Multi Module Model for Ultra-Relativistic Heavy Ion Collisions

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Abstract

The Multi Module Model for Ultra-Relativistic Heavy Ion Collisions at RHIC and LHC energies is presented. It uses the Effective String Rope Model for the calculation of the initial stages of the reaction; the output of this model is used as the initial state for the subsequent one-fluid calculations. It is shown that such an initial state leads to the creation of the third flow component. The hydrodynamical evolution of the energy density distribution is also presented.

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1 Introduction

A realistic and detailed description of an energetic heavy ion reaction requires a Multi Module Model, wherein the different stages of the reaction are each described with a suitable theoretical approach. It is important that these Modules are coupled to each other correctly: on the interface, which is a three 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 correct matching at FO in detail in Refs. [1].

Fluid dynamical models are widely used to describe ultra-relativistic 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. For example, the only models which may handle the supercooled QGP are hydrodynamical models with a corresponding EoS. In energetic collisions of large heavy ions, especially if a Quark-Gluon Plasma (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, Freeze-Out (FO), stages of the reaction are outside the domain of applicability of the fluid dynamical model. After hadronization and FO, the matter is already dilute and can be described well with kinetic models. The initial stages are the most problematic. Non of the theoretical models on the physics market can unambiguously describe the initial stages (see for example [2, 3] for discussion).

Thus, since we can not unambiguously describe the initial stages of relativistic heavy ion collisions in microscopic models, we have to use some phenomenological models. There are two phenomenological models, which are most frequently discussed in the literature - the Landau and the Bjorken scenarios. These models describe two extreme cases - complete stopping or complete transparency, respectively. Nowadays, experiments have entered the region where the Bjorken model is expected to be applicable, but there is no clear and unambiguous confirmation that experiments follow this scenario. The preliminary experimental results from RHIC do not show transparency - most particle multiplicities (except maybe the most

central collisions) do not show a dip in the rapidity spectra, but rather a plateau around mid rapidity [6, 7], which is a sign of strong stopping. Furthermore, very strong elliptic flow has been measured, which shows a clear peak around mid rapidity [6, 9]. 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 [10, 11] (preliminary) is still far from 1, which tells us that the middle region is not baryonfree.

2 Two Module Model

Our goal is to build a Multi Module Model for ultra-relativistic heavy ion collisions valid for RHIC and LHC energies, and maybe for the most energetic SPS collisions. In the present work only the first step is done - a Two Module Model [3, 4] - but a very important one, since the Effective String Rope Model (ESRM) [2, 3] has been developed for the most problematic module - the module describing the initial stages of collisions.

We describe the initial state with the ESRM; then the hydrodynamical evolution with a QGP EoS is used for the intermediate state. The hydrodymanical calculations are performed with the Los Alamos Particle-in-Cell (PIC) one fluid code [13, 14]. The hydro evolution stops at the FO hypersurface. We present a version of the code assuming that FO (simultaneous chemical and thermal) happens on the simplified toothed hypersurface, where it's normal vector, $d\sigma^\mu$, is parallel to the flow velocity for every cell. On average this hypersurface approximates the constant time hypersurface. Therefore the flow velocity does not change during the FO process, and the calculations can be done in local rest frame of the matter. Such a surface is also completely timelike; this allows us to avoid the problems discussed in Refs. [1]. The more advanced description of the FO process is planned to be separated into the Third Module.

The EoS presently used in the code was used and presented in Ref. [13]. This phenomenological phase transition model
A) takes the phenomenological EoS for hadronic matter in a simple form, which nevertheless allows one to check different parameterizations discussed in the literature;
B) uses the Bag model EoS to describe QGP;
C) creates a complete EoS, containing pure phases and a region where they coexist, by the Maxwell construction.

The reader may notice that the model is still in a formative stage and

a lot of further work remains necessary. We are not yet ready to present the quantitative calculations to be compared with data. Nevertheless we present some preliminary results. First of all, the flow component, v_1, as a function of rapidity, y, is presented in Fig. 1, to show that our expectation that the model will generate a third flow component (Refs. [2]) is reasonable [3, 4]. Our initial state generated by the ESRM indeed produces a strong antiflow in semi-central collisions. The directed v_1 component appears to be very small, as expected for RHIC energies (for example [8]). The peaks in v_1 (actually v_3) around $y = \pm 0.3$ look very high, but this is typical for calculations without thermal smearing [15]. Including thermal smearing will lead to smaller and wider peaks.

We also present in Fig. 2 the evolution of the energy density distribution, $e(r, t)$, during the hydrodynamic expansion (notice that $t = 0$ corresponds to the moment then we start the hydro description, i.e. 3.5 fm/c after the collision). We can see the development of the small but very dense, shock-like domains at the intermediate stages. This effect, at least to some extent, is due to numerical artifacts. The PIC method has a well-known defect called 'ringing' or marker-clustering [16]. It is called this way because early calculations in two dimensions resulted in density distributions that looked similar to the vibration patterns in sound vibrations - areas of higher and lower densities [16]. Advanced algorithms that mitigate this effect are being implemented in the code.

Another reason which may cause the development of the numerical artifacts is a step-like in beam direction initial energy density distribution (output of ESRM): it has a jump from $e(x, y) = const$ inside the matter to 0 in the outside vacuum. In order to avoid (or at least to suppress) the effect of this we are planning to smooth over initial energy density distribution, for example by a Gaussian shape, as proposed in Ref. [17]. Thus it is plausible that the development of the shock-like domains in the simulation is not a physical effect, although we can not rule out other possibilities.

To evaluate the observables a third, FO module is going to be attached to the model. Here the widely used Cooper-Frye model should be essentially improved and modified. First of all conservation laws and the requirement of increasing entropy should be enforced in the module. In addition, particularly for FO across space-like hypersurfaces, realistic, non-equilibrium post FO phase space distributions will have to be used to avoid negative contributions occuring in the naive use of the Cooper-Frye

model [1, 3].

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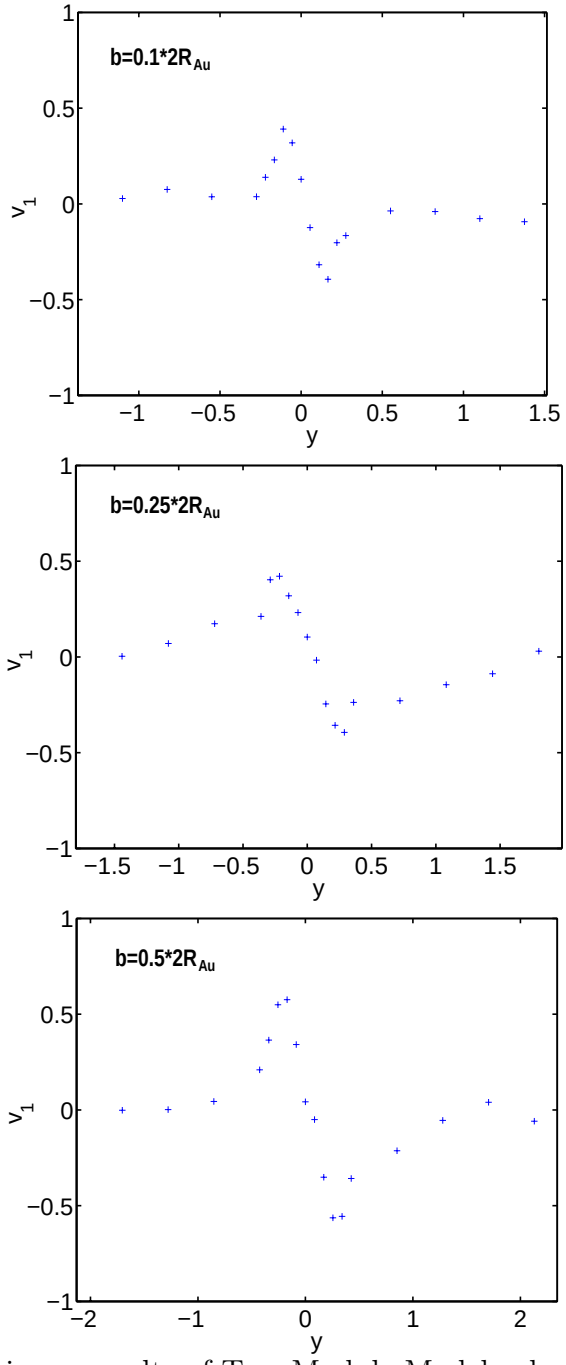

Figure 1: Preliminary results of Two Module Model calculations for v_1 vs rapidity, y. Au+Au collision at $\varepsilon_0 = 65\ GeV/nucl$ for different impact parameters. Initial state was generated with $A = 0.065$, $\tau = 3.5\ fm/c$ (see [2, 3] for details).

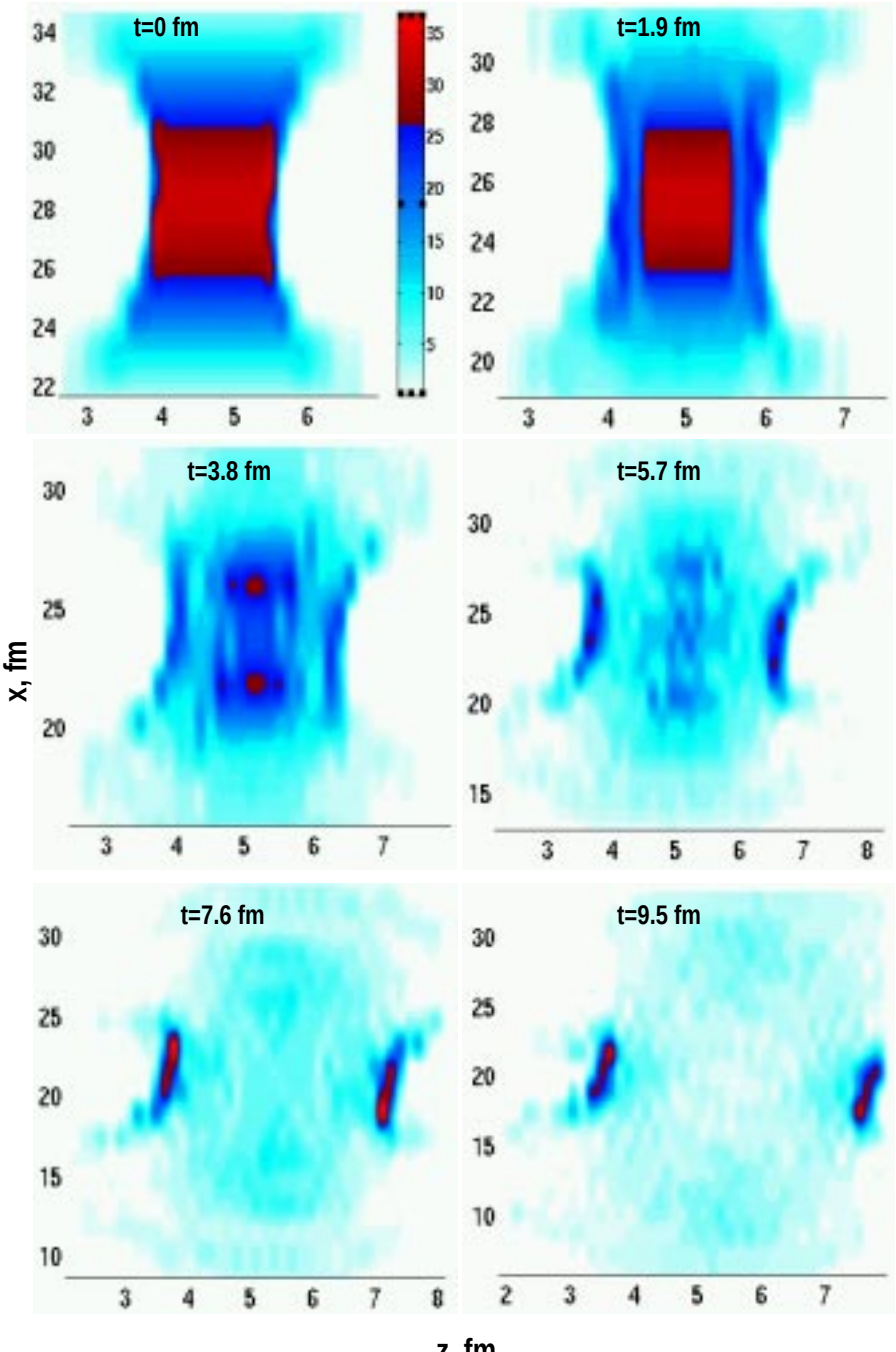

Figure 2: Preliminary results of Two Module Model calculations for energy density distribution in the reaction plane. Au+Au collision at $\varepsilon_0 = 65\ GeV/nucl$, $b = 0.1 \cdot 2R_{Au}$ for different moments of time; initial state was generated with $A = 0.08$, $\tau = 3.5\ fm/c$ (see [2, 3] for details).