LA-UR- 02-7616

Approved for public release;
distribution is unlimited.

Title: QCD Hydrodynamics for LHC and RHIC

Author(s): L. P. Csernai, M. I. Gorenstein, V. F. Magas
and D. D. Strottman

Submitted to: Proceedings of Diffraction, 2002

LOS ALAMOS NATIONAL LABORATORY

3 9338 00454 1438

Los Alamos National Laboratory, an affirmative action/equal opportunity employer, is operated by the University of California for the U.S. Department of Energy under contract W-7405-ENG-36. By acceptance of this article, the publisher recognizes that the U.S. Government retains a nonexclusive, royalty-free license to publish or reproduce the published form of this contribution, or to allow others to do so, for U.S. Government purposes. Los Alamos National Laboratory requests that the publisher identify this article as work performed under the auspices of the U.S. Department of Energy. Los Alamos National Laboratory strongly supports academic freedom and a researcher's right to publish; as an institution, however, the Laboratory does not endorse the viewpoint of a publication or guarantee its technical correctness.

Form 836 (8/00)

QCD HYDRODYNAMICS FOR LHC AND RHIC

L.P. CSERNAI

*Department of Physics, University of Bergen
Allegaten 55, N-5007 Bergen, Norway &
KFKI Research Institute for Particle and Nuclear Physics
P.O.Box 49, H-1525 Budapest 114, Hungary*

M.I. GORENSTEIN

*University of Frankfurt
Robert-Mayer St. 8-10, D-60054 Frankfurt am Main, Germany
& Bogolyubov Institute for Theoretical Physics
Metrologichna str. 14-b, 03143 Kiev, Ukraine*

V.K. MAGAS

*CFIF, Physics Department, Instituto Superior Tecnico
Av. Rovisco Pais, 1049-001 Lisbon, Portugal*

AND

D.D. STROTTMAN

*Theory Division, Los Alamos National Laboratory,
Los Alamos, NM 87545, USA*

Abstract. 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 a suitable theoretical approach. One fluid dynamical models provide an adequate and accurate description of the middle stages of the reaction. In addition, fluid dynamical calculations require initial and freeze out conditions. In this work we concentrate on the modeling of the initial stages of the reaction, before the local thermal equilibrium is achieved, and on the freeze out process. We discuss the possibility of the fast simultaneous hadronization and chemical freeze out of supercooled QGP, as a possible solution of the HBT "puzzle".

Fluid dynamical models are widely used to describe heavy ion collisions. Their advantage is that one can vary flexibly the Equation of State (EoS) of the matter and test its consequences on the reaction dynamics

and the outcome. This makes fluid dynamical (FD) models a very powerful tool to study possible phase transitions in heavy ion collisions - such as the liquid-gas or the Quark-Gluon Plasma (QGP) phase transition. For example, the only models that can handle the supercooled QGP (sQGP) are hydrodynamical models with a corresponding EoS.

For highest energies achieved nowadays at RHIC hydrodynamic models give a good description of the observed radial and elliptic flows [1, 2, 3, 4], in contrast to microscopic models, like HIJING [5] and UrQMD [6]. We would like to stress here that that "hydrodynamic model" means, apart of well known hydrodynamical equations, the particular choice of the initial conditions (usually fitted to reproduce the data), the particular choice of the EoS and the way freeze out (FO) is realized. In this work we are going to concentrate on the modeling of initial conditions for RHIC and LHC energies and on the FO.

Recent data from RHIC give a good test for all the models in ultra-relativistic heavy ion collisions business, namely the HBT radii. Two-particle interferometry has become a powerful tool for studying the size and duration of particle production from elementary collisions to heavy ions like Au+Au at RHIC or Pb+Pb at SPS. For the case of nuclear collisions, the interest mainly focuses on the possible transient formation of a deconfined state of matter. This could affect the size of the region from where the hadrons (mostly pions) are emitted as well as the time for particle production. Comparing recent data [7] from RHIC with SPS data one finds a "puzzle" [8]: all the HBT radii are pretty similar although the center of mass energy is changed by an order of magnitude. Discussions at "Quark Matter 2002" [9] lead to the conclusion that the duration of particle emission, as well as the lifetime of the system before Freeze Out, appear to be shorter than the predictions of most of the model at the physics market. Although there is a set of models based on very fast 3D Bjorken hydrodynamical expansion and hadronization from sQGP [10], which are in much better agreement with experimental data than all the others. We will discuss this possibility in the section 2.

1. Multi Module Model

A 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 a suitable theoretical approach.[29] It is important that these modules are coupled to each other correctly: on the interface, all conservation laws should be satisfied, and the entropy should not decrease. This last feature sometimes not given proper attention. The nondecreasing entropy condition should be satisfied at each "stage" or "Module" of our

collision model, as well as, at the transition between stages or modules.

In energetic collisions of large heavy ions, especially if a QGP is formed in the collision, 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., that assume binary collisions, with free propagation of constituents between collisions) have limited validity. On the other hand, the initial and final, FO, stages of reaction are outside the domain of the applicability of the fluid dynamical model.

After hadronization and FO, the matter is already dilute and can be described well with kinetic models. Note that even after the chemical FO the hadron species are not completely frozen - the resonance decays have to be taken into account.

The modeling of the initial stages is the most problematic. None of the theoretical models can unambiguously describe the initial stages. Therefore the phenomenological models are frequently used. Therefore the phenomenological models have to be used.

For the ultra-relativistic energies the boost invariant Bjorken models is frequently used (it requires only 2D hydro calculations in transverse plane), with the initial conditions fitted to the data. Usually the energy density profile in the plane transverse to beam direction is assumed to be proportional to the to the number of binary collisions or to number of participants and the central energy is used as a free parameter to fit the data (see [11] for recent overview). Unfortunately there is no clear and unambiguous confirmation that Nature follows the Bjorken scenario. The preliminary experimental results from RHIC do not show transparency - most particle multiplicities do not show a dip in the rapidity spectra, but rather a plateau around mid-rapidity [12], which is a sign of strong stopping. Furthermore, a very strong elliptic flow (v_2 flow component) has been measured, which shows a clear peak around mid rapidity [13]. To build such a strong elliptic flow, strong stopping and momentum equilibration are required. Also the $\bar{p}/p$ ratio at mid-rapidity measured at RHIC [14] (preliminary) is still far from one, which tells us that the middle region is not baryonfree.

Similar ideas led authors of Refs. [4, 15] to the two module model. Authors combine hydro and UrQMD - replacing the hadronic phase of hydrodynamics with hadronic transport model to describe properly chemical and thermal FO. We would like to underline the following: A) the initial state for hydro was not modeled, but fitted to the data; B) in this approach at some "point", i.e. 3D hypersurface in the space-time, we have to transfer our global hydro quantity into a distribution of different hadron species. This problem B) is absolutely similar FO problem. One has to specify the

condition for this transfer in order to define the transfer hypersurface (this is much harder and less certain than the FO condition). Again the transfer hypersurface may have both timelike and spacelike parts, where the modification of the Cooper-Frey formula is needed [16, 17, 18]. The nondecreasing entropy condition should be satisfied. In our opinion the realization of hydro-UrQMD transfer is a more difficult problem than FO modeling, since the sum of noninteracting ideal gases is a good and valid approximation for the post FO EoS, while the EoS of interacting hadronic matter is less certain. For the recent treatment of this problem see Ref. [19].

Perturbative Quantum Chromo Dynamics (pQCD) would be, in principle, the proper model for describing our systems at very high energies. Unfortunately, pQCD itself is not applicable for heavy ion reactions at RHIC energies. Nevertheless, the pQCD calculations with some extra non-perturbative, phenomenological assumptions, like saturation of a gluon plasma, can be performed. Different models following this scenario have been proposed – see for example [20, 21]. In this Ref. [21] authors combine Gyulassy-Levai-Vitev (GLV) non-abelian energy loss formalism with Bjorken 1+1D expansion and successfully reproduced $v_2(p_T)$ STAR Min. Bias Data up to $p_T \approx 2 - 2.5 \text{ GeV}$.

1.1. EFFECTIVE STRING ROPE MODEL

One important conclusion of heavy ion research in the last decade is that standard 'hadronic' string models fail to describe heavy ion experiments. All string models had to introduce new, energetic objects: string ropes [22, 23], quark clusters [24], or fused strings [25], in order to describe the abundant formation of massive particles like strange antibaryons. Based on this, we describe the initial moments of the reaction in the framework of classical, or coherent, Yang-Mills theory, following the Bjorken model with baryon recoil Ref. [26] assuming a larger field strength (string tension) than in ordinary hadron-hadron collisions. For example, calculations both in the Quark Gluon String Model [27, 28] and in the Monte Carlo string fusion model [25] indicate that the energy density of strings reaches $8 - 10 \text{ GeV/fm}$ already in SPS reactions. This is nearly 10 times more than the tension used in standard, 'hadronic', string models where $\sigma \approx 1 \text{ GeV/fm}$, what allows us to talk about string ropes. We also take care about exact satisfaction of all the conservation laws. Thus, in the framework of Effective String Rope Model (ESRM) for the first time the initial transparency/stopping and energy deposited into strings and string ropes was determined consistently with each other [29, 30].

We describe the hadronization of our string ropes in an effective way (see Refs. [29, 30] for more details). Thus, as the output of ESRM we get

Figure 1. Au+Au collision at $\varepsilon_0 = 100 \text{ GeV}/\text{nucl}$, $E = T^{00}$ is presented in the reaction plane as a function of x and z for $t_h = 5 \text{ fm}/c$. Subplot A) ($b = 0.5 \cdot 2 R_{Au}$), subplot B) ($b = 0.25 \cdot 2 R_{Au}$). The QGP volume has a shape of a tilted disk and may produce a third flow component.

energy and baryon density distributions and flow velocity field of the locally thermalized QGP. Then, the hydrodynamic evolution can be started for the intermediate state.

The initial dynamics using the ESRM led to an initial state with high energy density, reaching $20 \text{ GeV}/fm^3$ on the average and $60 - 80 \text{ GeV}/fm^3$ peak values in the middle. The model led to a QGP configuration which was similar to the initial state described in Landau's fluid dynamical model, with the difference that the relatively flat initial state was tilted – see Fig. 1. In a heavy ion reaction such a tilted initial state arises naturally as a consequence of the streak by streak momentum conservation, since at finite impact parameters streaks with different length and mass collide against each other, finally moving in the direction of the heavier streak (this is a base of firestreak model [36]). Such a tilted flat initial state results in a "third flow component" which is observed at the highest SPS energies and it was present in all FD model results which used QGP EoS [35]. Unfortunately the flow within reaction plane was not yet measured at RHIC – see section 3.

2. Supercooled QGP and HBT puzzle

It was demonstrated that a strong first-order QCD phase transition within continuous hydrodynamical expansion would lead to long lifetimes of the particle source [?, 37, 4], which would manifest itself as a large R_{out}/R_{side} ratio. Now this type of hadronization is excluded by experimental data.

An alternative possibility, discussed in Refs. [39, 40, 41, 33, 42, 43], is the hadronization from the sQGP. This is expected to be a very fast shock-like process. If the hadronization from sQGP coincides with freeze out, then this could explain a part of the HBT puzzle, i.e. the flash-like particle emission ($R_{out}/R_{side} \approx 1$). Now we would like to ask the question – can the hadronization from sQGP explain also the another part of the HBT puzzle, i.e. a very short ($\sim 6[10] - 10[9] \text{ fm}/c$) expansion time before freeze out?

2.1. HADRONIZATION OF THE SQGP WITHIN BJORKEN HYDRODYNAMICS

For a study of the expanding QGP we have chosen a framework of the 1+1D Bjorken model (actually our principal results will not change if we use 3+1D Bjorken model). Within the Bjorken model all the thermodynamical quantities are constant along constant proper time curves, $\tau = \sqrt{t^2 - z^2} = \text{const}$. The important result of Bjorken hydrodynamics (which assumes a perfect fluid) is that the evolution of the entropy density, is independent of

Figure 2. Different ways for a system to go from Q state (s_Q) to H state (s_H) are presented on $\{s, \tau\}$ plane. Subplot A shows continuous expansion, which takes time τ_H , eq. (4). Subplot B presents flash-like particle emission, i.e. simultaneous hadronization and freeze out; which takes time $\tau_H^{(1)}$, eq. (5). Subplot C shows several possibilities according to scenario 2 with shock-like hadronization into superheated HM. Time $\tau_H^{(2)}$ (7) can be smaller or larger than $\tau_H^{(1)}$, depending on details of the EoS, but always larger than τ_H .

the Equation of State (EoS), namely

$$s(\tau) = \frac{s(\tau_{init})\tau_{init}}{\tau}. \quad (1)$$

In Bjorken model the natural choice of the freeze out hypersurface is $\tau = \text{const}$ hypersurface, where normal vector is parallel to the Bjorken flow velocity, $v = z/t$. Thus, $d\sigma^\nu = (1, 0)$ in the rest frames of each fluid element. This leads to the simple solution of the time like shock equations (see Ref. [43]):

$$\tilde{v}^2 = \tilde{v}_o^2 = 0, \quad \epsilon = \epsilon_o, \quad n = n_o, \quad p \neq p_o. \quad (2)$$

The entropy condition is reduced to

$$s \geq s_o. \quad (3)$$

Now let us try to answer the main question of this work – can QGP expansion with t.l. shock hadronization of supercooled state be faster than the hadronization through the mixed phase? The initial state is given at the proper time $\tau_{init} \equiv \tau_Q$, when the local thermal equilibrium is achieved in the QGP state $Q \equiv (\epsilon_Q, p_Q, s_Q)$. The final equilibrium hadron state is also fixed, by experiment or otherwise, as $H \equiv (\epsilon_H, p_H, s_H)$. For the continuous expansion given by eq. (1) the proper time for the $Q \rightarrow H$ transition is (see Fig. 2 - subplot A):

$$\tau_H = \frac{s_Q \tau_Q}{s_H}. \quad (4)$$

If our system enters the sQGP phase and the particle emission is flash-like, i.e. the system hadronizes and freezes out at the same time, then eq. (1) is also valid all the time with final t.l. shock transition to the same H state. We call this as a scenario number one (see Fig. 2 - subplot A). Our system should go into supercooled phase to the point where $\epsilon_o^{(1)} = \epsilon_H, n_o^{(1)} = n_H$, as it is required by eq. (2). At this point our sQGP has entropy density $s_o^{(1)}$. Its value depend on the EoS, but t.l. shock transition is only possible if $s_o^{(1)} \leq s_H$ according to eq. (3). Thus, for the proper time of $Q \rightarrow H$ transition according to first scenario we have:

$$\tau_H^{(1)} = \frac{s_Q \tau_Q}{s_o^{(1)}} \geq \tau_H. \quad (5)$$

We can also study a scenario number two when our system supercools to the state $(\epsilon_o^{(2)}, p_o^{(2)}, s_o^{(2)})$, then hadronizes to a superheated HM state $(\epsilon^{(2)}, p^{(2)}, s^{(2)})$, and then this HM state expands to the same freeze out state $H \equiv (\epsilon_H, p_H, s_H)$. (see Fig. 2 - subplot C). At the point of the shock transition one has:

$$\tau_o^{(2)} = \frac{s_Q \tau_Q}{s_o^{(2)}}, \quad (6)$$

Then we have a t.l. shock transition satisfying eq. (2), and following the HM branch of the hydrodynamical expansion we find:

$$\tau_H^{(2)} = \frac{s^{(2)} \tau_o^{(2)}}{s_H} = \frac{s_Q \tau_Q}{s_H} \frac{s^{(2)}}{s_o^{(2)}} \geq \tau_H, \quad (7)$$

since $s^{(2)} \geq s_o^{(2)}$ due to non-decreasing entropy condition (3). In this second scenario the value of the of entropy density $s_o^{(2)}$ of sQGP can be both smaller and larger than HM final value s_H . Depending on details of the EoS the proper time $\tau_H^{(2)}$ (7) of the $Q \rightarrow H$ transition can also be smaller as well as larger than $\tau_H^{(1)}$ (5), but always larger than τ_H .

One can think about choosing some other hypersurface for FO and hadronization (this is, of course, a violation of the Bjorken assumptions, but in our opinion it can be accepted for the late stages of the reaction). This possibility was discussed in Ref. [33], where the FO and hadronization of sQGP happened at a constant time after Bjorken hydro expansion. Our results show that such a process is very sensitive on the properties of the EoS and the nondecreasing entropy conditions works very restrictively. Also the fast simultaneous hadronization and chemical freeze out of sQGP leads to the re-heating of the expanding matter and to the change in a collective flow profile.

3. Determining the reaction plane at RHIC

At RHIC the directed transverse flow was not measured up to now. Different experimental difficulties were mentioned as the reason. In particular that the reaction plane could not be identified, although the so called v_2 parameter was measured.

This problem is partly due to the method used to determine v_2 , which did not explicitly required the parallel determination of the reaction plane. It is, however, clear that the existence of strong elliptic flow indicates a strong collective correlation among the particles in every event: particles are preferably emitted upwards (+x) and downwards (-x) in the reaction plane and much less to the sides. Thus, if this correlation is detected and strong, the plane must be identifiable also! It is relatively easy to design methods, which work well statistically for very low event multiplicities.

Of course, to tell which is the target and projectile side of the plane may be difficult. If in a symmetric, A+A reaction one assumes, the idealized Bjorken picture with infinite length in the [z]-direction, and the lens shape source in the transverse plane, the target and projectile side cannot be distinguished in principle.

On the other hand, if one takes a more realistic three dimensional model, one will get both azimuthal asymmetry and forward/backward asymmetry. This can be used then to determine which side of the plane is which.

As v_2 is measured, the reaction plane, $[x, z]$, is known, just the target/projectile side should be selected. This is not done due to the prejudice that the distribution of emitted particles is mirror-symmetric in Central Mass Frame (CM):

$$f_{CM}(p_x, p_y, p_z) = f_{CM}(p_x, p_y, -p_z) .$$

However, at finite impact parameters (2–15%) there is a forward/backward asymmetry, which we can utilize the following way to determine the reaction plane.

The Q -vector (a la Danielewicz, and Odyniecz (1985), see in section 7.7 of ref. [34]) has to be calculated event by event:

$$Q_k = \sum_{ik} y_{CM,i} p_{x,i}$$

has to be calculated, event by event, for all particles, i , of type k . Only the sign is relevant, as the plane is known already. This Q -vector will select the same side (e.g. projectile) in each event.

4. Conclusions

In conclusion we can say that the hydrodynamic modeling of heavy ion reactions is alive and is better than ever. Clear hydrodynamic effects are seen everywhere, and from early on.

The recent results from RHIC show the we are in the regime where collective matter type of behavior is dominant. We hope to gain more and more detailed information on QGP and its dynamical properties. Continued hard work is needed to exploit all possibilities, and the task of theoretical modeling and analysis is vital in future progress of the field.

Acknowledgments

Three of us (M.G., V.M. and D.S.) acknowledge the support of the Bergen Computational Physics Laboratory in the framework of the European Community - Access to Research Infrastructure action of the Improving Human Potential Programme.

References

1. P.F. Kolb, J. Sollfrank, U. Heinz (2000) Anisotropic transverse flow and the quark-hadron phase transition, *Phys. Rev.* **C62**, 054909.

2. P.F. Kolb, P. Huovinen, U. Heinz, H. Heiselberg (2001) Elliptic flow at SPS and RHIC: from kinetic transport to hydrodynamics, *Phys. Lett. B* **500** pp. 232-240.
3. P. Huovinen, P.F. Kolb, U. Heinz, H. Heiselberg (2001) Radial and elliptic flow at RHIC: further predictions, *Phys. Lett. B* **503** pp. 58-64.
4. D. Teaney, J. Lauret, and E.V. Shuryak (2001) Flow at the SPS and RHIC as a Quark Gluon Plasma Signature, *Phys. Rev. Lett.* **86** pp. 4783-4786; A Hydrodynamic Description of Heavy Ion Collisions at the SPS and RHIC, nucl-th/0110037.
5. D. Molnar and M. Gyulassy (2002) Saturation of Elliptic Flow and the Transport Opacity of the Gluon Plasma at RHIC, *Nucl. Phys. A* **697** pp. 495-520.
6. M. Bleicher and H. Stöcker (2002) Anisotropic flow in ultra-relativistic heavy ion collisions *Phys. Lett. B* **526** pp. 309-314.
7. RHIC data: STAR Collaboration (2001) Pion Interferometry of $\sqrt{s_{NN}} = 130$ GeV Au+Au Collisions at RHIC, *Phys. Rev. Lett.* **87** 082301; PHENIX Collaboration (2002) Transverse mass dependence of two-pion correlations in Au+Au collisions at $\sqrt{s_{NN}} = 130$ GeV, *Phys. Rev. Lett.* **88** 192302; SPS data: NA49 Collaboration (2002) New Results From Na49, *Nucl. Phys. A* **698** pp. 104-; H. Appelshäuser Pion interferometry: Recent results from SPS, hep-ph/0204159.
8. M. Gyulassy Lectures on the theory of high energy A + A at RHIC, nucl-th/0106072.
9. S. Pratt, talk at the Quark Matter 2002, July, Nantes, France.
10. T. Csörgő, A. Ster The reconstructed final state of Au+Au collisions from PHENIX and STAR data at $\sqrt{s_{NN}} = 130$ AGeV - indication for quark deconfinement at RHIC, nucl-th/0207016.
11. P.F. Kolb, U. Heinz, P. Huovinen, K.J. Eskola, K. Tuominen Centrality dependence of multiplicity, transverse energy, and elliptic flow from hydrodynamics, *Nucl. Phys. A* **696** pp. 197-215.
12. STAR Collaboration (2001) Multiplicity distribution and spectra of negatively charged hadrons in Au+Au collisions at $\sqrt{s_{NN}} = 130$ GeV, *Phys. Rev. Lett.* **87** 112303.
13. PHENIX Collaboration (2002) Elliptic Flow Measurements with the PHENIX Detector, *Nucl. Phys. A* **698** pp. 559-563; PHOBOS Collaboration (2002) Charged particle flow measurement for $|\eta| < 5.3$ with the PHOBOS detector, *Nucl. Phys. A* **698** pp. 564-567; STAR Collaboration (2002) Elliptic flow in Au+Au collisions at $\sqrt{s_{NN}} = 130$ GeV, *Nucl. Phys. A* **698** pp. 193-198.
14. STAR Collaboration (2001) Mid-rapidity anti-proton to proton ratio from Au+Au collisions at $\sqrt{s_{NN}} = 130$ GeV, *Phys. Rev. Lett.* **86** pp. 4778-4782.
15. S. Bass, A. Dumitru (2000) Dynamics of Hot Bulk QCD Matter: from the Quark-Gluon Plasma to Hadronic Freeze-Out, *Phys. Rev. C* **61** 064909.
16. Cs. Anderlik, Z.I. Lázár, V.K. Magas, L.P. Csernai, H. Stöcker, W. Greiner (1999) Nonideal particle distributions from kinetic freeze-out models, *Phys. Rev. C* **59** pp. 388-394.
17. Cs. Anderlik, L.P. Csernai, F. Grassi, W. Greiner, Y. Hama, T. Kodama, Zs. Lázár, V. Magas, H. Stöcker (1999) Freeze out in hydrodynamical models, *Phys. Rev. C* **59** pp. 3309-3316 ; (1999) Large p_t enhancement from freeze out, *Phys. Lett. B* **459** pp. 33-36.
18. V.K. Magas, Cs. Anderlik, L.P. Csernai, F. Grassi, W. Greiner, Y. Hama, T. Kodama, Zs. Lázár, H. Stöcker (1999) Kinetic freeze out models , *Heavy Ion Phys.* **9** pp. 193-216 ; (1999) Freeze-out in hydrodynamical models in relativistic heavy ion collisions, *Nucl. Phys. A* **661** pp. 596-599 .
19. K.A. Bugaev Relativistic Kinetic Equations for Finite domains and Freeze-Out Problem, nucl-th/0210087.
20. K.J. Eskola, P.V. Ruuskanen, S.S. Rasanen, K. Tuominen (2001) Multiplicities and Transverse Energies in Central AA Collisions at RHIC and LHC from pQCD, Saturation and Hydrodynamics, *Nucl. Phys. A* **696** pp. 715-728.

21. M. Gyulassy, I. Vitev, X.-N. Wang (2001) High p_T Azimuthal Asymmetry in Non-central A+A at RHIC, *Phys. Rev. Lett.* **86** pp. 2537-2540.
22. T.S. Biró, H.B. Nielsen, J. Knoll (1984) , *Nucl. Phys.* **B245** pp. 449-.
23. H. Sorge (1995) Flavor Production in Pb(160A GeV) on Pb Collisions: Effect of Color Ropes and Hadronic Rescattering, *Phys. Rev.* **C52** pp. 3291-3314.
24. K. Werner, J. Aichelin (1996) Linking Dynamical and Thermal Models of Ultrarelativistic Nuclear Scattering, *Phys. Rev. Lett.* **76** pp. 1027-1030.
25. N.S. Amelin, M.A. Braun, C. Pajares (1993) Multiple Production In The Monte Carlo String Fusion Model, *Phys. Lett.* **B306** pp. 312-318 ; (1994) String Fusion And Particle Production At High-Energies: Monte Carlo String Fusion Model, *Z. Phys.* **C63** pp. 507-516.
26. M. Gyulassy, L.P. Csernai (1986) Baryon Recoil And The Fragmentation Regions In Ultrarelativistic Nuclear Collisions, *Nucl. Phys.* **A460** pp. 723-754.
27. N. S. Amelin, E.F. Staubo, L.P. Csernai, V.D. Toneev, K.K. Gudima, D.D. Strottman (1991) Collectivity, Energy Density And Baryon Density In Pb On Pb Collisions, *Phys. Lett.* **B261** pp. 352-356; (1991) Transverse Flow And Collectivity In Ultrarelativistic Heavy Ion Collisions, *Phys. Rev. Lett.* **67** pp. 1523-1526.
28. N.S. Amelin, L.P. Csernai, E.F. Staubo, and D. Strottman (1992) Collectivity in ultrarelativistic heavy ion collisions, *Nucl. Phys.* **A544** pp. 463-466.
29. V. Magas, L.P. Csernai, D. Strottman (2001) The initial state of ultra-relativistic heavy ion collision, *Phys. Rev.* **C64** 014901.
30. V. Magas, L.P. Csernai, D. Strottman (2002) Effective String Rope Model for the initial stages of Ultra-Relativistic Heavy Ion Collisions, *Nucl. Phys.* **A712** pp.167.
31. V.K. Magas, L.P. Csernai, D.D. Strottman The source of the Elliptic Flow and Initial Conditions for Hydrodynamical Calculations, nucl-th/0009049; The source of the "third flow component", hep-ph/0101125; Multi Module Model for Relativistic Heavy Ion Collisions, hep-ph/0110347. Initial conditions for RHIC collisions, hep-ph/0202118.
32. L.P. Csernai, Cs. Anderlik, V.K. Magas Phase transitions in high energy heavy ion collisions within fluid dynamics, nucl-th/0010023.
33. A. Keränen, J. Manninen, L.P. Csernai and V.K. Magas Statistical Hadronization of Supercooled Quark-Gluon Plasma, nucl-th/0205019.
34. L.P. Csernai (1994) *Introduction to Relativistic Heavy Ion Collisions*, Willey.
35. L.P. Csernai, D. Röhrich (1999) Third flow component as QGP signal, *Phys. Lett.* **B458** pp.454-465.
36. D. Myers (1978) A Model For High-Energy Heavy Ion Collisions, *Nucl. Phys.* **A296** pp. 177-188; J. Gosset, J.I. Kapusta, G.D. Westfall (1978) Calculations With The Nuclear Firestreak Model, *Phys. Rev.* **C18** pp. 844-855.
37. D. Rischke, M. Gyulassy (1996) The Time-Delay Signature of Quark-Gluon-Plasma Formation in Relativistic Nuclear Collisions, *Nucl. Phys.* **A608** pp. 479-512.
38. L.P. Csernai, J.I. Kapusta (1992) Dynamics Of The QCD Phase Transition, *Phys. Rev. Lett.* **69** pp. 737-740; (1992) Nucleation of relativistic first order phase transitions, *Phys. Rev.* **D46** pp. 1379-1390.
39. T. Csörgő, L.P. Csernai (1994) Quark-Gluon Plasma Freeze-Out from a Supercooled State?, *Phys. Lett.* **B333** pp. 494-499.
40. L.P. Csernai, I.N. Mishustin (1995) Fast Hadronization Of Supercooled Quark - Gluon Plasma, *Phys. Rev. Lett.* **74** pp. 5005-5008.
41. M.I. Gorenstein, H.G. Miller, R.M. Quick, R.A. Ritchie (1994) Time-Like Shock Hadronization of a Supercooled Quark-Gluon Plasma, *Phys. Lett.* **B340** pp. 109-114.
42. L.L. Jenkovszky, B. Kampfer, V.M. Sysoev (1990) On The Expansion Of The Universe During The Confinement Transition, *Z. Phys.* **C48** pp. 147-150.
43. L.P. Csernai, M.I. Gorenstein, L.L. Jenkovszky, I. Lovas, V.K. Magas Can supercooling explain the HBT puzzle?, hep-ph/0210297.