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Early Stages of Relativistic Heavy Ion Collisions

Lucia Oliva*, **Armando Puglisi, Salvatore Plumari, Francesco Scardina, Vincenzo Greco**
Department of Physics and Astronomy, University of Catania, Via S. Sofia 64, 95123 Catania, Italy and INFN-Laboratori Nazionali del Sud, Via S. Sofia 62, 95123 Catania, Italy
E-mail: lucia.oliva@lns.infn.it, puglisia@lns.infn.it, salvatore.plumari@hotmail.it, scardinaf@lns.infn.it, greco@lns.infn.it

Marco Ruggieri
Department of Physics and Astronomy, University of Catania, Via S. Sofia 64, 95123 Catania, Italy and College of Physics, University of Chinese Academy of Sciences, Yuquanlu 19A, Beijing 100049, China
E-mail: marco.ruggieri@ucas.ac.cn

We investigated isotropization and thermalization of the quark-gluon plasma produced by decaying color-electric flux tubes created at the very early stages of ultra-relativistic heavy ion collisions. The dynamical evolution of the initial classical field, which decays to a plasma by the Schwinger mechanism, is coupled to the dynamics of the many particles system produced. The evolution of such a system is described by relativistic transport theory at fixed values of the viscosity over entropy density ratio. With a single self-consistent computation we obtained quantities which serve as indicators of the equilibration of the plasma for a 1+1 dimensional expanding geometry and for the more realistic 3+1 dimensional case. 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 whole 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 hydrodynamics.

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*Speaker.

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1. Introduction

Heavy ion collisions at ultra-relativistic energy are the main tool to experimentally investigate the high temperature and small barion density region of the QCD phase diagram and study the creation and the evolution of a deconfined phase of nuclear matter, called quark-gluon plasma. The early times of such processes just after the collision of the two heavy nuclei are characterized by a strongly out of equilibrium stage, which is not well understood until now.

A possible scenario of these first moments of relativistic heavy ion collisions is that 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 is known as Glasma and should become an isotropic and thermalized quark-gluon plasma in a very short time, a small fraction of fm/c. The Schwinger effect could be responsible of such particle formation and equilibration. This mechanism, first theorized by Schwinger in 1951 [1], consists of a vacuum instability towards the formation of particles pairs by a strong electric field. In our approach a longitudinal color-electric field decays to a plasma of quarks and gluons through the Schwinger effect; the temporal evolution of the particles system is given by relativistic transport equation, which are coupled with evolution equation of the initial field. With this self-consistent description, which leads to an isotropic and thermalized state by means of collisions among particles, we model early time dynamics of relativistic heavy ion collisions.

2. Flux tube model with Schwinger mechanism

In our study we simulate the very early stage of relativistic heavy ion collisions implementing the Abelian flux tube model [2, 3, 4], with focus on a single flux tube of a given transverse area. This geometry is a strong simplification of the realistic initial condition relevant for heavy ion collision experiments, but our model allows to better understand the physics which underlies the formation of the quark-gluon plasma and to compute quantities, such as momentum spectra and pressure ratios, which serve as indicators of thermalization and isotropization of the system and of timescales of such processes. Moreover, our initial condition is a purely longitudinal color-electric field E, neglecting for simplicity initial longitudinal color-magnetic fields which should be taken into account in a more appropriate description of the Glasma state. The initial field then decays into particle quanta by the Schwinger mechanism, which predicts pair formation in a strong electric field and is related to the existence of an imaginary part in the quantum effective action of a pure electric field [1, 5, 6].

Assuming massless particles, the decay probability per unit of spacetime and invariant momentum space produced by the decay of the electric field through the Schwinger effect is

$$\frac{dN_{jc}}{d\Gamma} \equiv p_0 \frac{dN_{jc}}{d^4x d^2p_T dp_z} = \frac{\mathscr{E}_{jc}}{4\pi^3} \left| \ln\left(1 \pm e^{-\pi p_T^2/\mathscr{E}_{jc}}\right) \right| \delta(p_z) p_0, \tag{2.1}$$

where the plus (minus) sign corresponds 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; $\mathscr{E}$ is the effective force which acts on the tunneling pair, depends on color and flavor and is given by $\mathscr{E}_{jc} = (g|Q_{jc}E| - \sigma_j)\,\theta\,(g|Q_{jc}E| - \sigma_j)$, where σ_j corresponds to the string tension depending on

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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, because we assume that the initial color field is polarized along the third direction of adjoint color space; 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.

Moreover, because 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

We study the evolution of the system in a self-consistent way coupling the dynamical evolution of the color-electric 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

$$\left(p^\mu \partial_\mu + gQ_{jc}F^{\mu\nu} p_\nu \partial_\mu^p\right) f_{jc}(x,p) = \frac{dN_{jc}}{d\Gamma} + C_{jc}[f], \tag{3.1}$$

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 quark-antiquark pairs and gluon pairs due to the decay of the color field and is given by Eq. 2.1, and $C[f]$ represents the collision integral, which accounts for change of f due to collision processes and is responsible for a finite value of the viscosity ($\eta/s \neq 0$). In order to solve numerically the Boltzmann equation we divide the space into a tridimensional lattice and use the test particle method to sample $f(x,p)$; then the collision integral is computed by means of a stochastic algorithm [7, 8, 9, 10, 11, 12, 13, 14, 15]. With this theoretical approach one can follow the entire dynamical evolution of the system produced in relativistic heavy ion collisions. Usually input of a transport code are cross sections of a fixed set of microscopic processes, but in our model we start from a fixed viscosity over entropy density ratio $\eta/s \neq 0$ and compute cross sections σ_{tot} according to the Chapman-Enskog equation [12]:

$$\sigma_{tot} = \frac{1}{5}\frac{T}{\rho g(a)}\frac{1}{\eta/s}, \tag{3.2}$$

where g is a function of $a = m_D/2T$ and T and ρ are respectively temperature and density of the system. Simulating in this way a fluid with the desired shear viscosity, we make a more direct link between transport theory, which is based on a description in terms of parton distribution functions, and hydrodynamical formulations, in which the dynamics is governed by macroscopic quantities.

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Finally, we assume that the dynamics of the color field is Abelian and invariant for boosts along the longitudinal directions, as done in previous works on the same subject [4]; hence the color-electric field E satisfies the classical Maxwell equations which, in a boost-invariant formulation, are given by:

$$\frac{dE}{d\tau} = -j_M - j_D, \tag{3.3}$$

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 self-consistently and to take into account the back-reaction of particles on the field. See [2, 3] for more details.

4. Results for a 1+1D expansion

In this section we show the effect of a boost-invariant longitudinal expansion on a color-electric flux tube which decays in particles pair.

In the left panel of Fig. 1 the color-electric field strength is plotted 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. [3]. We find that the color-electric field shows a quick decay for small values of viscosity, because in this case the coupling among particles is large, meaning collisions are very efficient in making isotropic particle momenta in each cell, thus damping conductive currents that might sustain the field through Eq. 3.3. For larger values of viscosity the electric field is affected by strong fluctuations during the whole 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 η/s, the particles are produced very early, 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 with a different initial value E_0 of the electric field the production time does not change in a considerable way unless E_0 is very small, namely $E_0 \ll 1$ GeV^2. Moreover, the value of the viscosity affects the conversion of the initial color-field to pairs only within a few percent. This proves that the Schwinger effect is 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 versus time, where P_L and P_T are longitudinal and transverse pressure respectively. These quantities are computed cell by cell in the local rest frame of the fluid and then averaged in the midrapidity region $|y| < 0.5$. At initial time $P_L/P_T = -1$ because the system is made of pure longitudinal color-electric field, to which corresponds a negative longitudinal pressure. As soon as particles are produced, they give a positive contribution to P_L 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 corre-

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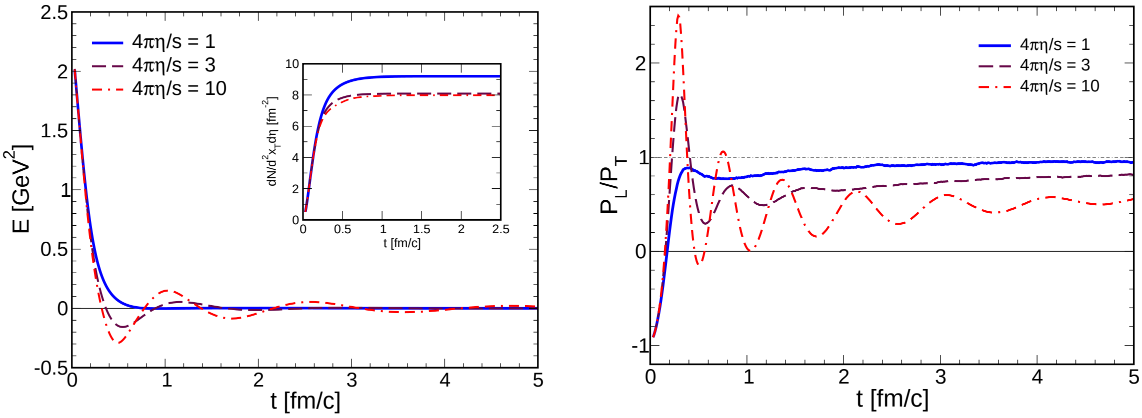

Figure 1: *Left panel.* Color-electric field strength averaged in the central rapidity region $|y| < 0.5$ (main panel) and particle number produced per unit of transverse area and rapidity (inset panel) versus time; the different curves correspond to different values of η/s. *Right panel.* Longitudinal over transverse pressure ratio as a function of time for several values of η/s. Figures are adapted from [2].

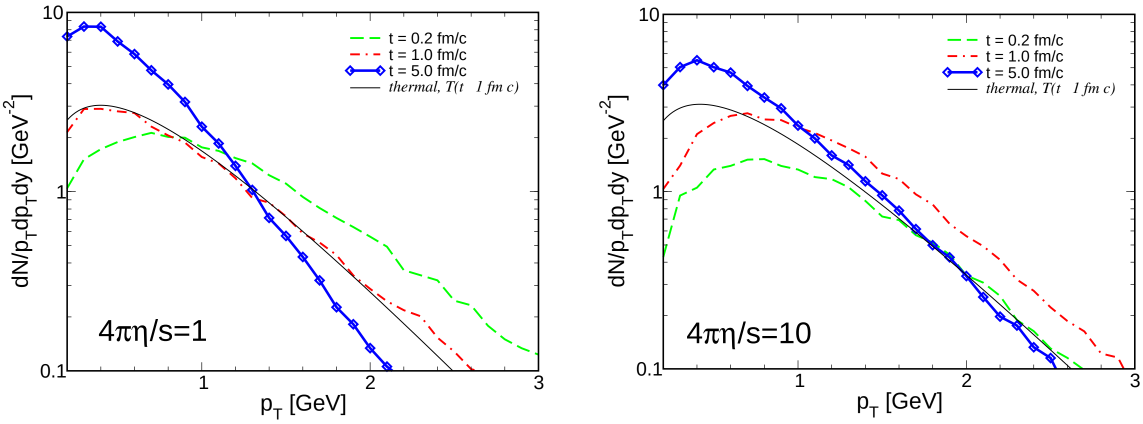

Figure 2: Particle spectra at midrapidity $|y| < 0.5$ for $\eta/s = 1/4\pi$ (*left panel*) and $\eta/s = 10/4\pi$ (*right panel*). For each values of η/s the spectrum at three different times is shown. The black thin solid lines correspond to the thermal spectrum at $t = 1$ fm/c. Figures are adapted from [2].

sponds 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 system 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 the ratio P_L/P_T is quite smaller than 1.

In Fig. 2 the gluon spectra at midrapidity $|y| < 0.5$ is plotted 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

$$\frac{dN}{p_T dp_T dy} \propto p_T e^{-\beta p_T}, \tag{4.1}$$

which describes a thermalized system in three spatial dimensions at the temperature $T = 1/\beta$

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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 within 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 partons 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, as expected because the larger the viscosity the larger is the energy dissipated into heat; therefore the system cools down more slowly than in the case of small viscosity.

5. Results for a 3+1D expansion

The case of a 1+1D expansion is interesting because a longitudinal expansion characterizes the very early times on ultra-relativistic heavy-ion collisions. Nevertheless, in this section we show results for the more realistic case of a 3+1D expanding flux tube with the same initial longitudinal color-electric field of $E_0 = 2.2$ GeV^2 of the one-dimensional case. While in the longitudinal expansion transverse components of the color-electric field do not develop since j_x and j_y are zero due to periodic conditions in the transverse plane, in the three-dimensional expansion we allow to the formation of longitudinal as well as transverse components of currents and field. In this case a magnetic field can be produced dynamically, even if absent in the initial condition, because of the transverse components of the electric field ($d\mathbf{B}/dt = -\nabla \times \mathbf{E}$); however, we have checked that the magnitude of the transverse components of $\mathbf{E}$ as well as of its curl are negligible so the magnetic field behaves just as a very small fluctuation and does not affect the dynamics of the plasma.

The Maxwell equations for the color-electric field are in this case given by

$$\nabla \cdot \mathbf{E} = \rho, \qquad \frac{\partial \mathbf{E}}{\partial t} = -\mathbf{j}, \tag{5.1}$$

where t is the time in the laboratory frame and the current and the charge density depend also on transverse coordinates x and y. The initial field is still only longitudinal, whereas transverse components of $\mathbf{E}$ will be generated by transverse currents according to Eq. 5.1.

In the left panel of Fig. 3 we plot the components of the color-electric field strength averaged in the central rapidity region $|y| < 0.5$ as a function of time. The behaviour of E_z, plotted in the main panel for three different values of viscosity, is similar to the one-dimensional case, but with weaker fluctuations in the case of large viscosity; this is due to the fact that in the three-dimensional case a smaller longitudinal current which sustains the field develops, because of transverse expansion of particles. In the inset graph the transverse components of the electric field are shown for $\eta/s = 1$; such components are tiny and do not affect the dynamics of the system, since there is no substantial formation of electric currents in the transverse plane.

In the right panel of Fig. 3 we show the number of particles produced per unit of transverse area and rapidity versus time. We find that as in the 1+1D result particles are produced very early, within 0.5 fm/c, independently of the value of η/s, which affects very mildly the conversion of the initial field to a plasma.

In the left panel of Fig. 4 we show the ratio P_L/P_T as a function of time. Pressures are computed cell by cell in the local rest frame of the fluid and then averaged in the midrapidity region $|y| < 0.5$

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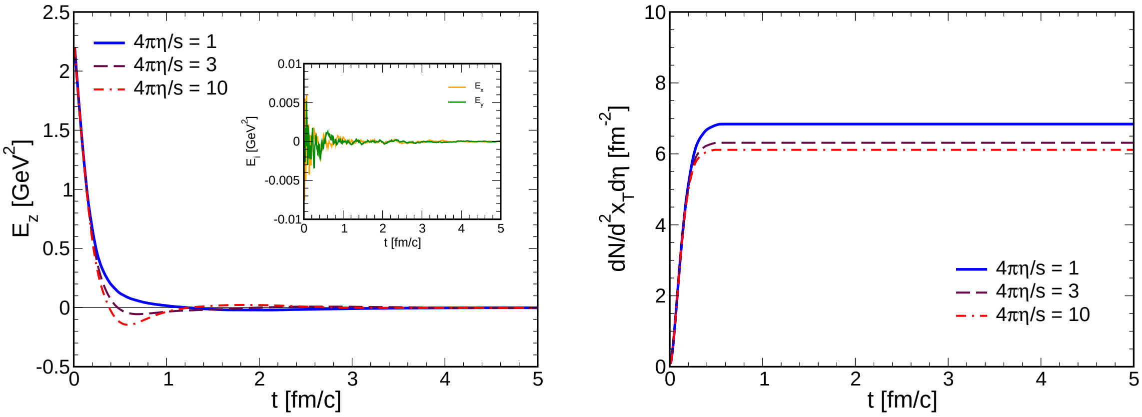

Figure 3: *Left panel.* Longitudinal (main graph) and transverse (inset) components of the color-electric field strength averaged in the central rapidity region $|y| < 0.5$ as a function of time. *Right panel.* Particle number produced per unit of transverse area and rapidity (inset panel) versus time. The different curves correspond to different values of η/s.

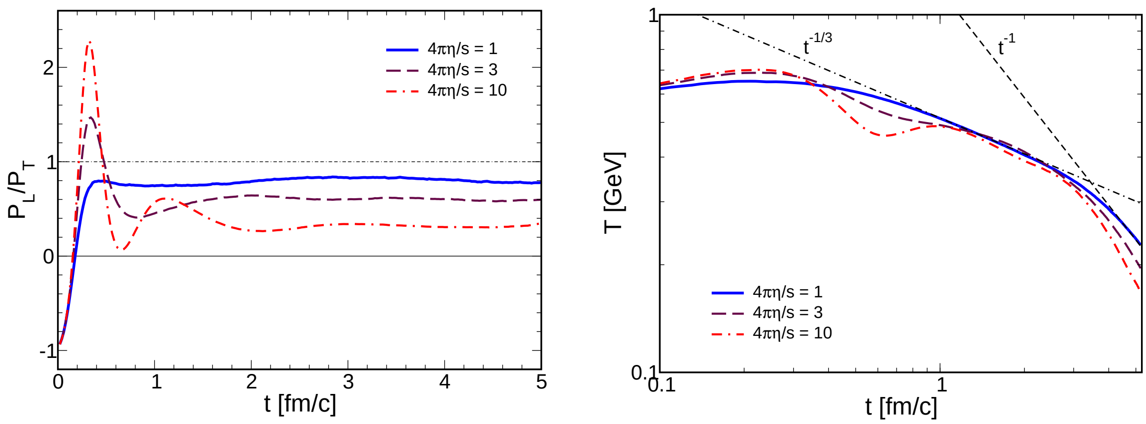

Figure 4: Temporal evolution of longitudinal over transverse pressure ratio (*left panel*) and local temperature (*right panel*) as a function of time for several values of η/s. Both quantities are averaged in the central rapidity region $|y| < 0.5$ and in a central region of the transverse plane

and in a central portion of transverse plane. For all the values of viscosity considered, the pressures ratio shows the same behaviour of the 1+1D case: the larger the viscosity of the fluid the larger are the oscillations of P_L/P_T.

In the right panel of Fig. 4 we plot the temporal evolution of the temperature of the fluid, defined by the ratio $T = E/3N$, as in the case of a thermalized system. T is evaluated in the local rest frame of the fluid and averaged in the same rapidity and transverse plane regions of the pressures. We find that the temperature scales as $t^{-1/3}$ for about $t = 1-2$ fm and as t^{-1} for $t > 4$ fm, meaning the longitudinal expansion characterizes early times after particles production ceases while the three-dimensional expansion becomes dominant at later times. These time dependences of temperature are in agreement with expectations from ideal hydro for a longitudinal and 3D expansion respectively, see for example [16, 17]. For what concerns spectra we have checked that their qualitative behaviour is similar to that found in the one-dimensional case: for $\eta/s = 1/4\pi$ the spectrum is completely thermalized in three dimensions within 1 fm/c, whereas for larger viscosity

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the system does not cool down in efficient way.

6. Conclusions

We have reported some of our results on the study of the initial stages of relativistic heavy ion collisions, describing in particular 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 shown decay time of the color-electric field, ratio of longitudinal over transverse pressure P_L/P_T, that we take as a measure of isotropization, and thermalization rates of the fluid produced by the decay of the field, which indicates how and with which timescales the particle plasma equilibrates. We have found that thermalization and partial isotropization occur on a time scale of the order of 1 fm/c for small viscosities; on the other hand in the case of large η/s the plasma does not thermalize, and P_L/P_T versus time is characterized by oscillations which make impossible to talk about isotropization. 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 times. We have studied the case of flux-tube decay in a box with a longitudinal expansion as well as for a three-dimensional expansion, finding that the aforementioned timescales are not affected by turning from one-dimensional to three-dimensional expansion. The approach used here, based on a stochastic solution of the relativistic Boltzmann equation, has the advantage to be easily extended to simulations with more realistic initial conditions, making it possible to study the impact of the early dynamics on observables like elliptic flow, photon and dilepton production.

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