QGP evolution from an ideal gas to perfect fluid

Captain R. Singh* and M. Mishra
Department of Physics, Birla Institute of Technology and Science, Pilani - 333031, INDIA

Introduction

Quantum chromodynamics (QCD) predicts that under extreme condition strongly interacting quarks and glouns go through a phase transition from hadronic matter to a free state of quarks and gluons, named as quark gluon plasma (QGP). The definition of QGP has changed over the time, earlier it was thought that QGP is a medium similar to an ideal gas. But the medium formed in heavy-ion collisions experiments at Relativistic Heavy Ion Collider (RHIC) and Large Hadron Collider (LHC) shows collective behavior, this medium is assumed to be QGP. In current scenario, QGP is a thermalized state of strongly interacting quarks and gluons exhibiting collectivity in medium. Ideal QGP is considered as massless non viscous medium and it uses bag model (BM) equation of state to compute the evolution of the medium. While in perfect QGP quarks are massive particle and medium is viscous. Here we are studying the evolution of QGP formed in heavy ion collisions at RHIC and LHC. The motivation of the study is to provide more realistic equation of state for QGP, to explain its signature like quarkonia suppression, jet quenching, etc. In present work, we are using quasi particle model (QPM) equation of state (EoS) to study the QGP medium evolution and compared our results with ideal QGP equation of state. Here we are considering (1+1)-dimensional expansion of QGP medium with incorporating the transverse expansion as a correction to it [1].

Time Evolution of QGP

The thermal excitations of the strongly interacting quarks and gluons are called Quasi-particles. quasi particle model (QPM) a phenomenological model, widely used to explain the more realistic and non-ideal behavior of QGP medium [2, 3]. QPM EoS considers QGP as a viscous medium and accounts for partonic interactions as well. It has been frequently used to analyze data. We use cooling law of temperature derived by using QPM EoS incorporating transverse expansion correction. It takes the following form after combining with the its variation with the centrality ($N_{part}(b)$) of heavy ion collisions;

$$T_{tr}(\tau_{tr}, b) = T_c \left(\frac{N_{part}(b)}{N_{part}(b_0)}\right)^{1/3} \times \left[\left(\frac{\tau_{tr}}{\tau_{QGP}}\right)^{\left(\frac{1}{R}-1\right)} \left(1 + \frac{a}{b' T_c^3}\right) - \frac{a}{b' T_c^3}\right]^{1/3} \tag{1}$$

Here T_c is the critical temperature for QGP formation and τ_{QGP} is the lifetime of the QGP. The τ_{tr} is the proper time after incorporating the transverse expansion, it is estimated by considering that thermodynamical densities are homogeneous in the transverse direction, so τ_{tr} can be written as: $\tau_{tr} \cong \tau + \frac{r}{c_s}(\frac{\sqrt{2}-1}{\sqrt{2}})$, where r is the transverse distance and c_s is speed of sound in the QGP medium. The values of parameters $a = 4.829 \times 10^7\ MeV^3$ and $b^{'} = 16.46$, are obtained from the fit as given in ref. [3]. The Raynold's number (R) is the measure of the medium viscosity, given as; $R^{-1} = \frac{3\eta}{4sT\tau_{tr}}$, here η is shear viscosity and s is entropy density of the medium. Also The volume of evolving QGP depends on the centrality of the collision and proper time τ, volume profile of the medium,$V(\tau, b)$, given as; $V(\tau,\ b) = v_0(b)\left(\frac{\tau_0}{\tau}\right)^{\left(\frac{1}{R}-1\right)}$. Here, $v_0(b)$ is the initial volume at time τ_0, obtained using Monte Carlo Glauber (MCG) model package. Similarly we have obtained the energy density ($\epsilon(\tau_{tr}, r)$) and pressure profile ($p(\tau_{tr}, r)$) of QGP using QPM EoS, given as;

$$\epsilon(\tau_{tr}, r) = c_1 + \frac{c_2}{\tau_{tr}^{c_s^2+1}} + \frac{4\eta}{3c_s^2\tau_{tr}}, \tag{2}$$

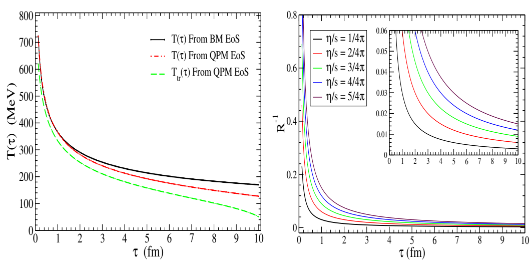
*Electronic address: captainriturajsingh@gmail.com

$$p(\tau_{tr}, r) = -c_1 + \frac{c_2 c_s^2}{\tau_{tr}^{c_s^2+1}} + \frac{c_3}{\tau_{tr}^{c_s^2}} + \frac{4\eta}{3\tau_{tr}}\left(\frac{c_s^2+1}{c_s^2-1}\right). \tag{3}$$

where c_1, c_2, and c_3 are constants which can be determined by imposing the initial boundary conditions on energy density and pressure.

Results and Discussions

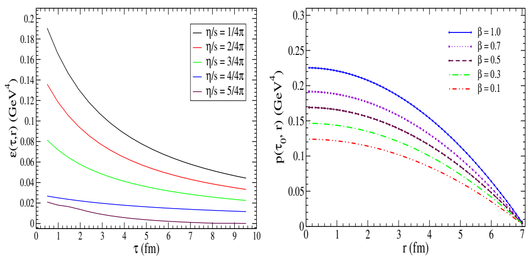
In Fig. 1(a), we have compared the temperature cooling law for QGP medium corresponding to the bag model (BM) and quasi-particle model (QPM) equation of states. Initially at $\tau \sim 0.1 - 1.0$ fm, QGP medium cools down with the same rate for both, BM as well as QPM EoS based expansion. Because at initial time medium is too hot and less interactive such that $R \approx 0$, which is almost similar to an ideal gas. The change in R with time is plotted in Fig. 1(b), in terms of R^{-1} for various values of η/s ratio, it shows that, in the due course of time, R increases, which leads to the faster cooling of QGP medium corresponding to QPM EoS based expansion which consideres QPG as a perfect fluid. Transverse correction in (1+1)-dimensional expansion makes the cooling more faster, as shown in Fig. 1(a). Also the time taken by the QGP to reach its temperature to T_c from T_0 i.e., QGP life-time would be reduced if transverse expansion is included. Fig 2(a), depicts that as



(a) (b)

FIG. 1: (a) Temperature with time (τ) is compared in between BM EoS and QPM EoS. (b) The variation of medium viscosity with time (τ) is plotted in terms of R^{-1}.

viscosity increases energy loss in the medium increases with time. For $\eta/s = 1/4\pi$ there is a significant change in the energy density, this change slows down with increase in the medium viscosity and becomes almost negligible for $\eta/s = 5/4\pi$. Indirectly, energy density cooling law support the faster cooling of the QGP medium in the scenario of QPM EoS than BM EoS. In Fig. 2(b), we have shown that the change in the pressure profile at $\tau = \tau_0$ with respect to transverse distance (r), corresponding to various values of β. Here β is a parameter depends on the energy deposition in the medium, $\beta = 1.0$ refers to almost non-viscous medium while $\beta < 1.0$ corresponds to relatively viscous medium. As shown, in Fig. 2(b) pressure is maximum at the central axis and it vanishes at the transverse boundary ($r = R_T$) of the cylindrically symmetric QGP medium. In our study we have found that at



(a) (b)

FIG. 2: (a) Energy density is plotted as the function of τ for various values of η/s ratio. (b) Pressure profile, $p(\tau_0, r)$ is plotted against the transverse distance, r for various values of β.

initial thermalization time ($\tau \sim 0.1 - 1.5$ fm,) QGP behave like an idea gas, but later when medium interaction dominates it becomes a perfect fluid. That is the reason, initial values of temperature, energy density and pressure obtained from QPM EoS are almost same to BM EoS but later time these values differs. Here we may conclude, that QGP for its whole lifetime is neither an ideal gas nor a perfect fluid, it evolves from an ideal gas and end up as a perfect fluid. In refs. [1, 2] we used QPM EoS to investigate QGP in heavy-ion collisions through quarkonia suppression and our model calculation agrees well with available experimental results.

References

[1] Captain R. Singh et.al., arXiv:1802.09918.
[2] Captain R. Singh et. al., Phys. Rev. C **92**, 034916 (2015).
[3] P.K. Srivastava et. al., Phys. Rev. C **87**, 034903 (2013).