The source of the "third flow component"

V. K. Magas, L. P. Csernai
Section for Theoretical and Computational Physics, Department of Physics
University of Bergen, Allegaten 55, 5007 Bergen, Norway
E-mail: vladimir@fi.uib.no, csernai@fi.uib.no

D. D. Strottman
Theoretical Division, Los Alamos National Laboratory
Los Alamos, NM, 87454, USA
E-mail: dds@lanl.gov

A model for energy, pressure and flow velocity distributions at the beginning of relativistic heavy ion collisions has been developed to be used as initial condition for hydrodynamical calculations. The results show that at the early stages QGP forms a tilted disk, such that the direction of the largest pressure gradient stays in the reaction plane, but deviates from both the beam and the usual transverse flow directions. Such initial conditions may lead to the creation of the "antiflow" or the "third flow component".

1 Introduction

Fluid dynamics is probably the most frequently used model to describe heavy ion collisions. It assumes local equilibrium, i.e. the existence of an Equation of State (EoS), relatively short range interactions and conservation of energy and momentum as well as of conserved charge(s). Thus, in ultra relativistic collisions of large heavy ions, especially if Quark-Gluon Plasma (QGP) is formed, one-fluid dynamics is a valid and good description for the intermediate stages of the reaction. Here interactions are strong and frequent, so that other models, (e.g. transport models, string models, etc., assuming binary collisions, with free propagation of constituents between collisions) have limited validity. On the other hand, the initial and final, Freeze-Out (FO), stages of the reaction are outside the domain of applicability of the fluid dynamical model.

We believe that the realistic and detailed description of an energetic heavy ion reaction requires a Multi Module Model, where the different stages of the reaction are each described with suitable theoretical approach. It is important that these Modules are coupled to each other correctly: on the interface, which is a 3 dimensional hyper-surface in space-time, all conservation laws should be satisfied and entropy should not decrease. These matching conditions were worked out and studied for the matching at FO in detail in refs.

---

1 Talk given at the 30th International Symposium on Multiparticle Dynamics, October 9-15, 2000, Tihany, Lake Balaton, Hungary
The final FO stages of the reaction, after hadronization, can be described well with kinetic models, since the matter is already dilute.

The initial stages are more problematic. Frequently two or three fluid models are used to remedy the difficulties and to model the process of QGP formation and thermalization. Here the problem is transferred to the determination of drag-, friction- and transfer- terms among the fluid components, and a new problem is introduced with the (unjustified) use of EoS in each component in nonequilibrated situations, where EoS does not exist. Strictly speaking this approach can only be justified for mixtures of noninteracting ideal gas components. Similarly, the use of transport theoretical approaches assuming dilute gases with binary interactions is questionable, since, due to the extreme Lorentz contraction in the C.M. frame, enormous particle and energy densities with the immediate formation of perturbative vacuum should be handled. Even in most parton cascade models these initial stages of the dynamics are just assumed in form of some initial condition with little justification behind.

Our goal in the present work is to construct a model, based on the recent experience gained in string Monte Carlo models and in parton cascades, describing energy, pressure and flow velocity distributions at the beginning of relativistic heavy ion collisions.

2 The effective string rope model

One of the important results of the last decade is that all string models had to introduce new, energetic objects: string ropes, quark clusters, fused strings, in order to describe the abundant formation of massive particles like strange antibaryons. Based on this, we describe the initial stages of the reaction in the framework of classical (or coherent) Yang-Mills theory, generalizing ref. 10 assuming larger field strength (string tension) than in ordinary hadron-hadron collisions. In addition we now satisfy all conservation laws exactly, while in ref. 10 infinite projectile energy was assumed, and so, overall energy and momentum conservation was irrelevant.

First of all, we would create a grid in \([x, y]\) plane \((z – \text{is the beam axes, } [z, x] – \text{is the reaction plane})\) and describe the nucleus-nucleus collision in terms of steak-by-streak collisions, corresponding to the same transverse coordinates, \([x_i, y_j]\). We assume that baryon recoil for both target and projectile arise from the acceleration of partons in an effective field \(F^{\mu\nu}\), produced in the interaction. Of course, the physical picture behind this model should be based on chromoelectric flux tube or string models, but for our purpose we consider \(F^{\mu\nu}\) as an effective abelian field. A single phenomenological parameter describing this field must be fixed from comparison with experimental data. For detailed
description we would call the attention of the reader to refs. 11, 12, 13.

Briefly speaking, after two streaks cross each other they create a "string rope" with constant string tension $\sigma$ in the middle. The typical values of the string tension, $\sigma$, are of the order of $10 \text{ GeV/fm}$, and these may be treated as several parallel strings or "string rope". In further evolution this "string rope" accommodates more and more energy by stopping the initial target and projectile streaks. If we let system evolve, the "string rope" will stop streaks completely, then will accelerate them backward, and the analog of Yo-Yo motion may occur. We do not solve simultaneously the kinetic problem leading to parton equilibration, just assume that the arising friction is such that the heavy ion system will be an overdamped oscillator, i.e. yo-yoing of the two heavy ions will not occur. This assumption is based on recent string and parton cascade results.

To proceed one has to make more assumptions. We assume that the final result of collisions of two streaks, after stopping the string’s expansion and after its decay, is one streak of the length $\Delta l_f$ with homogeneous energy density distribution, $e_f$, and baryon charge distribution, $\rho_f$, moving like one object with rapidity $y_f$. We assume that this is due to string-string interactions and string decays. The homogeneous distributions are the simplest assumptions, which may be modified based on experimental data. Its advantage is a simple expression for $e_f$, $\rho_f$, $y_f$.

The final energy density, baryon density and rapidity, $e_f$, $\rho_f$ and $y_f$, should be determined from conservation laws. Unfortunately, the assumptions we made above oversimplify the real situations and do not allow us to satisfy exactly all the conservation laws. The reason for this is well known and has been discussed in the Refs. 1, 2: two possible definitions of the flow, Eckart’s and Landau’s definition. If we are following the energy flow, we satisfy exactly the energy and momentum conservation and violate the baryon current conservation. Otherwise if we are drifted by baryon flow, we violate the energy-momentum conservation.

In the refs. 11, 12, 13 we choose the Landau’s definition of the $y_f$, i.e. the exact conservation of the energy and momentum.

3 Initial state of QGP

Let us review the results of our calculations. We are interested in the shape of QGP formed, when the final streak formation is finished (at least in the most central region) and their matter is locally equilibrated. This will be the initial state for further hydrodynamical calculations. The time, where we expect a local equilibrium, is also a parameter of our model - it should be large.
Figure 1: The Au+Au collisions, $\varepsilon_0 = 100\text{ GeV/nucl}$, $b = 0.5(r_1 + r_2)$, $A = 0.051$ (parameter $A$ introduced in refs. 11, 12, 13 to determine the “string rope” tension), $y = 0$ (ZX plane through the centers of nuclei). We would like to notice that final shape of QGP volume is a tilted disk $\approx 45^0$, and the direction of the fastest expansion will deviate from both the beam axis and the usual transverse flow direction, and might be a reason for the third flow component, as argued in 14.

enough to allow the final streak formation, but we can’t wait too long, since the transverse expansion can’t be neglected in this case.

We see in Figs. 1, 2 that QGP forms a tilted disk for $b \neq 0$. So, the direction of fastest expansion, the same as largest pressure gradient, will deviate from both the beam axis and the usual transverse flow direction and the new flow component, called “antiflow” or ”third flow component”, may appear in the reaction plane. With increasing beam energy the usual transverse flow is getting weaker, while this new flow component is strengthened. The mutual effect of the usual directed transverse flow and this new ”antiflow” or ”third flow component” leads to an enhanced emission in the reaction plane. This was actually observed and widely studied earlier and was referred to as "elliptic
Conclusions

Based on earlier Coherent Yang-Mills field theoretical models and introducing effective parameters based on Monte-Carlo string cascade and parton cascade model results, a simple model is introduced to describe the pre fluid dynamical stages of heavy ion collisions at the highest SPS energies and above.

Contrary to earlier expectations, — based on standard string tensions of $1 \text{GeV/fm}$ which lead to the Bjorken model type of initial state, — the effective string tension introduced for collisions of massive heavy ions, as a consequence of collective effects related to QGP formation, appears to be of the order of $10 \text{GeV/fm}$ and consequently causes much less transparency. The resulting initial locally equilibrated state of matter in semi central collisions takes a
rather unusual form, which can be then identified by the asymmetry of the caused collective flow.

Detailed fluid dynamical calculations as well as flow experiments at semi-central impact parameters for massive heavy ions are needed at SPS and RHIC energies to connect the predicted special initial state with observables.

References

1. Cs. Anderlik, Z.I. Lázár, V.K. Magas, L.P. Csernai, H. Stöcker and W. Greiner, (nucl-th/9808024), Phys. Rev. C 59, 388 (1999).
2. V.K. Magas, Cs. Anderlik, L.P. Csernai, F. Grassi, W. Greiner, Y. Hama, T. Kodama, Zs. Lázár and H. Stöker, (nucl-th/9806004), Phys. Rev. C 59, 3309 (1999); (nucl-th/9903043), Heavy Ion Phys. 9, 193 (1999); (nucl-th/9905054), Phys. Lett. B 459, 33 (1999); (nucl-th/0001049), Nucl. Phys. A 661, 596 (1999).
3. A.A. Amsden, A.S. Goldhaber, F.H. Harlow and J.R. Nix, Phys. Rev. C 17, 2080 (1978).
4. L.P. Csernai, I. Lovas, J. Maruhn, A. Risenhauer, J. Zimanyi, W. Greiner, Phys. Rev. C 26, 149 (1982).
5. J. Brachmann, S. Soff, A. Dumitru, H. Stöker, J.A. Maruhn, W. Greiner, D.H. Rischke, L. Bravina, Phys. Rev. C 61, 024909 (2000).
6. T.S. Biro, H.B. Nielsen, J. Knoll, Nucl. Phys. B 245, 449 (1984).
7. K. Wegner, J. Aichelin, Phys. Rev. Lett. 76, 1027 (1996).
8. N.S. Amelin, M.A. Braun, C. Pajares, Phys. Lett. B 306, 312 (1993), Z. Phys. C 63, 507 (1994).
9. H. Sorge, Phys. Rev. C 52, 3291 (1995).
10. M. Gyulassy, L.P. Csernai, Nucl. Phys. A 460, 723 (1986).
11. V.K. Magas, L.P. Csernai, D.D. Strottman, (hep-ph/0010307).
12. V.K. Magas, L.P. Csernai, D.D. Strottman, (nucl-th/0009049), Proceedings of New Trends in High-Energy Physics, Yalta (Crimea), Ukraine, May 27 - June 4, 2000, p. 93.
13. L.P. Csernai, Cs. Anderlik, V.K. Magas, (nucl-th/0010022), Proceedings of the Symposium on Fundamental in Elementary Matter, Bad Honnef, Germany, September 25 -29, 2000.
14. L.P. Csernai, D. Röhrich, (nucl-th/9908031), Phys. Lett. B 458, 454 (1999).