Magneto-Vortical evolution of QGP in heavy ion collisions

Ashutosh Dash,* Victor Roy,† and Bedangadas Mohanty‡
School of Physical Sciences,
National Institute of Science Education and Research,
HBNI, Jatni - 752050, Odisha, India.

Introduction

Due to the relativistic speed of the charged protons inside the colliding nucleus large magnetic field is produced in mid-central heavy ion collision, for example in a typical Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV magnetic field as large as 10^{19} Gauss is produced. Understanding the space-time evolution of such intense electromagnetic field produced in the initial stage of heavy ion collisions is an important subject, particularly the interplay of magnetic field and quantum anomalies, which includes the chiral magnetic effect, chiral vortical effect etc. However, the subsequent space-time evolution of the initial magnetic field inside the Quark Gluon Plasma (QGP - deconfined state of partons created in the heavy-ion collisions) is still uncertain. The main uncertainty coming from the poorly known value of the electrical conductivity in the QGP.

The space-time evolution of QGP in the presence of magnetic field is governed by the relativistic magneto-hydrodynamic (MHD) equations. Depending on the value of magnetic Reynolds number $R_m = \sigma_e v l \mu$, where l is a characteristic length scale of the QGP; v is the fluid velocity; μ is the magnetic permeability of the QGP, one can approximate the MHD evolution as ideal (when $R_m \gg 1$) or resistive ($R_m \ll 1$). However, note that it is still an open question whether the QGP is in ideal MHD regime [1] or in the resistive regime [2].

We also know that in the initial stage of heavy ion collisions (particularly in non-central collisions) the colliding nucleus carry large angular momentum. A fraction of this large angular momentum might give rise to finite fluid vorticity. The existence of strong magnetic fields and large flow vorticity in the reaction zone may have interesting consequences. In fact magnetic field and fluid vorticity can be coupled together and they follow a generalized form of advection equation [3]. The origin of this generalized form of coupled magneto-vortical evolution trace back to the fact that the equations governing fluid vorticity and magnetic field is of common form and we can take a linear combination of both of them. It is a well known fact that in the limit of vanishing electrical conductivity, plasma retains the initial magnetic flux passing through it, this phenomenon is known as *Alfvén's frozen in theorem* and similar relation holds for vorticity in the limit of vanishing viscosity called *Kelvin's circulation theorem.*

However, in a relativistic covariant formulation of the ideal fluid, the interplay of magnetic field and thermal vorticity generates a non-trivial source term which breaks the constraints imposed by the above theorems, provided the flow fields and the entropy density of the fluid are inhomogeneous [3]. Exploiting this fact and assuming large magnetic Reynolds number we study the evolution of generalised magnetic field ($\hat{B}$) which is defined as a combination of the usual magnetic field ($\vec{B}$) and relativistic thermal vorticity ($\omega^{\mu\nu}$), in a 2(space)+1(time) dimensional isentropic evolution of QGP with longitudinal boost invariance [4].

*Electronic address: ashutosh.dash@niser.ac.in
†Electronic address: victor@niser.ac.in
‡Electronic address: bedanga@niser.ac.in

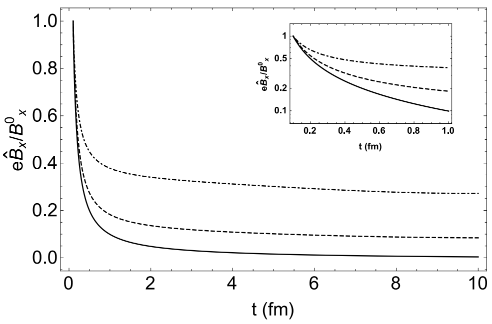

FIG. 1: Temporal evolution of normalized $\hat{B}_x$ for z>0. Solid line corresponds to the usual magnetic field evolution, dashed line corresponds to $\hat{B}_x$ for $\gamma = 3$, whereas dot dashed line corresponds to $\hat{B}_x$ for $\gamma = 10$. The inset figure shows the same result but with log scale.

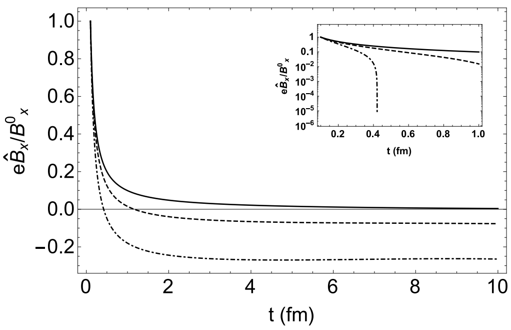

FIG. 2: Same as Fig.1 but for z<0.

Formulation and Result

For an ideal relativistic barotropic fluid we have the following induction equation [3, 4]:

$$\frac{\partial \hat{B}}{\partial t} - \vec{\nabla} \times \left(\vec{v} \times \hat{B}\right) = \frac{\gamma T}{2q} \vec{\nabla} v^2 \times \vec{\nabla}\left(\frac{s}{n}\right) \quad (1)$$

where the generalized magnetic field in the relativistic scenario is $\hat{B} = \vec{B} + \vec{\nabla} \times (f\gamma\vec{v})$, $\vec{B}$ is the usual magnetic field, $\vec{v}$ is the fluid velocity, γ is the Lorentz factor, $f = h/n$ is the enthalpy density (h) per unit conserved charge (n), q is the absolute magnitude of the electric charge of the fluid particles and T is the temperature of the fluid. The term in the right hand side of Eq.(1) has its origin in the space-time distortion caused by the demands of special relativity and is non existent in the non-relativistic formulation.

We consider a 2+1 dimensional ideal MHD evolution of QGP. The velocity $v_z = \frac{z}{t}$, follow Bjorken one dimensional expansion along the longitudinal direction and the transverse velocity is obtained by assuming a Gaussian transverse entropy density profile.

Solving the first order inhomgeneous PDE Eq.(1) with the above assumptions gives us the temporal evolution of $\hat{B}$ that is plotted in Fig. 1 and Fig. 2.

The solutions Fig. 1 and Fig. 2 compare the evolution of the usual magnetic field and the generalised magnetic field for $z < 0$ and $z > 0$ for two different Lorentz factor $\gamma = 3$ and 10. The result shows some non-trivial dependence on the position of the fluid with respect to midplane (z=0). If one assumes that $\hat{B}$ acts similarly as $\vec{B}$ then our finding suggests that the temporal evolution of magnetic field in heavy ion collisions will be changed in presence of finite fluid vorticity. This may gives rise to rapidity dependence of the predicted chiral magnetic effect and other related phenomenon.

Acknowledgments

We would like to thank S. M. Mahajan for helpful discussion.

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