GLISSANDO: GLauber Initial-State Simulation AND mOre... \star

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Abstract

We present a Monte-Carlo generator for a variety of Glauber-like models (the wounded-nucleon model, binary collisions model, mixed model, model with hot spots). These models describe the early stages of relativistic heavy-ion collisions, in particular the spatial distribution of the transverse energy deposition which ultimately leads to production of particles from the interaction region. The original geometric distribution of sources in the transverse plane can be superimposed with a statistical distribution simulating the dispersion in the generated transverse energy in each individual collision. The program generates *inter alia* the fixed-axes (standard) and variable-axes (participant) two-dimensional profiles of the density of sources in the transverse plane and their azimuthal Fourier components. These profiles can be used in further analysis of physical phenomena, such as the jet quenching, event-by-event hydrodynamics, or analysis of the elliptic flow and its fluctuations. Characteristics of the event (multiplicities, eccentricities, Fourier coefficients, etc.) are stored in a ROOT file and can be analyzed off-line. In particular, event-by-event studies can be carried out in a simple way. A number of ROOT scripts is provided for that purpose. Supplied variants of the code can also be used for the proton-nucleus and deuteron-nucleus collisions.

Key words: Glauber model, wounded nucleons, Monte Carlo generator, relativistic heavy-ion collisions, particle production *PACS:* 25.75.-q, 25.75.Dw, 25.75.Ld

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Program summary

Title of the program: GLISSANDO October 2007, ver. 1.5 Catalog identifier: Program summary URL: http://www.pu.kielce.pl/homepages/mryb/GLISSANDO/index.html Program obtainable from: http://www.pu.kielce.pl/homepages/mrvb/GLISSANDO/index.html Licensing provisions: none Computer: any computer with a C++ compiler and the ROOT environment [1], tested with Intel Core 2 Duo T5200, 1.6 GHz, 1 GB RAM Operating system under which the program has been tested: Linux Ubuntu 7.04-8.04 (gcc 4.1.3-4.2.3), Scientific Linux Linux CERN 3.08 (gcc 3.2.3), Windows XP with Cygwin (gcc 3.4.4 cygwin special), MacBook Pro OSX 10.5.2 (gcc 4.0.1), ROOT ver. 5.08–5.18 Programming language used: C++ with the ROOT libraries Memory required to execute with typical data: below 120 MB No. of lines in distributed program, including test data: 2000 No. of bytes in distributed program, including test data: 35 kB Distribution format: tar.gz Nature of physical problem: Glauber-like models of the initial state in relativistic heavy-ion collisions Method of solution: Glauber Monte-Carlo simulation of collision events, analyzed with ROOT Restrictions concerning the complexity of the problem: none Typical running time: 40 s/10000 events for the wounded-nucleon model and

60 s/10000 events for the mixed model with the Γ distribution, minimum-bias Au+Au collisions with the fixed-last algorithm for nuclear repulsion, dispersion of sources, and hard-sphere wounding profile. A typical "physics" run with 500000 events takes about 1 hour. The use of the Gaussian wounding profile increases the time about 6 times. (All times for Intel Core 2 Duo T5200 1.6 GHz)

1 Introduction

The Glauber Monte-Carlo simulations have become a basic tool in the analysis of relativistic heavy-ion collisions (for a review and the discussion of physics issues see the recent review [2] and references therein). The approach provides the initial condition arising just after the collision of two relativistic nuclei. Within the semiclassical Glauber model, during the first stage of the collision, individual interactions between the nucleons deposit transverse energy. These elementary processes are classified as *wounded nucleons* or *binary collisions*. In this paper the individual deposition of the transverse energy at a definite position in the transverse plane is called a **source** and the distribution of all the sources created in an event, weighted by their individual deposited strength, is called the **fireball**. A **weight**, called **relative deposited strength** or **RDS**, is assigned to each source when the distribution of sources in the transverse plane is convoluted with a statistical distribution. This convolution simulates the dispersion in the generated transverse energy (particle production) from each elementary collision. The normalization of the deposited weight can be treated as a additional parameter. This parameter can be separated in the form of an overall factor multiplying the fireball density profile. In the following the deposited weight in each interaction is defined relatively to the one corresponding to an elementary nucleon-nucleon (NN) interaction. The RDS strength from an elementary interaction encompasses the contribution of two wounded nucleons and one collision and gives on average 1 (see section3).

The Glauber Monte-Carlo methods are used to determine the centrality classes in the experiment, since the total nucleus-nucleus cross section is not measured at RHIC. Many analysis use the Glauber-model initial state, which can serve as input for cascade simulations or hydrodynamics. Moreover, the initial eccentricity of the shape of the fireball carries over to the elliptic flow coefficient v_2 in the momenta of produced particles. The behavior of v_2 and its fluctuations is a sensitive probe of the dynamics.

Although numerous codes exist for the Glauber Monte-Carlo calculations and the simplicity of the algorithm allows anybody to produce his own with no difficulty, we have decided to make ours publicly available for several reasons. Firstly, to our knowledge there is no published publicly available package specifically dedicated to Glauber Monte-Carlo calculations. Most popular codes are much broader in their scope [3,4], having the initial-state generation only as one of the stages. This makes modifications, extensions, or comparisons more difficult. Many details of the model and algorithm implementations are different in these codes, such as the choice of the nuclear density profiles, the variant of the Glauber model used, the implementation of nucleon-nucleon repulsion, *etc.* **GLISSANDO** offers flexibility here:

- There is practically no constraint on the form of the nuclear density profile. In Sec. 2.1 we discuss the subtleties related to the choice of the distribution of the centers of nucleons in the nucleus such that the profiles determined in the electron-nucleus scattering are reproduced.
- We allow for superimposing a distribution of weights over the distribution of individual sources (wounded nucleons, binary collisions), since elementary collisions may result in the deposition of a varying amount of transverse energy.
- Hard-sphere or Gaussian wounding profiles may be chosen (see Sect. 2.2).
- The position of the source may fluctuate relative to the center of the wounded nucleon or binary collision from which it originates, which accounts for the

finite size of the nucleons.

• We offer two different algorithms to simulate the short-range nucleon-nucleon repulsion in the generation of the distribution of nuclei in the nucleon.

In short, **GLISSANDO** tries to encompass all features and details of the used approaches. Moreover,

- The *variable-geometry* analysis [5–8], accounting for the fluctuation of the center of mass and the direction of the axes of the moment of inertia of the fireball, is built-in in the code. This phenomenon is responsible for an increased eccentricity of the initial condition and thus is important in the studies of the elliptic flow.
- We compute the two-dimensional density profiles for both the fixed-axes (standard) and variable-axes (participant) geometry, as well as the corresponding Fourier radial profiles. These are stored and can be used "off-line" in other physics analysis, such as the jet quenching, the initial condition for hydrodynamics, *etc.*
- GLISSANDO can also be helpful for studies of event-by-event fluctuations of multiplicities, as measured for instance at the CERN SPS by the NA49 collaboration [9].
- Basic characteristics of the events are also stored, allowing for event-byevent analysis of various quantities.
- The code can also be used for proton-nucleus and deuteron-nucleus collisions. The Hulthen distribution is used to describe the NN separation in the deuteron.
- The code is written in C++ and uses the ROOT libraries and data structures. That way it is tailored for the experimental community. We have taken an effort to document the program such that it can easily be modified or extended.
- As an option, GLISSANDO generates the full event tree containing the positions and RDS of the sources within fireballs. This information may be further processed "off-line" by other existing codes.

We hope GLISSANDO will prove useful for heavy-ion physicists.

2 Basic method

The simulation of an event consists of three stages: 1) generation of the positions of nucleons in the two nuclei according to the nuclear density distribution, 2) generation the transverse positions of sources and their *relative deposited strength* (RDS) – see Sect. 3.1, and 3) calculation of the event-by-event averaged physical quantities and fireball profiles and writing the results to the output file. Stage 3) is performed on-the-fly with stage 2).

2.1 Generation of positions of nucleons

The radial nuclear density distribution determined from electron-nucleus scattering has the form

$$n_e(r) = c \frac{4\pi r^2 (1 + W_e \frac{r^2}{R_e^2})}{1 + \exp(\frac{r - R_e}{a_e})},\tag{1}$$

where the constant c is such that the normalization $\int dr n_e(r) = A$ is fulfilled, and the parameters R_e , a_e , and the Fermi parameter W_e can be found in Ref. [10]. For sufficiently heavy nuclei the radii are well described by the formula

$$R_e = (1.12A^{1/3} - 0.86A^{-1/3}) \text{ fm}, \qquad (2)$$

while $a_e = 0.54$ fm and $W_e = 0$, which is the case of the heavy nuclei used at RHIC. From now on we set $W_e = 0$, although the user may assign any value to this parameter (WF) in the input to GLISSANDO.

In Glauber Monte-Carlo calculations one generates the positions of *centers* of nucleons in the nucleus of mass number A. A relevant point needs to be discussed here [11]. The nucleons are not point-like, hence they cause some washing out of the surface. Therefore the parameters R and a in the distribution of centers of nucleons, n(r), must be such that when n(r) is folded with the charge distribution of the single nucleon, $n_N(r)$, the distribution $n_e(r)$ is reproduced. We take the nucleon charge profile in the Gaussian form,

$$n_N(r) = \frac{1}{(2\pi\sigma^2)^{3/2}} \exp\left(-\frac{r^2}{2\sigma^2}\right),$$
(3)

where $\sigma = 0.79/\sqrt{3}$ fm reproduces the nucleon rms charge radius of 0.79 fm. The folding gives

$$n_e(\vec{r}) = \int d^3r' \int d^3r'' n(\vec{r}') n_N(\vec{r}'') \delta^3(\vec{r} - \vec{r}' - \vec{r}''), \tag{4}$$

which for the distribution in the radial variable becomes

$$n_e(r) = 2\pi \int_{-1}^{1} dz \int_0^\infty r'^2 dr' n(r') n_N(\sqrt{r'^2 + r^2 - 2rr'z}).$$
(5)

Now, it turns out that the Woods-Saxon form of $n_e(r)$ is well reproduced with

a Woods-Saxon form of n(r), albeit with different parameters. A fairly good fit is achieved with the formula

$$R = (1.12A^{1/3} - 0.622A^{-1/3}) \text{ fm},$$
(6)

$$a = 0.46 \text{ fm}, \quad \text{(distribution of centers)}.$$

Note a shrinkage of the surface thickness parameter a and a slight increase of R, with an overall effect of a sharper distribution of the centers than the electron scattering profile.

For the convenience of a user wishing to further study these issues, we include a Mathematica script profile_folding.nb, where the folding of the Woods-Saxon profile with the nucleon profile is analyzed. This script is an additional tool and is not an integral part of GLISSANDO.

There are two more effects that influence the nuclear density distribution in the Monte Carlo approach. The first one is the shift of the generated coordinates to the center-of-mass frame of the nucleus. This causes some shrinkage of the distribution. The other effect is the introduction of nucleon-nucleon ex*pulsion* distance, which is a popular way to simulate the short-range repulsion in Glauber-like calculations. The centers of nucleons in each nucleus cannot be closer to each other than a certain expulsion distance d. The magnitude of d should be of the order of the hard-core repulsion range in the nuclear potential. Typically, values of a fraction of a fm are used. GLISSANDO offers two ways of generating locations of nucleons satisfying the expulsion constraint. In the first method, labeled "fix-last", the positions are generated subsequently. When the currently generated nucleon is in the forbidden region, *i.e.* its center is closer than d to a center of any other previously generated nucleons, it is then generated anew. The procedure is repeated, until a "good" location is found. In the second method, labeled "return-to-beginning", when a nucleon is generated in the forbidden region the whole sequence of locations of the previously found nucleons is discarded and the procedure is started from the beginning, until a "good" sequence of nucleon locations is formed. The two methods yield virtually the same results for all investigated observables, and since the "fix-last" method is a few times faster (with d = 0.4 fm), it is preferred. Nevertheless, the user has a choice between the two generation methods. The value d = 0.4 fm is a typically range of the repulsive core in the NN interaction and is used as default in our input files.

The repulsion implemented via the condition d > 0 increases somewhat (at the level of 1%) the size R of the nucleus, which is noticeable in both abovedescribed methods. This effect, and the previously mentioned shrinkage due to the shift to the center of mass, must be compensated by changing appropriately the parameters of the "bare" distribution from which the positions of centers of nucleons are generated. This is important, as otherwise a distribution different from the desired one will be effectively obtained. We find that the following parameterizations do a fairly good job (here we give them for the "fixed-last" method only):

$$R = (1.114A^{1/3} - 0.246A^{-1/3}) \text{ fm},$$
(7)

$$a = 0.45 \text{ fm} \quad (d = 0 \text{ fm} - \text{no expulsion}),$$
(8)

$$R = (1.113A^{1/3} - 0.277A^{-1/3}) \text{ fm},$$
(8)

$$a = 0.45 \text{ fm} \quad (d = 0.4 \text{ fm}),$$
(9)

$$a = 0.455 \text{ fm} \quad (d = 0.8 \text{ fm}).$$
(9)

These formulas are implemented in GLISSANDO. In order to use them, one needs to set RWSA=-1 and RWSB=-1 in the input file. The parameterizations are provided only for the cases d = 0, 0.4, or 0.8 fm and for RET=0 (fixed-last method). Otherwise the user must explicitly give the values for the distribution parameters in the input file.

We summarize: parameters (7-9) produce approximately the Woods-Saxon distributions of centers of nucleons with parameters (6), which upon folding with the finite-size charge distribution of the nucleon reproduce to a very good approximation formula (1) with parameters (2).

The user can override the default parameters in the input file, as explained below, as well as examine the resulting distribution of centers of nucleons. The functional form of the distribution may be changed straightforwardly by modifying the formulas in functions.cpp.

For the special case of the deuteron we use the Hulthen distribution [12] for the distance between the centers of the two nucleons,

$$n_d(r) = \frac{2a_d b_d(a_d + b_d)}{(a_d - b_d)^2} \left[\exp(-2a_d r) + \exp(-2b_d r) - 2\exp(-(a_d + b_d)r) \right],$$
(10)

with $a_d = 0.228 \text{ fm}^{-1}$ and $b_d = 1.118 \text{ fm}^{-1}$.

2.2 Collision

After generating the two nuclei, their centers-of-masses must be separated by the impact parameter **b**. Technically, the (x, y) coordinates of the nucleons in

nucleus A are shifted by a fixed transverse vector such that their center-ofmass position is (bB/(A+B), 0), while the nucleons in nucleus B are shifted such that their center-of-mass is at (-bA/(A+B), 0). In this frame we call the point (0, 0 the geometric center of mass. Next, the wounded nucleons and the binary collisions are counted.

2.2.1 Hard-sphere wounding

In the hard-sphere wounding prescription, a nucleon from one nucleus is wounded if its center passes closer (in the transverse plane) to the center of any of the nucleons from the second nucleus than the wounding distance

$$r_0 = \sqrt{\sigma_w/\pi},\tag{11}$$

where σ_w is equal to the NN inelastic cross section at a given collision energy. The standard implementation of the wounded nucleon model at the RHIC $\sqrt{s_{NN}} = 200$ GeV energy assumes that the inelastic cross-section in the nucleon-nucleon collision is [13]

$$\sigma_w = 42 \text{ mb.} \tag{12}$$

The cooresponding value for the LHC energies of $\sqrt{s_{NN}} = 5500 \text{ GeV}$ is $\sigma_w \simeq 63 \text{ mb}$, while for the SPS energies of $\sqrt{s_{NN}} = 19 \text{ GeV}$ one uses $\sigma_w \simeq 32 \text{ mb}$.

Similarly, a binary collision occurs if centers of two nucleons, the first one from the nucleus A and the second from B, pass closer to each other than the distance r_0 . This means that in this model binary collisions are counted as if occuring with the same inelastic cross-section as for wounded nucleons.

2.2.2 Gaussian wounding

Instead of the hard-sphere method, one may use a smooth function to determine the probability distribution of wounding or a binary collision. An option in GLISSANDO allows the user to use the Gaussian wounding function,

$$p(r) = G \exp\left(-\frac{Gr^2}{r_0^2}\right),\tag{13}$$

where r is the transverse distance between the centers of nucleons and the normalization is $\int_0^\infty 2\pi r p(r) dr = \pi r_0^2 = \sigma_w$. The parameter G controls the central value of the profile. The default value is G = 0.92, which is taken from the experimental pp analysis of [14, 15]. In order to switch on this feature the preprocessor option $-D_{gauss=1}$ must be used in the makefiles.

2.2.3 Displacement of sources

Since the nucleons have a finite size, the location of the source may be somewhat displaced relative to the center of the wounded nucleon or the mean of the centers of the two nucleons for the case of the binary collisions. GLISSANDO may include this effect by randomly displacing the x and y coordinates with a Gaussian distribution of width DWS for the wounded nucleons and DBIN for the binary collisions. Non-zero values of these parameters increase somewhat the size of the fireball, as well as reduce the eccentricity. This has also been noticed in later studies of Ref. [16]. Although the displacement effect is very physical, it is non-standard, hence is not included in the default parameters. If the user wishes to put it in, the typical values for the parameters DW and DBIN should be around 0.7 fm, a typical nucleon size.

3 Models

In this section we describe the models implemented in GLISSANDO.

3.1 The relative deposited strength

The collisions between nucleons (wounding or binary collisions) result in deposition of a certain amount of the transverse energy (or entropy) at the location of the source in the transverse plane, which is then carried away by the produced particles. This quantity may be different for the wounded nucleons and the binary collisions, as well as can fluctuate from source to source. For the studies of fluctuations the absolute normalization of the strength of the sources is irrelevant, hence we use the measure proportional to the deposited transverse energy, the **relative deposited strength** (RDS). For the wounded nucleon model RDS is just half of the number of wounded nucleons, which is a convention. For more involved models it is composed of the number of wounded nucleons and binary collisions, possibly with an overlayed statistical distribution of strength (see the following).

3.2 Wounded nucleon model

In the wounded-nucleon model the RDS of 1/2 is attributed to each point in the transverse plane at the center of a wounded nucleons. This complies to the original convention of Ref. [18], where the average multiplicity of produced particles is $N_{\text{part}} = N_{pp}N_w/2$, with N_{pp} denoting the average multiplicity in proton-proton collisions.

3.3 Binary collisions

For binary collisions the RDS of 1 is attributed to each collision point, which is taken as the mean of the transverse coordinates of the two colliding nucleons.

3.4 Mixed model

A successful description of multiplicities at RHIC has been achieved with a mixed model [17], amending the wounded nucleon model [18] with some binary collisions [19, 20]. In this case a wounded nucleon obtains the RDS of $(1 - \alpha)/2$, and a binary collision the RDS of α . The total RDS averaged over events is then $(1 - \alpha)N_w/2 + \alpha N_{bin}$. The fits to particle multiplicities of Ref. [20] give $\alpha = 0.145$ for collisions at $\sqrt{s_{NN}} = 200$ GeV, and $\alpha = 0.12$ for $\sqrt{s_{NN}} = 19.6$ GeV.

Thus the α (ALPHA) parameter in the code controls the proportion of wounded nucleons to binary collisions, with $\alpha = 0$ corresponding to the pure wounded-nucleon model, $\alpha = 1$ to binary collisions only, and the intermediate values to the mixed model.

3.5 The hot-spot model

We also implement a model with *hot spots* in the spirit of Ref. [21], assuming that the cross section for a semi-hard binary collision producing a hot spot is small, $\sigma_{\rm bin} \simeq 2$ mb, which is a parameter of the model. Importantly, when such a rare collision occurs it produces on the average a large amount of transverse energy, with RDS equal to $\alpha \sigma_{\rm w}/\sigma_{\rm bin}$. Technically, the hot spots are implemented as follows: the binary collision is generated according to the criterion of Sect. 2.2, but is accepted with the probability $\sigma_{\rm bin}/\sigma_{\rm w}$, *i.e.* the RDS of $\alpha \sigma_{\rm w}/\sigma_{\rm bin}$ is assigned to the hot spot at its position in the transverse plane. Otherwise the RDS is zero. All the wounded nucleons have the RDS assigned to $(1 - \alpha)/2$. In this paper we label any model with $\sigma_{\rm bin} < \sigma_{\rm w}$ the hot-spot model, although it should actually mean $\sigma_{\rm bin} \ll \sigma_{\rm w}$. The weight an an event is on average equal to $(1 - \alpha)N_{\rm w}/2 + \alpha N_{\rm bin}$, the same as in the mixed model, but it can fluctuate considerably from event to event depending on how many hot spots are created.

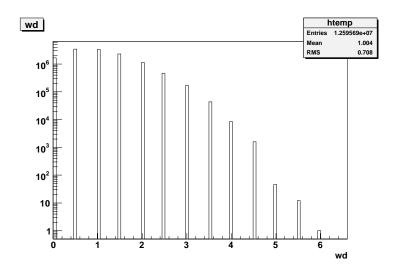


Fig. 1. Histograms for the superposition distribution generated by GLISSANDO from the Poisson distribution, $\kappa = 2$, 20000 events. The figure is generated by running ./glissando_profile.exe input_profile_0.dat and then using the wd branch in the density tree of the output file glissando.root. Horizontal axis: weight, vertical axis - probability distribution. Normalization arbitrary. Plot generated with ROOT.

3.6 Superposition

Each source from the previously described models (wounded-nucleon, binary, mixed, or hot-spot) may deposit the transverse energy with a certain probability distribution. To incorporate this effect, we superimpose a statistical distribution of weights over the distribution of sources. GLISSANDO has three options here, controlled by the parameter MODEL: 0 - no superposition (all superimposed weights equal to one), 1 - superposition of the Poisson distribution, and 2 - superposition of the gamma distribution.

The Poisson distribution generates the discrete weights according to the formula

$$g(w,\kappa) = \frac{\kappa^{w\kappa} \exp(-\kappa)}{(w\kappa)!}, \quad w = 0, \frac{1}{\kappa}, \frac{2}{\kappa}, \frac{3}{\kappa}, \dots$$
(14)

This distribution has $\langle w \rangle = 1$ and $\sigma(w) = 1/\sqrt{\kappa}$.

The Γ distribution generates continuous weights according to the density

$$g(w,\kappa) = \frac{w^{\kappa-1}\kappa^{\kappa}\exp(-\kappa w)}{\Gamma(\kappa)}, \quad w \in [0,\infty).$$
(15)

This distribution also gives $\langle w \rangle = 1$ and $\sigma(w) = 1/\sqrt{\kappa}$.

The superposition distributions can be supplied independently for the wounded nucleons and binary collisions. The parameters κ for both distributions are denoted as Uw and Ubin, respectively.

The preprocessor variable _weight_ controls the output of the superposition density to the output ROOT tree. The binary glissando_profile.exe writes out the superposition weights for the wounded nucleons.

The fact that the chosen superposition distributions have $\langle w \rangle = 1$ is at no loss of generality, since, as already stated, the individual RDS used for carrying the statistical averages can be normalized arbitrarily. The average RDS per event is still $(1-\alpha)N_w/2 + \alpha N_{bin}$ and does not change due to the superposition procedure.

For the general case we assign the RDS of $(1 - \alpha)w/2$ for the wounded nucleons and $\alpha w \sigma_w / \sigma_{bin}$ for those binary collisions which are accepted with the probability σ_{bin} / σ_w . The variable w is generated with one of the distributions described above. The wounded-nucleon model corresponds to $\alpha = 0$, the mixed model to $\alpha > 0$ and $\sigma_{bin} = \sigma_w$, and the hot-spot model to $\alpha > 0$ and $\sigma_{bin} < \sigma_w$.

4 Fixed- and variable-axes quantities

We use the standard convention for the axes of the reference frame: the zaxis is along the beam, the x-axis lies in the reaction plane, and the y-axis is perpendicular to the reaction plane. The azimuthal angle $\phi \in [-\pi, \pi]$ is measured relative to the y-axis, hence

$$y = \rho \cos \phi, \quad x = \rho \sin \phi, \tag{16}$$

where $\rho = \sqrt{x^2 + y^2}$ is the transverse radius.

We refer to the analysis in the reference frame fixed by the reaction plane as **fixed-axes** (also called *standard* in the literature), and to the analysis where the particles in each event are translated to the center-of-mass frame and aligned with the major principal axis of the second harmonic moment of the fireball as **variable-axes** (also called *participant*).

If the reaction plane is determined in each event (which of course can never be achieved precisely in the experiment [22,23]), one can choose the reference frame fixed by the reaction plane. The boost-invariant (in the central rapidity region) two-dimensional profile of the fireball density, $f(\rho, \phi)$, is obtained by averaging the RDS distribution over the events belonging to a particular centrality class. Thus the normalization is $\int d\phi \rho d\rho f(\rho, \phi) =$ average total RDS. For instance, in the wounded nucleon model $\int d\phi \rho d\rho f(\rho, \phi) = N_w/2$. The symmetry $f(\rho, \phi) = f(\rho, \pi - \phi)$, occurring also for unequal nuclei, excludes odd cosine and even sine components in the Fourier decomposition, hence in the general case of unequal nuclei we have

$$f(\rho, \phi) = f_0(\rho) + 2f_2(\rho)\cos(2\phi) + 2f_4(\rho)\cos(4\phi) + \dots + 2g_1(\rho)\sin(\phi) + 2g_3(\rho)\sin(3\phi) + \dots \quad (A \neq B).$$
(17)

For equal colliding nuclei the symmetry $f(\rho, \phi) = f(\rho, -\phi)$ eliminates the sine functions,

$$f(\rho,\phi) = f_0(\rho) + 2f_2(\rho)\cos(2\phi) + 2f_4(\rho)\cos(4\phi) + \dots, \quad (A = B).$$
(18)

If the switch SHIFT is set to 0, the fixed-axes distance $\rho = \sqrt{x^2 + y^2}$ is measured from the center of the geometric overlap of the two nuclei, which is the traditional way. For equal nuclei it is just the mid-point between their centers of mass. If SHIFT=1, then ρ is computed in each event relative to the center of mass of the fireball, *i.e.*, the center of mass of the RDS deposited in that event. The harmonic moments obtained from (17,18), which we call *fixed-axes*, are also called "standard" in the literature.

In order to have some convenient quantitative measures of the profiles of Eq. (18) one introduces their radial moments

$$\epsilon_{k,l} = \frac{\int 2\pi\rho f_l(\rho)\rho^k d\rho}{\int 2\pi\rho f_0(\rho)\rho^k d\rho}.$$
(19)

The choice of the weighting power k is arbitrary, with the typical choice k = 2. Higher values of k would make the measure more sensitive to the outer region of the system, see Ref. [8] for a discussion of this point. We note that in the popular notation

$$\epsilon_{\rm std} = \epsilon_{2,2} \equiv \epsilon. \tag{20}$$

Experimentally, the reaction plane cannot be determined accurately. Numerous methods have been developed to analyze the azimuthal asymmetry in heavy-ion collisions. The role of the purely statistical fluctuations caused by the finite number of particles has been described in [5–8, 16, 24–29]. As shown in these papers, the effects of the *variable geometry* in the initial stage of the collision lead to important effects, in particular to an increase of the shape eccentricity resulting in increased values of the elliptic flow coefficient v_2 .

In the variable-axes calculations the coordinates of the elementary sources in the given event are first shifted to the center-of-mass of the fireball. One then computes the principal axes of the ellipse of inertia of the fireball generated in the event, which is twisted relative to the reaction plane coordinate system. The angle between the major half-axis of the ellipse and the y axis is given by the relation

$$\tan(2\phi^*) = 2\frac{\langle xy\rangle - \langle x\rangle\langle y\rangle}{\operatorname{var}(y) - \operatorname{var}(x)},\tag{21}$$

where var denotes the variance. The brackets denote the average over the sources in the given event. The angle ϕ^* fluctuates from event to event. The superscript * indicates quantities averaged in such a way, that first in each event one computes from Eq. (21) the rotation angle ϕ^* , then the rotation is performed to the current principal-axis system, and finally averaging over events is performed. The procedure results in the "variable-axes" density

$$f^{*}(\rho,\phi) = f_{0}^{*}(\rho) + 2f_{2}^{*}(\rho)\cos(2\phi - 2\phi^{*}) + 2f_{4}^{*}(\rho)\cos(4\phi - 4\phi^{*}) + \dots + 2g_{1}^{*}(\rho)\sin(\phi - \phi^{*}) + 2g_{3}^{*}(\rho)\sin(3\phi - 3\phi^{*}) + \dots \quad (A \neq B), (22)$$

or for the case of equal nuclei

$$f^*(\rho,\phi) = f_0^*(\rho) + 2f_2^*(\rho)\cos(2\phi - 2\phi^*) + 2f_4^*(\rho)\cos(4\phi - 4\phi^*) + \dots$$

$$(A = B). (23)$$

We refer to the above density profiles as to the *variable-axes* profiles.

In analogy to Eq. (19) we introduce the variable-axes moments

$$\epsilon_{k,l}^* = \frac{\int 2\pi\rho f_l^*(\rho)\rho^k \, d\rho}{\int 2\pi\rho f_0^*(\rho)\rho^k \, d\rho},\tag{24}$$

In the commonly-used notation for the variable-axes or *participant* deformation parameter one has

$$\epsilon_{\text{part}} = \epsilon_{2,2}^* \equiv \epsilon^*. \tag{25}$$

The profiles and moments for higher harmonics are suppressed, similarly to the fixed-axes case. This is clear, as the higher harmonics are evaluated relative to the axes determined by maximizing the quadrupole moment. As a result, only a few moments are needed to effectively parameterize the profile.

The shift to the center-of-mass of the fireball results in a slightly more compact distribution $f_0^*(\rho)$ than $f_0(\rho)$ in the geometric center-of-mass frame, see Fig. 6 below.

In Ref. [8] we show that many of the qualitative and quantitative features of the Fourier distributions displayed above result from purely statistical considerations.

GLISSANDO generates and stores the fixed- and variable-axes moments, as well as the two-dimensional density profiles of the fireball and their harmonic decomposition. They can be later used in other studies involving the shape of the medium, such as jet quenching [8], setting the initial condition for cascade or hydrodynamic studies, *etc.* The included program interpolation shows a sample use of the profiles in a C++ code.

5 Typical sequence of running

5.1 Installation

It is necessary to have the ROOT package installed. After obtaining the GLISSANDO distribution the user should unpack

tar -xzvf glissando_1_5.tar.gz

and run the installation script

sh install

As a result, executable binaries are created. Five of them perform simulations: glissando.exe for the nucleus-nucleus (A+B) collisions, glissando_prot.exe for the proton-nucleus (p+A) collisions, glissando_deut.exe for the deuteronnucleus (d+A) collisions, and also glissando_profile.exe, which in addition generates the nuclear profile of nucleus A while running the (A+B)collisions. All these codes implement the hard-sphere wounding profile, see Sect. 2.2.1. The binary glissando_gauss.exe performs the (A+B) collisions with the Gaussian wounding profile, see Sect. 2.2.2. The wounding profile is controlled with the _gauss_ flag in the makefiles (-D_gauss_=0 for hard sphere, -D_gauss_=1 for Gaussian), hence the user may easily implement his choice also in the codes for the (p+A) and (d+A) collisions. The code interpolation.exe provides an example of creating interpolating functions of the two-dimensional density profiles and their Fourier-decompositions, based on the stored histograms. The code retrieve.exe illustrates a use of the full

```
Table 1
Typical output to the console from GLISSANDO.
                                  ******
GLISSANDO ver. 1.6 (http://arxiv.org.abs/0710.5731)
             tested with ROOT ver. 5.08--5.18
Start: Tue Feb 5 20:47:46 2008
nucleus - nucleus collisions
------
parameters reset in input file input.dat :
EVENTS
      100000
ALPHA
       0
BMAX
       20
generates output file glissando.root
random seed: 1202240866, number of events: 100000
197+197, RA=6.43, aA=0.45, RB=6.43, aB=0.45, d=0.4fm
wounded nucleon model: sig_w=42mb
   (binary collisions not counted)
hard sphere NN collision profile
window: b_min=Ofm, b_max=20fm
fix-last algorithm
event: 100000
                (100%)
Quantities for the specified b, N_w, and RDS window:
A+B cross section = 6436.6mb, equiv. hard-sphere radius = 7.15687fm
efficiency (accepted/all) = 51.2208%
N_w = 103.179 + / -105.16
RDS = 51.5897 + / -52.58
eps_fix_2 (std.) = 0.315127+/-0.316701
eps_var_2 (part.) = 0.475002+/-0.275256
eps_fix_4 = 0.0872776 + / -0.281066
eps_var_4 = 0.240773 + / - 0.31374
x_cm = -0.000206385 + / -0.482281, y_cm = 0.00400375 + / -0.732762
Finish: Tue Feb 5 20:54:11 2008
(Oh:6m:25s)
```

event tree, optionally generated by GLISSANDO. Several useful ROOT scripts are described in Appendix C.

5.2 Running the simulations

For simulations of the A+B collisions the running command has the syntax

```
./glissando.exe [input_file] [output_file]
```

and analogously for the p+A (glissando_prot.exe) and d+A (glissando_deut.exe) cases. When the input and output file-name arguments are absent, their default values are

input.dat - default input
glissando.root - default output

Typical input files are also provided with the distribution. The input parameters and their defaults are described in Appendix B. Thus we may simply type

./glissando.exe

The output to the console shown in Table 1 contains basic information on the run. The subsequent lines give the info on the input: the version of the code, initial time, type of reaction, name of the input file used and the values of parameters reset from the default, the seed for the ROOT random-number generator, the number of events, the mass numbers of nuclei, the "bare" (see Sect. 2.1) Woods-Saxon parameters and the expulsion distance, the type and parameters of the model (wounded, binary, mixed, hot-spot), the window in the impact parameter (and the number of wounded nucleons and the value of total weight), the type of the algorithm for the short-range repulsion, the dispersion parameters for the location of sources, and the counter for events. The final output consists of the total nucleus-nucleus cross section in the given window, σ_{AB} , the equivalent hard-sphere radius defined as $\sqrt{\sigma_{AB}/\pi/2}$, and the efficiency parameter, denoting the ratio of events where the nuclei collided to all the Monte-Carlo generated events. Next come averages of basic quantities with their standard deviations: the number of the wounded nucleons, binary collisions, hot spots, RDS, eccentricity ϵ in the fixed- and variable-axes frame, ϵ_4 in the fixed- and variable-axes frame, the center-of-mass of the fireball. Finally, the execution time is printed.

The user may first wish to verify the resulting nuclear density profile. For the case with no expulsion distance (d = 0 fm) simply run

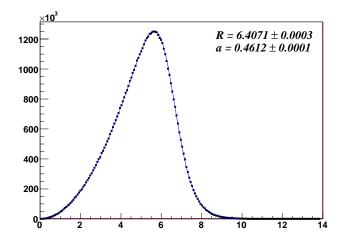
./glissando_profile.exe input_profile_0.dat

The file input_profile_0.dat sets the bare (as explained in Sect. 2.1) Woods-Saxon parameters for the distribution of the nucleon centers to R = 6.44 fm, a = 0.45 fm (gold) and uses no short-range expulsion (d = 0 fm). The code generates the ROOT output file glissando.root. The user should then enter the ROOT interpreter

root

GLISSANDO ver. 1.5, 100000 events

A=197 Woods-Saxon fit to the radial distribution of centers of nucleons



GLISSANDO ver. 1.5, 100000 events A=197 Woods-Saxon fit to the radial distribution of centers of nucleons

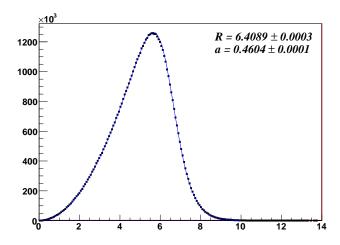


Fig. 2. The histogram of the radial density for the distribution of centers of nucleons in the gold nucleus for the case of no expulsion distance (top), and with d = 0.4 fm (bottom). Fixed-last algorithm, the bare parameters given in the text.

and execute the script

.x fitr.C("")

The histogram of the nuclear density of nucleus A stored in glissando.root is fitted to the Woods-Saxon shape. The script generates the top panel of

GLISSANDO ver. 1.5 197+197, 1 events b=0.0 fm mixed model with hotspots: σ_w =42.0 mb, σ_{bin} =1.0 mb, α =0.145 overlayed Gamma distribution with parameters U_w =2.0 (wounded) and U_{bin} =2.0 (binary)

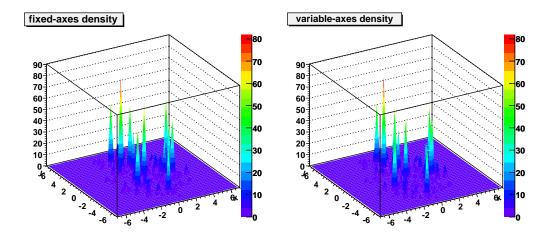


Fig. 3. The spatial distribution of RDS generated in the single event in the hot-spot model.

Fig. 2 and displays the parameters R and a, which are very close to the values of parameterization (7).

For the case with expulsion distance of d = 0.4 fm the "bare" Woods-Saxon parameters are R = 6.43 fm, a = 0.45 fm. The running sequence is as follows:

```
./glissando_profile.exe input_profile_04.dat
root
.x fitr.C("")
```

The resulting plot and the fit parameters are shown in the bottom panel of Fig. 2.

In studies of reactions involving new nuclei the user may tune the values of R and a in such a way, that with a chosen value of d a proper density profile of nuclear centers is obtained.

Now we are ready to run the simulations. First, let us look at a *single* event and make a snap-shot of the transverse-energy distribution in the x - y plane. We use here for illustration the hot-spot model and fix the seed for the Monte Carlo generator, such the result is repeatable.

```
./glissando.exe input_snap.dat
root
.x density.C("")
```

Table 2

Centrality classes in the impact parameter b, number of wounded nucleons N_w , and RDS for the mixed model with $\alpha = 0.145$, gold-gold collisions.

b min: 0.0199137, b max: 19.3733 N_w min: 2, N_w max: 391 RDS min: 1, RDS max: 377.349 c --> b N_w RDS 0-5% --> 3.10707, 326.834, 282.757 0-10% --> 4.59742, 277.708, 233.45 0-15% --> 5.44904, 236.603, 192.193 0-20% --> 6.30067, 200.51, 158.986 0-25% --> 7.1523, 170.433, 130.811 0-30% --> 7.79102, 142.361, 106.661 0-35% --> 8.42974, 118.299, 85.5293 0-40% --> 9.06847, 98.2481, 68.4228 0-45% --> 9.70719, 80.2018, 54.3351 0-50% --> 10.133, 64.1607, 42.2599 0-55% --> 10.5588, 51.1273, 32.1973 0-60% --> 10.9846, 39.0964, 24.1472 0-65% --> 11.6234, 30.0733, 18.1096 0-70% --> 12.0492, 22.0527, 13.0783 0-75% --> 12.475, 16.0373, 9.05324 0-80% --> 12.9008, 11.0244, 6.03445 0-85% --> 13.1137, 8.01671, 5.02819 0-90% --> 13.7524, 5.009, 3.01566 0-95% --> 14.3911, 3.00386, 2.0094

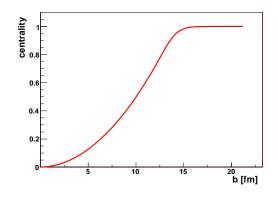
The produced plots are shown in Fig 3 (of course, for a single event the fixedand variable-axes distributions are the same up to a rotation in the x - yplane).

Next comes a full-fledged minimum-bias simulation for the *mixed* model for Au+Au collisions with 500000 events:

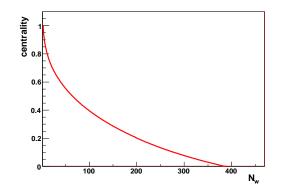
```
./glissando.exe input_minbias.dat
root
.x centrality.C("")
```

The script centrality.C determines the centrality classes in the *b*-parameter, in the number of wounded nucleons, N_w , and RDS. Since the number of produced particles is proportional to the RDS, the last case corresponds in essence to the determination of centrality via the multiplicity of produced particles. The output of centrality.C is generated to the console as well as to the file centrality.dat. The file contains the information on the centrality classes in steps of 5%, as shown in Table 2. Graphical representation of the results is

GLISSANDO ver. 1.5 197+197, 500000 events b=0.0 - 22.0 fm displacement par.: DW=0.7 fm, DBIN=0.7 fm mixed model: σ_w= 42.0 mb, σ_{bin}=42.0 mb, α;=0.145



GLISSANDO ver. 1.5 197+197, 500000 events b=0.0 - 22.0 fmdisplacement par.: DW=0.7 fm, DBIN=0.7 fm mixed model: σ_{y} = 42.0 mb, σ_{hn} =42.0 mb, α =0.145



GLISSANDO ver. 1.5 197+197, 500000 events b=0.0 - 22.0 fm displacement par. DW=0.7 fm, DBIN=0.7 fm mixed model: σ_w^{-2} 42.0 mb, $\sigma_{bin}^{-42.0}$ mb, $\alpha=0.145$

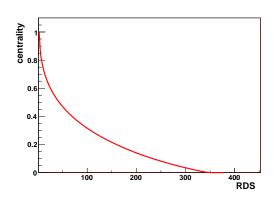


Fig. 4. Centrality as the function of the impact parameter b, the number of wounded nucleons N_w , and the relative deposited strength (RDS).

shown in Fig. 4 generated by the script.

A major interest has been recently attracted by the fixed- and variable-axes eccentricity, as its event-by-event fluctuations are linked to the fluctuations of the elliptic flow coefficient v_2 . The following scripts show the dependence of ϵ , ϵ^* , and their scaled standard deviations $\Delta \epsilon / \epsilon$ and $\Delta \epsilon^* / \epsilon^*$ as functions of N_w and b:

root
.x epsilon.C("")
.x epsilon_b.C("")

The scripts ask for a rebinning parameter (a small natural number) which smooths out the plots. This is desired when the statistics is small. Originally, 200 bins for the impact parameter are used. If the rebinning parameter is greater than 1, then this number of neighboring bins is grouped together. The result for the dependence on N_w are shown in Fig. 5. The horizontal solid line indicates the value $\sqrt{4/\pi - 1} \simeq 0.52$, which is the limit of $\Delta \epsilon^* / \epsilon^*$ for most central events [8].

Similarly, the script dxdy.C shows the dependence of the event-by-event standard deviation of the center-of-mass coordinates of the fireball on N_w :

root
.x dxdy.C("")

We may now select the centrality window of interest and perform a simulation for that centrality class. For instance, for c = 0 - 5% in N_w we run

```
./glissando.exe input_0_5.dat glissando_0_5.root
```

(note that for better book keeping we now use a name for the ROOT output file, which is stored for a potential later use). The choice of the centrality in N_w needs a careful selection of the window in b. Of course, one may use a minimum-bias window such as b = 0 - 25 fm, but this causes a waste of time, as many events are not recorded and the efficiency is low. For the present case, we have found from Table 2 (or in centrality.dat) that the selected centrality window corresponds to $N_w = 327 - 394$. Thus, we have set W0=328 and W1=1000 (of course, any number ≥ 394 is good) in the file input_0_5.dat. It turns out that in this case it is enough to use b = 0 - 4.5 fm. In order to verify if this selection is proper, we may perform a test by executing

root TBrowser a GLISSANDO ver. 1.5 197+197, 500000 events b=0.0 - 22.0 fmdisplacement par.: DW=0.7 fm, DBIN=0.7 fm mixed model: σ_w = 42.0 mb, σ_{bin} =42.0 mb, α =0.145

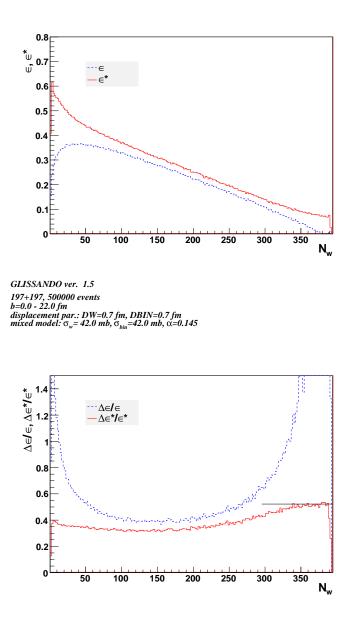


Fig. 5. Fixed- and variable-axes eccentricities and their scaled standard deviations plotted as functions of N_w . The rebinning parameter was set to 1.

Selecting glissando_0_5.root and clicking on the leaf b generates a histogram of b. The supplied range in b should be sufficiently wide, such that the histogram is not chopped off on the sides.

Next, the scripts density. C and profile2. C generate plots of the two-dimensional fixed- and variable-axes profiles in the x - y plane and their Fourier components. Note that large statistics is required for the higher Fourier profiles.

GLISSANDO ver. 1.5 197+197, 500000 events b=0.0 - 4.5 fm displacement par.: DW=0.7 fm, DBIN=0.7 fm $N_{w}=328 + 1000$ mixed model: $\sigma_{w}=42.0$ mb, $\sigma_{bin}=42.0$ mb, $\alpha=0.145$

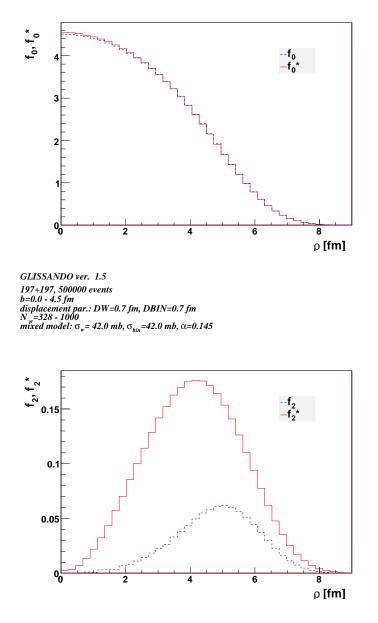


Fig. 6. Fixed- and variable-axes Fourier profiles for c = 0 - 5%.

root

```
.x density.C("glissando_0_5.root")
.x profile2.C("glissando_0_5.root")
```

An example is shown in Fig. 6, where we give the fixed- and variable-axes profiles for l = 0 and 2 harmonics.

The two-dimensional fireball profiles and their Fourier components may be used in further analyses, for instance in the calculation of jet quenching, where we need the shape of the absorbing medium, in event-by-event hydrodynamics, where the initial conditions undergo fluctuation, in studies of the elliptic flow, *etc.* For that purpose we also provide the template C++ code interpolation.exe which generates interpolated values of the functions from the stored two-dimensional or one-dimensional histograms. The typical running is

```
./interpolation.exe glissando_0_5.root
Test of normalization
Mean RDS= 311.818
Integral over 2 Pi rho f0(rho) drho= 311.824
Integral over (xyhist) f(rho_x,rho_y) drho_x drho_y= 311.869
INTERPOLATION
ver 1.0
1 - One Dimensional Interpolation
2 - Two Dimensional Interpolation
Type 1 or 2 (any other - Exit)
1
1D Interpolation
Give name of 1D histogram
c0rhp
Give value of rho: 1.5
Interpolated value at 1.5 equals 4.31756
Once more?(y/n)
n
```

The available names of one-dimensional histograms are

cOhp, cOrhp, c2hp, c2rhp, c4hp, c4rhp, c6hp, c6rhp, s3hp, s3rhp,

where c indicates the cosine, s the sine moments (for unequal nuclei), the number 0, 2, . . . denotes the index of the Fourier harmonic, and r labels the variableaxes profiles. Similarly, the two-dimensional interpolation may be tested. The names of histograms for the fixed- and variable-axes two-dimensional densities are:

```
xyhist, xyhistr.
```

The code serves as a template example for interfacing the GLISSANDO results to other applications in C++.

GLISSANDO ver. 1.5 197+197, 100000 events b=10.0 - 18.0 fmdisplacement par.: DW=0.7 fm, DBIN=0.7 fm $N_{\mu}=3 - 11$ mixed model: $\sigma_w=42.0 \text{ mb}, \sigma_{bin}=42.0 \text{ mb}, \alpha=0.145$

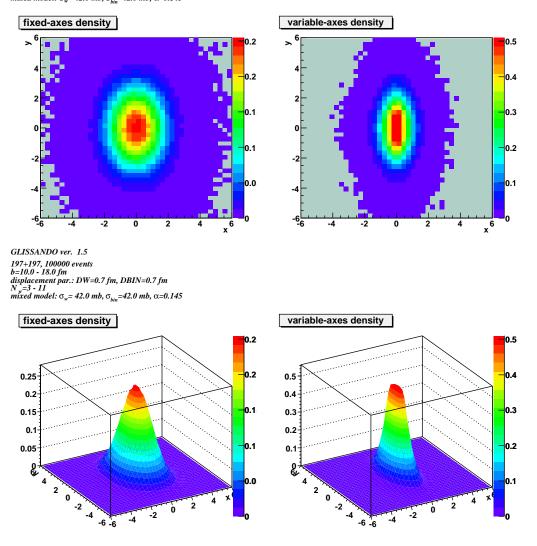


Fig. 7. Three-dimensional density profiles for centrality 80-95%.

The analysis shown above may be repeated for other centralities, e.g.

```
./glissando.exe input_30_40.dat glissando_30_40.root
...
./glissando.exe input_80_95.dat glissando_80_95.root
```

Figure 7 shows the two-dimensional profiles for c=80-95% obtained with the command

```
root
.x density.C("glissando_80_95.root")
```

We may carry out the calculation for other variants of the Glauber model, for instance for the hot-spot model with superimposed Γ distribution

```
./glissando.exe input_hotspot.dat hs.root
root
.x centrality.C("hs.root")
.x epsilon.C("hs.root")
```

The code can be run for different nuclei (for the case of light nuclei the parameters of the nuclear distribution should be examined case by case, as the global parameterizations do not work accurately in this case).

```
./glissando.exe input_S_Pb.dat
root
.x centrality.C("")
.x epsilon.C("")
...
```

In the case of different nuclei it makes sense to shift the fireball to its center of mass also in the fixed-axes case, which is made by setting SHIFT=1 in the input file.

For the proton-nucleus collisions we execute

```
./glissando_prot.exe input_prot.dat
root
.x centrality.C("")
```

and for the deuteron-nucleus collisions

```
./glissando_deut.exe input_deut.dat
root
.x centrality.C("")
```

We can obtain predictions for the upcoming LHC experiment by increasing the σ_w cross section to 63 mb (which is the appropriate value for the energy $\sqrt{s_{NN}} = 5500$ GeV [13]) and making an educated guess for the mixing parameter, $\alpha = 0.2$:

```
./glissando.exe input_minbias_LHC.dat
root
.x centrality.C("")
.x epsilon.C("")
```

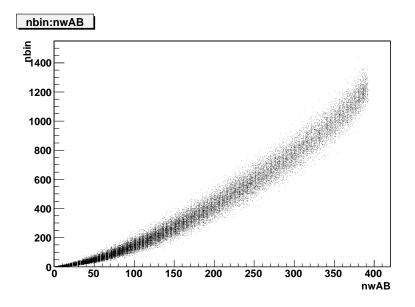


Fig. 8. Scattered plot for the correlation of numbers of wounded nucleons and binary collisions for the minimum-bias gold-gold collisions at RHIC.

6 Muliplicity fluctuations

Histograms ntarg, nbinar, and nwei in the GLISSANDO output file contain, respectively, the average number of wounded nucleons in nucleus B, average number of binary collisions, and average RDS, obtained for a fixed number of wounded nucleons in nucleus A. Similarly, ntarg2, nbinar2, and nwei2 contain the scaled variances of these quantities. Such calculations are relevant for the multiplicity fluctuations at CERN SPS, where the number of wounded nucleons in nucleus A (projectile) is measured with the help of the VETO calorimeter.

7 Other results

Numerous other results may be obtained interactively by entering the ROOT interpreter and accessing the GLISSANDO output file. As an example, we show in Fig. 8 the event-by-event correlation plot between the number of wounded nucleons and the number of binary collisions for the minimum-bias gold-gold collisions at RHIC (input file input_minbias.dat). The plot is generated by the following interactive sequence of instructions:

```
root
TBrowser a
[select the output file from GLISSANDO]
[select events tree]
```

```
[right-click on the events tree in the left window
  and select Start Viewer]
[drop leaves nwAB and nbin on the x and y fields]
[hit draw from the bottom menu of the Viewer]
```

8 Using the full event tree

Setting the input parameter FULL to 1 causes the generation of the full event tree, stored in the output GLISSANDO file in the full_event tree. A sample run can be made as follows:

./glissando.exe input_full.dat

The saved information contains the x and y coordinates (X, Y) and the RDS (W) of the source, as well as the event number (KK). Technically, a structure is formed

```
typedef struct {Float_t X,Y,W; UInt_t KK;} SOURCE;
static SOURCE tSource;
...
TTree *full_event;
full_event = new TTree("full_event","full event");
full_event -> Branch("full_source",&tSource,"X:Y:W:KK");
```

consecutively filled with information on each source, and written to the branch full_source. Other useful information, such as the impact parameter in the given event, is stored in the events tree. A template use of the full event tree is shown in the program retrieve.exe.

```
./retrieve.exe [glissando output file]
```

The full event information may be processed "off-line" with other existing programs. The user should be warned that the FULL=1 option results in generating a lot of data, about 10MB/10000 events. Thus the option should only be used if the full results are to be used for analysis by another existing program.

9 Summary

We hope that with its flexibility and simplicity GLISSANDO will become a useful tool for the heavy-ion community. The fact that the code is publicly

available allows for check-ups, additions and improvements. We have provided examples of numerous applications: determination of the A+B cross-section and centrality classes, analysis of eccentricities of the fireball both in the fixedand variable axes frames, study of event-by-event fluctuations or correlation of various quantities.

The authors are grateful to Adam Trzupek, Janusz Krywult, and Grzegorz Stefanek for useful comments, to Constantin Loizides for helpful e-mail exchanges concerning the fluctuations of the center-of-mass of the fireball, and to Adam Bzdak for a discussion of the Gaussian wounding profile. We also thank Vittorio Soma for carrying out tests on the MacBook computer.

A Content of the package

file name	description
glissando.cpp	the GLISSANDO source file
functions.cpp	the function source file
functions.h	the functions header file
interpolation.cpp	template interpolation code source file
retrieve.cpp	template code for retrieving info from the full event tree
install	the installation shell script
Makefile	makefile for glissando.exe, nucleus-nucleus collisions
Makefile.prot	makefile for glissando_prot.exe, proton-nucleus collisions
Makefile.deut	makefile for glissando_deut.exe, deuteron-nucleus collision
Makefile.profile	makefile for glissando_profile.exe, profile for nucleus A
Makefile.inter	makefile for interpolation.exe
Makefile.retr	makefile for retrieve.exe
input.dat	the generic input
input_profile_0.dat	input for glissando_profile.exe, $d = 0$ fm
input_profile_04.dat	input for glissando_profile.exe, $d = 0.4$ fm
input_snap.dat	input for generating a single event
input_minbias.dat	input for minimum-bias gold-gold collisions at RHIC
input_0_5.dat	input for centrality 0-5%, gold-gold at RHIC
input_30_40.dat	input for centrality 30-40%, gold-gold at RHIC
input_80_95.dat	input for centrality 80-95%, gold-gold at RHIC
input_S_Pb.dat	input for S-Pb collisions at SPS
input_prot.dat	input for proton-nucleus collisions
input_deut.dat	input for deuteron-nucleus collisions
input_hotspot.dat	input for the hot-spot model
input_minbias_LHC.dat	input for LHC predictions for Pb-Pb collisions
input_full.dat	input generating the full event tree
info.C	script giving information on the stored output file
fitr.C	script for producing and fitting the nuclear profile
centrality.C	script for centrality classes
epsilon.C	script for eccentricity vs. N_w , etc.
epsilon_b.C	script for eccentricity vs. b, etc.
dxdy.C	script for center-of-mass coordinates vs. N_w
density.C	script for two-dimensional profiles
profile2.C	script for Fourier profiles
label.C	script generating the label used by other scripts
readme_run	short instructions for typical running
profile_folding.nb	Mathematica file for folding the profile

B Description of input and output

The basic model parameters, collected in Table B.1 can be supplied in the input file. The sign # at the beginning of the line comments out the line and then the default value of the parameter is used. See the sample file input.dat.

The variables stored in the output **GLISSANDO** file are explained in Tables B.2 and B.3.

Table B.1			
Parameters	of the	input	file.

name	default	description
ISEED	0	seed for the random number generator, if 0 a random seed is generated
EVENTS	50000	number of generated events
NBIN	40	number of bins for histograms in ρ , x, or y
FBIN	72	number of bins for histograms in the azimuthal angle
NUMA	197	mass number of nucleus A
NUMB	197	mass number of nucleus B
RWSA	6.43	Woods-Saxon radius for the distribution of centers, nucleus A [fm]
		gold with the fix-last method
AWSA	0.45	Woods-Saxon width, nucleus A [fm]
RWSB	6.43	Woods-Saxon radius for the distribution of centers, nucleus B [fm]
AWSB	0.45	Woods-Saxon width, nucleus B [fm]
WFA	0	the w parameter of the Fermi distribution, nucleus A
WFB	0	the w parameter of the Fermi distribution, nucleus B
CD	0.4	closest allowed distance between centers of nucleons [fm]
SNN	42.	NN "wounding" cross section [mb]
SBIN	42.	NN binary cross section [mb]
ALPHA	0	0 - wounded, 1 - binary, 0.145 - PHOBOS for RHIC@200 GeV
MODEL	0	0 - constant superimposed weight=1, 1 - Poisson, 2 - Gamma
Uw.	2	Poisson or Gamma parameter for wounded
Ubin DW	$\begin{array}{c}2\\0.7\end{array}$	Poisson or Gamma parameter for binary
DW DBIN		dispersion of the location of the source for wounded nucleons [fm]
WMIN	$\begin{array}{c} 0.7 \\ 2 \end{array}$	dispersion of the location of the source for binary collisions [fm] minimum number of wounded nucleons to record event
W0	$\frac{2}{2}$	minimum allowed number of wounded nucleons
W0 W1	1000^{2}	maximum allowed number of wounded nucleons
RDS0	1000	minimum allowed RDS
RDS0 RDS1	100000	maximum allowed RDS
GA	0.92	central value of the Gaussian wounding profile
SHIFT	0.52	1 - shift the coordinates of the fireball to the c.m. in the fixed-axes case
51111 1	0	0 - do not shift
RET	0	0 - fix-last algorithm
1021	0	1 - return-to-beginning algorithm for nuclear density
FULL	0	1 - provide the full information on events (coordinates and RDS of sources)
1011	Ŭ	0 - do not
DOBIN	0	1 - compute the binary collisions also for the case ALPHA=0
DODIN	0	0 - do not compute the binary collisions for the case ALPHA=0
BMIN	0.	minimum impact parameter [fm]
BMAX	25.	maximum impact parameter [fm]
BTOT		range parameter for histograms [fm]

Table B.2 $\,$

Histograms stored in the output ROOT file. $\langle . \rangle$ denotes the	he mean and var the variance
of the specified quantity.	

xyhist xyhistr	fixed-axes density in the $x - y$ variables variable-axes density in the $x - y$ variables
xyhistr c0hist c0rhist c0hp c2hp c4hp c6hp c0rhp c2rhp c4rhp c6rhp s3hp s3rhp nx nx2 ny ny2 neps neps2 nepsp2 nuni neps2b nepsp2b nepsp2b nunib	variable-axes density in the $x - y$ variables fixed-axes density in the $\rho - \phi$ variables (not normalized) f_0 f_2 - fixed-axes density in the $\rho - \phi$ variables (not normalized) f_1 f_2 - fixed-axes cosine harmonics f_4 f_6 f_7 f_2 - variable-axes cosine harmonics f_4 f_6 f_7 f_8
ntarg ntarg2 nbinar nbinar2 nwei	$\langle N_w^B \rangle$ vs. N_w^A
nwei2	$\operatorname{var}(RDS)/\langle RDS \rangle$ vs. N_w^A

C Description of the ROOT scripts

Each script is called with the name of the ROOT file generated by GLISSANDO,

root

.x <script>.C("[{\tt GLISSANDO} file]")}

The empty string in the argument of <script>.C("") is equivalent to the default <script>.C("glissando.root").

```
info.C("[output ROOT file]")
```

Trees and their contents stored in the output ROOT file.			
TTree param		all parameters of the calculation	
TTree density		(generated only by glissando_profile.exe)	
r wd		radius of the nucleon in nucleus A [fm] weight generated by the superposition distribution	
TTree phys	TTree phys		
sitot eps_fixed eps_variable sigma_eps_fixed sigma_eps_variable		the nucleus-nucleus cross section [mb] event-by-event average ϵ event-by-event average ϵ^* event-by-event standard deviation of ϵ event-by-event standard deviation of ϵ^*	
TTree events			
nwA nwB nwAB nbin npa b	number of wounded nucleons in A number of wounded nucleons in B total number of wounded nucleons number of binary collisions RDS impact parameter		
es ep es 3 es 4 ep 4 es 6 ep 6 es 3 s phir	fixed-axes epsilon (standard), $\langle r^2 \cos(2\phi) \rangle$ variable-axes epsilon (participant), $\langle r^2 \cos(2(\phi - \phi^*)) \rangle$ $\langle r^2 \cos(3\phi) \rangle$ $\langle r^2 \cos(4\phi) \rangle$ $\langle r^2 \cos(4(\phi - \phi^*)) \rangle$ $\langle r^2 \cos(6\phi) \rangle$ $\langle r^2 \cos(6(\phi - \phi^*)) \rangle$ the rotation angle ϕ^*		
хх уу	x c.m. coordinate [fm] y c.m. coordinate [fm]		

Table B.3 Trees and their contents stored in the output ROOT file.

produces info on the stored ROOT file.

fitr.C("[output ROOT file]")

produces the density profile of centers of nucleons and its Woods-Saxon fit. The script works on ROOT files generated with glissando_profile.exe, which contain the tree1 tree an the leaf r.

```
centrality.C("[output ROOT file]")
```

produces centrality windows for the stored $\tt ROOT$ file. This makes sense for minimum-bias calculations.

```
epsilon.C("[output ROOT file]")
```

produces plots of the mean and scaled standard deviation of the deformation parameters ϵ and ϵ^* as functions of N_w . The script asks for a rebinning parameter (a natural number).

```
epsilon_b.C("[output ROOT file]")
```

same as epsilon. C but with N_w replaced by the impact parameter b.

dxdy.C("[output ROOT file]")

produces the event-by-event standard deviation of the coordinates of the center-of-mass of the fireball as a function of N_w .

density.C("[output ROOT file]")

produces plots of the two-dimensional fixed-axes and variable-axes spatial distribution of RDS.

profile2.C("[output ROOT file]")

produces plots of the fixed-axes and variable axes Fourier profiles of spatial distribution of RDS.

References

- [1] R. Brun et al., ROOT Users Guide 5.16 (CERN, 2007), http://root.cern.ch.
- [2] M. L. Miller, K. Reygers, S. J. Sanders and P. Steinberg, Ann. Rev. Nucl. Part. Sci. 57, 205 (2007) [arXiv:nucl-ex/0701025].
- [3] X. N. Wang and M. Gyulassy, Phys. Rev. D44 (1991) 3501.
- [4] K. Werner, Phys. Lett. B208 (1988) 520.
- [5] S. A. Voloshin, (2006), nucl-th/0606022.
- [6] S. Manly *et al.* [PHOBOS Collaboration], Nucl. Phys. A **774**, 523 (2006) [arXiv:nucl-ex/0510031].
- B. Alver *et al.* [PHOBOS Collaboration], Phys. Rev. Lett. **98**, 242302 (2007)
 [arXiv:nucl-ex/0610037].
- [8] W. Broniowski, P. Bożek and M. Rybczyński, Phys. Rev. C 76, 054905 (2007) [arXiv:0706.4266 [nucl-th]].
- C. Alt *et al.* [NA49 Collaboration], Phys. Rev. C75, 064904 (2007) [arXiv:nucl-ex/0612010].

- [10] C. W. De Jager, H. De Vries and C. De Vries, Atom. Data Nucl. Data Tabl. 36 (1987) 495.
- [11] P. Steinberg, (2005), http://hep.phy.uct.ac.za/~steinber/lectures/Steinberg_UCT_05.htm.
- [12] L. Hulthen and M. Sagawara, Handbuch der Physik 39 (1957).
- [13] W.-M. Yao et al (Particle Data Group), J. Phys. G 33, 1 (2006).
- [14] U. Amaldi and K. R. Schubert, Nucl. Phys. B **166**, 301 (1980).
- [15] A. Bialas and A. Bzdak, Acta Phys. Polon. B 38, 159 (2007).
- [16] B. Alver *et al.* [PHOBOS Collaboration], arXiv:0711.3724 [nucl-ex].
- [17] D. Kharzeev and M. Nardi, Phys. Lett. B 507 (2001) 121 [arXiv:nucl-th/0012025].
- [18] A. Białas, M. Błeszyński and W. Czyż, Nucl. Phys. B111 (1976) 461.
- [19] PHOBOS, B. B. Back et al., Phys. Rev. C65 (2002) 031901, nucl-ex/0105011.
- [20] PHOBOS, B. B. Back et al., Phys. Rev. C70 (2004) 021902, nucl-ex/0405027.
- [21] M. Gyulassy, D. H. Rischke and B. Zhang, Nucl. Phys. A613 (1997) 397, nucl-th/9609030.
- [22] A. M. Poskanzer and S. A. Voloshin, Phys. Rev. C58 (1998) 1671, nucl-ex/9805001.
- [23] J. Y. Ollitrault, Phys. Rev. D46 (1992) 229.
- [24] C. E. Aguiar et al., J. Phys. G27 (2001) 75, hep-ph/0006239.
- [25] C. E. Aguiar et al., Nucl. Phys. A698 (2002) 639, hep-ph/0106266.
- [26] M. Miller and R. Snellings, (2003), nucl-ex/0312008.
- [27] R. S. Bhalerao et al., Phys. Lett. B627 (2005) 49, nucl-th/0508009.
- [28] R. Andrade et al., Phys. Rev. Lett. 97 (2006) 202302, nucl-th/0608067.
- [29] S. A. Voloshin, A. M. Poskanzer, A. Tang and G. Wang, Phys. Lett. B 659, 537 (2008) [arXiv:0708.0800 [nucl-th]].