P. Romatschke, Phys. Rev. C 78, 034915 (2008) Erratum: [Phys. Rev. C 79, 039903 (2009)].
[18] H. Song and U. W. Heinz, Phys. Rev. C 77, 064901 (2008).
[19] K. Dusling and D. Teaney, Phys. Rev. C 77, 034905 (2008).
[20] D. Molnar and P. Huovinen, J. Phys. G 35, 104125 (2008).
[21] P. Bozek, Phys. Rev. C 81, 034909 (2010).
[22] A. K. Chaudhuri, J. Phys. G 37, 075011 (2010).
[23] B. Schenke, S. Jeon and C. Gale, Phys. Rev. Lett. 106, 042301 (2011).
[24] V. Skokov, A. Y. Illarionov and V. Toneev, Int. J. Mod. Phys. A 24, 5925 (2009).
[25] D. E. Kharzeev, L. D. McLerran and H. J. Warringa, Nucl. Phys. A 803, 227 (2008).
[26] K. Tuchin, Adv. High Energy Phys. 2013, 490495 (2013).
[27] K. Hattori and X. G. Huang, Nucl. Sci. Tech. 28, 26 (2017).
[28] D. E. Kharzeev, K. Landsteiner, A. Schmitt and H. U. Yee, Lect. Notes Phys. 871, 1 (2013).
[29] B. Singh, J. R. Bhatt and H. Mishra, Phys. Rev. D 100, 014016 (2019).
[30] P. Romatschke, Int. J. Mod. Phys. E 19, 1 (2010).
[31] M. Luzum and P. Romatschke, Phys. Rev. C 78, 034915 (2008) Erratum: [Phys. Rev. C 79, 039903 (2009)].