# Effect of magnetic field on flow fluctuations in relativistic heavy-ion collisions

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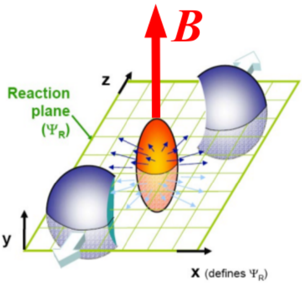
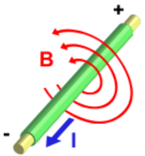
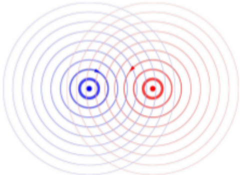
# Introduction

- Terrestrial heavy ion collision experiments like **RHIC** at BNL and **LHC** at CERN, produced new state of QCD matter which shows many features of hot **QGP**.
- Two colliding nuclei generate **two electric currents in opposite directions**, and produce a **magnetic field perpendicular to the reaction plane**[1].



[1] QCD in strong magnetic field, talk given by M.N.Chernodub

- Much work has been done regarding effect of magnetic field in HIC, some of them are [2]
  1. Chiral Magnetic effect,
  2. Magnetic Catalysis and Inverse magnetic catalysis,
  3. Effect on HRG model ,
  4. Effect on the flow etc.
- Most of the earlier works have not taken into account evolution of the magnetic field in plasma. We have done ideal MHD simulation to study evolution of magnetic field.

  It can lead to qualitative effects on the plasma dynamics. Important results are summarized below.
- Strong enhancement of $v_2$ due to presence of $\vec{B}$.
- Reorganization of local magnetic field due to presence of fluctuations. Due to this, $\vec{B}$ in some regions can increase during early stage instead of decreasing. It may be important for chiral magnetic effect.

[2] McLerran et. al. Nucl Phys A 803, 227, H. Taya PRD 92, 014038,

- Group velocity of magnetosonic wave depends on the local energy density and magnetic field. Due to energy density fluctuations direction of group velocity keeps changing. We find that non zero vorticity can be generated in the flow due to presence of fluctuations. It has important implication for Chiral Vortical effect.
- Power spectrum in the presence of $\vec{B}$ and in the absence of $\vec{B}$ are qualitatively different.
- Magnetic field can have dramatic effect for deformed nucleus like, Uranium. In this case the direction of $\vec{B}$ and the shape of event depends on the orientation of the colliding nuclei.
- We find, for deformed nucleus case, a spherical plasma region can have non trivial $v_2$ arising due to non zero $\vec{B}$.

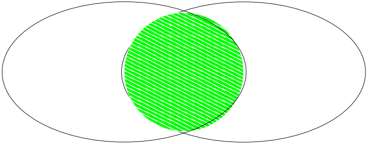


Figure : Spherical overlap and non zero magnetic field.

- For deformed nucleus with elliptical plasma region magnetic field can be generated along the semi-minor axis. For this configuration we see suppression in $v_2$.

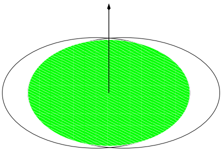



Figure : Elliptical overlap region and magnetic field along semi minor axis.

- We also consider low energy collisions corresponding to high baryon density, e.g. FAIR and NICA. It is well established that at high $\mu_B$ and low $T$ superfluid phases of QCD (CFL/2SC) exist.
- Symmetry breaking pattern for CFL phase is $(G \to H)$ $SU(3)_c \times SU(3)_L \times SU(3)_L \times SU(3)_R \times U(1)_B \to SU(3)_{c+L+R} \times Z_2$. $\pi_1(\frac{G}{H}) = Z \to$ String defect.
- Superfluid phase transition inevitably gives rise to formation of superfluid vortices.

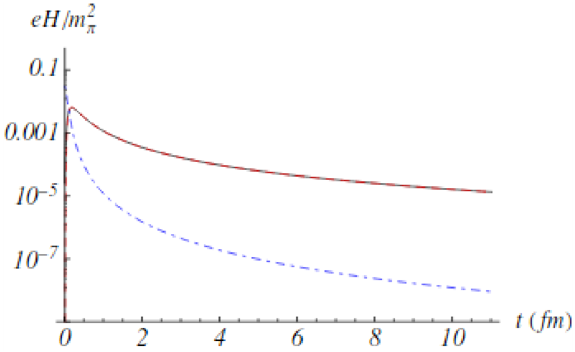
- It is known that turbulence can lead to enhancement of $\vec{B}$ via Dynamo effect. In 1978 Vainshtein and Zel'dovich proposed enhancement of $\vec{B}$ even for ideal MHD because of flux folding.
- We show strong enhancement in $\vec{B}$ in the presence of vortex, showing dynamo like effect in QGP.
- This is first example of dynamo like effect in plasma with relativistic EOS.

## Magnetic field in HIC

- Naive estimate $eB \sim \gamma\alpha_{EM} Z/R^2 \Rightarrow$ at RHIC Au + Au collisions at $\sqrt{s} = 200$ GeV is of order $10^{19}$ Gauss [3].
- $m_\pi^2 \simeq 0.02 GeV^2 \simeq 3 \times 10^{14}$ Tesla $= 3 \times 10^{18}$ Gauss.
- In systematic studies one finds $\mathbf{eB} \sim (\mathbf{0.1} - \mathbf{1})\mathbf{m_\pi^2}$ at **RHIC** energies.

[3] K. Hattori et. al, Nucl.Sci.Tech.28(2017), 26

- But for how long this large magnetic field survives in the medium?




- For conducting medium with $\sigma \sim 5.8 MeV$, $B$ is shown by the red curve. Blue curve shows vacuum solution [4].
- For non zero conductivity the magnetic field does not decay very quickly.

[4] K. Tuchin PRC 88(2013) 024911

# Relativistic Magnetohydrodynamics : Formalism

- The motion of an ideal relativistic magnetized fluid is described by [5],
  1. Mass conservation $\partial_\alpha(\rho u^\alpha) = 0$
  2. Conservation of energy momentum tensor:
     $$\partial_\alpha \left[ (\rho h + |b|^2) u^\alpha u^\beta - b^\alpha b^\beta + p\eta^{\alpha\beta} \right] = 0$$
  3. Maxwell's equations: $\partial_\alpha(u^\alpha b^\beta - u^\beta b^\alpha) = 0$
- $\rho$ is the rest mass density, $u^\alpha$ is the four velocity,
- $b^\alpha$ covariant magnetic field,
- $h$ is specific enthalpy
- $p = p_g + |b|^2/2$ is the total pressure.
- $u^\alpha = \gamma(1, \vec{v})$
- $b^\alpha = \gamma(\vec{v}.\vec{B}, \frac{\vec{B}}{\gamma^2} + \vec{v}(\vec{v}.\vec{B}))$
- Normalizations: $u^\alpha u_\alpha = -1$, $u^\alpha b_\alpha = 0$, $|b|^2 = b^\alpha b_\alpha = \frac{|B|^2}{\gamma^2} + (\vec{v}.\vec{B})^2$,
- $\gamma = (1 - \vec{v}.\vec{v})^{-1/2}$

[5] A.Mignone et. al, Mon.Not. R. Astron.Soc. 000, 1 (2005)

- For computational purpose, the above equations can be conveniently put in the following form,

$$\frac{\partial U}{\partial t} + \sum_k \frac{\partial F^k(U)}{\partial x^k} = 0$$

- where,

$$U = (D, m_x, m_y, m_z, B_x, B_y, B_z, E)$$

- $$F^x(U) = \begin{bmatrix} Dv_x \\ m_x v_x - B_x \frac{b_x}{\gamma} + p \\ m_x v_x - B_x \frac{b_y}{\gamma} \\ m_x v_x - B_x \frac{b_z}{\gamma} \\ 0 \\ B_y v_x - B_x v_y \\ B_z v_x - B_x v_z \\ m_x \end{bmatrix}$$

- $D = \rho\gamma$, $m_k = (\rho h \gamma^2 + B^2) v_k - (\vec{v}.\vec{B}) B_k$, $E = \rho h \gamma^2 - p_g + \frac{\vec{B}^2}{2} + \frac{v^2 B^2 - (\vec{v}.\vec{B})^2}{2}$

- Independent variables, $(\rho, \vec{v}, p_g, \vec{B})$, which have to be extracted from $U$.
- Set, $W = \rho h \gamma^2$, $S = \vec{m}.\vec{B}$, then

$$E = W - p_g + (1 - \frac{1}{2\gamma^2})|B^2| - \frac{S^2}{2W^2}$$

$$|m|^2 = (W + |B|^2)^2(1 - \frac{1}{\gamma^2}) - \frac{S^2}{W^2}(2W + |B|^2)$$

- In the beginning of each time step, $\vec{m}$, $\vec{B}$, $S$ are known. $\gamma$ in-terms of known quantities,

$$\gamma = \left(1 - \frac{S^2(2W+|B|^2)+|m|^2W^2}{(W+|B|^2)^2W^2}\right)^{-\frac{1}{2}}, \; p_g(W) = \frac{(W-D\gamma)(\Gamma-1)}{\Gamma\gamma^2}$$

- Unknown quantity W can be found out from,

$$f(W) = W - p_g + \left(1 - \frac{1}{2\gamma^2}\right)|B|^2 - \frac{S^2}{2W^2} - E = 0$$

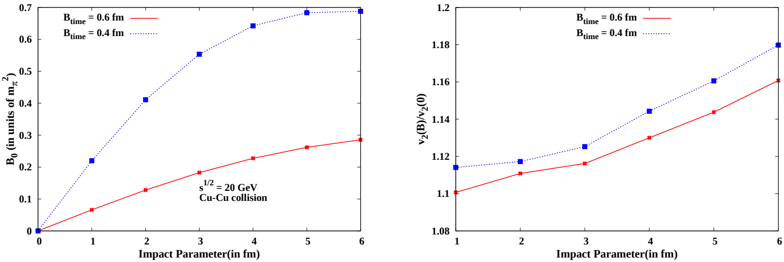
- Once $W$ has been computed, one can get back $\gamma$ and $p_g$. Velocities can be found by,

$$v_k = \frac{1}{W + |B|^2}\left(m_k + \frac{S}{W}B_k\right)$$

# Details of simulation

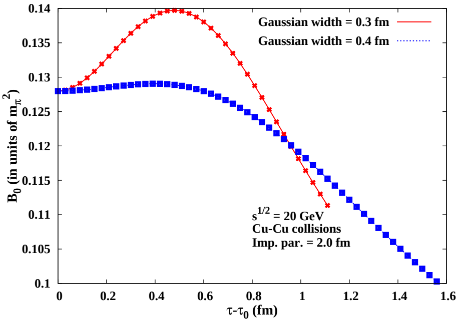
- We use Leap-Frog 2nd order method to solve ideal MHD equations numerically in (3+1)D, with system size 20 fm.
- We use ideal MHD, hence we focus on qualitative nature of result.
- Magnetic field produced by two oppositely moving uniform charged spheres is taken with appropriate Lorentz $\gamma$ factor as the initial magnetic field profile.
- Glauber like initial conditions are taken into account.
- We have taken EOS of ideal relativistic gas $p_g = \frac{\rho}{3}$.
- *Cu* nucleus with radius 4.0fm and mass number 64 is taken as target as well as projectile.

# Results: Enhancement of $v_2$ with magnetic field



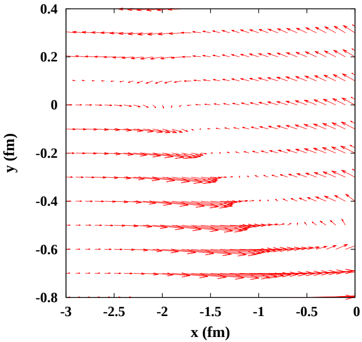

- Left fig. shows variation of initial magnetic field at the center as a function of impact parameter. Magnetic field is along semi major axis. Two curves show the value of the initial $\vec{B}$ at different times.
- Right fig. shows the effect of $\vec{B}$ on $v_2$. It is clear that magnetic field can increase $v_2$ by 15 %. Because of the stiffness of EOS in the direction perpendicular to $\vec{B}$, sound speed is larger in that direction, which eventually gives rise to large $v_2$.

# Growth of local magnetic field during plasma evolution by flux reorganization:



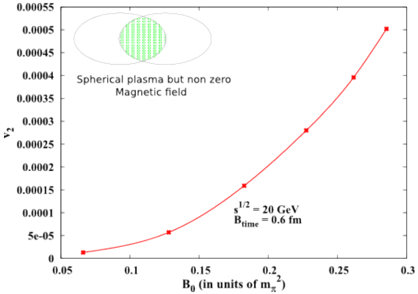

- Above fig shows increase in $\vec{B}$ due to reorganization of the local magnetic field due to the presence of fluctuations of different width.
- It is clear from the plot that for sharper fluctuations can lead to larger increase the local magnetic field.
- Eventually the local magnetic field decreases during evolution of the plasma.

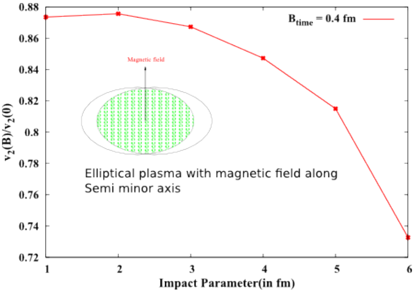
# Vorticity generation due to fluctuation:




- Above fig. shows the fluid velocity vector plot and generation of vorticity in the presence of $\vec{B}$ along with density fluctuations. Velocity vector plot clearly shows rotation pattern.
- Note, in the beginning velocity field is zero. This fluid vortex arises entirely due to complex spatial variation of Magnetosonic waves. It can have important implication for chiral vortical effect.

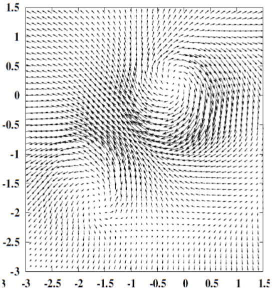
# Deformed Nucleus:

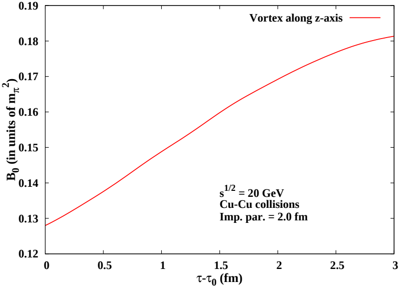



- Left fig shows variation of $v_2$ as a function of $\vec{B}$ for isotropic overlap region. Non zero $v_2$ arises in spherical QGP region but still having non zero $\vec{B}$ in the collision of deformed nuclei , e.g. Uranium.
- Right fig shows suppression of elliptic flow in the presence of magnetic field along x-axis. Magnetic field is along the semi minor axis, for elliptical overlap region in the collision of deformed nucleus, which is different from the standard situation. Magnetic field makes EOS stiffer along y axis.

# Dynamo like effect in QGP due to Superfluid vortex






- Left figure shows fluid velocity vector plot in the presence of vortex-anti vortex pair. It clearly shows the turbulence in the fluid.
- We have studied dynamo like effect in the presence of single vortex. Right figure shows increase of magnetic field due to dynamo like effect. In this case vortex is along z direction and $\vec{B}$ is along y direction. It clearly shows more than 30% increase in $\vec{B}$.