Effect of intense magnetic fields on reduced-MHD evolution in $\sqrt{s_{\rm NN}} = 200$ GeV Au+Au collisions

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Introduction

Two positively charged heavy nuclei produce ultra-intense magnetic fields in collider experiments at the Relativistic Heavy Ion Collider (RHIC) and at the Large Hadron Collider (LHC), e.g. $B \sim 10^{18} - 10^{19}$ G for $\sqrt{s_{\rm NN}} = 200$ GeV Au+Au collisions. The intensity of the magnetic field in the transverse plane grows approximately linearly with the center-of-mass energy ($\sqrt{s_{\rm NN}}$) [1]. The corresponding electric field in the transverse plane also becomes very large since it is enhanced by a Lorentz factor. Such intense electric and magnetic fields are believed to have a strong impact on the dynamics of high-energy heavy-ion collisions. For example, in the case of an imbalance in the number of left- vs. right-handed fermions, a charge current is induced in the Quark-Gluon Plasma (QGP), leading to the separation of electrical charges, which is known as the "chiral magnetic effect" (CME) [2].

Relativistic dissipative hydrodynamics has so far been successfully applied to explain the experimentally measured flow harmonics in heavy-ion collisions. The success of hydrodynamics implies that a QGP with small shear-viscosity to entropy-density ratio is formed in Au+Au collisions at top RHIC energies within a short time interval $\sim 0.2 - 0.6$ fm. However, the possible effect of a magnetic field on the hydrodynamical evolution has so far not been studied extensively, except for some simplified cases and most recently using some approximate form of the equations of relativistic magnetohydrodynamics (MHD). Here we will study the $2+1$ dimensional expansion of matter with vanishing magnetization in terms of the dynamics of a perfect fluid in the presence of an external magnetic field. We refer to this approach as to "reduced MHD" and we note that this is not a self-consistent solution of the full set of MHD equations, since we only use a parametrized form for the evolution of the magnetic field and do not solve Maxwell's equations together with the conservation equations of energy and momentum. For the sake of simplicity, we also assume that the electrical conductivity is infinite (i.e., the ideal-MHD limit), since this allows to eliminate the electric field in favor of the magnetic field. Assuming a perfectly conducting fluid under the influence of an external magnetic field still represents a reasonable first approximation, which however calls for a future improvement towards a self-consistent MHD solution. We also assume that the magnetic field only points into the y-direction. The goal of our study is to clarify how large the external magnetic field has to be and how slowly it has to decay in order to make a sizable impact on the momentum anisotropy of charged particles. We use natural units $\hbar = c = \epsilon_0 = \mu_0 = 1$.

Mathematical setup and Results

We solve the energy-momentum conservation equations $\partial_\mu T^{\mu\nu} = 0$ by using an appropriately modified version of the publicly available $2+1$ dimensional perfect fluid dynamics code "`AZHYDRO`". The energy momentum

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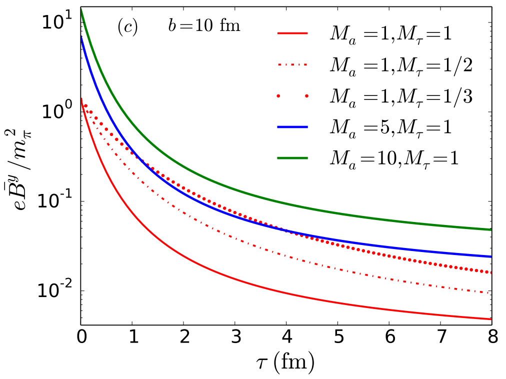

FIG. 1: Time evolution of $e\bar{B}^y$ in medium with a finite conductivity for $b = 10\,\mathrm{fm}$ collisions, the red solid line is a fit of data given in Ref. [3]. Other lines correspond to various values of fit parameter.

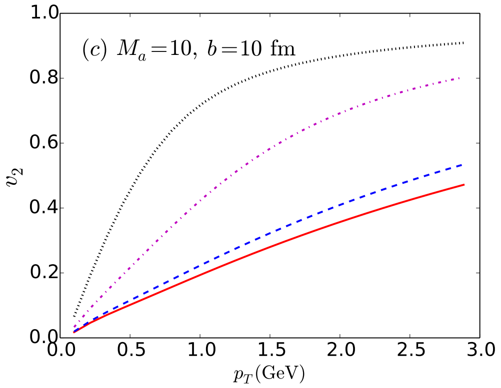

FIG. 2: The elliptic-flow coefficient v_2 for π^- as a function of transverse momentum p_T for $b = 10\,\mathrm{fm}$ collisions. The solid red line corresponds to the result for zero magnetic field, the dashed blue, dash-dotted magenta, and dotted black lines correspond to results for an external magnetic field with $M_\tau = 1, 1/2$, and $1/3$, respectively.

tensor is given as $T^{\mu\nu} = T^{\mu\nu}_{fluid} + T^{\mu\nu}_{field} = \left(\varepsilon + p + B^2\right) u^\mu u^\nu - \left(p + \frac{B^2}{2}\right) - B^\mu B^\nu$, here $\varepsilon, p, u^\mu, B^\mu$ are fluid energy density, pressure, four velocity and magnetic field four vector respectively. In a QGP with nonzero electrical conductivity we parametrize the evolution of the magnetic field as in Ref. [3]

$$f(\tau) = M_a a_3 e^{b_3/(M_\tau \tau + c_3)} \,. \tag{1}$$

We fit these data setting $M_a = M_\tau = 1$ and adjusting the constants, giving $a_3 = 1.99 \times 10^{-3}$, $b_3 = 8.1306$ fm, and $c_3 = 1.2420$ fm.

Fig. 1 shows the temporal evolution of magnetic field for various values of M_a and M_τ which gives different initial value of magnetic field and different time evolution respectively. The space variation of magnetic field is taken as a two dimensional Gaussian, for details see Ref. [4]. Fig. 2 shows the elliptic-flow coefficient v_2 of π^- as a function of the transverse momentum p_T for non-central collisions with $b = 10\,\mathrm{fm}$. The solid red line corresponds to the result for zero magnetic field, the dashed blue, dash-dotted magenta, and dotted black lines correspond to results with external magnetic field for $M_\tau = 1, 1/2$, and $1/3$, respectively. It is clear from Fig. 2 that changes in v_2 are noticeable when the magnetic field decay is substantially delayed. For the largest initial value of the magnetic field considered here, i.e., for $e\bar{B}^y \simeq 10\, m_\pi^2$, we notice a considerable enhancement of the elliptic-flow coefficient, which can become as large as $v_2 \lesssim 0.9$ for $p_T \sim 2.5\,\mathrm{GeV}$ (cf. dotted black line in Fig. 2). More realistic magnetic field evolution with initial $e\bar{B}^y \simeq 10\, m_\pi^2$, leads to a smaller increase of the elliptic-flow coefficient (blue dashed line), thus highlighting that quite realistic values of the magnetic field can have a considerable impact on the ellipticity of the flow of particles. Overall, these results and their implications for the understanding of the physics of ultra-relativistic heavy-ion collisions clearly call for the extension of this study towards a fully self-consistent MHD treatment of the evolution of hot and dense strongly interacting matter created in heavy-ion collisions.

References

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