Pressure isotropization of an equilibrating quark-gluon plasma

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Abstract. Pressure isotropization of an equilibrating quark-gluon plasma produced in relativistic heavy ion collisions is studied within the framework of a multi-phase transport model (AMPT). The time evolution of the bulk properties of the quark-gluon plasma is found to depend on its expansion dynamics and hadronization scheme as well as the scattering cross sections among quarks and gluons. It is further found that the pressure isotropy of the produced quark-gluon plasma can only be achieved temporarily, indicating that there is only partial thermalization during the time evolution of the quark-gluon plasma.

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1. Introduction

Both ideal hydrodynamics and non-equilibrium transport models can describe many of the RHIC data on the collective dynamics of produced matter. Although ideal hydrodynamics assumes local thermal equilibrium, its underlying equations of motion can also be used for the case when only local pressure isotropization is achieved \cite{1}. It is thus of interest to know whether pressure isotropization is achieved in transport models. Using the AMPT model \cite{2}, we have examined the pressure isotropization of the equilibrating quark-gluon plasma produced in relativistic heavy ion collisions by focusing on the central cell of the collisions where high density matter is produced. Only contributions from active particles, i.e., those that still undergo scattering, are included. Particles that have already frozen-out are not considered
as participants in the equilibration process and are excluded from the calculations. To obtain the connection with the hydrodynamical approach, we have considered the energy-momentum tensor of produced matter and extracted from it the energy density and pressure. The pressure isotropy is then characterized by the ratio of the longitudinal pressure to the transverse pressure. In the following, after a brief review of the AMPT model, we study the evolution of the bulk properties and the pressure anisotropy of the matter in the AMPT models and then give a brief summary.

2. The AMPT model

The AMPT model \cite{3, 4, 5, 6} is a hybrid model that uses different programs for different stages of relativistic heavy ion collisions. The publicly available AMPT code has two options: the default model and the string melting model. While both models use initial conditions from the Heavy Ion Jet Interaction Generator (HIJING) model \cite{7}, they treat differently the partonic stage and its hadronization. The default model extracts mini-jet partons from HIJING and uses Zhang’s Parton Cascade (ZPC) \cite{8} to evolve the parton system. At partonic freeze-out, these partons are reconnected with their parent strings and then hadronize via the Lund string fragmentation model \cite{9}. The produced hadrons undergo further interactions in A Relativistic Transport (ART) model \cite{10} until hadronic freeze-out. In the string melting model, instead of using the mini-jet partons, the partonic matter is formed by breaking up all the hadrons from HIJING according to their valence structures. The resultant quark-anti-quark plasma is again evolved using the ZPC parton cascade. As there are no strings in the system, quarks and anti-quarks hadronize by recombining with each other according to a coalescence model. The produced hadrons enter the ART model for final hadron evolution. It has been found that the default model gives a good description of particle spectra, but it underestimates their elliptic flows. The string melting model, on the other hand, can describe only spectra below 1 GeV/c and it gives, however, a good description of the anisotropic flows of hadrons. Other observables, such as $J/\psi$ production \cite{11}, strange \cite{12} and charm \cite{13} flows, and the two-pion correlation functions \cite{14}, have also been studied in the AMPT model.

3. Pressure isotropization of quark-gluon plasma

The bulk properties of the hot and dense matter in the central cell of central relativistic heavy ion collisions can be studied via its pressure to energy density ratio as a function of energy density (Fig. 1). This ratio gives the equation of state when the matter under study is infinitely large and in equilibrium. The central cell is specified by the space-time rapidity, and the local rest frame momentum is used for the calculation of energy density and momentum. The default model is seen to hadronize at higher energy density (about 5 GeV/fm$^3$) compared to the string
Isotropization of quark-gluon plasma melting model (hadronization is completed at about two orders of magnitude below). This shows that these two models serve as two limits: one is dominated by the hadron description and the other by the parton description. A careful examination further shows that in the default model, the system is hadronic at 3 fm/c while in the string melting model, the formation of the hadronic matter is delayed to 13 fm/c. Furthermore, the hadronization energy density becomes smaller as the parton cross section increases. Unlike for a resonance gas in equilibrium, the hadronic stage in the default model has a pressure to energy density ratio that decreases as energy density decreases. This happens when both the average hadron mass and average hadron kinetic energy decrease as functions of time while the mass to kinetic energy ratio increases. In other words, heavier particles are left behind in the central cell, leading to a reduced pressure to energy density ratio. The partonic stage in the string melting model also has a decreasing pressure to energy density ratio, and this is caused by the strange quarks that are left behind. Consequently, the strange quark percentage in the central cell increases with time.

![Graph](image)

**Fig. 1.** Pressure to energy density ratio as a function of energy density from the AMPT model.

Pressure isotropization can be characterized by the time evolution of the longitudinal pressure (pressure along the direction of the incoming nuclei (or beams)) to transverse pressure ratio (Fig. 2). In the AMPT model, particle production follows the inside-outside cascade picture of the Gyulassy-Wang model [15]. After two incoming nuclei pass through each other, particles are first produced in the center...
of the space between two receding nuclei and then produced near the nuclei with higher longitudinal velocities. In the local rest frame of produced matter, particles start with only transverse pressure. The anisotropy then increases as thermalization proceeds. It is clearly seen from Fig. 2 that in the string melting model there is a faster increase of the pressure anisotropy as a function of time. The pressure anisotropy crosses one at some time, but it does not stay at one for any significant period of time. This crossing is caused by the onset of transverse expansion as also seen from the time evolution of the energy density. In the string melting model, as the partonic cross section becomes larger, the initial anisotropy growth increases and its asymptotic value in the longitudinal expansion stage is also higher. The case with a 10 mb parton cross section can be characterized by a relaxation time of about 0.5 fm/c and an asymptotic pressure anisotropy value of about 0.8. As full pressure isotropization is only achieved temporarily, the system can only reach partial thermalization during the collisions. Whether this can lead to a large deviation from ideal hydrodynamical solutions is yet to be studied.

Fig. 2. Evolution of pressure anisotropy.

4. Conclusions

In summary, the pressure to energy density ratio in the default AMPT model is much smaller than that in the string melting AMPT model over a wide range of energy density. This also depends on the partonic cross section. Both the longitudinal
expansion and the transverse expansion can affect the pressure anisotropy. The hot and dense matter in the AMPT model does not reach full pressure isotropization. This may have implications on the difference in the description of the HBT radii by ideal hydrodynamics and by transport models.

The default model and the string melting model in the current AMPT model are two extreme descriptions of relativistic heavy ion collisions. Improvements on the model, such as hadronization at fixed time and inclusion of fragmentation processes, can be made for a more coherent description of the collisions. In addition, the effects of including parton number changing processes, plasma instabilities, and mean fields in the partonic matter are expected to lead to a better understanding of the underlying physics in relativistic heavy ion collisions.

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