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Modelling early stages of relativistic heavy-ion collisions

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Abstract

In this study we model early time dynamics of relativistic heavy ion collisions by an initial color-electric field which then decays to a plasma by the Schwinger mechanism. The dynamics of the many particles system produced by the decay is described by relativistic kinetic theory, taking into account the backreaction on the color field by solving self-consistently the kinetic and the field equations. Our main results concern isotropization and thermalization for a $1+1$D expanding geometry. In case of small η/s ($\eta/s \lesssim 0.3$) we find $\tau_{isotropization} \approx 0.8$ fm/c and $\tau_{thermalization} \approx 1$ fm/c in agreement with the common lore of hydrodynamics.

1 Introduction

According to the general understanding of relativistic heavy ion collisions, in the overlap region of the two colliding nuclei a peculiar ensemble of (almost) longitudinal color fields named the Glasma is produced soon after the collision. One of the main problems is then how the Glasma, which corresponds to a configuration of classical fields, evolves to a quark-gluon plasma. In this talk we present one possible approach to this problem, presenting our recent results about modelling early time dynamics of relativistic heavy ion collisions by coupling the dynamics of the initial color field to that of the quark-gluon plasma. More specifically we assume that initially the system consists of a classical color field only, which then decays according to the Schwinger mechanism into a plasma of quarks and gluons; the dynamics of the system particles+field is studied self-consistently by coupling evolution equations for distribution function and field.

2 The flux tube model

Here we briefly summarize the flux tube model which we implement in our simulations of the initial stage of relativistic heavy ion collisions [1]. Due to lack of space we skip all the unnecessary details, referring to the original literature for a more complete treatment [1–3]. In the present study we limit ourselves to a simple geometrical initial condition with just one flux tube of a given transverse area. Although this is an oversimplified version of the appropriate initial condition for high energy nuclear collisions, this model permits to understand the main physical mechanisms which lead to particle production, thermalization and isotropization, as well as to compute the time scales for such processes. Hence our work is a necessary step for the study of a more realistic initial condition which will be the subject of forthcoming work.

The main assumptions of the model are that in the initial condition a color electric field is present, which decays into particle quanta by the Schwinger mechanism; the equations of motion for the classical fields are assumed to be the Maxwell equations, in which we introduce the backreaction to the field due to polarization and conduction currents. We assume the electric field, which we denote by E in the following, to be purely longitudinal, and limit ourselves to a one dimensional expansion calculation. Within this simplified geometry, given a pure longitudinal initial field, E remains longitudinal along all the time evolution since transverse currents are not produced.

3 Relativistic transport theory

Our calculation scheme is based on the Relativistic Transport Boltzmann equation which, in the presence of a gauge field $F^{\mu\nu}$, can be written as follows:

$$\left(p^\mu \partial_\mu + g Q_{jc} F^{\mu\nu} p_\nu \partial^p_\mu\right) f_{jc}(x,p) = \frac{dN_{jc}}{d\Gamma} + \mathcal{C}_{jc}[f] \ , \tag{1}$$

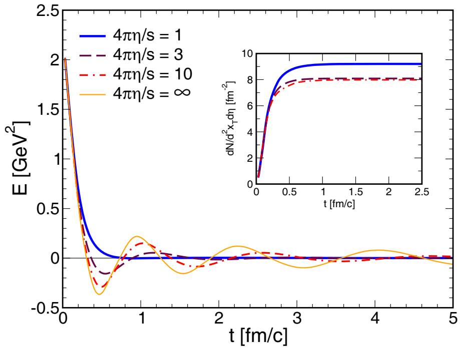
where $f_{jc}(x, p)$ is the distribution function for flavour j and color c, $F^{\mu\nu}$ is the field strength tensor. On the right hand side we have the source term $dN/d\Gamma$ which describes the creation of quarks, antiquarks and gluons due to the Schwinger effect [1] and $\mathcal{C}[f]$ which represents the collision integral, which is responsible of the change of distribution function due to stochastic collisions in the system and which is responsible for viscous corrections to ideal hydrodynamics. In our calculations we solve Eq. (1) by mapping the phase space of the fluid by means of test particles; the collision integral is computed using Monte Carlo methods based on the stochastic interpretation of transition amplitude [4–12].

At variance with the standard use of transport theory, in which one fixes a set of microscopic processes into the collision integral, we have developed an approach that fixes the total cross section cell by cell in configuration space in order to have the wished η/s. By means of this scheme we are able to use the Boltzmann equation to simulate the dynamical evolution of a fluid with specified shear viscosity, in analogy to what is done within hydrodynamical simulations. Once again, due to lack of space we refer to [7–12] for more details.

We assume the dynamics of the classical field is invariant for boosts along the longitudinal directions; in this case the relevant Maxwell equations can be combined to give a boost invariant equation

$$\frac{dE}{d\tau} = -j \ , \tag{2}$$

where τ corresponds to proper time and j is the total current computed in the local rest frame of the fluid which is given by the sum of two contributions, $j = j_D + j_M$: in fact the Schwinger effect can be described as a dielectric breakdown in which dipoles are produced by quantum tunneling hence changing the local dipole moment of the vacuum, with the corresponding current given by j_D; then the charges move in the medium due to the residual electric field giving rise to a conductive current, j_M. The color charge and current densities depend on the particle distribution function: hence they link the Maxwell equations (2) to the kinetic equation (1). We solve self-consistently the field and kinetic equations: in this way we take into account the back reaction of particle production and propagation on the color field.



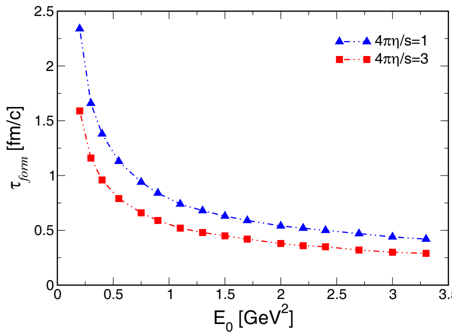


Figure 1: *Left panel.* Chromoelectric field strength (main panel) and particle number produced per unit of transverse area and rapidity (inset panel) as a function of time. *Right panel.* Proper formation time of quark-gluon plasma as a function of the initial field strength.

4 Results and discussion

In the right panel of Fig. 1 we plot the color electric field strength averaged in the central rapidity region $|\eta| < 0.5$ (main panel) and particle number produced per unit of transverse area and rapidity (inset panel) as a function of time. The calculations are shown for several values of η/s. The chromoelectric field experiences a rapid decay for small values of η/s, which in fact is a power law decay as it can be proved analytically [1]. On the other hand for intermediate and large values of η/s the electric field experience fluctuations during time evolution, due to the formation of plasma modes which affect the late time evolution of the system. In the inset of Fig. 1 we plot the number of produced gluons per unit of transverse area and rapidity versus time. We find that regardless of the value of η/s the particles are produced at very early time, approximately within 0.5 fm/c, with the only expection of very few particles produced at later times in the case $4\pi\eta/s = 10$.

On the right panel of Fig. 1 we plot the proper formation time of the quark-gluon plasma, for two values of η/s, as a function of the initial electric field strength, E_0. These data complete the ones shown in the left panel of Fig. 1 in which only one value of E_0 is considered. It is interesting that unless E_0 is too small, quark-gluon plasma is formed by the field decay within the first fm/c.

On the left panel of Fig. 2 we plot the ratio among longitudinal and transverse pressures, respectively P_L and P_T, as a function of time, for several values of η/s. These quantities are computed cell by cell in the local

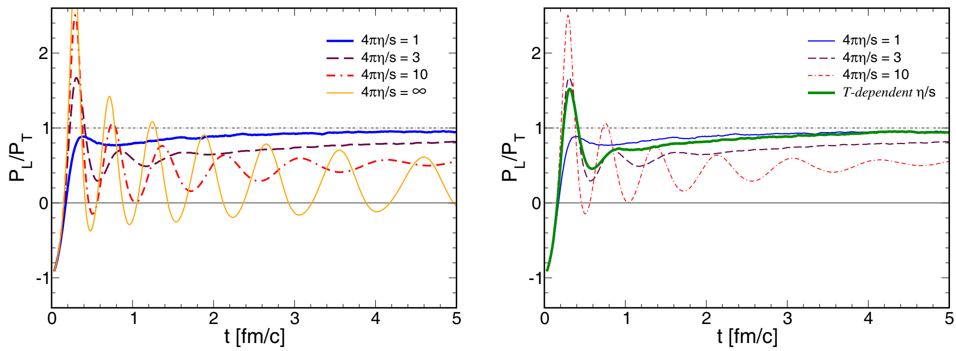


Figure 2: *Left panel.* Ratio P_L/P_T versus time for several values of η/s. *Right panel.* Same quantity for the case of a temperature dependent η/s (few results with fixed η/s are shown to ease comparison).

rest frame of the fluid, then averaged in the rapidity range $|\eta| < 0.5$; both particles and field contributions are taken into account in this calculation. A perfect isotropy requires $P_L = P_T$. The initial longitudinal pressure at initial time is negative and $P_L/P_T = -1$ because at initial time the system is made of pure longitudinal chromoelectric field. Hence the initial condition is highly anisotropic. However as soon as particles are produced, they give a positive contribution to the longitudinal pressure and the field magnitude decreases, eventually leading to a positive pressure. For all the value of η/s we consider in our simulations we find that the time needed to the total longitudinal pressure to be positive is about 0.2 fm/c. Moreover in the case $4\pi\eta/s = 1$ the strong interactions among the particles remove the initial pressure anisotropy quite efficiently and quickly: in this case $P_L/P_T \approx 0.7$ within 0.6 fm/c, then the ratio tends to increase towards 1 within the time evolution of the system. This would justify the use of viscous hydrodynamics with $\tau_0 \approx 0.6$ fm/c as commonly done. On the other hand for larger values of η/s plasma oscillations govern the evolution of P_L/P_T; moreover at large times P_L/P_T is quite smaller than 1, hence in these cases the system is quite far from the isotropic regime.

On the right panel of Fig. 2 we superimpose P_L/P_T obtained with a temperature dependent η/s. This temperature dependence is borrowed from Ref. [14], which is linearly increasing for $T \geq T_c$ while linearly decreasing for $T \leq T_c$; such a temperature dependence might be relevant for collisions at the LHC energy in which a large temperature range is expected to be experienced by the quark-gluon plasma; moreover it permits to implement a kinetic freezout at $T \approx T_c$ then mimicking some milder interaction in the hadron phase. We notice that besides a bump at initial times, the behaviour of P_L/P_T is comparable to the one we obtain for $4\pi\eta/s = 1$ after ≈ 1.5 fm/c, signaling that the larger initial η/s delays isotropization time, but the delay does not change drastically the picture obtained for $4\pi\eta/s = 1$.

5 Conclusions

In conclusions, in this work we have discussed a model for early stages of relativistic heavy ion collisions, coupling the dynamics of a color field to that of the quark-gluon plasma produced by the decay of the field itself. We have studied self-consistently the dynamics of the system field+particles by coupling field and relativistic Boltzmann equations, assuming a simplified initial condition consisting of a single color flux tube and a 1+1 dimensional expansion. Our main results concern about isotropization, thermalization and formation of the quark-gluon plasma: we have found that unless we consider values of η/s very large, thermalization, isotropization and particle creation occur within a time of ≈ 1 fm/c. Improvements of the present results include a realistic initial condition as well as 3+1 dimensional expansion, which will permit the computation of collective flows: these interesting improvements will be the subject of forthcoming publications.

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