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Modeling early time dynamics of relativistic heavy ion collisions

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Abstract. We studied isotropization and thermalization of the quark-gluon plasma produced by decaying color-electric flux tubes created at the very early stages of relativistic heavy ion collisions. We coupled the dynamical evolution of the initial field, which decays to a plasma by the Schwinger mechanism, to the dynamics of the many particles system produced by the decay. The evolution of such a system is described by relativistic transport theory at fixed values of the viscosity over entropy density ratio. Within a single self-consistent calculation scheme we computed quantities which serve as indicators of the equilibration of the plasma for a 1+1 dimensional expanding geometry. We find that the initial color-electric field decays within 1 fm/c and particles production occurs in less than 1 fm/c; however, in the case of large viscosity oscillations of the field appear along the entire time evolution of the system, affecting also the behaviour of the ratio between longitudinal and transverse pressure. In case of small viscosity we find that the isotropization time is about 0.8 fm/c and the thermalization time is about 1 fm/c, in agreement with the common lore of hydrodynamic approaches.

1. Introduction

Ultra-relativistic heavy ion collisions represent the only way to have experimental access to the high temperature and small barion density region of the QCD phase diagram and study the formation and the evolution of the quark-gluon plasma. One of the most compelling issues in this framework is the understanding of the early stages of such collision processes which are strongly out of equilibrium. In the general picture of relativistic heavy ion collisions, just after the two colliding nuclei had passed one through each other, a peculiar configuration of longitudinal color-electric and color-magnetic fields is produced. This state of classical color flux tubes, known as Glasma, should become an isotropic and thermalized quark-gluon plasma in a very short time, a small fraction of fm/c. It is very interesting to understand which are the mechanisms responsible of such particle formation and equilibration. In our approach a longitudinal color-electric field decays to a particle plasma through the Schwinger effect; the evolution equation of the initial field is coupled to the relativistic transport equation which describes the evolution of the many particle system and leads to an isotropic and thermalized state by means of collisions. Thus, we

model early time dynamics of relativistic heavy ion collisions treating in a self-consistent way color-electric field and particles produced by its decay.

2. Abelian flux tube model and Schwinger mechanism

In our simulation of the very early stage of relativistic heavy ion collisions we implement the Abelian flux tube model [1, 2, 3], focusing on a single flux tube of a given transverse area. Although this geometry is a strong simplification of the realistic initial condition relevant for heavy ion collision experiments, in which one should consider an ensemble of several tubes more similar to the Glasma configuration, our model allows to better understand the physics which underlies the formation of the quark-gluon plasma and to compute quantities which serve as indicators of thermalization and isotropization of the system and of timescales of such processes. Moreover, we neglect for simplicity initial longitudinal color-magnetic fields which should be taken into account in a more appropriate description of the Glasma state. Thus, our initial condition is a purely longitudinal color-electric field E which then decays into particle quanta by the Schwinger mechanism, which consists in a vacuum instability towards the creation of particle pairs by a strong electric field and is related to the existence of an imaginary part in the quantum effective action of a pure electric field [4, 5, 6].

The decay probability per unit of spacetime and invariant momentum space produced by the decay of the electric field through the Schwinger effect is

$$\frac{dN_{jc}}{d\Gamma} \equiv p_0 \frac{dN_{jc}}{d^4x \, d^2p_T \, dp_z} = \frac{\mathcal{E}_{jc}}{4\pi^3} \left| \ln \left(1 \pm e^{-\pi p_T^2 / \mathcal{E}_{jc}} \right) \right| \delta(p_z) p_0, \tag{1}$$

assuming massless quanta and the plus (minus) sign corresponding to the creation of a boson (fermion-antifermion) pair. In this equation p_T and p_z refer to each of the two particles created from the vacuum; $\mathcal{E}$ is the effective force which acts on the tunneling pair, depends on color and flavor and is given by $\mathcal{E}_{jc} = (g|Q_{jc}E| - \sigma_j)\,\theta\,(g|Q_{jc}E| - \sigma_j)$, where σ_j corresponds to the string tension depending on the flavor considered and $p_0 = \sqrt{p_T^2 + p_z^2}$ is the single particle kinetic energy. The Q_{jc} are color-flavor charges which in the case of quarks are $Q_{j1} = 1/2$, $Q_{j2} = -1/2$, $Q_{j3} = 0$, for $j = 1, N_f$; for antiquarks, corresponding to negative values of j, the color-flavor charges are just minus the corresponding charges for quarks; finally for gluons (which in our notation correspond to $j = 0$) the charges are $Q_{01} = 1$, $Q_{02} = 1/2$, $Q_{03} = -1/2$, $Q_{04} = -Q_{01}$, $Q_{05} = -Q_{02}$, $Q_{06} = -Q_{03}$. We have only six gluons, corresponding to the non-diagonal color generators; the two gluon fields corresponding to the diagonal color generators have vanishing coupling with the background field, hence they cannot be produced by the Schwinger mechanism.

Since the dynamics is assumed to be Abelian, classical field dynamics is governed by Maxwell equations, in which the back-reaction of particle production and propagation on the color field is taken into account by means of polarization and conductive currents. We limit our simulation to a one dimensional expansion along the direction of the initial color-electric field which, being longitudinal at the beginning, remains longitudinal along all the time evolution, since transverse currents are not produced.

3. Relativistic transport theory and field equations

In order to study the evolution of the system self-consistently we couple the dynamical evolution of the color field to the dynamics of the many-particle system produced by the decay. The latter is described by the relativistic Boltzmann transport equation which, in presence of a gauge field $F^{\mu\nu}$, is given by

$$\left(p^\mu \partial_\mu + g Q_{jc} F^{\mu\nu} p_\nu \partial_\mu^p \right) f_{jc}(x,p) = \frac{dN_{jc}}{d\Gamma} + C_{jc}\,[f], \tag{2}$$

where $f_{jc}(x,p)$ is the distribution function for flavor j and color c and $F^{\mu\nu}$ is the color-electromagnetic tensor. On the right hand side $dN/d\Gamma$ is the source term, which describes the creation of quarks, antiquarks and gluons due to the decay of the color-electric field and is given by Eq. 1, and $C[f]$ represents the collision integral, which accounts for change of f due to collision processes and is responsible for a finite viscosity ($\eta/s \neq 0$). To solve numerically the Boltzmann equation we divide the space into a tridimensional lattice and use the standard test particle method to sample $f(x,p)$; then the collision integral is solved by means of a stochastic algorithm [7, 8, 9, 10, 11, 12, 13, 14, 15]. Within one single theoretical approach one can follow the entire dynamical evolution of the system produced in relativistic heavy ion collisions. Usually input of a transport approach are cross sections of a fixed set of microscopic processes, but in our model we start from a fixed value of the viscosity over entropy density ratio $\eta/s \neq 0$ and compute cross sections according to the Chapman-Enskog equation [12], simulating a fluid with the desired shear viscosity. In this way we make a more direct link between transport theory, based on a description in terms of parton distribution functions, and hydrodynamical formulations, in which the dynamics is governed by macroscopic quantities.

Following previous work on this subject, we assume that the dynamics of the color field is Abelian and invariant for boosts along the longitudinal directions [3]; hence the color-electric field E satisfies the classical Maxwell equations which assume a boost-invariant formulation:

$$\frac{dE}{d\tau} = -j_M - j_D, \tag{3}$$

where τ is the proper time and the right hand side corresponds to the opposite of the total current computed in the local rest frame of the fluid, given by two contributions: the conductive current which depends on the motion of the charges and the polarization current which is due to the dipoles created by the Schwinger effect. Color charges and currents depend on parton distribution functions as well as the kinetic equations, hence allowing to solve field and particles equations in a self-consistent way and to take into account the back-reaction of particles on the field. Refer to [1, 2] for more details.

4. Results for a 1+1D expansion

In this section we show the effect of a boost-invariant longitudinal expansion on pair production due to the decay of a color-electric flux tube.

In the left panel of Fig. 1 we plot the color-electric field strength as a function of time for three different values of η/s. The electric field is averaged in the central rapidity region $|y| < 0.5$. The initial value of the color-electric field used in the simulations is $E_0 = 2.2$ GeV^2, in agreement with the CERN Large Hadron Collider case of Ref. [2]. We find that the color-electric field shows a quick decay for small values of viscosity, due to the fact that in this case the coupling among particles is large, meaning collisions are very efficient in randomizing particle momenta in each cell, hence damping conductive currents that might sustain the field. For larger values of η/s the electric field experiences stronger fluctuations during all its time evolution. In the inset of the left panel of Fig. 1 we plot the number of particles produced per unit of transverse area and rapidity versus time. We find that regardless of the value of the viscosity, the particles are produced at very early times, approximately within 0.5 fm/c, with only few more particles produced at later times in the case $\eta/s = 10/4\pi$. We have checked that changing the initial value E_0 of the electric field does not modify the production time in a considerable way unless E_0 is very small, namely $E_0 \ll 1$ GeV^2. Moreover, the value of η/s affects the conversion of the initial classical field to particles only within a few percent. This indicates the Schwinger effect provides an efficient mechanism to produce a plasma from a classical field.

In the right panel of Fig. 1 we plot the ratio P_L/P_T, where P_L and P_T correspond to the longitudinal and transverse pressures respectively. These quantities are computed cell by cell in
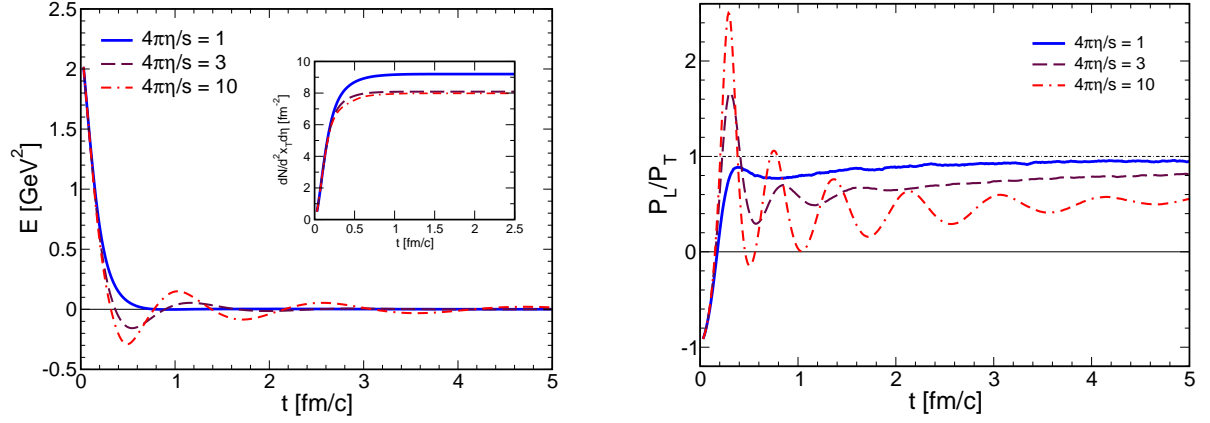
Figure 1. *Left panel.* Color-electric field strength averaged in the central rapidity region $|y| < 0.5$ (main panel) and particle number produced per unit of transverse area and rapidity (inset panel) versus time; the different curves correspond to different values of η/s. *Right panel.* Longitudinal over transverse pressure ratio as a function of time for several values of η/s. Figures are adapted from [1].
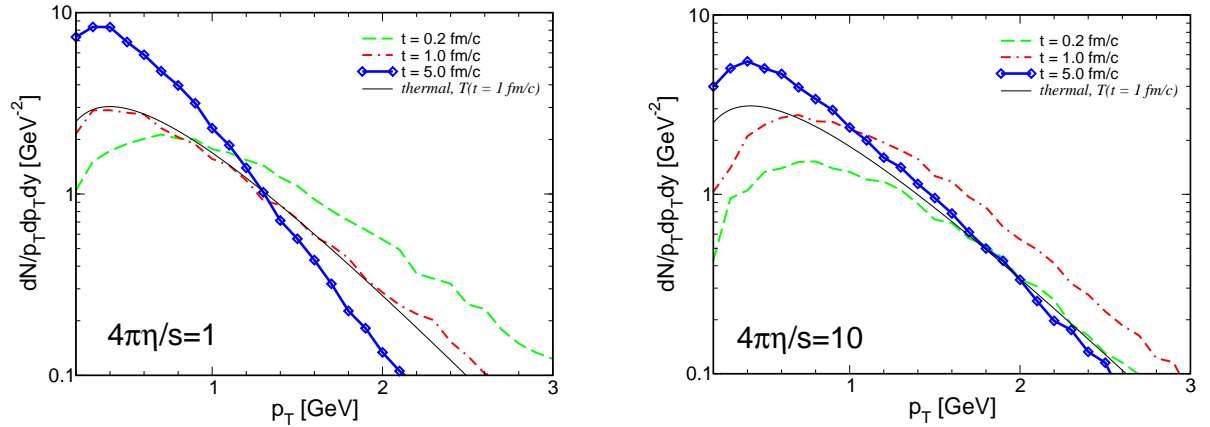
Figure 2. Particle spectra at midrapidity $|y| < 0.5$ for $\eta/s = 1/4\pi$ (left panel) and $\eta/s = 10/4\pi$ (right panel). For each values of η/s the spectrum at three different times is shown. The black thin solid lines correspond to the thermal spectrum at $t = 1$ fm/c. Figures are adapted from [1].

the local rest frame of the fluid and then averaged in the midrapidity region $|y| < 0.5$. The initial longitudinal pressure is negative and $P_L/P_T = -1$ because at initial time the system is made of pure longitudinal color-electric field. As soon as particles are produced, they give a positive contribution to the longitudinal pressure and the field magnitude decreases leading to a positive pressure. For all the values of viscosity considered, we find that the total longitudinal pressure becomes positive in about 0.2 fm/c. Moreover, in the case $\eta/s = 1/4\pi$ the strong interactions among the particles remove the initial pressure anisotropy quite efficiently and quickly, then the ratio tends to increase towards 1, which corresponds to an isotropic system. This would justify the use of viscous hydrodynamics with an initial time of 0.6 fm/c in which the pressure ratio is about 0.7. However, the larger the viscosity of the fluid the larger are the oscillations of P_L/P_T; for example, in the case $\eta/s = 10/4\pi$ the pressure ratio experiences several oscillations which follow the alternation of maxima of $|E|$ (corresponding to minima of P_L because the field gives a negative contribution to P_L) and zeros of E (corresponding to maxima of P_L). Moreover, at large times P_L/P_T is quite smaller than 1.

In Fig. 2 we plot the gluon spectra at midrapidity $|y| < 0.5$ for two different values of viscosity: left panel corresponds to $\eta/s = 1/4\pi$, right panel to $\eta/s = 10/4\pi$. For each value of the viscosity the spectrum at three different times is shown. The thin solid black line corresponds to a thermal spectrum, namely

$$\frac{dN}{p_T dp_T dy} \propto p_T e^{-\beta p_T}, \tag{4}$$

which describes a thermalized system in three spatial dimensions at the temperature $T = 1/\beta$ corresponding to the same energy density of the produced particles spectrum at $t = 1$ fm/c. We find that for $\eta/s = 1/4\pi$ the system efficiently thermalizes in $t = 1$ fm/c, as evident by comparing the thermal spectrum (black thin line) with simulation data (dot-dashed thin red line). For $\eta/s = 10/4\pi$ the spectrum of produced particles at $t = 1$ fm/c is in disagreement with the corresponding thermal spectrum, meaning the system is not completely thermalized in three dimensions. Moreover, the very mild change in the slope of the spectrum we measure from $t = 1$ fm/c to $t = 5$ fm/c shows that the system does not cool down efficiently in this case; this is expected because the larger the viscosity the larger is the energy dissipated into heat, hence the system cools down more slowly than in the case of small viscosity.

5. Conclusions

In this work we have reported some of our results on simulations of the evolution of color-electric flux tubes which decay to a quark-gluon plasma by means of the Schwinger mechanism, coupling relativistic transport theory to Maxwell equations for a self-consistent solution. We have focused on quantities like decay time of the color-electric field, isotropization and thermalization rates of the fluid produced by the decay of the field in the tube, which serve as indicators of the equilibration of the particle plasma. These simulations are important in the context of ultra-relativistic nuclear collisions, where flux tubes of strong color fields are expected to be produced in the very early stage. We have studied the case of flux-tube decay in a box with a longitudinal expansion. The approach developed here, based on a stochastic solution of the relativistic Boltzmann equation, has the advantage to be easily extended to more realistic simulations, making it possible to study the impact of the early dynamics on observables like elliptic flow, photon and dilepton production.

References
[1] Ruggieri M, Puglisi A, Oliva L, Plumari S, Scardina F and Greco V 2015 *Phys. Rev.* C **92** 064904
[2] Ryblewski R and Florkowski W 2013 *Phys. Rev.* D **88** 034028
[3] Florkowski W 2010 *Phenomenology of Ultra-Relativistic Heavy-Ion Collisions* (Singapore: World Scientific) p 416
[4] Heisenberg W and Euler H 1936 *Z. Phys.* **98** 714-32
[5] Schwinger J S 1951 *Phys. Rev.* **82** 664-79
[6] Dunne G V in 2005 *From Fields to Strings: Circumnavigating Theoretical Physics* vol 1 ed Shifman M, Vainshtein A and Wheater J (Singapore: World Scientific) pp 445522
[7] Xu Z, Greiner C and Stocker H 2008 *Phys. Rev. Lett.* **101** 082302
[8] Xu Z and Greiner C 2009 *Phys. Rev.* C **79** 014904
[9] Bratkovskaya E L, Cassing W, Konchakovski V P and Linnyk O 2011 *Nucl. Phys.* A **856** 162-82
[10] Ferini G, Colonna M, Di Toro M and Greco V 2009 *Phys. Lett.* B **670** 325-9
[11] Plumari S and Greco V 2012 *AIP Conf. Proc.* **1422** 56-61
[12] Plumari S, Puglisi A, Scardina F and Greco V 2012 *Phys. Rev.* C **86** 054902
[13] Plumari S, Puglisi A, Colonna M, Scardina F and Greco V 2013 *J. Phys. Conf. Ser.* **420** 012029
[14] Ruggieri M, Scardina F, Plumari S and Greco V 2013 *Phys. Lett.* B **727** 177-81
[15] Ruggieri M, Scardina F, Plumari S and Greco V 2014 *Phys. Rev.* C **89** 054914