Modeling of modifications induced by jets in the relativistic bulk nuclear matter

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Abstract. This work is focused on the influence of energy deposited by jets in the medium on the behavior of bulk nuclear matter. In the heavy ion reactions jets are widely used as probes in the study of Quark-Gluon-Plasma (QGP). Modeling using relativistic hydrodynamics with jets perturbation is employed to extract the properties of the QGP. In order to observe a modification of the collective characteristic of the matter, we use our (3+1) relativistic hydrodynamic code and jet energy loss algorithm implemented on the Graphics Cards (GPU). The program uses 7^{th} order WENO algorithm and the Cartesian coordinate system to provide high spatial resolution and high accuracy in hydrodynamic simulations required to analyze the propagation of jets in the nuclear matter. We present how the propagation of jets in the medium could affect the measurements of the properties of a strongly interacting nuclear matter.

1. Introduction

The subject of this study is connected with investigation properties of Strongly Interacting Matter (SIM) and its phases and transition between them. In order to produce the hot nuclear matter on such extreme conditions the heavy nuclei are collided. The evolution of a high energy nucleus-nucleus collision can be distinguished a several stages: pre-equilibrium phase, equilibrium stages - formation of Quark-Gluon Plasma (QGP) phase, hadron gas and finally after freeze-out free hadron. During this stages the jets are produced and affected on expanding bulk nuclear matter. Detected particles have anisotropy in measured momenta in result of the heavy ion experiments. The general question is understand the origin of this momentum anisotropy of the produced particles. We known about two group of effects: flow and non-flow which can be influenced on changes in the final distribution of measured hadrons. Study jet-medium interaction and jet-induced flow can provide information about properties of the QGP phase. Fluctuation in the pre-equilibrium phase might have an impact of the dynamics of the colliding nucleus-nucleus system. Angular triggered two-particle correlations are shown in Fig. 1. ALICE and ATLAS experiments at CERN explan in Ref. [1] the shape of double peak on away side can be naturally explained by sum of measured anisotropic flow Fourier coefficients. This question is still under consideration if this correlation can be assign only to flow effects. Thus there is another open question if this structure is due to jet-medium interaction which show up in two-particle flow measurement. The (3+1) hydrodynamic code + jet energy loss algorithm may help answer of this question. Moreover odd flow harmonics (v_3, v_5, ...) can be generate only due to initial state fluctuations. Fourier flow coefficients as a function of transverse momentum

p_T are shown in Fig. 2. Fast and efficient hydrodynamic code is needed to study event-by-event initial state fluctuations and flow. For this purpose hydrodynamic implementation on the Graphics Cards (GPU) may be useful. Nevertheless approximately studies using averaged fluctuations, are also possible but full event-by-event simulations give more flexibility.

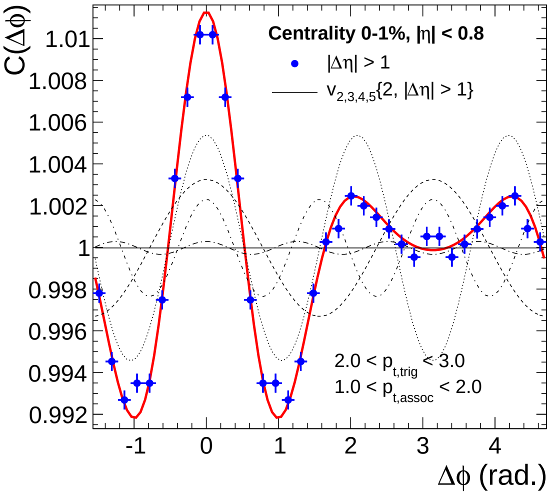

Figure 1. The two-particle azimuthal correlation, measured in $0 < \Delta\phi < \pi$ and shown symmetrized over 2π, between a trigger particle with $2 < p_T < 3$ GeV/c and an associated particle with $1 < p_T < 2$ GeV/c for the 0–1% centrality class. The solid red line shows the sum of the measured anisotropic flow Fourier coefficients v_2, v_3, v_4 and v_5 (dashed lines). Figure taken from [1].

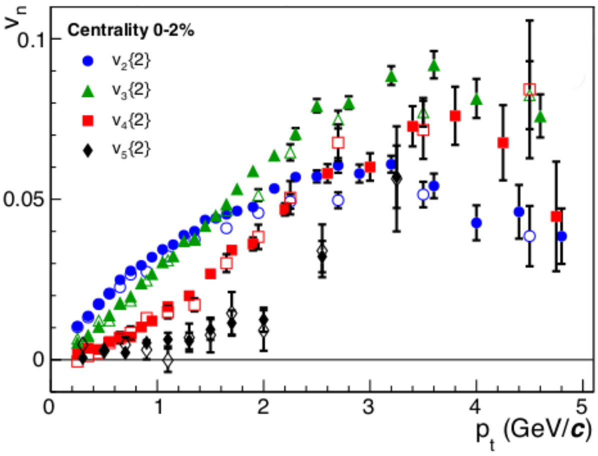

Figure 2. (color online) v_2, v_3, v_4, v_5 as a function of transverse momentum. The full, open symbols. are for $\Delta\eta > 0.2$ and $\Delta\eta > 1.0$, respectively. 0–2% centrality percentile. Figure taken from [1].

2. Hydrodynamics on the Graphics Cards (GPU)

Our hydrodynamic code can describe collective behaviors bulk nuclear matter. The Cartesian coordinate system is needed to study modification in the medium which affected by jets with high spatial resolution and high accuracy. Event-by-event flow fluctuations fast enough for good statistic are needed thus the fast and efficient hydrodynamic code can help. With this assumption we need a lot of computer power. Our GPU multi thread approach gives significant speed-up more than 2 orders of magnitude compared to single thread simulation [2, 3, 4, 5].

Our hydrodynamic program includes 4 major components:

(i) Initial condition for further hydrodynamic simulation,
(ii) Solving partial differential equations - hydrodynamic evolution of the system,
(iii) Freezee-out condition when the matter is not in the local thermal equilibrium.
(iv) Computing freeze-out hypersurface and particle emission function.

We begin our hydrodynamic simulation from generation initial condition based on UrQMD model [6] in order to prepare event-by-event simulation with fluctuating initial conditions what is also the point of interest in this investigation. Relativistic hydrodynamics simulations are based on universal hyperbolic equations of the conservation laws.

$$\frac{\partial U}{\partial t} + \frac{\partial F(U)}{\partial x} + \frac{\partial G(U)}{\partial y} + \frac{\partial H(U)}{\partial z} = 0 \tag{1}$$

with a determined Equation of State (EoS) $p = e^2/3$ where U is the vector of conserved quantities such as energy density (E), momenta density (M), net charge density (R) in the laboratory rest frame. Vectors of fluxes F, G, H in the x; y; z directions are defined as:

$$F(U) = \begin{bmatrix} (E+p)v_x \\ M_x v_x + p \\ M_y v_x \\ M_z v_x \\ R v_x \end{bmatrix}, \quad G(U) = \begin{bmatrix} (E+p)v_y \\ M_x v_y \\ M_y v_y + p \\ M_z v_y \\ R v_y \end{bmatrix}, \quad H(U) = \begin{bmatrix} (E+p)v_z \\ M_x v_z \\ M_y v_z \\ M_z v_z + p \\ R v_z \end{bmatrix}. \tag{2}$$

where v is the velocity, and p is pressure, defined by the energy e and charge density n in the local fluid rest frame, where velocity v vanishes ($v = (0,0,0)$). Additionally, the following relations occur:

$$\begin{aligned} E &= (\varepsilon + p)\gamma^2 - p \\ M_i &= (\varepsilon + p)\gamma^2 v_i, \qquad i = x, y, z \\ R &= n\gamma \end{aligned} \tag{3}$$

where ε is the energy density and $\gamma = \frac{1}{\sqrt{1-v^2}}$ is the Lorentz factor. Eq. 3 defines the transformation from local fluid rest frame variables to laboratory rest frame. There is the set of hyperbolic partial equations in the laboratory frame quantities defined in Eq. 2 In order to integrate them we use a finite-difference scheme on a Cartesian grid as follow:

$$\begin{aligned} U^{n+1}_{i,j,k} = U^{n}_{i,j,k} + \tfrac{\Delta t}{\Delta x}\left(F_{i-\frac{1}{2},j,k} - F_{i+\frac{1}{2},j,k}\right) + \\ + \tfrac{\Delta t}{\Delta y}\left(G_{i,j-\frac{1}{2},k} - G_{i,j+\frac{1}{2},k}\right) + \tfrac{\Delta t}{\Delta z}\left(H_{i,j,k-\frac{1}{2}} - H_{i,j,k+\frac{1}{2}}\right). \end{aligned} \tag{4}$$

For time propagation the standard 3^{th} order Runge-Kutta methods are employed [7]. The main part of our software is the numerical implementation of 7^{th} order WENO algorithm [8, 9] on the Graphics Cards (GPU) using nVidia CUDA framework [10]. The WENO is very accurrate algorithm. Numerical oscillation and numerical diffusion are balanced in this type of algorithm. The 7th order of WENO scheme tests gives very good performance in our implementation. We use energy loss $\frac{dE}{dx}$ procedure as a source in the hyperbolic equations.

$$\partial_\mu T^{\mu\nu} = J^\nu(x) \tag{5}$$

More details about Eq. 5 are described in Ref. [11]. The algorithm uses two mechanisms of jet energy loss which include gluon radiation and collision procedure of parton in dense medium. We used formula which is presented below:

$$\left(-\frac{\mathrm{d}E}{\mathrm{d}x}\right) = \kappa_{rad}\frac{C_R}{C_F}T^3 x + \kappa_{coll}\frac{C_R}{C_F}T^2 \tag{6}$$

where T is local temperature and $\kappa_{rad}, \kappa_{coll}, C_R, C_F$ coefficients depend on jet flavor (quark or gluon) and its energy [12]. In the simulations, we assumed $\kappa_{rad} = 4, \kappa_{coll} = 2.5, C_R/C_F = 1$. We assume that $\frac{\mathrm{d}E}{\mathrm{d}x}$ is small compared to the jet energy and the jet is not modified by the medium.

In order to accelerate of simulation we decided to use graphics processor GPU. The WENO algorithms have been implemented on a GPU with using the CUDA parallel programming model.

Our Hydro program starts on CPU in serial host mode. During this stage the initial data are copied to GPU coprocessor. Functions with numerical algorithm executed on a GPU are called kernels in parallel mode. Each kernel executed by launching blocks of threads. Threads form in block run together on the same stringing multiprocessor. Finally after parallel computation data are copied back to host and the program finished all tasks on CPU in serial mode.

Last stage of our simulation focuses on transformation of numerical grid quantities to kinetic description of particles produced during the nucleus-nucleus collision. Thus we use Cooper-Frye formula to obtain hypersurface in order to generate particles multiplicity spectra and momenta distribution.

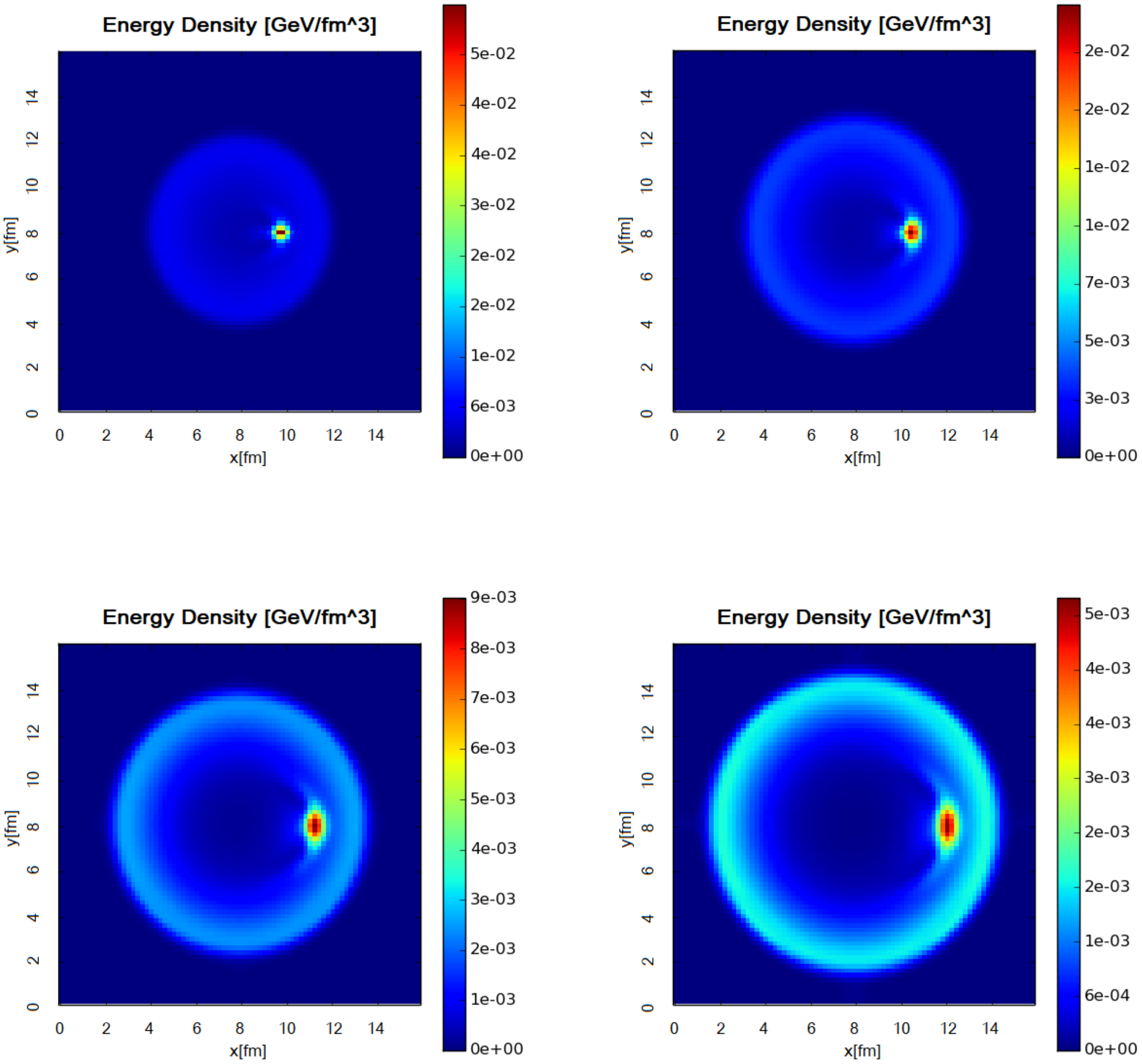

Figure 3. Energy density cross section with jet traveling trough the medium in xy plane at $z = 0$ after $t = 2.0$ fm/c see panel (a), $t = 2.8$ fm/c see panel (b), $t = 3.6$ fm/c see panel (c), $t = 4.4$ fm/c see panel (d).

3. Results

Our simulations are concentrated in modeling of modification induced by jets in the relativistic bulk nuclear matter [13]. In this section we present propagation of jets during the evolution of the medium. We simulate evolution of bulk matter together with energy loss $\frac{dE}{dx}$ of jet traveling through the medium. We performed ellipsoidal test in order to illustrate and validate our hydrodynamic code with jet energy loss algorithm. The initial condition of ellipsoidal test base on Ref. [14]. Response signal of the medium which is caused by jet propagation is observed in Fig. 3. During the matter evolution the Mach cone in the medium is visible. Energy profiles with time ($t = 2.0$ fm/c, $t = 2.8$ fm/c, $t = 3.6$ fm/c, $t = 4.4$ fm/c) are shown Fig. 4. It is clearly visible the propagation of jets in the medium could affect the properties of bulk nuclear matter. Surrounding matter where jet interacted with medium significantly increase due to jet energy loss. Employed realistic jet energy loss $\frac{dE}{dx}$ algorithm takes into account the decrease ionization of medium in time caused by jets. Initial condition from UrQMD model was prepared and preliminary hydrodynamic tests were performed in order to simulate comparable nucleus-nucleus interaction measured in the heavy ion experiments. Stability tests using implemented 7^{th} order WENO were performed. We plan to finish Freeze-out implementation which is in progress. It is necessary to employ commonly used Cooper-Frey formula in order to obtain hypersurface. In the future we plan to use existing hadron Monte-Carlo generator such as TERMINATOR2 [15]. The interface between our hydro program and THERMINATOR2 generator is being developed. After this efforts there is possible to study elliptic flow, higher harmonic flow and other observables in order to compare to simulations experimental results such as $Pb + Pb$ and $Au + Au$ interactions at RHIC and LHC energies.

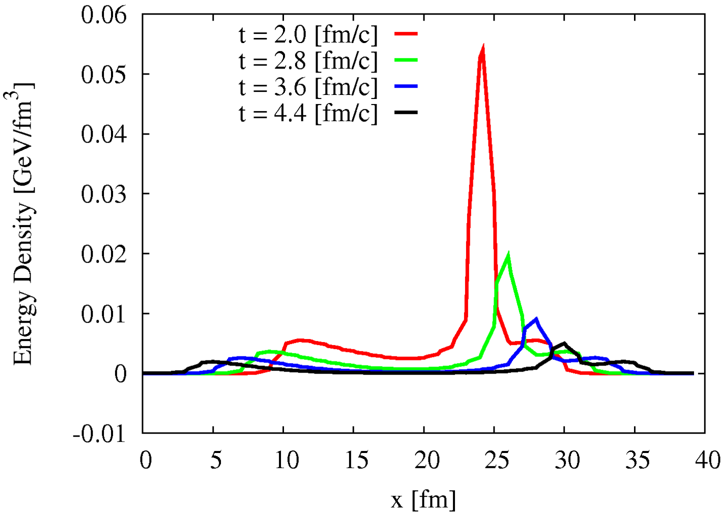

Figure 4. $1D$ projection $z = y = 0$ of energy density evolution in time with jet propagation

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