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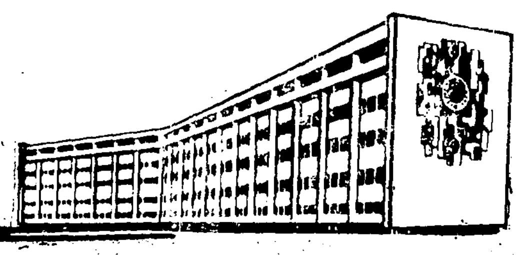
DYNAMICAL INSTABILITIES IN QUARK-GLUON PLASMA WITH HARD JET



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Динамические неустойчивости кварк-глюонной плазмы с жесткой струей

Анализируются динамические неустойчивости, развитие которых следует ожидать при прохождении жесткой струи через кварк-глюонную плазму. Обсуждаются возможные сигналы формирования кварк-глюонной плазмы в ультрарелятивистских столкновениях ядер, связанные с развитием плазменно-пучковых неустойчивостей.

O.P.Pavlenko

Dynamical Instabilities in Quark-Gluon Plasma With Hard Jet

The dynamical instabilities, whose development can be expected under the hard jet propagating through the quark-gluon plasma, are analysed. The possible signals of the quark-gluon plasma formation in ultrarelativistic nuclear collisions connected with the development of the plasma-jet instabilities are discussed.

Олег Павлович Павленко

Динамические неустойчивости кварк-глюонной плазмы с жесткой струей

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DYNAMICAL INSTABILITIES IN QUARK-GLUON PLASMA WITH HARD JET

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In connection with the current experiments on ultrarelativistic nuclear collisions much theoretical efforts have recently been focused on the processes which might be the signals of quark-gluon plasma (QGP) formation [1] . One of the attractive QGP processes of this kind is the development, under specific conditions, of unstable collective oscillations (instabilities), whose amplitudes increase exponentially in time. A transparent example of the system, where one can expect the development of the instabilities, is the system of two colliding plasma streams as it is well-known from the theory of the electrodynamic (electron-ion) plasma [2].

In Ref.[3] it was shown the development of dynamic instabilities can be expected in the system of two initially homogeneous oppositely directed streams of the hadron plasma. Such system was considered as a model for the initial stage of relativistic nuclei-nuclei (AA) collisions. In this case the so called filamentation mode appears to be the most unstable. The distinctive point of the filamentation instability is that it causes the breaking of the homogeneous system into separate filaments.

The development of the filamentation instability in the system of two QGP streams of equal densities was analysed in [4,5] as a signal of the QGP formation at the initial stage of ultrarelativistic AA-collisions.

In the present paper the dynamical instabilities in the QGP with the hard jet of quarks, antiquarks and gluons are studied. The parton density in the jet differs from the QGP density. It is pointed out that similarly to the case of plasma streams of equal densities in the QGP with hard jet one can expect the development of the filamentation instability. This result may happen to be useful for the diagnostics of the QGP in ultrarelativistic AA-collisions because the filamentation is accompanied with the experimentally accessible phenomena, in particular, the characteristic emission of photons and pions [3-5].

It should be noted that the possibility to use the hard jets as a specific tool for the QGP diagnostics in AA-collisions had been analysed in some different aspect in Ref.[6] where the signal connected with the jet partons scattering of the QGP constituents was proposed. The validity of the very picture of the hard jet propagating through the QGP formed in the ultrarelativistic AA-collisions is mainly based on the assumption that jets are produced just in that region where the QGP can be formed. As far as the initial transverse size of the QGP formation is expected to be $R \gtrsim$ 3-5 fm and the formation time of the QGP is about $\tau_0 \simeq$ 1 fm/c then the jet produced at the very beginning of the AA-collision by the hard collision of nucleon constituents has to propagate through the QGP for the time $\tau_j \simeq R/c - \tau_0$ Under the optimistic estimations τ_j is in the interval from a few fm/c to 5-7 fm/c.

Our analysis of the dynamical instabilities in the QGP with the hard jet is based on the kinetic theory of the quark-gluon matter [7,8] which gives us the physical transparent picture of the plasma oscillations. In the semi-classical limit this theory describes the gas of quarks, antiquarks and gluons interacting via the classical non-Abelian SU(3) potentials $A_a^\mu(x)$ [8]. We shall suppose that at the stationary (unperturbed) state there are no colour currents in the QGP+jet system. The small deviations from the stationary state are chosen in the diagonal form in colour space. In this case the components of colour current $j_a^\mu(x)$ and potential $A_a^\mu(x)$ only for a=3,8 are nonzero.

Because of the complexity of the processes of the formation and evolution of the QGP in ultrarelativistic AA-collisions we have to simplify the picture of the development of instabilities and to consider the idealized system of the spatially homogeneous collisionless QGP through which the hard jet propagates. We also do not take into account the collisional interaction of the jet with the plasma constituents.

To clarify the qualitative picture of instabilities in the QGP with the hard jet one can first neglect the internal motion of partons in the jet and the thermal motion of the plasma constituents. Using these simplifications we obtain the set of the linearized equations for the perturbations of colour current $j_a^\mu(x) \equiv (j_a^0, \vec{j}_a)$ and potential $A_a^\mu(x)$ in the QGP+jet system:

$$j_a^0(x) = g \sum_i \left[n_a^{(i)}(x) - \tilde{n}_a^{(i)}(x) + 6 \rho_a^{(i)}(x) \right], \quad (1)$$

$$\vec{j}_a(x) = g\sum_i \Big[n_0^{(i)} \vec{V}_a^{(i)}(x) + n_a^{(i)}(x)\vec{V}_0^{(i)} - \tilde{n}_0^{(i)} \vec{U}_a^{i}(x) - \tilde{n}_a^{(i)}(x)\vec{V}_0^{(i)} + 6\left(\rho_0^{(i)} \vec{W}_a^{(i)}(x) + \rho_a^{(i)}(x)\vec{V}_0^{(i)}\right)\Big] \tag{2}$$

where $x = (t, \vec{r})$ is the space-time coordinate; g is the colour coupling constant; the index i denotes what group of partons the corresponding values belong to: i =(plasma, jet); $3n_0^{(i)}, 3\tilde{n}_0^{(i)}$ and $8\rho_0^{(i)}$ can be interpreted as the quark, antiquark and gluon densities, respectively, at the stationary state in the plasma rest frame; $\vec{V}_0^{(i)}$ is the velocity which describes the stationary motion of the plasma (or jet) as a whole. For values $n_a^{(i)}(x)$ and $\vec{V}_a^{(i)}(x)$ determining the quark contribution in the perturbations of color current we have the following equations

$$\frac{\partial \vec{V}_a}{\partial t} + (\vec{V}_0 \cdot \nabla)\vec{V}_a = \frac{g}{m\gamma_0}\Big[\vec{E}_a - \vec{V}_0(\vec{E}_a \vec{V}_0) + (\vec{V}_0 \times \vec{B}_a)\Big] \tag{3}$$

$$\frac{\partial n_a}{\partial t} + \nabla(\vec{V}_0 n_a + \vec{V}_a n_0) = 0\ ; \quad \gamma_0 \equiv (1 - \vec{V}_0^2)^{-1/2}, \tag{4}$$

here the summation with respect to index i is absent, therefore, this index is omitted for simplicity; $\vec{E}_a(x)$ and $\vec{B}_a(x)$ are the chromoelectric and chromomagnetic field strengths; m is the quark mass. The equations (1)-(4) are written for spinless quarks of one flavor only. The inclusion of several flavors is straightforward. The equations for values $\tilde{n}_a^{(i)}(x)$ and $\vec{U}_a^{(i)}(x)$ determining the antiquark contribution into color current are obtained from equations (3) and (4) by means of the replacement: $g \to -g$, $\vec{V}_a^{(i)}(x) \to \vec{U}_a^{(i)}(x)$, $n_a^{(i)}(x) \to \tilde{n}_a^{(i)}(x)$. The values $\rho_a(x)$ and $\vec{W}_a(x)$ relating to the gluon contribution into color current satisfy the equations which look similar to (3) and (4). Hereinafter, we shall assume that the masses of all partons are approximately equal.

The mean fields $A_a^{\mu}(x)$ are generated by color current in the self-consistent way:

$$\partial_\mu F_a^{\mu\nu}(x) = j_a^\nu(x) \ ; \quad F_a^{\mu\nu}(x) = \partial^\mu A_a^\nu(x) - \partial^\nu A_a^\mu(x) \qquad (5)$$

In virtue of the linear approximation used here the mean field strengths $\vec{E}_a(x)$, $\vec{B}_a(x)$ are expressed in terms of the potential $A_a^\mu(x)$ analogously to electrodynamics and for $a=3,8$ equations (5) are formally similar to Maxwell's equations.

We shall look for the solutions of the equations (1)-(5) in the form $f(x) = f(\omega,\vec{k})\exp(-i\omega t + i\vec{k}\vec{r})$ where $f(x)$ denotes unknown values (perturbations) depending on the space-time x and coming in these equations; ω is the frequency and $\vec{k}$ is wave vector of oscillations. Let us remind that we are interested in unstable modes with the positive imaginary part of the frequency $Im\,\omega(\vec{k}) > 0$.

To begin with let us examine the simple form of the perturbations: $\vec{B}_a = 0$, $\vec{E}_a = -\nabla\varphi_a$ (potential perturbations). The following dispersion equation is obtained as a result of solving the equations (1)-(5)

$$1 - g^2 \sum_i \frac{\tilde{n}_0^{(i)} + n_0^{(i)} + 6\rho_0^{(i)}}{m\gamma_0^{(i)}(\omega - \vec{k}\cdot\vec{V}_0^{(i)})^2}\left[1 - \frac{(\vec{V}_0^{(i)}\cdot\vec{k})^2}{\vec{k}^2}\right] = 0 . \qquad (6)$$

Considering the QGP being at rest $\vec{V}_0^{(pl)} = 0$, $\vec{V}_0^{(jet)} \equiv \vec{V}^0$ and choosing the wave vector $\vec{k}$ along the jet axis (longitudinal oscillations) we have from (6):

$$1 - \frac{\omega_p^2}{\omega^2} - \gamma_0^{-3}\frac{\omega_j^2}{(\omega - kV_0)^2} = 0 , \qquad (7)$$

where $k = |\vec{k}|$, $V_0 = |\vec{V}_0|$; $\omega_p^2 \equiv g^2(n_0^{(pl)} + \tilde{n}_0^{(pl)} + 6\rho_0^{(pl)})/m$, $\omega_j^2 \equiv g^2(n_0^{(j)} + \tilde{n}_0^{(j)} + 6\rho_0^{(j)})/m$.

As far as $\gamma_0^{-3} \ll 1$ then for $\omega_j < \omega_p$ there are unstable modes only in the vicinity of the pole $\omega \sim kV_0$. The most unstable mode among the longitudinal oscillations appears to be the one represented by frequency ω_L having the positive imaginary part:

$$Im\,\omega_L \simeq (\sqrt{3}/2^{4/3}\gamma_0)\,\omega_j^{2/3}\omega_p^{1/3} . \qquad (8)$$

The unstable mode ω_L has the analog in the electrodynamic plasma [9].

Let us now consider the transverse modes ($\vec{K}$ is perpendicular to the jet axis). We direct the coordinate axes of the plasma rest frame so that $\vec{K}=(K,0,0)$ and $\vec{V}^{(jet)}=\vec{V}_0=(0,0,V_0)$. To simplify the further calculations it is convenient to choose the perturbations of the chromoelectric field and color current in the form $\vec{E}_a=(E_{ax},0,E_{az})$, $\vec{j}_a=(j_{ax},0,j_{az})$ then from the equation (5) we get $\vec{B}_a=(0,B_{ay},0)$. In this case the dispersion equation for transverse modes reads

$$\left(K^2-\omega^2+\omega_p^2+\omega_j^2\gamma_0^{-3}\right)\left(1-\frac{\omega_p^2}{\omega^2}-\frac{\omega_j^2}{\omega^2}\gamma_0^{-1}\right)+ \\ +\frac{K^2V_0^2}{\omega^2}\omega_j^2\gamma_0^{-1}\left(1-\frac{\omega_p^2}{\omega^2}\right)=0 \ . \tag{9}$$

Among the solutions of the equation (9) there are unstable modes of the filamentation type. If the parton density in the jet is less than that in the plasma (this condition may happen to be the most probable for the QGP+jet system formed in ultrarelativistic AA-collisions) then the frequency of the filamentation mode ω_F for $K^2\gg\omega_p^2$ is as follows:

$$Im\,\omega_F\simeq V_0\omega_j/\gamma_0^{1/2}\left[1+(\omega_p/K)^2\right]^{1/2}. \tag{10}$$

The real part of ω_F is equal to zero. Unstable mode ω_F has an analog in the electrodynamic plasma [9].

Let us estimate the characteristic time $\tau_{ins}=1/Im\,\omega$ of the development of the considered instabilities in connection with the QGP formation in AA-collisions. One should compare the value τ_{ins} with the time τ_j which it takes the jet to pass through the QGP. In order to make the estimations of τ_{ins} more realistic it is first necessary to take into account the thermal motion of partons in the QGP. According to [5], for baryonless plasma it can be done by means of the following replacement $\omega_p^2\to g^2(3n_f+12)\zeta(3)T^2/3\pi^2$, where n_f is the number of quark flavours, T is the plasma temperature. Since in the ultrarelativistic AA-collisions the QGP formation is expected at temperature $T\simeq$ 0.2-0.4 GeV then for $n_f=2$, $g=1$ we get $\omega_p^2\simeq$ 1-2 fm^{-1}. The internal motion of partons in the jet can be taken into account in the expression for ω_j^2 by means of replacement $m \to m_{eff} = (m^2 + p_t^2)^{1/2} \simeq 0{,}2-0{,}3$ GeV, where p_t is the average transverse momentum of partons with respect to the jet axis. This replacement together with the data [10] on the parton density in jets at γ_0 =5-10 gives us the value of $\omega_j \gamma_0^{-1/2} \simeq$ $\simeq 0{,}4-0{,}6$ fm^{-1}. Substituting these estimations in (8) we obtain for longitudinal unstable modes $\tau_{ins} = \tau_L \gtrsim 5$ fm/c. Comparison τ_L with τ_j shows that it takes the development of these instabilities too large time interval to expect their appearance in the system of the QGP+jet formed in AA-collisions. The estimation of τ_{ins} for the transverse unstable modes looks more encouraging. According to (10) for $K^2 \gg \omega_p^2$ we get $\tau_{ins} = \tau_F \simeq$ $\simeq 1.7-2.5$ fm/c. This estimation allows us to conclude that if in the ultrarelativistic nuclear collisions equally with the QGP formation the hard jets are produced then in such events one can expect the development of the filamentation instability.

The characteristic gluon production followed by the transformation into pions can be one of the possible signals to develop the filamentation in the QGP+jet system. Such production is caused by the perturbation of color current which is proportional to exp($\omega_F \cdot \tau_F$). The important peculiarity of the noted gluon production is that the direction of its maximal intensity correlates with the jet axis. In particular, if the parton density in the jet is small as compared to the QGP density the gluon production will mainly take place in the direction perpendicular to the jet axis. The photon production accompanying also the development of the filamentation in the QGP+jet system has the analogous properties.

In conclusion some remarks should be done. To be convinced in the reliability of the signals connected with the dynamical instabilities in the QGP+jet system it is necessary, of course, to clear up how they depend on the space-time evolution of the QGP formed in AA-collisions. The influence of parton collisions on the development of the noted instabilities requires also the special treatment. It is undoubtedly important to consider the nonlinear effects connected with the non-Abelian interaction which may happen to play the crucial role for the development of the instabilities of the QGP.

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