Abstract

Nuclear matter when subjected to extremes of temperature or/and densities, it undergoes a deconfining phase transition to a new phase called Quark-Gluon plasma (QGP). Study of colour gauge theory (Quantum Chromodynamics) of quark-gluon interaction has shown the critical density to be $n_{cr} \approx (5-10)n_0$, where $n_0 \approx 0.15 GeV/fm^3$ is the density of cold nuclear matter, and the critical temperature to be $T_{cr} \approx 150-200 MeV$. This exotic phase of matter certainly existed in the early universe about a microsecond after the big bang and probably exists in the core of massive neutron stars. In the laboratory, its existence is indicated in some ultra-relativistic heavy ion collisions (URHIC) experiments.

The present interest in studying QGP dynamics is driven by the possibility of its creation in URHIC. Because of high collision energies involved, it is expected that, if the plasma is formed, then it will be in a state which is far away from thermodynamic equilibrium. This brings in questions related to the dynamics of pre-equilibrium phase, which include plasma formation and mechanisms of attaining thermodynamic equilibrium. The subject of investigation in this thesis has been mainly confined to the mechanisms of attaining thermodynamic equilibrium (thermalization). The study of themalization is crucial both from a fundamental sense as it throws light on pre-equilibrium phase and also from an experimental viewpoint, because if the plasma does not equilibrate during its lifetime then experimental signatures estimated by assuming an equilibrated QGP are of limited value. Earlier studies in this area have been based on well known models which describe the thermalization of the plasma formed in URHIC in a relatively incomplete manner. The main deficiencies are (i) a lack of simultaneous description of long and short wavelength gluon components (ii) absence of quarks and antiquarks (iii) ignoring collective dynamics altogether, and lastly (iv) incomplete treatment of non-perturbative aspect of plasma evolution. One of the main objectives of this thesis has been to study the problem (mechanism) of thermalization using a method which not only addresses the above deficiencies, but also paves way for further work in the direction of non-perturbative aspects of a coloured parton plasma. It is well known that, a partonic system comes to thermodynamic equilibrium through both collisional and collective chaotic processes. The relative importance of the two processes is determined by the plasma parameter $\Lambda_D \equiv n\lambda_D^3$ (number of particles in a Debye sphere); And if $\Lambda_D \gg 1$, collective chaotic processes dominate over collisional ones. In a relativistic system, Λ_D goes

as $n\lambda_D^3 \sim 1/g^3$. Therefore as one approaches the higher end of the energy scale in heavy ion collisions, g decreases because of asymptotic freedom, and collective mechanisms start playing a dominating role in the thermalization process. Further, thermalization has been shown to be intimately related to the chaotic dynamics of a system. Therefore, it becomes essential from the viewpoint of pre-equilibrium dynamics to chalk out parameter regimes where the collective modes become chaotic.

With the above facts as guidelines, we have investigated the mechanism of thermalization through an intensive study of collective non-abelian modes and parameter regimes in which these modes become chaotic. To study the collective non-abelian modes non-perturbatively and the parameter regimes in which chaos appears, we have written a relativistic particle-in-cell simulation code - QGP1. Introduction of colour dynamics in a relativistic PIC simulation scheme makes our work first one of its kind.

Using the code, we have first done a study of nonlinear phase mixing of plasma oscillations in an electrodynamic plasma. This work not only served as a validation of our code but also facilitated the study of some aspects of thermalization through phase mixing, without the associated contamination by non-abelian terms. The main conclusion of this study is that phase mixing process can provide a channel for transferring energy from the long wavelength modes to the bulk of the distribution function, thereby causing heating of the plasma. Since phase mixing process only depends on the nonlinearity of the system, it also occurs in a coloured parton plasma (there being an abundance of nonlinear terms). So as a next step, using our code (QGP1) we have examined coherent modes in a coloured plasma and identified parameter regimes, where these coherent modes become chaotic through phase mixing type of damping of longitudinal fields, leading to thermalization of the plasma. Actually thermalization in case of a coloured plasma involves both momentum and colour relaxation. We have done a study of both. In case of momentum relaxation, we have measured the lyapunov exponent from the chaotic evolution of nearby colour gauge fields, and shown that the momentum of the particles relaxes to a Jüttner form in a time given by few e-folding times. We have also verified that in this time scale, field energy per mode approaches $3T$, in conformity with equipartition theorem. The colour relaxation study was done with the same input parameters. Here we have clearly shown, by numerically performing a "Perrin" like experiment that colour relaxation is a diffusive process. We have related this diffusion time scale to the lyapunov exponent time scale. With our study of colour diffusion, we have clearly brought out the difference between relaxation through collisional processes and relaxation through collective processes. All these studies on thermalization involved a coloured parton plasma which is out of equilibrium, in $1+1$ dimensions. Since in a realistic situation, transverse modes of interaction also plays a significant role towards thermalization, we have done a semi-analytic study of the chaotic dynamics of transverse modes alone, i.e. decoupled from longitudinal modes. Here again we have delineated regimes, where these transverse modes become chaotic.

The main focus of the thesis is, firstly to present a method which can non-perturbatively deal with several interesting questions related to non-abelian physics, and secondly to throw some light on the pre-equilibrium dynamics. Thermalization being related to chaotic dynamics, throughout this thesis, we have devoted our attention to the investigation of collective non-abelian modes and the parameter regimes in which these modes become chaotic. We believe that chaotic dynamics plays a significant role in pre-equilibrium scenarios in URHIC.