Quantum chromodynamics (QCD) is the accepted theory of the strong interactions responsible for the binding of quarks into hadrons such as protons and neutrons, and the binding of protons and neutrons into atomic nuclei. The fundamental particles of QCD, the quarks and gluons, carry a new form of charge, which is called color because of its triplet nature in the case of the quarks (e.g. red, green, blue); gluons come in eight different colors which are composites of color and anticolor charges. However, quarks and gluons have never been observed as free particles. Nevertheless, because quarks have also electrical charge, they can literally be seen as constituents of hadrons by deep inelastic scattering using virtual photons. The higher the energy of the probing photon, the more the quarks appear as particles propagating freely within a hadron. This feature is called “asymptotic freedom”. It arises from so-called nonabelian gauge field dynamics, with gluons being the excitations of the nonabelian gauge fields similarly to photons being the excitations of the electromagnetic fields, except that gluons also carry color charges.

At low energy, the fact that only colorless hadrons can exist as asymptotic states is called “confinement”. This confinement can in fact be broken in a medium if the density exceeds significantly that of nuclear matter. When hadrons overlap so strongly that they lose their individuality, quarks and gluons come into their own as the elementary degrees of freedom. Indeed, lattice gauge theory simulations have demonstrated that deconfinement also occurs at small baryon densities for temperatures above approximately $2 \times 10^{12}$ Kelvin (100,000 times the temperature in the interior of the sun), corresponding to mean energies of about 200 MeV.

At present there are experiments being carried out in the Relativistic Heavy Ion Collider (RHIC) at the Brookhaven National Laboratory (BNL), where a tiny fire-ball with temperatures larger than the deconfinement temperature can be produced and the resulting “quark-gluon plasma” [1] can be investigated. From 2009 on, similar experiments at even larger energies and thus higher temperatures will be carried out at the European collider center CERN in Geneva. There is now ample evidence for the generation of a new state of matter in these experiments, which however involved a couple of surprises.
One of the surprises of the experiments at RHIC was the extremely fast apparent thermalization of the quark-gluon plasma and its extremely low shear viscosity (as judged from hydrodynamical model simulations), which would make the quark-gluon plasma the most perfect fluid ever to be produced in the laboratory.

The fast apparent thermalization cannot be explained by extrapolations of the existing perturbative calculations in QCD and various strong-coupling scenarios have been discussed in the literature. However, it is still not excluded that these phenomena could be due to essentially weak-coupling physics involving quark-gluon plasma instabilities, which are nonabelian generalizations of the so-called Weibel instabilities in ordinary plasma physics [2].

One of the first results on their dynamics have been obtained at the Institute of Theoretical Physics of our university [3], with follow-up work by other groups from the US and Europe [4]. Numerical simulations of collective chromomagnetic and electric fields in an anisotropic quark-gluon plasma show exponential growth of unstable modes which in the nonlinear regime lead to complicated dynamics, eventually leading to fast isotropization of the plasma.

These studies have so far been done for plasmas with a stationary anisotropic particle distribution and have now been generalized to the case of a longitudinally expanding quark-gluon plasma fireball [5,6]. Fig. 1 visualizes just the color degrees of freedom in collective fields as they evolve from small initial fluctuations in such a fireball. The horizontal axis is the spatial direction in which there is expansion of the plasma with the speed of light, with fields taken as constant with respect to transverse directions (out of the plane), and time flows from bottom to top.

![Fig. 1: Visualization of the time evolution of the color degrees of freedom in the chromomagnetic field associated with instabilities in a longitudinally expanding quark-gluon plasma fireball.](image-url)
In this plot one can see how the initial random fluctuations are swamped by the exponentially growing collective modes which involve a characteristic wavelength and locally fixed color charges (the absolute amplitudes of the fields are not shown). After these perturbations have grown such that non-Abelian self-interactions come into the play, there is a certain disturbance in the color distribution along a hyperbolic shell after which the color inhomogeneities are enhanced. The crucial finding, which cannot be read from this visualization but is shown in Fig. 2, is that the near exponential growth of these intrinsically non-Abelian plasma instabilities continues until the collective fields give significant backreaction on the plasma constituents, rapidly eliminating their momentum-space anisotropies. This isotropization is much faster than the processes leading to thermalization, which occur somewhat later in the evolution of the fireball created in relativistic heavy-ion collisions.

![Graph](image)

**Fig. 2:** The time evolution of various energy densities in the chromodynamical collective fields associated with instabilities in a longitudinally expanding quark-gluon plasma fireball with realistic initial parton densities, with $\tau/\tau_0 = 100$ corresponding to 20 (7) fm/c for the RHIC (LHC) heavy-ion collision experiments.

These results have now been extended to the case of realistic initial parton densities that occur at the RHIC collider and also the somewhat higher ones that are expected at the LHC (corresponding to the different time scales mentioned in the caption of Fig. 2), with the result that non-Abelian plasma instabilities are expected to become a dominant effect for the new generation of heavy-ion collisions at the LHC. These new findings have been published in Physical Review D [6] and presented at several international conferences [7-9].
These numerical simulations were carried out at the Phoenix cluster using C++ programs developed by the authors. They involve lattices which are one-dimensional in configuration space, but three-dimensional in momentum space (1D+3V). At present the lattices used in the simulations are such that they fit into the RAM of a single node. Extensions to 2D+3V and 3D+3V are now being prepared which require extensive parallelization.

References


9. A. Rebhan: “Hard loop effective theory of the (anisotropic) quark gluon plasma”; Talk: International School of Nuclear Physics, 30th Course: Heavy-Ion Collisions from the Coulomb Barrier to the Quark-Gluon Plasma, Erice (invited); 09-16-2008 - 09-24-2008.