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Charge-dependent flow induced by electromagnetic fields in heavy ion collisions

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Abstract

The colliding heavy ions create extremely strong magnetic and electric fields that significantly affect the evolution of the produced quark-gluon plasma (QGP). The knowledge of these fields is essential for establishing the role of topological fluctuations in the QGP through the chiral magnetic effect and related anomaly-induced phenomena. In this talk, we describe our work on the evolution of the QGP in electric and magnetic fields in the framework of hydrodynamics supplemented, in a perturbative fashion, by the dynamical electromagnetism. The evolution of the QGP fluid is described within the `iEBE-VISHNU` framework. We find that the electromagnetically induced currents result in a a charge-odd directed flow Δv_1 and a charge-odd Δv_3 flow both of which are odd in rapidity. While the predicted magnitude of these charge-odd flows agrees with the data from RHIC and LHC, the sign of the predicted asymmetry between the flows of positive and negative hadrons is opposite to the data.

Keywords: quark-gluon plasma, heavy ion collisions, collective flow

1. Introduction

Non-central heavy ion collisions produce extremely strong magnetic fields [1, 2, 3]. For such strong fields, electromagnetic interactions significantly affect the evolution of the produced quark-gluon plasma (QGP). In particular, the interplay between magnetic fields and chiral anomaly has been predicted to lead to interesting phenomena including the chiral magnetic effect [4, 1, 5] and the chiral magnetic wave [6, 7]. These quantum chiral effects, if observed, would reveal the existence of topological charge fluctuations in the QGP that are similar to the topological fluctuations in the primordial electroweak plasma responsible for the baryon asymmetry of the Universe.

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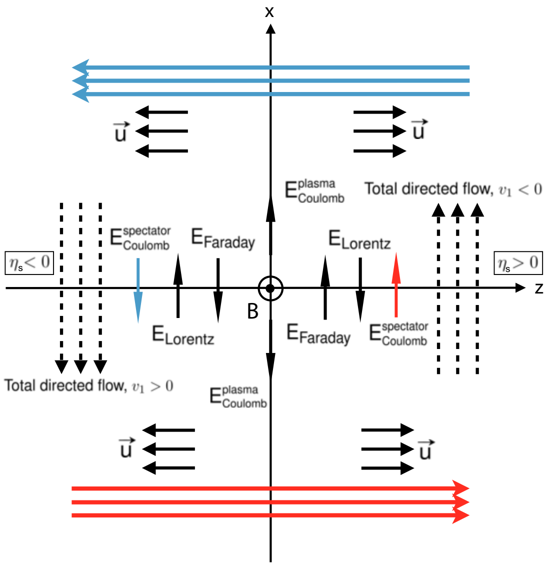

Fig. 1. Schematic illustration of how the electromagnetic fields in a heavy ion collision result in a directed flow of electric charge, Δv_1, see text for explanation. From [9].

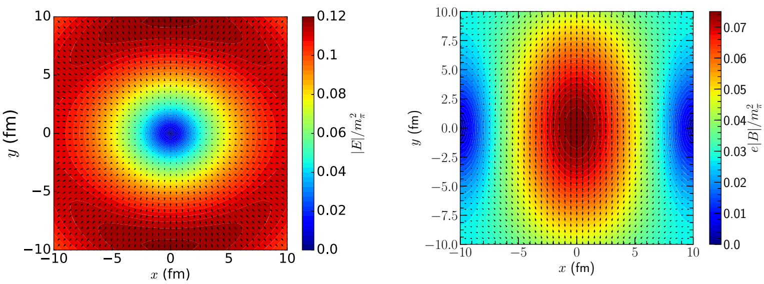

Fig. 2. The electric (left) and magnetic (right) fields in the transverse plane at $z = 0$ in the lab frame at a proper time $\tau = 1$ fm/c after a Pb+Pb collision with 20-30% centrality (impact parameters in the range 6.24 fm $< b <$ 9.05 fm) and with a collision energy $\sqrt{s}$ = 2.76 ATeV. From [9].

This motivation drives the need for establishing the presence and the magnitude of electromagnetic fields in the QGP. Here we report on the results of our studies [8, 9] of the effects of electromagnetic fields on the collective flow of charged hadrons. Our treatment of electromagnetic effects is perturbative: we solve the Maxwell equations to evaluate the currents induced by electromagnetism on top of the conventional hydrodynamical evolution (no back-reaction is included).

2. Electromagnetic fields in heavy ion collisions: a qualitative discussion

As illustrated in Fig. 1, there are three distinct electromagnetic effects on charged components of the fluid, resulting in a sideways current:

1. *Faraday:* as the magnetic field decreases in time, Faraday's law implies the induction of an electric field and, since the QGP possesses mobile charges, an electric current. We denote this electric field

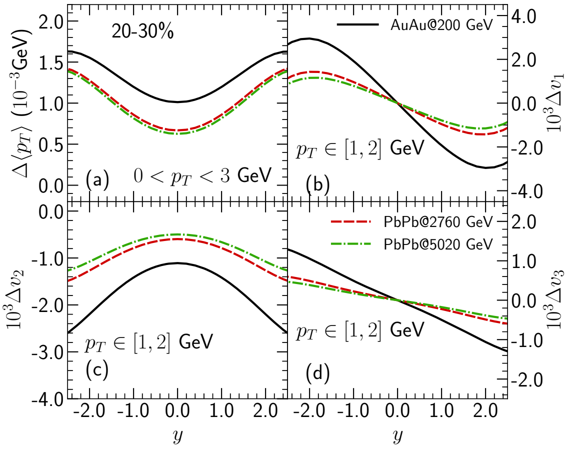

Fig. 3. The collision energy dependence of the electromagnetically induced charge-odd contributions to flow observables. The difference of particle mean p_T and v_n between π^+ and π^- are plotted as a function of particle rapidity for collisions at the top RHIC energy of 200 GeV and at two LHC collision energies; from [9]..

by $\vec{E}_F$. Since $\vec{E}_F$ curls around the (decreasing in time) $\vec{B}$ that points in the y-direction, the sideways component of E_F points in opposite directions at opposite rapidity, see Fig. 1.

2. *Lorentz:* since the QGP fluid exhibits a strong longitudinal flow velocity $\vec{v}_{\text{flow}}$ denoted by $\vec{u}$ in Fig. 1 pointing along the beam direction (and hence perpendicular to $\vec{B}$), the Lorentz force exerts a sideways push on charged particles in opposite directions at opposite rapidity. Equivalently, upon boosting to the local fluid rest frame, the lab frame $\vec{B}$ yields a fluid frame $\vec{E}$ in which the effects on the charged components of the fluid are equivalent to the effects of the Lorentz force in the lab frame. We denote this electric field by $\vec{E}_L$. Both $\vec{E}_F$ and $\vec{E}_L$ originate from the magnetic field.
3. *Coulomb:* The positive spectators exert an electric force on the charged plasma produced in the collision, which again points in opposite directions at opposite rapidity; the corresponding electric field is denoted by $\vec{E}_C$.

All three of these electric fields — and the electric currents induced by them — have opposite directions at positive and negative rapidity. As shown in Fig. 1, $\vec{E}_F$ and $\vec{E}_C$ have the same sign, whereas $\vec{E}_L$ opposes them. Therefore, the sign of the total rapidity-odd, charge-odd, directed flow charge dependence Δv_1 that results from these electric fields depends on whether $\vec{E}_F + \vec{E}_C$ or $\vec{E}_L$ is dominant. The relative magnitude of these fields is quite sensitive to the space-time evolution of the fluid.

3. Electromagnetic fields in heavy ion collisions: numerical results

Our numerical results were obtained, as explained in [9], by describing the evolution of the QGP fluid within the `iEBE-VISHNU` framework [10], and by solving Maxwell equations on top of this hydrodynamical background. The hydrodynamic calculation assumes longitudinal boost-invariance and begins at $\tau_0 = 0.4$ fm/c. We evolve the relativistic viscous hydrodynamic equations for a fluid with an equation of state based upon lattice QCD calculations [11]. The electromagnetic fields generated by the charges and currents evolve according to the Maxwell equations, in which we assume a constant conductivity.

Our calculation yields the momentum distribution for hadrons with different charge, from which we evaluate the difference between the flow for positively and negatively charged hadrons $\Delta v_n \equiv v_n(h^+) - v_n(h^-)$ shown in Fig. 3 for the top RHIC and LHC energies.

4. Conclusions

The data from RHIC [12] and LHC [13] show that the observed Δv_1 is similar in magnitude to the one that we have predicted, but has an *opposite sign*. This indicates that the electromagnetic fields of expected magnitude are indeed present in the QGP, but our treatment of magnetohydrodynamics of the plasma has to be improved. This can be done along two directions: i) improve the computation within the perturbative framework, e.g. by including the time-dependent conductivity; and ii) perform a full magnetohydrodynamical (MHD) simulation. The recent pilot MHD simulation [14] however indicates the same sign of Δv_1 as our perturbative result. Clearly, more work is needed to improve our understanding of this important issue.

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