ISSN 1818-331X ЯДЕРНА ФІЗИКА ТА ЕНЕРГЕТИКА 2012 Т. 13 № 1

УДК 539.12

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BUMPING STRUCTURE OF INITIAL ENERGY DENSITY DISTRIBUTIONS AND PECULIARITIES OF PION SPECTRA IN A + A COLLISIONS

The effect of a fluctuating bumping structure of the initial conditions on spectra and the collective evolution of matter created in heavy-ion collisions in the frameworks of the Hydro-Kinetic Model is investigated. As motivated by the glasma-flux-tube scenario, the initial conditions are modeled by the set of four high energy-density tube-like fluctuations with longitudinally homogeneous structure within some space-rapidity region in a boost-invariant 2D geometry. It was found that the presence of transversally bumping tube-like fluctuations in initial conditions strongly affects the hydrodynamic evolution and leads to emergence of conspicuous structures in the calculated pion spectra. It was observed that the 4 tube initial configuration generates a four-peak structure in the final azimuthal distributions of one-particle spectra.

Keywords: nucleus-nucleus collisions, hydrodynamics, fluctuating initial conditions, pion spectrum.

Introduction

One of the most exciting results firstly measured in the relativistic heavy-ion collisions by the STAR collaboration [1] is the existence of ridge structures in the two-particle correlations [1 - 7] plotted as function of the pseudorapidity difference and the angular spacing $\Delta\varphi$. Moreover, as the particle densities produced in the highest multiplicity pp collisions at Large Hadron Collider energies started to approach those in high energy nuclear collisions, the emergence of new features in the two-particle correlation function from high multiplicity pp events also was observed [8].

The discovery of the ridge has provoked a lot of theoretical analyses. Currently available models of the ridge formation (at times strikingly different) [9 - 18] provide only qualitative guidance about the underlying physics of the ridge, rather than quantitative predictions.

It was shown that the long-range structure of two-particle angular correlation functions is significantly modified by the presence of inhomogeneities in a hot and dense matter formed in relativistic heavy ion collisions [19]. It has been argued also that the joint interplay of the longitudinal high-energy density tubes (remnants from initial particle collisions) and transverse expansion is responsible for the ridge formation [10, 15, 17, 19, 20]. As showed by the study of near-side correlations, this elongated contribution has the properties analogous to a bulk particle production (transverse momentum spectra, baryon/meson ratio, etc). Due to the resemblances between bulk matter and ridge, the explanations based on the relativistic hydrodynamics are often used.

Usually, the initial conditions (IC) in the relativistic hydrodynamic description of the high-energy nuclear collisions are assumed to be smooth [21, 22]. However, some data require knowledge of the event-by-event fluctuating IC (for example fluctuations in elliptic flow [23] or the dependence of the elliptic flow on pseudorapidity [24]). The event-by-event approach in which the following sequence is repeated many times: for each collision some IC are generated, hydrodynamics is run and results are stored, was firstly implemented by the SPheRIO collaboration [25 - 27] then used by other groups [28, 29]. Despite the fact that different models have been suggested to explain the structures in the two particle correlations but even those based on the relativistic hydrodynamics have strong differences between them: for each high-energy density fluctuation, there is the emission in one direction [10, 19, 20], in two directions [30] or there is no emission [31]. Three-particle correlations have been suggested as a possible test to distinguish between various scenarios [31].

It was proposed recently [32] to study the possible typical (or “representative”) configuration of initial fluctuations which are already maximally symmetric in the azimuthal plane, instead of averaging the result over many fluctuations. It was found that for the different initial energy-density configurations, the effect of the initial bumping-like fluctuations is not washed out during the system expansion and preserve in the final energy density of hadronic matter. Probably, it could lead to the ridges structures of the correlations, which are caused by these fluctuations [32, 33]. To test the influence of this effect on the observed particle spectra and appearance of the ridge structure, this paper examines the angular dependence of the particle (pion) spectra for such IC. For this purpose we use the Hydro-Kinetic Model (HKM) [34] which incorporates description of all the stages of the system evolution as well as a formation of the particle momentum at the decoupling stage, with longitudinally homogeneous and a transversally bumping IC.

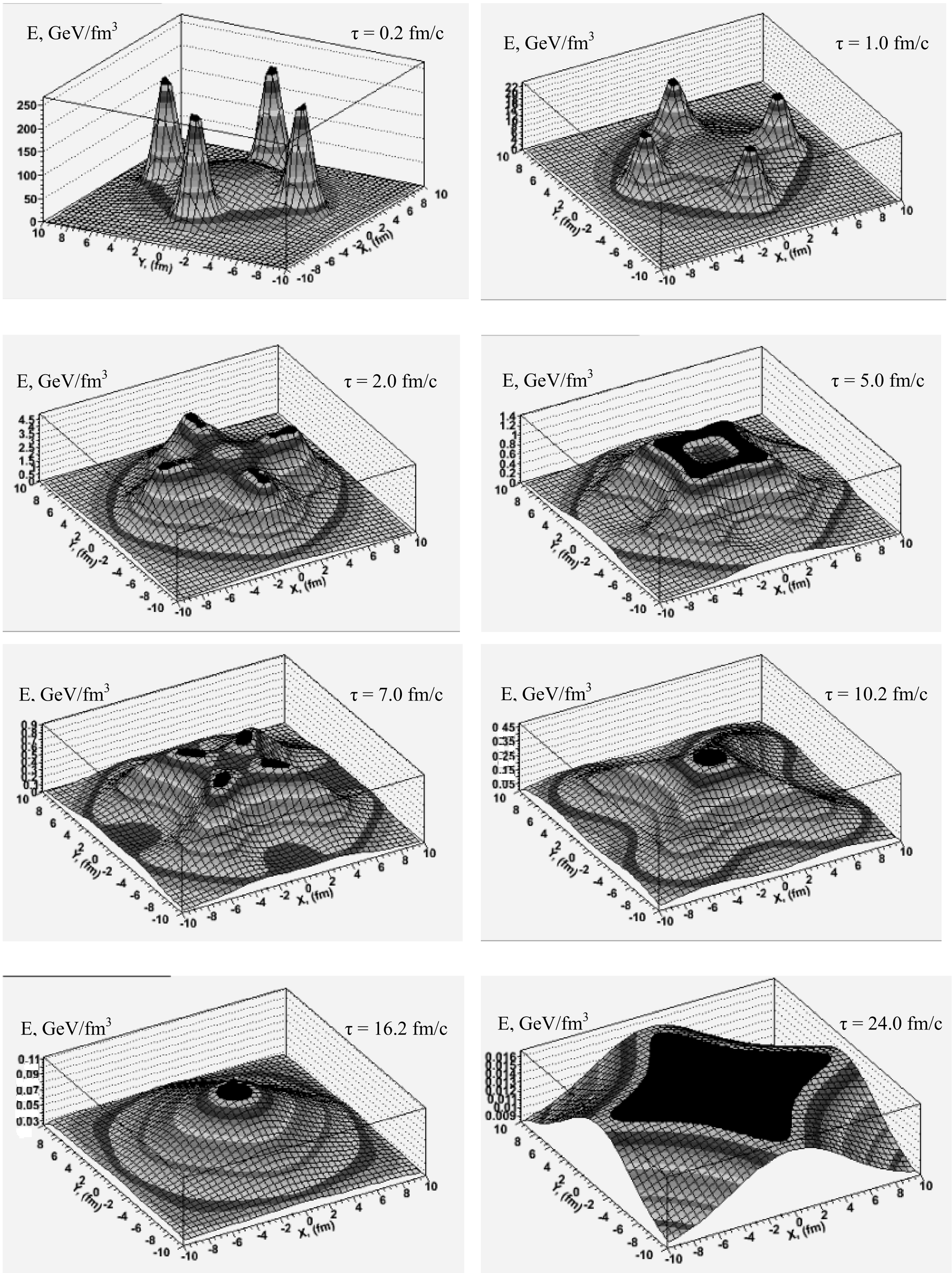

Fig. 1. 3D plots of the energy (1) density profiles with the 4 tube-like initial conditions for different values of τ.

Methods, results and discussion

In this section the results obtained by numerical calculations with the concrete realization of the HKM are presented and discussed. For the sake of simplicity, the emission of the only one kind of particles (negative pions, π^-) from the expanding fireball is considered. The numerical results presented in this section were obtained on the basis of the 2 + 1 HKM that includes the transversally bumping tube-like IC with the aim to study how the initial fluctuations in the energy density distribution affect the spectra. The analysis is based on the Boltzmann equations of the hydrodynamic approach to relativistic nucleus-nucleus (A + A) collisions. It is consistent with the conservation laws and accounts for the opacity effects. We use Bjorken-type IC of quasi-inertial flow at proper time $\tau = \sqrt{t^2 - z^2} = \tau_0$: Boost-invariance of the system in the longitudinal *z*-direction and zero initial longitudinal flow without transverse collective expansion in *xy*-plane. The hydrodynamic evolution starts at the time τ_0. Two initial configurations were examined. The first one corresponds to the smooth Gaussian profile with a radius *R* and energy density *E* as was considered in [35] at the time τ_0 = 0.2 fm/c. The second initial scenario is based on bumping tube-like initial fluctuations at τ_0. These tubes are rather thin transversally and relatively long in the direction of beam axis, with the transverse (gaussian) radii a_i in the energy density *E*. The general initial energy-density distribution *E* at τ_0 is given by

$$E = E_b \exp\left[-\frac{x^2+y^2}{R^2}\right] + \\ +\sum_{i=0}^{N_t} E_i \exp\left[-\frac{(x-x_i)^2+(y-y_i)^2}{a_i^2}\right], \quad (1)$$

where $R_i = x_i^2 + y_i^2$ are the positions of the fluctuation locations and N_t is the number of tubes mentioned above. E_b is the maximum value of the average energy-density distribution while E_i are the values of energy density maxima of the tube-like fluctuations.

In present calculations the parameters of the initial configurations without tubes (fluctuations) is specified by E_b = 130 GeV/fm^3, R = 5.4 fm and a_i = 1 fm. The other configuration with four tubes (fluctuations) is defined by E_b = 85 GeV/fm^3, R = 5.4 fm, E_i = 250 GeV/fm^3, R_i = 5.6 fm and a_i = 1 fm. The hydrodynamic evolution of the energy density profiles for the case of the 4 symmetrically placed high-energy density tubes is presented in Fig. 1.

The energy density profiles were evolved in time till the chemical freeze-out temperature (T = = 165 MeV) and then, the corresponding spectra were calculated for two cases. The chemical freeze-out hypersurface at the T = 165 MeV that marks the end of the applicability of hydrodynamics and start of the kinetic mode of calculation is presented in the Fig. 2.

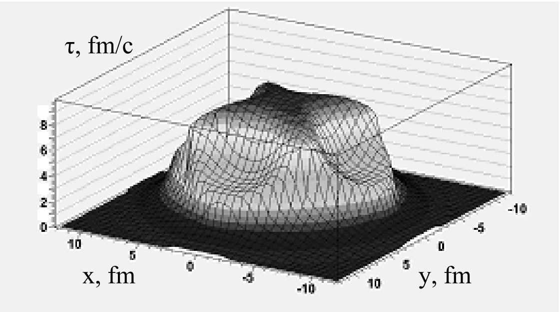

Fig. 2. The chemical freeze-out hypersurface τ (x, y) at the T = 165 MeV.

As it was shown in [36] there is a significant impact of particle emission from the boundary surface of the hot and dense system formed in the high energy heavy ion collisions on the observed spectra. To calculate spectra the yield of particles from volume and surface parts of the chemical freeze-out hypersurface were taken into account.

For the considered set of 4 tubes the traces of the initial fluctuations (the bumping final energy distributions) remain after the system evolution and lead to a non-trivial structures in observed spectra. The corresponding pronounced peaks could be seen in the calculated pion spectra (see the azimuthal dependencies of the pion spectra dN/dφ for different transversal momenta p_T in Fig. 3 and polar diagrams in Fig. 4).

In Fig. 5 the comparison between two cases of the initial energy-density distribution is presented. As expected, the azimuthal dependencies of pion spectra for the medium transversal momenta for the case of 4 tube-like fluctuations have shown the remnants of these bumping structures. The deviations from the azimuthal symmetry which can be seen through the compared spectra are a consequence of coarse structure of the cell in grid calculations. These technical issues impair observed effects in the case of bumping structure of the initial energy-density distributions but nevertheless, they have a small scale and cannot affect the results and further inferences.

As shown in Fig. 3 the results demonstrate that if one particle with relatively large p_T is triggered, most probably, its azimuthal direction will correspond to one of the peaks in the distributions dN/dφ. Then, as follows from dN/dφ distribution, the probability to find the second particle with the same or smaller transverse momentum will be maximal in a narrow range Δ φ near this peak. Inclusive correlations between the triggered particle

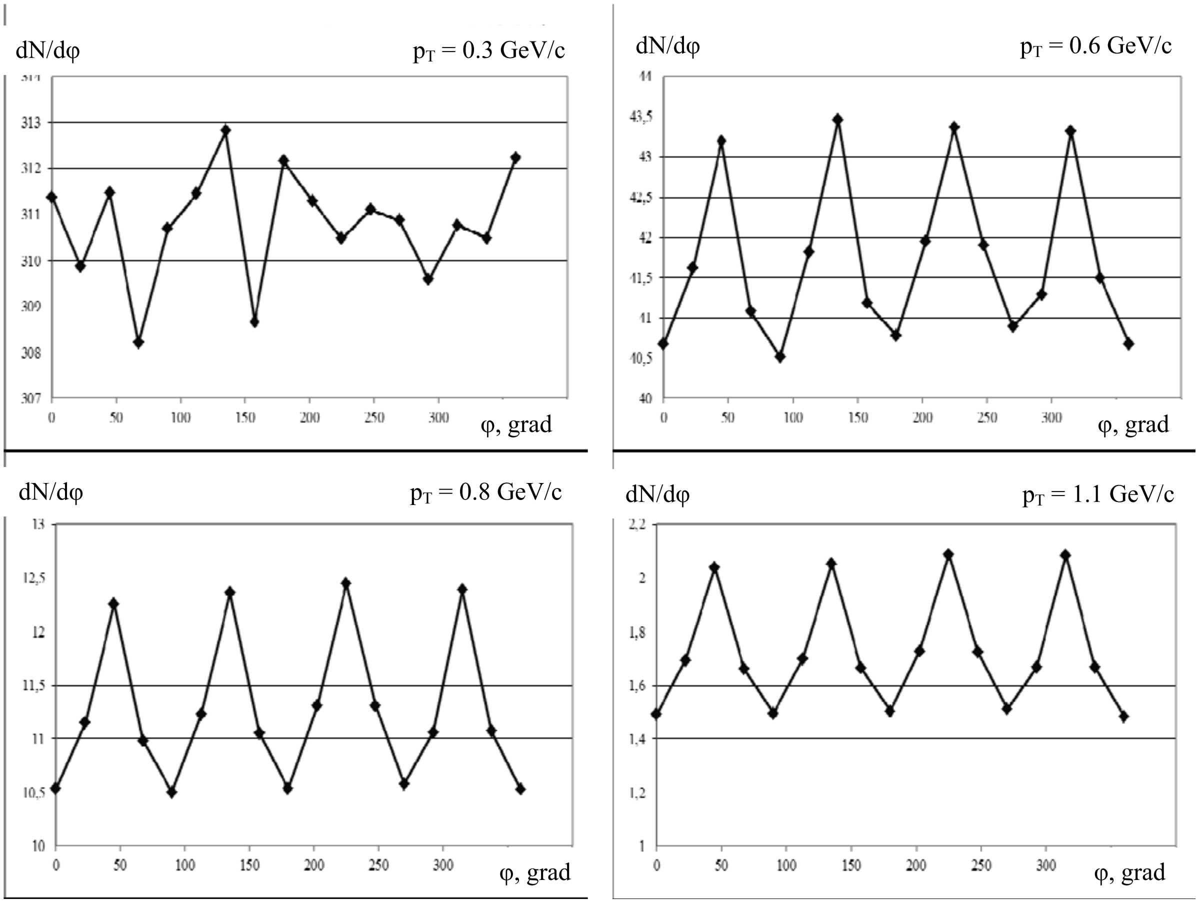

Fig. 3. Pion spectra distributions dN/dφ vs. the azimuthal angle φ for different transversal momenta p_T.

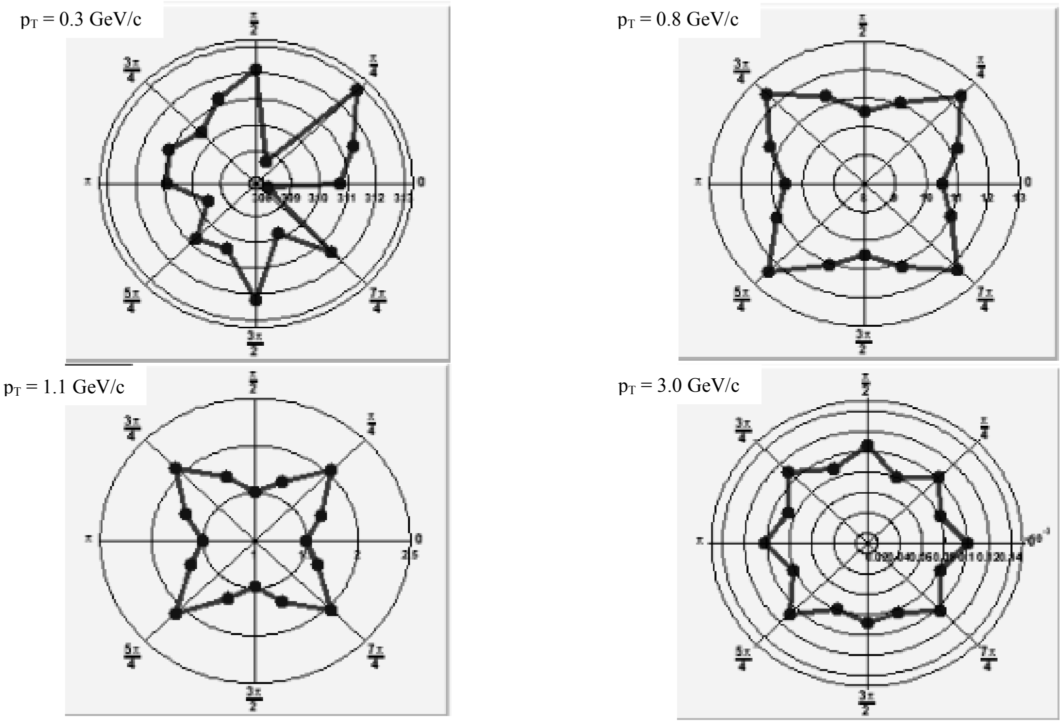

Fig. 4. Polar plots of the spectra dN/dφ vs. the azimuthal angle φ
for different transversal momenta p_T.

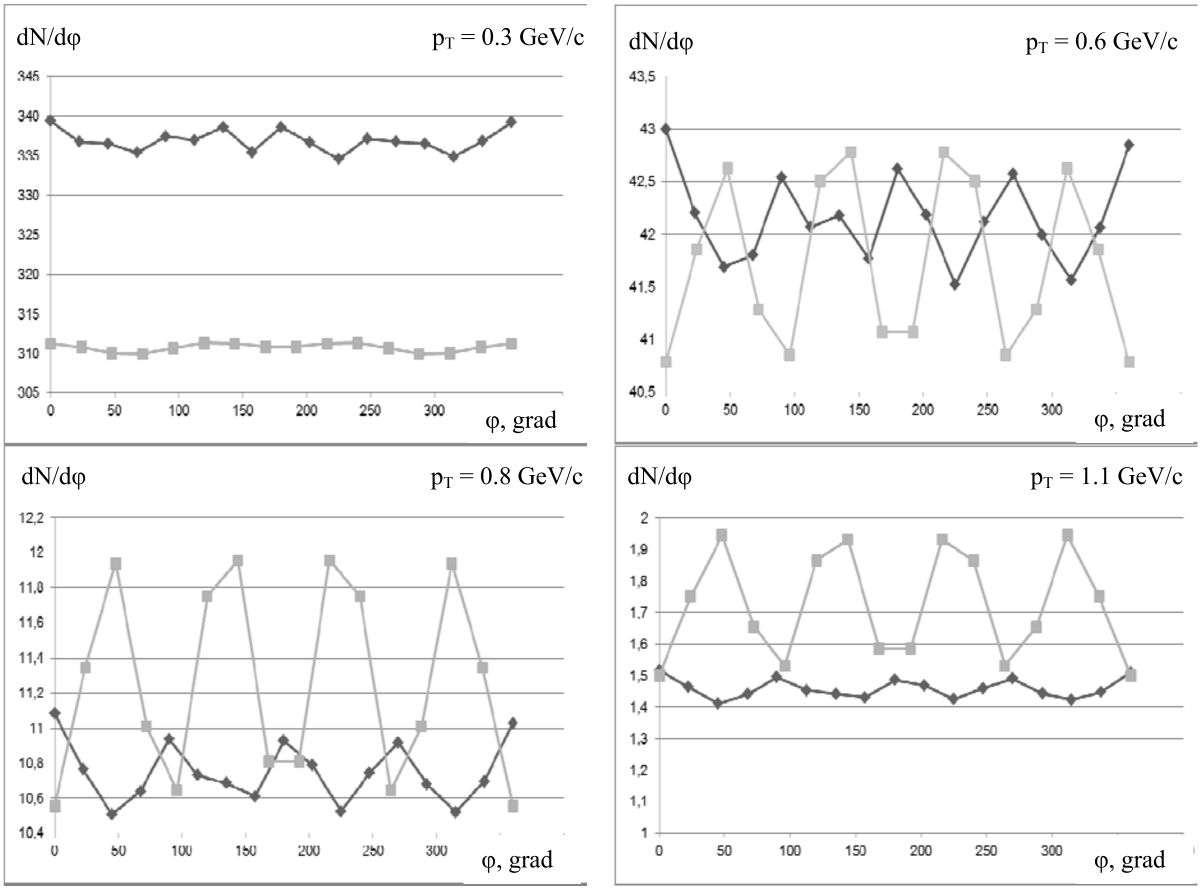

Fig. 5. Transverse pion spectra dN/dφ for the cases of no tubes (light grey) and set of 4 tubes (deep grey) in the initial energy-density distributions as function of the azimuthal angle for different transversal momenta p_T = 0.3, 0.6, 0.8 and 1.1 GeV/c.

and particle corresponding to other peaks will be relatively weak since these peaks will change from the event to the event of their angular location as for the “triggered peak”. It happens because the fluctuations in the bumping structure will washed out the two particle correlations in the inclusive spectra. This is the mechanism of the formation of the so called “soft ridges”.

Conclusions

In contrast to the traditional hydrodynamic description of the relativistic nuclear collisions with smooth IC, the transversally bumping tube-like fluctuations in the initial energy-density distributions are considered with the aim to study the influence of its presence on the pion spectra and ridges formation. These very dense color-field flux tubes are formed at a very initial stage of the nucleus-nucleus collision leftovers. For example of 4 tubes, it was found that such an initial structure affects essentially the final spectra and two-particle correlations. It could be the reason of a “soft ridge” formation. This leads to an emergence of the corresponding peaks in azimuthal distributions of the particle spectra pronounced especially for the medium transverse momenta. As the result, the hydrodynamic mechanism of the “soft ridges” formation becomes sufficiently plausible. To constrain the IC for hydrodynamic expansion in the heavy-ion collisions a further systematic analysis within the HKM will be performed and published elsewhere. It is hope that the multi-particle ridge-like correlations could offer us a chance to get a glimpse of the IC and to extend our knowledge about the strong interactions in A + A collisions.

Acknowledgments

The author thanks Prof. Yu. M. Sinyukov for many fruitful discussions regarding the subject treated in this work and efforts for observed data interpretations. I like to thank to Dr. Yu. Karpenko and also Dr. O. Borysov for the important help in adjusting hydrokinetic code for 2D numerical calculations. The research was carried out within the scope of the European Ultra Relativistic Energies Agreement (EUREA) of the European Research Group GDRE: Heavy ions at ultrarelativistic energies and is supported by the Fundamental Researches State Fund of Ukraine, Agreement No.

F33/305-2011 and the National Academy of Sciences of Ukraine (Agreement No F8-2011). The numerical calculations were done using the cluster and GRID environment of the Bogolyubov Institute for Theoretical Physics of the National Academy of Sciences of Ukraine.

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ПІКОПОДІБНА СТРУКТУРА ПОЧАТКОВИХ РОЗПОДІЛІВ ГУСТИНИ ЕНЕРГІЇ ТА ОСОБЛИВОСТІ СПЕКТРІВ ПІОНІВ У А + А ЗІТКНЕННЯХ

У рамках гідрокінетичної моделі досліджується вплив флуктуючої пікоподібної структури в початкових умовах на спектри та колективну еволюцію матерії, що утворилась у зіткненнях важких іонів. Керуючись сценарієм трубкоподібних потоків у глазмі, початкові умови моделюються набором із чотирьох трубкоподібних флуктуацій високої густини енергії з поздовжньо-однорідною структурою в деякій просторово-бистротній області в буст-інваріантній 2-вимірній геометрії. Було виявлено, що присутність трансверсальних трубкоподібних флуктуацій у початкових умовах сильно впливає на гідродинамічну еволюцію і призводить до появи помітних структур в обчислених спектрах піонів. Зазначається, що початкова конфігурація з чотирма трубками генерує чотири пікові структури в кінцевих азимутальних розподілах одночастинкових спектрів.

Ключові слова: ядро-ядерні зіткнення, гідродинаміка, флуктуючі початкові умови, спектр піонів.

М. С. Борисова

ПИКООБРАЗНАЯ СТРУКТУРА НАЧАЛЬНЫХ РАСПРЕДЕЛЕНИЙ ПЛОТНОСТИ ЭНЕРГИИ И ОСОБЕННОСТИ СПЕКТРОВ ПИОНОВ В А + А СТОЛКНОВЕНИЯХ

В рамках гидрокинетической модели исследуется влияние флуктуирующей пикообразной структуры в начальных условиях на спектры и коллективную эволюцию материи, созданной в ядро-ядерных столкновениях. Руководствуясь сценарием трубкообразных потоков в глазме, начальные условия моделируются набором из четырех пикообразных флуктуаций высокой плотности энергии с продольно однородной структурой в некоторой пространствевенно-быстротной области в буст-инвариантной 2-размерной геометрии. Было обнаружено, что присутствие трансверсальных трубко-подобных флуктуаций в начальных условиях сильно влияет на гидродинамическую эволюцию и приводит к появлению заметных структур в рассчитанных спектрах пионов. Было отмечено, что начальная конфигурация с четырьмя трубками генерирует четырехпиковые структуры в конечных азимутальных распределениях одночастичных спектров.

Ключевые слова: ядро-ядерные столкновения, гидродинамика, флуктуирующие начальные условия, спектр пионов.

Received 10.10.2011.