Estimates of the baryon densities attainable in heavy-ion collisions from the beam energy scan program

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The baryon and energy densities attained in fragmentation regions in central Au+Au collisions in the energy range of the Beam Energy Scan (BES) program at the Relativistic Heavy-Ion Collider (RHIC) are estimated within the model of the three-fluid dynamics. It is shown that a considerable part of the baryon charge is stopped in the central fireball. Even at 39 GeV, approximately 70% of the total baryon charge turns out to be stopped. The fraction of this stopped baryon charge decreases with collision energy rise, from 100% at 7.7 GeV to ~40% at 62 GeV. The highest initial baryon densities of the equilibrated matter, \(n_B/n_0 \approx 10\), are reached in the central region of colliding nuclei at \(\sqrt{s_{NN}} = 20–40\) GeV. These highest densities develop up to quite moderate freeze-out baryon densities at the midrapidity because the matter of the central fireball is pushed out to fragmentation regions by one-dimensional expansion. Therefore, consequences of these high initial baryon densities can be observed only in the fragmentation regions of colliding nuclei in AFTER@LHC experiments in the fixed-target mode.

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I. INTRODUCTION

At ultra-relativistic energies the colliding nuclei pass through each other, compressing and depositing energy in each other, rather than mutually stopping as at lower energies. The net-baryon charge remains concentrated in the fragmentation regions, which are well separated in the configuration and momentum space from the midrapidity fireball. Therefore, it is generally accepted that the maximal baryon density is achieved in heavy-ion collisions at moderately high energies of the Nuclotron-based Ion Collider fAcility (NICA) in Dubna \(^2\) and the Facility for Antiproton and Ion Research (FAIR) in Darmstadt \(^2\).

Analysis of midrapidity hadron yields within the statistical model \(^3\)\(^4\) supports this viewpoint.

However, analysis \(^3\) of bulk observables recently measured by the STAR collaboration \(^6\) in the BES-RHIC energy range indicated a high degree of stopping of the baryon matter in the central region of colliding nuclei even at the collision energy of \(\sqrt{s_{NN}} = 39\) GeV \(^7\). The analysis was performed within model of three-fluid dynamics (3FD) \(^8\). This finding suggests that transition from complete stopping of the baryon matter to the asymptotic transparency at ultra-relativistic energies is quite gradual. The stopped equilibrated baryon matter is formed even at BES-RHIC energies. Only its observable consequences are manifested in fragmentation regions of colliding nuclei rather than in the midrapidity as at NICA-FAIR energies. The stopped baryon matter produced at \(\sqrt{s_{NN}} = 39\) GeV is pushed out to fragmentation regions because of its almost one-dimensional (1D) expansion at later stages of the reaction \(^7\).

Properties of the baryon-rich fragmentation regions (i.e. the fragmentation fireballs) produced in central heavy-ion collisions were discussed long ago \(^9\)\(^10\). Recently the theoretical considerations on the internal properties of the fragmentation fireballs were updated in Ref. \(^17\) based on the McLerran-Venugopalan model \(^18\). The BES-RHIC energies are too low for applicability of the McLerran-Venugopalan model \(^17\). Therefore, phenomenological approaches are required. In Ref. \(^7\) the baryon and energy densities attained in the fragmentation regions at the collision energy of 39 GeV were estimated within the 3FD model \(^8\).

The properties of the fragmentation fireballs in heavy-ion collisions at energies \(\sqrt{s_{NN}} < 18\) GeV can be and have already been studied at the Super Proton Synchrotron (SPS) at CERN. Recent proposal \(^19\) to perform experiments at the Large Hadron Collider (LHC) at CERN in the fixed-target mode (AFTER@LHC), if it will be realized, will extend this range to higher collision energies. The LHC beam of lead ions interacting on a fixed target would provide an opportunity to carry out measurements in the kinematical range of the target fragmentation region at collision energies up to 2.76 GeV per nucleon which is equivalent to \(\sqrt{s_{NN}} = 72\) GeV in terms of the center-of-mass energy.

In the present paper we estimate the baryon and energy densities attained in the central and fragmentation regions in heavy-ion collisions in the BES-RHIC energy range rather than at the single energy as in Ref. \(^7\). The calculations are done within the 3FD model \(^8\)\(^20\) that is quite successful in reproducing the bulk observables \(^3\), the elliptic \(^21\) and, though imperfect, directed flow \(^22\) in the midrapidity region at the BES-RHIC energies.

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II. THE 3FD MODEL

Unlike the conventional hydrodynamics, where local instantaneous stopping of the projectile and target matter is assumed, the 3FD description \[8\] takes into account a finite stopping power resulting in a counterstreaming regime of leading baryon-rich matter. This generally nonequilibrium regime of the baryon-rich matter is modeled by two interpenetrating baryon-rich fluids initially associated with constituent nucleons of the projectile (p) and target (t) nuclei. In addition, newly produced particles are attributed to a fireball (f) fluid. Each of these fluids is governed by conventional hydrodynamic equations coupled by friction terms in the right-hand sides of the Euler equations. These friction terms describe energy–momentum loss of the baryon-rich fluids. A part of this loss is transformed into thermal excitation of these fluids, while another part gives rise to the particle production into the fireball fluid. The produced fireball fluid in its turn also interacts with other fluids by means of friction forces. Thus, the 3FD approximation is a minimal way to simulate the early-stage nonequilibrium at high collision energies. The 3FD model describes the nuclear collision from the stage of the incident cold nuclei approaching each other to the final freeze-out stage.

A hybrid model based on similar concepts was recently developed in Ref. \[23\]. Unlike the 3FD, the hybrid hydrodynamics \[23\] deals with a single equilibrated fluid that however does not involve all the matter of colliding nuclei. Therefore, this hybrid hydrodynamics contains source terms describing gain of the equilibrated matter in the course of the collision. This is similar to the production of the f-fluid in the 3FD, while the baryon-rich matter in the 3FD is described by two separate (p and t) fluids which are locally unified (i.e. equilibrated) into a single baryon-rich fluid only when they are sufficiently decelerated.

The physical input of the present 3FD calculations is described in Ref. \[20\]. The simulations in \[5\,\[20\,\[22\] were performed with different equations of state (EoS’s): a purely hadronic EoS \[24\] and two versions of the EoS involving the deconfinement transition \[25\], i.e. a first-order phase transition and a smooth crossover one. In the present paper we demonstrate results with only the first-order-transition and crossover EoS’s as the most successful in reproduction of various observables at the BES-RHIC energies \[5\,\[21\,\[22\].

Friction forces between fluids are key constituents of the model that determine dynamics of the nuclear collision. In the hadronic phase the friction forces, estimated in Ref. \[20\], are used in simulations. There are no theoretical estimates of the friction in the quark-gluon phase (QGP) so far. Therefore, the phenomenological friction in the QGP was fitted to reproduce the baryon stopping at high incident energies within the deconfinement scenarios as it is described in Ref. \[20\] in detail. This fit resulted in the friction in the QGP that strongly differs from that in the hadronic phase estimated in Ref. \[20\]. At low relative velocities of the interpenetrating baryon-rich fluids (\(\sqrt{s} < 20–30\) GeV, depending on the EoS)\[1\] the QGP friction considerably exceeds the hadronic one, while at high relative velocities (\(\sqrt{s} > 20–30\) GeV) the QGP friction becomes lower than the hadronic one. This is illustrated in Fig. \[i\] (\[i\]). The weak friction at \(\sqrt{s} > 20–30\) GeV does not actually mean high transparency of the counterstreaming fluids. An efficient stopping of the baryon-rich fluids takes place here because of the friction with the f-fluid that is quite dense at these energies. Transition from the hadronic to QGP friction is gradual because even the first-order transition proceeds through the mixed phase and gradually starts from the central region of the colliding nuclei.

Figure 2 demonstrates the reproduction of midrapidity densities, \(dN/dy\), of various particles produced in central (impact parameter \(b = 2\) fm) Au+Au collisions at the BES-RHIC energies. Experimental data are taken from Ref. \[6\]. A more detailed comparison with the STAR data on bulk observables \[6\] can be found in Ref. \[5\]. The BES RHIC energy range partially overlaps with that of the SPS, where data are available in a wide range of rapidities. At SPS energies the 3FD model reproduces data in this wide rapidity range \[20\,\[27\] rather than only at the midrapidity.

A numerical ”particle-in-cell” scheme is used in the simulations, see Ref. \[8\] and references therein for more details. The accuracy requirements result in a high computation memory consumption rapidly increasing with

\[1\] \(\sqrt{s}\) is a running variable locally characterizing this relative velocity in terms of the center-of-mass energy of two nucleons belonging to these counterstreaming fluids. This variable changes in time and space \[8\,\[20\].
III. EVOLUTION OF THE MATTER IN CENTRAL REGION OF COLLIDING NUCLEI

Figure 3 presents the dynamics of nuclear collisions at BES-RHIC energies in the central region of colliding nuclei. Similarly to Ref. [29], the figure displays dynamical trajectories of the matter in the central box placed around the origin \( r = (0, 0, 0) \) in the frame of equal velocities of colliding nuclei: \( |x| \leq 2 \text{ fm}, \ |y| \leq 2 \text{ fm} \) and \( |z| \leq \gamma_{cm} \text{ 2 fm} \), where \( z \) is the direction of the beam and \( \gamma_{cm} \) is the Lorentz factor associated with the initial nuclear motion in the c.m. frame. The size of the box was chosen to be small enough to consider the matter in it as a homogeneous medium. Only expansion stages of the evolution are displayed. Evolution proceeds from the top point of the trajectory downwards.

The trajectories are plotted in terms of baryon density \( n_B \) and the energy density \( \varepsilon = m_N n_B \). The trajectories are displayed by solid lines, while the stage before the equilibration - by dashed lines. The trajectories are presented for the first-order-transition EoS. The mixed phase is displayed by the shadowed region. Inaccessible region is restricted by \( \varepsilon(n_B, T = 0) - m_{NNB} \) from above. The bold gray line displays the boundary of initial equilibration. The freeze-out area is displayed by the cyan shaded region.

The trajectories are presented in terms of baryon density \( n_B \) and the energy density \( \varepsilon \). These quantities require definitions in view of the three-fluid nature of the 3FD model. Within the 3FD model the system is characterized by three hydrodynamical velocities, \( u_\alpha \) with \( \alpha = p, t \) and \( f \), attributed to these fluids. We define a col-
lective 4-velocity of the baryon-rich matter associating it with the total baryon current,

$$u^\mu_B = J^\mu_B / |J_B|,$$  \hspace{1cm} (1)

where $J^\mu_B = n_p u^\mu_p + n_t u^\mu_t$ is the baryon current defined in terms of proper baryon densities $n_\alpha$ and hydrodynamic 4-velocities $u^\mu_\alpha$, and

$$|J_B| = (J^\mu_B J_B)^{1/2} = n_B$$  \hspace{1cm} (2)

is the proper (i.e. in the local rest frame) baryon density of the p and t fluids. The total proper energy density of all three fluids in the local rest frame, i.e. where the composed matter is at rest, is defined as follows

$$\varepsilon = u_\mu T^{\mu\nu} u_\nu.$$  \hspace{1cm} (3)

It is defined in terms of the total energy–momentum tensor

$$T^{\mu\nu} \equiv T^{\mu\nu}_p + T^{\mu\nu}_t + T^{\mu\nu}_\text{matter}$$  \hspace{1cm} (4)

being the sum of conventional hydrodynamical energy–momentum tensors of separate fluids and the total collective 4-velocity of the matter

$$u^\mu = u_\mu T^{\mu\nu} / (u_\lambda T^{\lambda\nu} u_\nu).$$  \hspace{1cm} (5)

Note that definition (5) is, in fact, an equation determining $u^\mu$. In general, this $u^\mu$ does not coincide with 4-velocities of separate fluids. This definition of the collective 4-velocity is in the spirit of the Landau–Lifshitz approach to viscous relativistic hydrodynamics.

At a given density $n_B$, the zero-temperature compressional energy, $\varepsilon(n_B, T = 0)$, presents a lower bound on the energy density $\varepsilon$, therefore the accessible region is correspondingly limited. The non-equilibrium stage of the expansion is displayed by dashed lines in Fig. 2. The criterion of the equilibration is equality of longitudinal ($P_{\text{long}} = T_{xx}$) and transverse ($P_{\text{tr}} = (T_{xx} + T_{yy})/2$) pressures in the box with the accuracy better than 10%. Here $T_{\mu\nu}$ is the energy–momentum tensor of composed matter [4]. The spatial components of the hydrodynamical four-velocity of the composed matter in the considered central box are zero due to symmetry reasons. Therefore, the c.m. frame of colliding nuclei coincides with the local rest frame of composed matter in the box. Note that the equilibration of the medium was not analyzed in the original paper [29].

The trajectories for the first-order-transition and crossover EoS’s are very similar, as shown in Ref. 5. Therefore, here we present only the trajectories for the first-order-transition EoS. The above-mentioned similarity is not because of similarity of these two EoS’s. It takes place because the friction forces in the QGP were independently fitted for each EoS in order to reproduce observables in the midrapidity region. As an estimate for the top LHC energy in the fixed-target mode the trajectory for energy of 62 GeV is also presented in spite of not quite reliable numerics.

Comparison of the 3FD results in the central box with similar results of Ref. [30] allows us to reveal the effect of the enhanced friction in the QGP. Two models were used in Ref. [30] to study the equilibration in the central box: the Quark-Gluon String Model (QGSM) [31] and the model of the Ultrarelativistic Quantum Molecular Dynamics (UrQMD) [32]. The baryon stopping and hence equilibration are treated in hadronic terms within these models. At the collision energy of 7.7 GeV (or 30A GeV in the lab. frame) the equilibration time in a small box (0.5 fm x 0.5 fm x 0.5 fm) within the QGSM and UrQMD [30] is very similar to the 3FD time. We do not compare with the results in the large box (5 fm x 5 fm x 5 fm) [30] because it is too large to consider the matter in it as homogeneous medium. At the top SPS energy the QGSM and UrQMD equilibration times are noticeably longer than the 3FD time at the similar energy of 19.6 GeV. Respectively, the higher equilibrium densities are reached within the 3FD simulations. This is the effect of the stronger QGP friction required for reproduction of the SPS data [20][22].

In contrast to the conventional scenario at top RHIC and LHC energies, the equilibration in the central region at BES-RHIC energies, including 62 GeV, is achieved at quite high baryon densities. The bold gray line in Fig. 3 indicates the boundary of the initial equilibration in the central region. In a way it is an analog of the hadronic freeze-out line in Ref. [3, 4] which is displayed by a cyan shaded area in the lower left corner of Fig. 3. The borders of this area correspond to the freeze-out in terms of the hadronic gas EoS without an excluded volume [3] (the upper boundary) and that with the excluded volume, $c = 0.3$ fm, [4] (the lower boundary). Similarly to the hadronic freeze-out line the equilibration line also manifests a maximum baryon density attained at the equilibration. It occurs at $\sqrt{s_{NN}} \approx 20–40$ GeV in central Au+Au collisions, while for the hadronic freeze-out line [3, 4] – at $\sqrt{s_{NN}} \approx 8$ GeV. As seen from Fig. 3 the equilibration line is converted into the freeze-out line along the displayed trajectories. In particular, the highest equilibrated baryon densities evolve to quite moderate freeze-out baryon densities because the baryon-rich matter is pushed out to peripheral regions by almost 1D hydrodynamic expansion discussed below.

The above features of the evolution in the central box are consequences of interplay of the enhanced friction in the QGP (see Fig. 1) and the finite thickness of colliding Au nuclei. In particular, the maximal equilibrated baryon density would be lower and attained at low collision energies in collisions of lighter nuclei. On the other hand, in collisions of infinitely thick slabs the strength of friction affects only the equilibration time, while the maximal equilibrated baryon and energy densities would be the same as in the shock-wave scenario and monotonically increase with the collision energy rise. The same interplay determines the global evolution displayed in Figs. 4 and 5 below.
IV. GLOBAL EVOLUTION OF THE MATTER

Figure 4 presents the time evolution of the QGP fraction, the proper baryon and energy densities, Eqs. (3) and (4), respectively, in the reaction plain \((x_{\eta_s})\) of central \((b = 2 \text{ fm})\) Au+Au collision at \(\sqrt{s_{NN}} = 39 \text{ GeV}\), where

\[
\eta_s = \frac{1}{2} \ln \left( \frac{t + z}{t - z} \right) \tag{6}
\]

is the space-time rapidity and \(z\) is the coordinate along the beam direction. The advantage of this longitudinal space-time rapidity is that it is equal to the kinematic longitudinal rapidity [see Eq. (9)] in the self-similar 1D expansion of the system. The figure also displays the fluid unification measure

\[
1 - \frac{n_p + n_t}{n_B} \tag{7}
\]

and the baryon-fireball relative velocity

\[
v_{tB} = \sqrt{(u_B \cdot u_t)^2 - 1}. \tag{8}
\]

The equilibration criterion based on the difference of longitudinal and transverse pressures, as it was used in Fig. 3, is not practical outside the central region because of nonzero spatial components of the velocity. We demonstrate results only for the first-order-transition EoS because the crossover scenario gives a very similar picture. Moreover, the pattern displayed in Fig. 4 for \(\sqrt{s_{NN}} = 39 \text{ GeV}\) is also representative for \(\sqrt{s_{NN}} = 19.6\) and 27 GeV.

As seen, at \(\sqrt{s_{NN}} = 39 \text{ GeV}\) the baryon-rich fluids are mutually stopped and unified already at \(t \gtrsim 1 \text{ fm/c}\) because the fluid unification measure [7] is small: it is less than \(0.015\) at \(t = 1 \text{ fm/c}\) and is practically zero inside the freeze-out contour at later instants. This unification measure is identically zero, when the \(p\) and \(t\) fluids are unified, and has a positive value increasing with the rise of the relative velocity of the \(p\) and \(t\) fluids. The baryon-fireball relative velocity [6] is small, \(v_{tB} \lesssim 0.2\) at \(t \geq 1 \text{ fm/c}\). This indicates that the system is close to the equilibrium. We would like to emphasize that this is kinetic (i.e. mechanical) rather than chemical equilibrium. For the baryon-rich (\(p\) and \(t\)) fluids the smallness of their local relative velocities is a trigger for their local unification into a unified baryon-rich fluid [8], while the \(f\)-fluid and the unified baryon-rich fluid keep their identity even at small \(v_{tB}\) and thus do not provide chemical equilibrium in the composed system. The \(f\)-fluid is gradually absorbed by the baryon-rich fluid [8], nevertheless, it survives until the very freeze-out. In particular, because of the absence of the chemical equilibrium a unified freeze-out for simultaneous description of \(p_T\) spectra and hadron abundances became possible [9]. Below, the term “equilibration” is understood precisely in this kinetic sense. Note that the above unification/equilibration measures are meaningful only within the borders of the freeze-out (bold contours in Fig. 4) because the matter is frozen out \([33]\) at this boundary and its further evolution has no practical meaning.

As seen from Fig. 4 at \(t = 1 \text{ fm/c}\) the matter of colliding nuclei has already partially passed though each other (two narrow bumps of the baryon density near \(\eta_s = \pm 1 \text{ fm}\)) and partially stopped in the center region (the center bump in \(n_B\) and \(z\)). This means that the central region and the primordial fragmentation regions have been already formed to this time instant. The matter in all these regions is in the quark-gluon phase. In contrast to high-energy scenarios (at the top RHIC and LHC energies) a large fraction of the baryon charge is stopped in the center region. The central baryon-rich fireball subsequently expands. This expansion predominantly is of the 1D nature at \(\sqrt{s_{NN}} > 10 \text{ GeV}\). It pushes out the baryon charge to the peripheral regions. The primordial fragmentation fireballs and the expanding central fireball temporally keep their identity, see energy density at \(t = 4 \text{ fm/c}\) in Fig. 4. Later on, at \(t \gtrsim 8 \text{ fm/c}\), the primordial fragmentation fireballs join with the pushed-out matter of the central fireball. These fireballs really join rather than merge, as seen from the last (right) column of Fig. 4. The white area inside the freeze-out contours is free of the matter of expanding central fireball and is solely occupied by the primordial fragmentation fireballs.

The fine structure of the evolving system along the beam axis \((\eta_s, x = y = 0)\) is displayed in Fig. 5 for central \((b = 2 \text{ fm})\) Au+Au collisions at several collision energies, including 62 GeV. As seen, the numerics at 62 GeV indeed is not quite good—large numerical fluctuations take place during all evolution period. The proper baryon density and the longitudinal rapidity

\[
y_z = \frac{1}{2} \ln \left( \frac{1 + v_z}{1 - v_z} \right), \tag{9}
\]

where \(v_z\) is the \(z\)-component of the collective velocity \([3]\) along the beam axis, are displayed in Fig. 5 for the first-order-transition EoS. The crossover results are very similar to those presented in Fig. 5. The time instants when the equilibration first occurs are marked by the “equil.” label. As seen, the equilibration occurs later at lower collision energies. At earlier time instants, i.e. at \(t = 2 \text{ fm/c}\) for 11.5 GeV and \(t = 1 \text{ fm/c}\) for 19.6 GeV, the absence of the equilibration is seen already from the velocity profile. A good estimate for the equilibration time at these energies within the 3FD model is \(t_{\text{equil}} \sim 2t_{\text{pass}}\), i.e. the doubled time during which two Lorentz-contracted nuclei (of \(R\) radius) pass each other moving in the opposite directions with the speed of light, \(\Delta t_{\text{pass}} \sim 4m_N R/\sqrt{s_{NN}}\). At time instants when the equilibration first occurs, the side bumps in the baryon density move in opposite directions with velocities close to the speed of light and thus indeed are the primordial fragmentation fireballs. The boundary between these primordial fragmentation fireballs and the central one is also seen from the longitudinal velocity profile in Fig. 5, even when the fragmentation density bumps are not well resolved at 11.5 GeV.
FIG. 4: QGP fraction (first column from the left), the proper baryon density in units of the normal nuclear density, \( n_0 = 0.15 \) \( 1/fm^3 \), see Eq. (2) (second column), the proper energy density, see Eq. (3) (3d column), the baryon-fluid unification measure, see Eq. (4) (4th column), the baryon-fireball relative velocity, see Eq. (5) (5th column) in the reaction plain (\( \eta_s \)) at various time instants in the central (\( b = 2 \) fm) Au+Au collision at √\( s_{NN} = 39 \) GeV. \( \eta_s \) is the space-time rapidity along the beam direction, see Eq. (6). Calculations are done with the first-order-transition EoS. The bold contours in the last three columns on the right display the boundary between the frozen-out matter and still hydrodynamically evolving matter.

The central equilibrated fireball is initially produced in the state of the expansion. At higher collision energies \( \sqrt{s_{NN}} > 10 \) GeV, the central fireball undergoes predominantly 1D expansion along the beam direction. The matter, and in particular the baryon charge, is pushed out to the periphery of this central fireball, i.e. closer to the primordial fragmentation regions, as it usually happens in the 1D expansion. At later time instants the pushed-out matter of the central fireball continue to move to higher \( |\eta_s| \), i.e. accelerate, while the primordial fragmentation fireballs stay approximately at the same space-time rapidity only slightly shifting to higher \( |\eta_s| \) because of the pressure exerted by the pushed-out matter on them. This is most clearly seen at the energy of 19.6 GeV in Fig. 5. The primordial fragmentation fireballs join with central contributions because of the counter expansion of these
fragmentation and central fireballs, see Fig. 4. Therefore, the final fragmentation regions consist of primordial fragmentation fireballs and baryon-rich regions of the central fireball pushed out to peripheral rapidities.

To gain an impression of the baryon charge accumulated in the primordial fragmentation and central regions we calculate the baryon number as $\int dx \ dy \ dz \ n_B / \sqrt{1 - v^2}$. Under the assumption of 1D expansion, which is a good approximation at $\sqrt{s_{NN}} > 10$ GeV, the $dx dy$ integration can be considered independent of $z$. The borders between these regions are determined by wiggles in the longitudinal velocity profile, as mentioned above. Thus integrating the $n_B$ distribution at the time instants (marked by "equil.") when the equilibration first occurs we arrive at the following estimate of the fraction of the baryon charge in the central fireball and primordial fragmentation regions, see Table I.

Note that this estimate at 62 GeV is very approximate because of unstable numerics. The above estimate has been done for both the first-order-transition and crossover EoS’s. When the results for these EoS’s do not coincide, they are hyphenated in Tab. I. The crossover EoS predicts

![Image of a page from a document](https://example.com/image.png)

**FIG. 5:** The proper baryon density ($n_B$) of colliding nuclei in units of the normal nuclear density, $n_0 = 0.15 \ 1/fm^3$ (dashed lines, right scale axis) and the longitudinal rapidity ($y_z$) of the matter (solid lines, left scale axis) along the beam axis $\eta_x$ ($x = y = 0$) at various time instants in the central ($b = 2$ fm) Au+Au collision at $\sqrt{s_{NN}} = 11.5, 19.6, 39$ and 62 GeV. Calculations are done with the first-order-transition EoS. The calculated densities at $\sqrt{s_{NN}} = 62$ GeV (thin lines) are interpolated by smooth (bold) lines when they reveal large numerical fluctuations, see ($t = 1$ and 2 fm)-panels. The time instants, at which the equilibration is first achieved, are marked by the “equil.” label.

| $\sqrt{s_{NN}}$ [GeV] | 11.5 | 19.6 | 39  | 62  |
|------------------------|------|------|-----|-----|
| central fireball        | 96%  | 85–90% | 65–75% | ~30–50% |
| fragmentation fireballs | 4%   | 10–15% | 25–35% | ~50–70% |

**TABLE I:** Fraction of the baryon charge in the central fireball and primordial fragmentation fireballs right after the initial equilibration in central ($b = 2$ fm) Au+Au collisions at various collision energies.
slightly larger baryon-charge fraction in the central fireball.

The fraction of the initially equilibrated matter accumulated in the central fireball is 100% at 7.7 GeV. This matter does not undergo strong 1D expansion along the beam direction. Therefore, the high baryon density in the midrapidity survives until the freeze-out, as it is seen from Fig. 3. With the collision energy rise the fraction of the initially equilibrated central fireball gradually drops. However, it amounts to ~40% even at the collision energy of 62 GeV. With the collision energy rise the observable region, i.e. that at the freeze-out stage, of the high baryon density gradually moves to fragmentation regions, i.e. to peripheral rapidities, while the midrapidity region becomes increasingly baryon-charge depleted.

At higher collision energies $\sqrt{s_{NN}} > 10$ GeV, the central part of the system gets frozen out at the later stage, see panels at $t \geq 10$ fm/c in Fig. 4, while the fragmentation regions continue to evolve being already separated in the configuration space. This longer evolution of the fragmentation regions is because of relativistic time dilation caused by the high-speed motion of the fragmentation regions with respect to the central region. Therefore, their evolution time is relativistically elongated in the c.m. frame of colliding nuclei and, e.g., at 39 GeV, lasts $\approx 40$ fm/c. At lower collision energies, $\sqrt{s_{NN}} < 10$ GeV, the single fireball survives until the very end of the freeze-out.

As seen from Figs. 1 and 5 at BES RHIC energies the friction forces mainly govern formation of the initially equilibrated state for the further hydrodynamic evolution. These friction forces result in a certain interplay between the incomplete baryon stopping and the subsequent almost 1D hydrodynamic expansion of the stopped matter. The dominance of the incomplete stopping is expected only at top RHIC energies. In more detail the nonequilibrium stage of the collisions was analyzed in Ref. [34] including the entropy production and the 3FD dissipation. At the expansion stage of the collision the friction forces provide a moderate dissipation that can be interpreted in terms of the shear viscosity [34]. The friction in the QGP was fitted to reproduce experimental data at midrapidity at BHES RHIC energies and in wider rapidity range at SPS energies. If the baryon diffusion is incorporated into the hydrodynamics, e.g., like in Ref. [25], it would certainly modify the final midrapidity baryon density. If the incorporation of the baryon diffusion gives a better reproduction of the experimental data, it may entail changes in the QGP friction and, in its turn, in properties of the initially equilibrated state.

It is shown that a considerable part of the baryon charge is stopped in the central fireball. Even at 39 GeV, approximately 70% of the total baryon charge turns out to be stopped. The fraction of the baryon charge stopped in the central fireball decreases with collision energy rise, from 100% at 7.7 GeV to 70% at 39 GeV. A tentative calculation at the energy of 62 GeV results in ~40% of the stopped baryon charge. At higher collision energies $\sqrt{s_{NN}} > 10$ GeV the final fragmentation regions are formed from not only primordial fragmentation fireballs, i.e. the baryon-rich matter traversed the interaction region, but also of the matter of the central fireball pushed out to peripheral rapidities because of 1D expansion of this central fireball.

The highest initial baryon densities of the equilibrated matter, $n_B/n_0 \approx 10$, are reached in the central region of colliding Au nuclei at $\sqrt{s_{NN}} = 20–40$ GeV. These highest densities evolve to quite moderate freeze-out baryon densities at the midrapidity because the central baryon matter is pushed out to peripheral regions by almost 1D hydrodynamic expansion. Therefore, consequences of these high initial baryon densities can be observed only in the fragmentation regions of colliding nuclei in experiments at the LHC in the fixed-target mode [19]. The highest midrapidity baryon density at the freeze-out is achieved at $\sqrt{s_{NN}} \approx 8$ GeV, which approximately agrees with the result of the analysis of midrapidity hadron yields within the statistical model [3, 4].

All the above features of the collision dynamics are consequences of the strong friction in the QGP, i.e. when the counter-streaming regime takes place in the deconfined phase. As has been mentioned above, this friction is completely phenomenological, it was fitted to reproduce observables at BES RHIC energies. This fit suggests that the transition into the QGP at the stage of interpenetration of colliding nuclei makes the system more opaque. It is consistent with jet quenching—if the system is opaque for the jets, it also should be opaque for the counter-streaming baryon flows. What is the mechanism of this counter-streaming opaqueness is still a question. It can be the same mechanism as that of the jet quenching. If applied to the counter-streaming regime, this mechanism can be associated with the Weibel instability [36, 37] that enhances the counter-streaming stopping because of the radiation of soft gluons similarly to the radiation in the hadronic phase due to the Weibel instability [38]. Alternatively, it can be due to formation of strong color fields between the leading partons [13, 15]. These fields may also enhance baryon stopping as compared to its estimate based on hadronic cross-sections [26].

V. SUMMARY

In the present paper we estimated the baryon and energy densities reached in the fragmentation regions in central Au+Au collisions at BES RHIC energies within the 3FD model.
