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A MUSTA-FORCE Algorithm for Solving Partial Differential Equations of Relativistic Hydrodynamics

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Abstract: Understanding event-by-event correlations and fluctuations is crucial for the comprehension of the dynamics of heavy ion collisions. Relativistic hydrodynamics is an elegant tool for modelling these phenomena; however, such simulations are time-consuming, and conventional CPU calculations are not suitable for event-by-event calculations. This work presents a feasibility study of a new hydrodynamic code that employs graphics processing units together with a general MUSTA-FORCE algorithm (Multi-Stage Riemann Algorithm – First-Order Centred Scheme) to deliver a high-performance yet universal tool for event-by-event hydrodynamic simulations. We also investigate the performance of selected slope limiters that reduce the amount of numeric oscillations and diffusion in the presence of strong discontinuities and shock waves. The numerical results are compared to the exact solutions to assess the code's accuracy.

Keywords: relativistic hydrodynamic, simulation of heavy ion collisions, quark-gluon plasma, high energy nuclear physics, numerical algorithms, MUSTA-FORCE, parallel computing, CUDA/GPU

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1 Motivation

Relativistic hydrodynamic simulations are widely used in the modelling of nuclear processes in high-energy nuclear physics when examining the properties of the quark-gluon plasma (QGP). Detailed information regarding the reactions that take place at the microscopic level is not required. Hydrodynamic model formalism treats QGP as a perfect fluid and assumes a single equation of state. The bulk and hot nuclear system can be described using hydrodynamic conservation laws and then solved numerically [1, 2]. Hydrodynamic models are extremely successful in describing experimental results for particles with low transverse momentum which is a behaviour of bulk nuclear matter. On the other hand, jets (narrow spays of hadrons and other particles produced by the hadronization of a high energy quark or gluon) are widely used to probe the properties of the QGP. This is an approach analogous to tomography: an external, penetrating probe, whose properties (like a production mechanism) are under experimental and theoretical control, is shot through the medium. We can then infer the properties of the analysed system from the modification of the probe's energy. Jets are such probes – external to the QGP. Because their production requires a large momentum transfer, they are produced very early in the collision, in the initial hard interaction, before the QGP phase. Their production is described well by perturbative quantum chromodynamic (pQCD) calculations. Thus, they are excellent tools for QGP research.

The mechanism involved in energy loss due to interactions with nuclear matter has been a topic of extensive theoretical and experimental studies over the last two decades. However, the energy dissipated by jets can also alter the properties of bulk nuclear matter (for instance, so-called elliptic flow) in the intermediate transverse momentum range. There is little understanding of such effects. For such studies, we need to efficiently model the soft particle evolution with a high spatial resolution to capture the jet-induced modification of the characteristics of the bulk nuclear matter. Moreover, the Cartesian coordinate system is preferred to ensure a high spatial resolution that is constant throughout the evolution of the system. Such calculations are necessary to fully understand the proprieties of this unique state of nuclear matter.

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