Wake in anisotropic quark-gluon plasma

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Introduction

In the early stage of heavy-ion collision, the high energy parton jet created by the hard scattering will travel through the hot and dense medium and loses energy, mainly by radiative processes. As a consequence high p_T hadrons produced due to parton fragmentation are suppressed. This phenomenon is the so-called jet quenching. Moreover the experimental azimuthal dihadron distribution at RHIC shows a double peak structure in the away side for intermediate p_T particles. Such peak indicates another mechanism related to the in-medium jet physics which leads to the formation of wakes, Mach cones and Cerenkov radiation and may be observable as collective excitations and shock wave in heavy-ion collision.

When a test charged parton is moving in the plasma, it creates a screening potential. The screening potential for a heavy quark-antiquark pair is strongly anisotropic and loses forward-backward symmetry with respect to the direction of the charge particle. First, Ruppert and Muller [1] have investigated that when a jet propagates through the medium, a wake of current and charge density is induced which can be studied within the framework of linear response theory in two different scenarios: (i) a weakly coupled quark-gluon plasma described by hard thermal loop(HTL) perturbation theory and (ii) a strongly coupled QGP, which has the properties of a quantum liquid. The result shows the wake in both the induced charge and current density due to the screening effect of the moving parton and also in the quantum liquid scenario, the wake exhibits a oscillatory behavior when the charge parton moves very fast. Later, Chakraborty et al [2] also found the oscillatory behavior of the induced charge wake in the back ward direction at large parton speed using the high temperature approximation.

In all the above calculation, the plasma is assumed to be isotropic in momentum space. However, in the very early stage of heavy-ion collision due to rapid longitudinal expansion the plasma may become anisotropic. The dielectric function contains all the information of chromoelectromagnetic properties of the plasma. Due to the momentum anisotropy, the distribution functions of the quark and gluon are modified and it will affect the dielectric function. In this paper, we will investigate the anisotropic effect on the charge wake and potential induced by a fast parton traveling through the anisotropic quark-gluon plasma(AQGP).

1. Dielectric Response Function

When a fast parton passes through the QGP; it will disturb the plasma and create induced color charge density[3]. Therefore the induced color charge density is explicitly written as

$$\rho^a_{ind}(\mathbf{k},\omega) = -\{1 - \frac{1}{\epsilon(\mathbf{k},\omega)}\}\rho^a_{ext}(\mathbf{k},\omega). \quad (1)$$

The dielectric function can be calculated from the dielectric tensor using the following relation

$$\epsilon(\mathbf{k},\omega) = \frac{k_i \epsilon^{ij}(\mathbf{k},\omega) k_j}{k^2}, \quad (2)$$

where the dielectric tensor ϵ^{ij} is given by,

$$\epsilon^{ij} = \delta^{ij} + \frac{\Pi^{ij}}{\omega^2}. \quad (3)$$

Here Π^{ij} is the hard-loop gluon polarization

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tensor

$$\Pi^{ij}(K) = -g^2 \int \frac{d^3p}{(2\pi)^3} v^i \partial^l f(\mathbf{p}) \Big(\delta^{jl} + \frac{v^j k^l}{K.V + i\epsilon}\Big). \tag{4}$$

The wake potential induced by the fast parton is determined from the Poisson equation leading to

$$\Phi^a(\mathbf{k},\omega) = \frac{4\pi\rho^a_{ext}(\mathbf{k},\omega)}{k^2\epsilon(\mathbf{k},\omega)}. \tag{5}$$

Now we consider a charge particle of charge Q^a moving with a constant velocity $\mathbf{v}$ and interact with the anisotropic plasma. The charge density associated due to the test charge particle can be written as [3]

$$\rho^a_{ext} \;=\; 2\pi Q^a \delta(\omega - \mathbf{k}.\mathbf{v}). \tag{6}$$

We assume that the phase-space distribution for the anisotropic plasma is given by the following ansatz:

$$f(\mathbf{p}) = f_\xi(\mathbf{p}) = N(\xi) f_{iso}(\sqrt{\mathbf{p}^2 + \xi(\mathbf{p}.\hat{\mathbf{n}})^2}). \tag{7}$$

$N(\xi)$ is a normalization constant, $\hat{\mathbf{n}}$ is direction of anisotropy taken to be along the beam direction, ξ is a parameter which represents the strength of anisotropy and f_{iso} is an arbitrary isotropic distribution function. Using the above ansatz one can simplify Eq.(4) to

$$\begin{aligned}\Pi^{ij}(K) \;&=\; m_D^2\sqrt{1+\xi}\int \frac{d\Omega}{(4\pi)} v^i \frac{v^l + \xi(\mathbf{v}.\hat{\mathbf{n}})n^l}{(1+\xi(\mathbf{v}.\hat{\mathbf{n}})^2)^2} \\ &\times \Big(\delta^{jl} + \frac{v^j k^l}{K.V + i\epsilon}\Big)\end{aligned} \tag{8}$$

where m_D is the Debye mass.

2. Induced charge density

In the presence of the test charge particle, the induced charge density and also wake potential depend on the velocity of the test charge and the distribution of the background particles. We assume that parton moves along x-z plane, $\mathbf{r} = (\rho, 0, z)$ and $\mathbf{k} = (k\sin\theta\cos\phi, k\sin\theta\sin\phi, k\cos\theta)$. The induced charge density in $r-t$ space reads as [4]

$$\begin{aligned}\rho^a_{ind}(\mathbf{r},t) = \frac{Q^a}{(2\pi)^3}\int k^2 dk dx d\phi \Big[\cos\Gamma(\frac{\text{Re}\epsilon}{\Delta} - 1) \\ + \sin\Gamma\frac{\text{Im}\epsilon}{\Delta}\Big]\end{aligned} \tag{9}$$

where $\Gamma = k((\rho - vt\sin\theta_v)\cos\phi\sqrt{1-x^2} + (z - vt\cos\theta_v)x)$ and $\Delta = [\text{Re}\epsilon]^2 + [\text{Im}\epsilon]^2$. We estimate the above equation numerically and it is found that the wake induced charge density depends on the velocity of the parton. The contour plot of the equicharge lines shows a sign flip along the direction of the moving parton. When the parton moves with speed less then the plasmon speed(v_p), the equicharge line in the induced charge density is modified in case of anisotropy plasma with respect to isotropic plasma, while for $v = 0.99c$, (larger than v_p) anisotropy enhance the distribution of negative and positive charge in the backward direction. Due to the anisotropy, the induce charge density is more oscillatory in nature. The supersonic nature of the parton leads to the formation of the Mach cone and the plasmon modes could emit a Cerenkov-like radiation, which spatially limits the disturbances in the induce charge density.

3. Wake potential in AQGP

The screening potential in $r-t$ space becomes

$$\Phi^a(\mathbf{r},t) = \frac{Q^a}{2\pi^2}\int dk dx d\phi \Big[\cos\Gamma\frac{\text{Re}\epsilon}{\Delta}. + \sin\Gamma\frac{\text{Im}\epsilon}{\Delta}\Big] \tag{10}$$

Numerically we found that when the fast parton moves with a speed greater then the average plasmon speed, the potential shows an oscillatory structure which is more pronounced for non-zero ξ. Also cone like structure increases for anisotropic plasma which leads to generation of Mach shock waves.

References

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