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FLUCTUATIONS IN INITIAL ENERGY DENSITY DISTRIBUTIONS IN A + A COLLISIONS

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The analysis of particle correlations as a function of relative pseudo-rapidity and azimuthal angle exhibit novel ridge-like structures that were discovered at RHIC in A + A collisions. Such an analysis is of great interest for forthcoming ALICE LHC experiment. This structure which is unusually wide in the longitudinal direction remains after removal of the known correlation-inducing effects such as elliptic flow and ordinary jet correlations. It could be probably explained only if one supposes that the ridge phenomenon in relativistic A + A collisions is rooted in the initial conditions of the thermal evolution of the system. The aim of this study is to check this hypothesis by an analysis of the evolution of the energy density in the system which at very initial stage of collisions has high density tube-like fluctuations with boost-invariant longitudinally homogeneous structure within some space-rapidity region. The transverse-velocity and energy density profiles, which develop in the system when it reaches the chemical freeze-out (T = 165 MeV) for different initial configurations at $\tau_0 = 0.2$ fm/c, are considered.

Keywords: nucleus-nucleus collisions, hydrodynamics, ridge, fluctuations.

Introduction

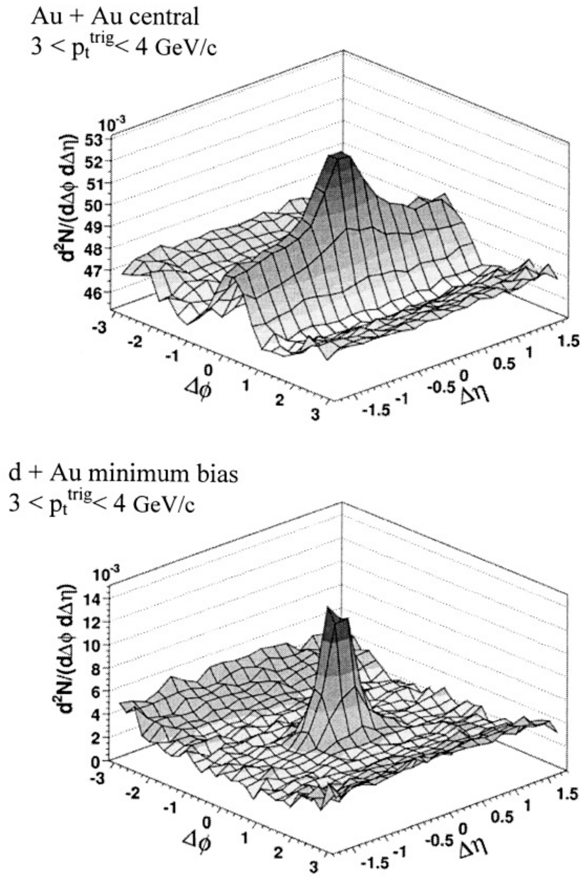
An analysis of the two- or the many-particle correlations in ultrarelativistic nuclear collisions is a powerful tool to study the dynamics of heavy ion collisions. In particular, signatures in measured two-particle hadron correlations indicate interesting structures near the trigger particle in azimuth and over a broad pseudo-rapidity range in the nucleus-nucleus collisions that were not observed in p + p and d+Au collisions. Studies of near-side correlations reveal besides jet-like peak with properties similar to correlations in p+p collisions, elongated contribution with properties analogous to bulk particle production – the ridge. It is termed the ridge because of its elongated shape in the pseudo-rapidity difference $\Delta\eta \equiv \eta_1 - \eta_2$ (where η_1 and η_2 are the pseudo-rapidities of the two particles in the pair analysis) and strongly collimated peak for azimuthal angles $\Delta\varphi = \varphi_1 - \varphi_2 = 0$ with width of about 1 radian. The first measurements of the ridge structure were reported by the STAR Collaboration on the basis of inclusive charged-particle correlations [1].

More recently, measurements were extended to include identified charged and neutral particles, studies of correlations in various momentum ranges, and system size dependencies [2].

Fig. 1 shows distributions of the associated particle yield measured by the STAR Collaboration for central Au + Au events (upper panel) and d + Au (bottom panel) in events containing a „trigger particle“ with trigger $3 < p_t^{trig} < 4$ GeV/c [3] defined as

$$\frac{d^2N}{d\Delta\phi d\Delta\eta}(\Delta\phi,\ \Delta\eta) = \frac{1}{N_{trig}} \frac{1}{\varepsilon(\phi,\ \eta,\ \Delta\phi,\ \Delta\eta)} \frac{d^2N_{raw}}{d\Delta\phi d\Delta\eta} \tag{1}$$

where $\Delta\varphi$ and $\Delta\eta$ are the azimuthal and pseudo-rapidity separation of the pair, N_{trig} is the number of trigger particles, and $\frac{d^2N_{raw}}{d\Delta\phi d\Delta\eta}$ is the measured di-hadron distribution. The factor $\frac{1}{\varepsilon(\phi,\ \eta,\ \Delta\phi,\ \Delta\eta)}$ accounts for the reconstruction efficiency of associated tracks.



Au + Au central
$3 < p_t^{trig} < 4$ GeV/c

d + Au minimum bias
$3 < p_t^{trig} < 4$ GeV/c

Fig. 1. Charged di-hadron distribution (Eq. (1)) for 2 GeV/c < $p_t^{assoc} < p_t^{trig}$, $3 < p_t^{trig} < 4$ GeV/c. Upper panel: central Au + Au, Bottom panel: minimum bias d + Au [3].

A peak centered on (Δη, Δφ) = (0; 0) is evident for two panels and consistent with jet fragmentation. A significant enhancement of near-side correlated yield is seen at large Δη for central Au + Au events, but not for d + Au events. It is the ridge.

An analysis of the measurements by the PHENIX [4] and PHOBOS [5] collaborations corroborates the STAR results. In the latter case, with a high momentum trigger, the ridge is observed to span the even wider PHOBOS acceptance in pseudo-rapidity of Δη ~ 6 units.

The discovery of the ridge has proven to be stubbornly resistant to a quantitative theoretical analysis. Currently available models of ridge formation [2, 6 - 14] provide only qualitative guidance about the underlying physics of the ridge, but not quantitative predictions. At times these models use strikingly different explanations. Some of them explore a final-state effect as the origin of the ridge [13]. In contrast, the authors of Ref. [14] argue that the correlations over several rapidity units can only originate at the earliest stages of heavy ion collisions when prethermal matter is produced. Then due to fluctuations of color charges in colliding nuclei the longitudinally boost-invariant and transversely inhomogeneous structure of the matter can be formed. The induced effects in space-time are limited to a horizon of ~1-2 rapidity units. Similarly to super-horizon fluctuations in the cosmos [15], these long range correlations can therefore reveal a bumping structure of the "little bang" in each nuclear collision at its birth. The evolution of the system and other later-stage effects can modify these correlations, which, in fact, are associated with fluctuations in the energy densities at the final stage.

To test the hypothesis that the ridge phenomenon in ultrarelativistic A + A collisions is rooted in longitudinally homogeneous and a transversally bumping distribution of the creating matter and such a structure is not washed out completely during the subsequent thermal evolution of the system, we shall study how the energy density profiles with different initial configurations evolve in time.

Results and discussion

The numerical results presented in this section were obtained on the basis of original 3D ideal hydro-code, described in details in [16]. The analysis is based on hydrodynamic approach to A + A collisions and considered within the Boltzmann equations. It is consistent with conservations laws and accounts for the opacity effects. The hydrodynamic evolution starts at the time τ_0. We use Bjorken-type initial conditions at τ_0: boost-invariance of the system in longitudinal direction, initial longitudinal flow $v_L = 0$ without transverse collective expansion.

In present calculation we compare the transverse-velocity profile of hydrodynamic flow and energy density profile which evolve in time till the chemical freeze-out (T = 165 MeV) in different initial scenarios. The one of them corresponds to the smooth Gaussian profile with radius R and energy density as it was considered in [17] at $\tau_0 = 0.2$ fm/c. The other scenarios are based on transversally bumping tube-like initial conditions at τ_0. These tubes are rather thin transversally and relatively long in the direction of beam axis; with radii a_i = 1 fm. The general energy density distribution at τ_0 could be written as:

$$E = E_b e^{-\frac{x^2+y^2}{R^2}} + \sum_{i=0}^{N_t} E_i e^{-\frac{(x-x_i)^2+(y-y_i)^2}{a_i^2}},$$

$$R_i = x_i^2 + y_i^2,$$

where E_b is the maximum of average energy density distribution, E_i are the maxima of tube-like fluctuations, R_i are the positions of the fluctuation locations.

Instead of a study of the result over very many fluctuations, that should be finally averaged over azimuthal angular (it brings symmetry), we will be based here on the possible typical, or "representative", initial fluctuation which are already maximally symmetric in azimuthal plane. The following initial configurations are considered:

the configuration without fluctuation: distribution of initial energy density corresponds to the Gauss distribution with R = 5,4 fm and maximum energy density at r = 0 is E_b = 90 GeV/fm^3;

the configuration with one tube (fluctuation) in the center: energy density profile is the Gauss distribution with a = 1.0 fm and the maxima value 270 GeV/fm^3;

the configuration with one tube (fluctuation) shifted from the center: E_b = 90 Gev/fm^3; R = = 5,4 fm; E_0 = 270 GeV/fm^3; R_0 = 3 fm; a_0 = 1 fm; The results of calculations are presented for initial time and for τ = 1, 2, 10 fm/c (Fig. 2);

the configuration with four tubes (fluctuations): E_b = 85 GeV/fm^3; R = 5,4 fm; E_i = 250 GeV/fm^3; R_i = 5,6 fm; a_i = 1 fm; The evolution of energy density profiles is presented in the Fig. 3;

the configuration with ten tubes (fluctuations): E_b = 25 GeV/fm^3; R = 5,4 fm; R_0 = 0 fm; $R_{1,2,3}$ = = 2,8 fm; $R_{i,j>3}$ = 4,7 fm; a_i = 1 fm; E_i = $= 4E_b \exp\left(-R_i^2/R^2\right)$. See the Fig. 4.

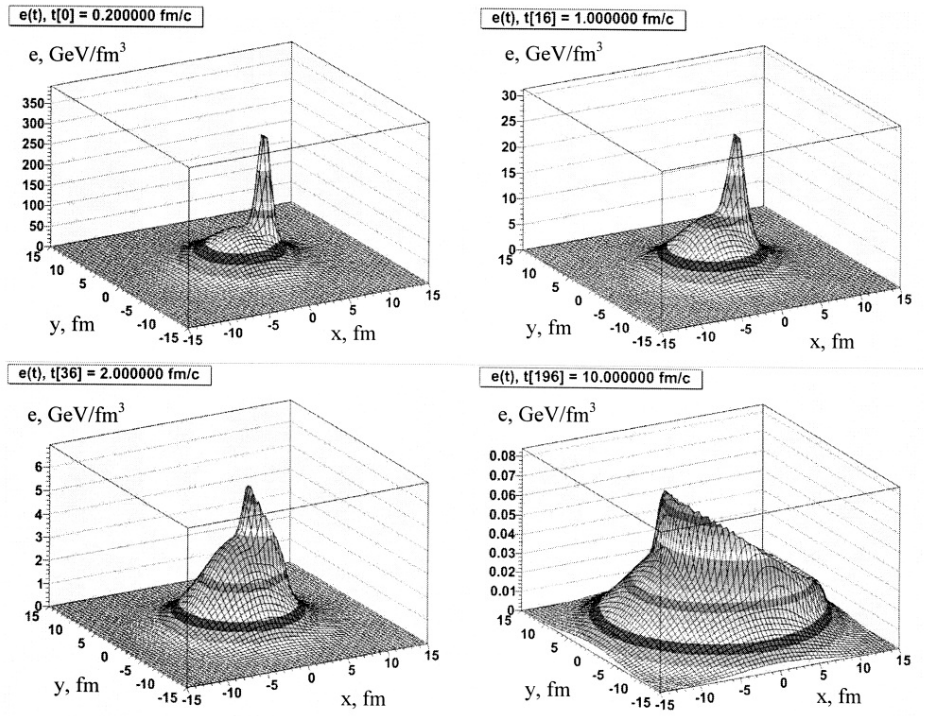


Fig. 2. 3D plots of energy density profiles with one tube-like initial conditions for initial time and for τ = 1, 2, 10 fm/c.

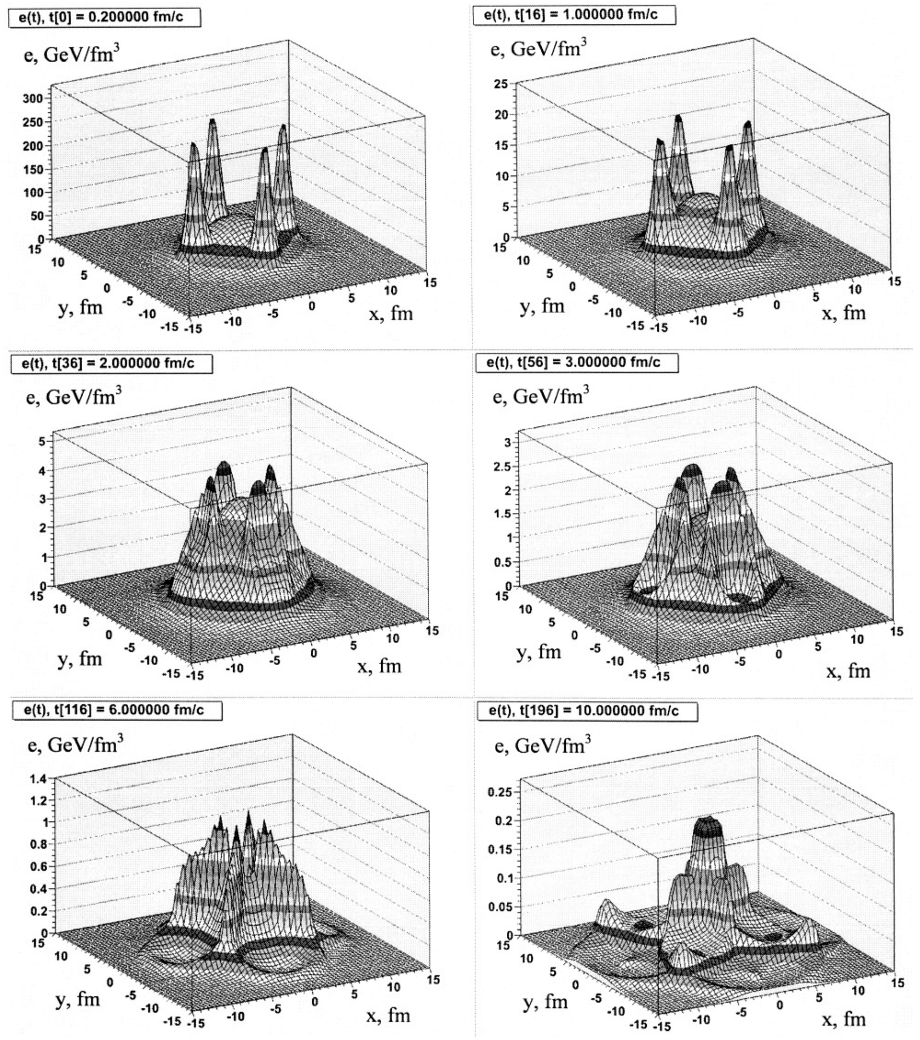


Fig. 3. 3D plots of energy density profiles with 4 tube-like initial conditions for τ = 0.2, 1, 2 3, 6 and 10 fm/c.

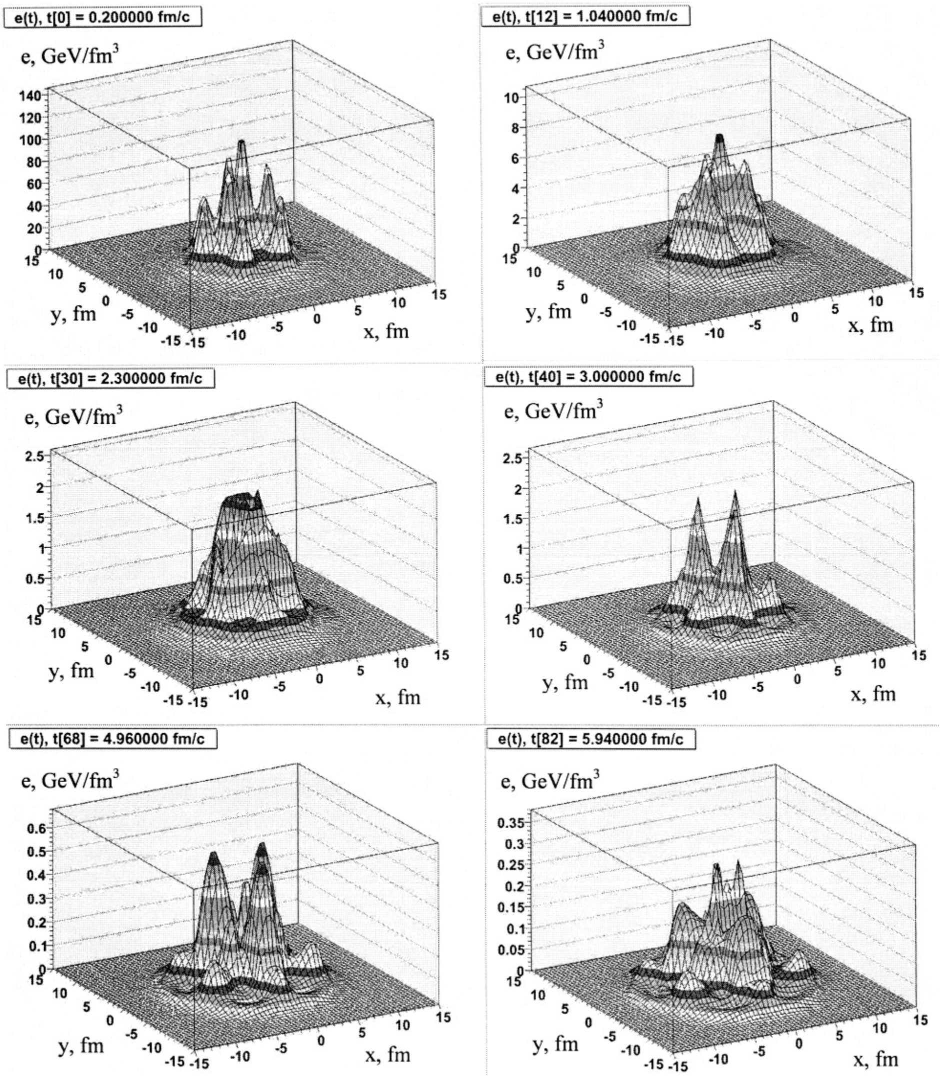


Fig. 4. 3D plots of energy density profiles with 10 tube-like initial conditions for τ = 0.2, 1.04, 2.3, 3, 4.96 and 5.94 fm/c.

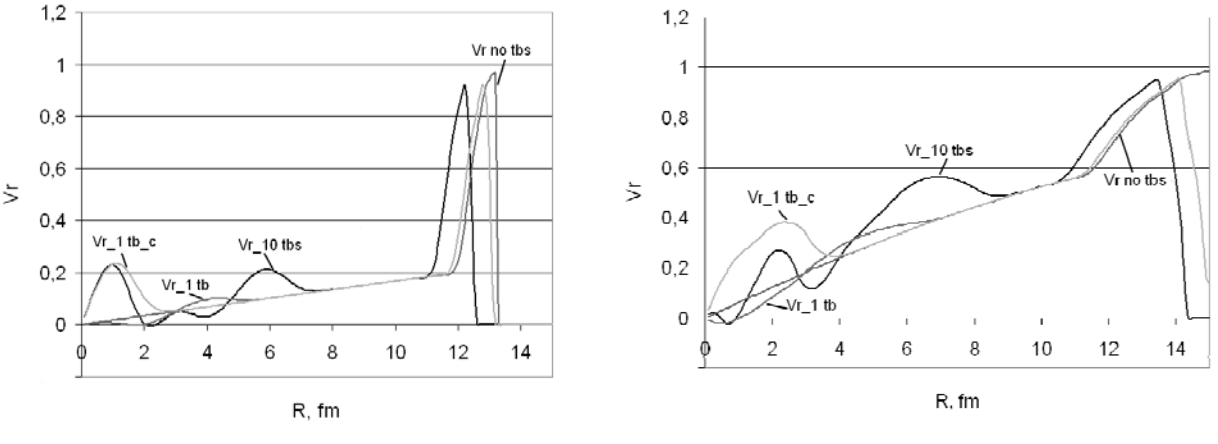


Fig. 5. The azimuthally averaged velocity in the system for different configurations and times.
Left panel: 1fm/c. Right panel: 3 fm/c.

For all the considered cases the traces of the initial fluctuations - bumping final energy distributions – remain after the system evolution that should lead to a non-trivial structure in observed correlations.

Besides the energy density profiles the evolution of transverse-velocity profiles f hydrodynamic flow in different scenarios also was considered. In Fig. 5 the transverse velocity radial profiles, integrated over angular, are presented for the cases: without fluctuations (Vr_no_tbs), with one tube in the center

(Vr_1tb_c), with one tube shifted (Vr_1tb) and with 10 tubes (Vr_10 tbs) for different slices of time: 1 fm/c (left panel) and 3 fm/c (right panel) respectively.

The totally averaged transverse velocities for the cases - one tube in the center and one shifted tube

τ , fm/c	$\langle V_r \rangle$ centered	$\langle V_r \rangle$ shifted
1	0.11	0.08
2	0.24	0.19
3	0.35	0.29
10	0.70	0.72

The fluctuations of the initial conditions also result in the fluctuation of the transverse velocity in the system. At early time (τ = 1 fm/c) the corresponding fluctuations in the transverse velocity averaged over azimuthal angular and radius are approximately 30 % between the cases when the fluctuation is in the center and when it is shifted while at the later times (τ = 10 fm/c) it is only 2 % (see the Table). This may lead to the important conclusions as for small fluctuations of the mean transverse momenta of observed particles, despite big initial fluctuations of transverse velocities.

Conclusions

The basic hydrokinetic code, proposed in [16], is modified now to include the transversally bumping tube-like initial conditions with the aim to study how the initial fluctuations in the energy density evolve with time. We found that the effect of fluctuations of the initial conditions was not washed out during the system expansion that, probably, leads to the ridges structures of the correlations, which are caused by these fluctuations. The evolution of the energy density distributions and velocity profiles are calculated in the framework of the 3D hydrodynamics. Possible physically grounded configurations of initial density profiles are proposed. The further studies of this issue and description of observed spectra and correlations could be done in the frameworks of the hydrokinetic model (HKM) [16, 18] which will allow one to describe all the stages of the system evolution as well as a formation of the particle momentum at the decoupling stage.

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ФЛУКТУАЦІЇ В ПОЧАТКОВИХ РОЗПОДІЛАХ ГУСТИНИ ЕНЕРГІЇ В А + А ЗІТКНЕННЯХ

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Аналіз кореляцій частинок в А + А зіткненнях як функції відносної псевдобистроти та азимутального кута демонструють нову структуру - рідж. Такий аналіз представляє великий інтерес для майбутнього експерименту ALICE на LHC. Ця структура, яка надзвичайно широка в поздовжньому напрямку, залишається після виділення еліптичних потоків і кореляцій струменів, які, як відомо, спричинюють появу кореляцій. Це можна пояснити, вважаючи, що явище появи ріджей у релятивістських ядро-ядерних зіткненнях, можливо, корениться в початкових умовах термальної еволюції системи. Основною метою цього дослідження є перевірка цієї гіпотези за допомогою аналізу еволюції густини енергії в системі, яка на самому початковому стані зіткнення має буст-інваріантну однорідну повздовжню структуру з трубкоподібними флуктуаціями високої густини. У перших розрахунках ми порівнюємо профілі поперечної швидкості та густини енергії, які розвиваються в системі при досягненні хімічного фріз-ауту (T = 165 МеВ), для різних початкових конфігурацій при τ_0 = 0,2 фм/с.

Ключові слова: ядро-ядерні зіткнення, гідродинаміка, рідж, флуктуації.

ФЛУКТУАЦИИ В НАЧАЛЬНЫХ РАСПРЕДЕЛЕНИЯХ ПЛОТНОСТИ ЭНЕРГИИ В А + А СТОЛКНОВЕНИЯХ

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Анализ корреляций частиц в А + А столкновениях как функции относительной псевдобыстроты и азимутального угла демонстрируют новую структуру - ридж. Такой анализ представляет большой интерес для предстоящего эксперимента ALICE на LHC. Эта структура, которая необычайно широкая в продольном направлении, остается после выделения эллиптических потоков и корреляций струй, которые, как известно, являются причиной появления корреляций. Это можно объяснить, считая, что появление риджа в релятивистских ядро-ядерных столкновениях, возможно, коренится в первоначальных условиях термальной эволюции системы. Основной целью этого исследования является проверка этой гипотезы с помощью анализа эволюции плотности энергии в системе, которая в самом начальном состоянии столкновения имеет буст-инвариантную продольно однородную структуру с трубкообразными флуктуациями высокой плотности. В первых расчетах мы сравниваем профили поперечной скорости и плотности энергии, развивающиеся в системе при достижении химического фриз-аута (T = 165 МэВ), для разных начальных конфигураций при τ_0 = 0,2 фм / с.

Ключевые слова: ядро-ядерные столкновения, гидродинамика, ридж, флуктуации.

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