Probing the QCD Critical Point with Relativistic Heavy-Ion Collisions

Research Article

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Abstract: We utilize an event-by-event relativistic hydrodynamic calculation performed at a number of different incident beam energies to investigate the creation of hot and dense QCD matter near the critical point. Using state-of-the-art analysis and visualization tools we demonstrate that each collision event probes QCD matter characterized by a wide range of temperatures and baryo-chemical potentials, making a dynamical response of the system to the vicinity of the critical point very difficult to isolate above the background.

1. Introduction

Over the past decade, significant progress has been made in our understanding of the QCD equation of state, in particular at small values of the baryo-chemical potential [1–3]. This progress has been due to improved Lattice Gauge Theory calculations as well as due to high quality data from RHIC and LHC that can be connected to the Lattice calculations via relativistic fluid dynamical simulations [4, 5]. With new data from the RHIC beam-energy scan and the start of construction of the FAIR project, renewed attention has been cast on the QCD equation of state at non-vanishing values of the baryo-chemical potential. Among the most intriguing features of the QCD equation of state in that regime is the possible existence of a critical point [6–8]. While current theoretical efforts in determining the position of the critical point – or even it's mere existence – are hampered by large systematic

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uncertainties, the presence of the critical point may affect the dynamics of heavy-ion collisions and manifest itself in measurable quantities, thus shedding light on its location from an experimental point of view.

A necessary prerequisite for any measurable response of the collision system to the presence of the critical point is that a sufficient volume of the created QCD matter at some point during its evolution attains values of the temperature and chemical potential within the critical region of T and μ_B values in which the properties of matter would be (significantly) modified due to the presence of the critical point. Whether or not satisfying this prerequisite will actually allow for an experimental estimate of the location of the critical point will depend on multiple other conditions such as the strength of the medium modification due to the critical point, the influence of the subsequent evolution in the hadronic phase on the observables, the width of the critical region and the range of temperatures and chemical potentials probed in a single collision at a given beam energy. In this paper, we shall focus on the latter point, namely conduct an analysis on the range of temperatures and chemical potentials that are probed at any given time in a single heavy-ion collision.
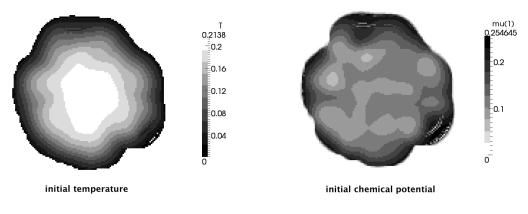
2.   Modeling of Heavy-Ion Collisions

For our analysis, we utilize a state-of-the-art (hybrid) hydrodynamic model with fluctuating initial conditions [9]. The initial conditions for the event-by-event hybrid approach are generated by the Ultra-relativistic Quantum Molecular Dynamics approach (UrQMD) [10, 11]. The nucleon distributions in the two nuclei are sampled according to Wood-Saxon profiles and the subsequent interactions among the nuclei as well as secondary produced particles are calculated in the hadron transport approach and include the excitation and fragmentation of strings as well as resonance dynamics . At that point in time when the two nuclei have passed through each other - this time depends on the beam energy of the collision - all particles are converted to an energy density distribution that serve as initial condition for the hydrodynamic expansion of the quark gluon plasma.

Naturally, these fluctuating initial conditions span a wide range in temperature and baryo- or quark-chemical potential as shown in Fig. 1. At a beam energy of $E_{\mathrm{lab}} = 25A$ GeV that is foreseen as an energy reached by the future FAIR-SIS300 accelerator, the initial temperatures in the central transverse slice range from 120-210 MeV. In the contour plot of the baryo-chemical potential even more granular structures are visible. This is a more realistic treatment than in the smooth averaged profiles that have been used in many hydrodynamical calculations before.

The equation of state (EoS) used for the hydrodynamic stage of our calculation incorporates a critical end point (CEP) in line with lattice data. The EoS has been constructed by coupling the Polyakov loop (as an order parameter for deconfinement) to a chiral hadronic $SU(3)_f$ model. In this configuration the EoS describes chiral restoration as well as the deconfinement phase transition (for more details on the EoS we refer to [12]).

The hybrid approach includes also a treatment of the hadronic phase by feeding the particles back into the hadron transport approach after the freeze-out criterion in the hydrodynamic calculation has been reached. This

Figure 1. Distribution of temperatures (left) and quark-chemical potential μ_q (right) for a single event initial condition at 25 GeV/u beam energy.

is important for the quantitative prediction of observables that are sensitive to the critical point. In this work, we concentrate on pointing out the spread in the phase-diagram of single collisions and therefore do not show the subsequent hadronic evolution.

3.   Results and Discussion

In our analysis we focus on the time-evolution of the hot and dense QCD medium in $T - \mu$ space to highlight the range of temperatures and baryo-chemical potentials present in the medium at any given time during the evolution. Figure 2 shows the analysis for three individual events at three different beam energies, 10, 25 and 40 GeV/u (in the left, center and right columns respectively) that are representative of the range of available beam energies at current and future facilities at RHIC and FAIR. The abscissa denotes the quark chemical potential in MeV and the ordinate shows the temperature (also in MeV). As can be clearly seen, a realistic event will not follow a single sharp trajectory of constant entropy per baryon in $T - \mu_q$ space, but will cover a wide range of T, μ_q values at any given time. For each event we have selected four time-steps at the early, intermediate and later stages of the evolution, with particular emphasis on capturing at least one time-step that is close to the CEP. The analysis has been performed utilizing the MADAI WORKBENCH visualization and analysis package [13], that is based on PARAVIEW [14] but contains additional tools, e.g. a Gaussian splatter filter that enables the use of the continuous shading seen in the figure with darker shades of grey representing a higher concentration of QCD matter at that particular point in the $T - \mu$ diagram. We find that for the particular EoS used in this calculation, an incident beam energy of 25 GeV/u seems to provide the best opportunity for creating and probing
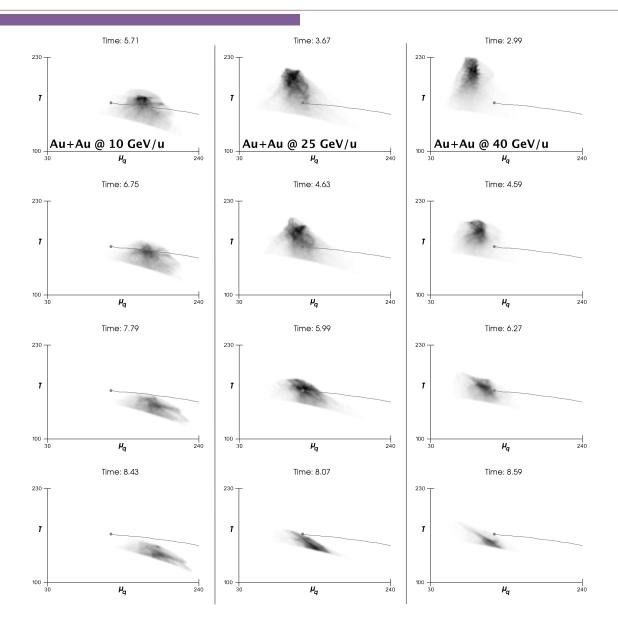
Figure 2. Time evolution (top to bottom) of QCD matter created in central Au+Au collisions at 10 (left), 25 (center) and 40 (right) GeV/u beam energy projected into the $T-\mu_q$ phase diagram. The grey shading represents the amount of matter present at the respective value of T and μ_q.

QCD matter in the vicinity of the CEP. This beam energy should be easily accessible in a systematic way with the FAIR facility at GSI.

While Figure 2 does make a promising case for collisions at ~ 25 GeV/u probing the CEP, it also clearly shows the challenges that an experimental determination of the CEP would face: each event contains QCD matter spread over at least 50 MeV in μ_q with the three beam energies being separated by a similar difference in terms of μ_q. Presumably, the largest response of the system would be obtainable if the critical range around the CEP were of similar width in μ_q as the event itself; for a range significantly smaller than that, matter outside the critical

range may very well overwhelm any signal stemming from matter passing through the critical region.

4. Summary and Outlook

We have shown that event-by-event hydrodynamic modeling of heavy-ion collisions creates QCD matter at a broad range of T and μ_q values for any given time during the evolution of the system, significantly complicating the possible response of the system to the presence of a CEP in the QCD phase-diagram via experimental/phenomenological methods. For the EoS used in our calculation, an incident beam energy of 25 GeV/u seems to provide the best opportunity for creating and probing QCD matter in the vicinity of the CEP. Any future realistic calculation of observable measures for the presence of a CEP will have to take multiple features of the systems's evolution into account, including the aforementioned range of T, μ_q values probed, the width of the critical region as well as the influence of the hadronic phase. We hope to address some of these additional items in the near future.

Acknowledgements

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