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FINAL REPORT ON THE INTEREST PROGRAMME

Study of bulk properties of the medium produced in heavy ion collisions at MPD

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Abstract

The heavy-ion collisions are fundamental for our understanding of the Universe at early stages. They recreate a new form of matter that is not formed by hadrons because is too hot for them to form, so we study particle creation mechanisms as this matter gets cold. The MPD experiment objective is to explore the phase diagram of the QCD searching for new phenomena. This project goal is to optimize the data storage files for the experimental data and Monte Carlo simulations. Software optimization can be further added to general software stack of MPDRoot.

Introduction

Why to study heavy-ion collisions?

The heavy-ion collisions are used to improve our understanding of the particle creation mechanisms, a subject that we have been working on for decades. They recreate the matter that filled the Universe in the early moments after the Big Bang. This is a new form of matter (called **q**uark **g**luon **p**lasma or QGP) because it is too hot to allow the formation of any hadron, it temperature is above Λ_{QCD}. This insight of primordial matter and the connection to the early universe are two powerful motivations to study the heavy-ion collisions. So, a central goal of these experiments is to recreate the Big Bang matter, to learn about its material properties and its phase diagram, in ways that no other observations allow (say telescopes or satellites). One of the most important discoveries made studying the heavy-ion collisions is that the matter that is a few trillions degrees hot is a liquid [1].
We expect that studying ultrarelativistic heavy ion collisions we will learn about the phase diagram of hot QCD matter, in thermal equilibrium, as a function of both temperature and baryon doping. By baryon doping (or net baryon density) we mean the excess of quarks over antiquarks in the hot matter. The standard parameter used to characterize the degree of baryon doping is the baryon chemical potential μ_B. To this point, we have set μ_B to zero, which describes matter with equal densities of quarks and antiquarks, and where the lattice QCD calculations can be applied to make quantitative assumptions. This is a very good approximation for the matter produced at midrapidity in the highest-energy heavy ion collisions at RHIC, an even better approximation at the LHC, and an exceedingly good approximation in the early Universe. In all these cases, ordinary hadronic matter forms via a continuous crossover as the liquid QGP expands and cools. However, matter with $\mu_B = 0$ and varying temperature is only one edge of a phase diagram. Mapping the full phase diagram is a substantial component of our understanding of the nature of any complex material in condensed matter physics, and QCD is no exception.

One way to study QGP doped with a significant excess of quarks over antiquarks would be to study the debris produced at very high rapidity in the highest-energy heavy ion collisions, the rapidities where QGP forms from the compressed remnants of the incident nuclei. Instead, we can scan a region of the phase diagram of QCD by looking at heavy ion collisions with lower and lower collision energies in which the initial baryon number found in the incident nuclei makes a larger and larger contribution to the matter formed in the collisions: Decreasing the collision energy increases μ_B, scanning the phase diagram.

The heavy-ion collision experiments can only control directly two quantities: which two nuclei are colliding and at what energy is the process happening. The energies can be mesured with high precision. However, knowing the colliding nuclei is not the same as knowing the colliding systems. Neither the impact parameter b (the transverse distance between the center of the two nuclei) nor the location and motion of the nucleons in the nuclei, let alone those ofthe quarks and gluons in the nucleons, are measurable quantities. They have to be inferred, as well as possible or as needed, event by event, from the observed outcome of the collision.

One of the central questions that the Nuclotron-Based Ion Collider fAcility (NICA) aims to answer is whether the continuous crossover between liquid QGP and hadronic matter turns into a first-order phase transition above some nonzero, critical value of μ_B, meaning in heavy ion collisions below some collision energy.

The MPD@NICA experiment

An essential part of the JINR scientific program resulting from many discussions in view of the Dubna Nuclotron upgrade is dedicated to the study of hot and dense baryonic matter. One of these detectors, the MultiPurpose Detector (MPD), is optimized for the study of heavy-ion collisions and the search for manifestations of the possible phase transition, mixed phase and critical end point [2].

The MPD detector has been designed as a 4π spectrometer capable of detecting charged hadrons, electrons and photons in heavy-ion collisions at high luminosity in the energy range of the NICA collider. To reach this goal, the detector will comprise a precise 3-D tracking system and a high- performance particle identifcation (PID) system based on the time projection chamber (TPC), time-of-flight measurements and calorimetry. The basic design parameters have been determined taking into account the physics measurements to be performed and several technical constrains guided by a trade-off of effcient tracking and PID against a reasonable material budget. At the NICA design luminosity, the minimum bias event rate in the MPD interaction region is about 6 kHz in Au+Au collisions and the total charged particle multiplicity exceeds 1000 in the most central collisions at $\sqrt{s_{NN}} = 11\text{GeV}$. As the average transverse momentum of the particles produced in a collision at NICA energies is below $500\,\text{MeV}/c_0$, the detector design requires a very low material budget [3].

The basic concept of the MPD is represented by a barrel and two endcaps located inside a magnetic field of a large solenoid. The barrel part is a shell-like set of various detector systems surrounding the interaction point and aimed to reconstruct and identify both charged and neutral particles in the region of $|\eta| \leq 1.0$. The two symmetric endcap parts are designed to reconstruct and to measure the momenta of charged particles with higher pseudorapidity. The physics goal of MPD is to explore the phase diagram of the strongly interacting matter in the region of highly compressed baryonic matter searching for new phenomena. It is necessary to study the in-medium properties of hadrons and the nuclear matter equation of state, including a search for possible signals of deconfinement and/or chiral symmetry restoration, phase transitions and the QCD critical end point in the region of the collider energy $\sqrt{s_{NN}} = 4 - 9$ GeV (for U92+).

Detector Simulation Software Packages

The software framework for the MPD experiment (mpdroot) is based on the FairRoot framework to provide a powerful tool for detector performance studies, development of pattern recognition algorithm for reconstruction and physics analysis. In the applied framework the detector response simulated by a package currently based on the Virtual Monte Carlo concept allows performing simulation using Geant3, Geant4 or Fluka without changing the user code. The same framework is used for simulation and data analysis. For a realistic simulation of various physics processes an interface to the Monte Carlo event generators for nuclear collisions (UrQMD and FastMC) was provided. Superposition of minimum-bias events can also be generated with the programme [2].

Project Goals

- Optimize the MPD software.
- Reduce the storage used for the reconstruction of the Monte-Carlo simulations (*mpddst* files).
- Use the information of TpcKalmanTrack instead of MPDEvent->GlobalTracks.
- Produce a code reusable in real experiment conditions.

Scope of work

As a part of preparations for the start of NICA collider with MPD experiment designed for the studies of hot and dense nuclear matter we analyse Monte-Carlo model data on identified particle production at a set of different collision energies.

Method

For the Monte-Carlo simulation we used `BOX` event generator for the project purposes of working with dst format as these are simple models requiring less time to generate the output. Also, we chose `GEANT4` over `GEANT3` because it is more up-to-date.

```
//FRAGMENT OF THE CODE USED TO GENERATE THE MONTE-CARLO EVENTS
#define BOX //choose generator
#define GEANT4
void runMC(TString inFile = "auau.04gev.0_3fm.10k.f14.gz", Int_t nStartEvent = 0, Int_t
Bool_t flag_store_FairRadLenPoint = kFALSE, Int_t FieldSwitcher = 0)
{
FairRunSim* fRun = new FairRunSim();
// Choose the Geant Navigation System
fRun->SetName("TGeant4");

geometry_stage1(fRun); // load mpd geometry

// Create and Set Event Generator
FairPrimaryGenerator* primGen = new FairPrimaryGenerator();
fRun->SetGenerator(primGen);

// smearing of beam interaction point
primGen->SetBeam(0.0,0.0,0.1,0.1);
primGen->SetTarget(0.0,24.0);
primGen->SmearGausVertexZ(kTRUE);
primGen->SmearVertexXY(kTRUE);

// Use user defined decays https://fairroot.gsi.de/?q=node/57
fRun->SetUserDecay(kTRUE);

#ifdef BOX // <---- Box Generator
gRandom->SetSeed(0);
FairBoxGenerator* boxGen = new FairBoxGenerator(13, 100); // 13 = muon; 1 = multipl.
boxGen->SetPRange(0.25, 2.5); // GeV/c, setPRange vs setPtRange
boxGen->SetPhiRange(0, 360); // Azimuth angle range [degree]
boxGen->SetThetaRange(0, 180); // Polar angle in lab system range [degree]
boxGen->SetXYZ(0., 0., 0.); // mm o cm ??
primGen->AddGenerator(boxGen);

// Magnetic Field Map - for proper use in the analysis MultiField is necessary here
```

```
MpdMultiField* fField = new MpdMultiField();

if (FieldSwitcher == 0) {
MpdConstField* fMagField = new MpdConstField();
fMagField->SetField(0., 0., 5.); // values are in kG:  1T = 10kG
fMagField->SetFieldRegion(-230, 230, -230, 230, -375, 375);
fField->AddField(fMagField);
fRun->SetField(fField);
cout << "FIELD at (0., 0., 0.) = (" <<
fMagField->GetBx(0., 0., 0.) << "; " << fMagField->GetBy(0., 0., 0.) << "; "
<< fMagField->GetBz(0., 0., 0.) << ")" << endl;
}

fRun->SetStoreTraj(kTRUE);
fRun->SetRadLenRegister(flag_store_FairRadLenPoint); // radiation length manager

fRun->Init();
}
```

Results

We successfully generated 20 `.root` files with 250 events each and applied the reconstruction process, seeking similarity with experimental outputs. The ROOT macro used to reduce the `dst` files resulting from reconstruction presented some problems that were fixed like the proper inclusion of `FairMCTrack.h` and `utility.h`

```
//#include "FairMCTrack.h"
#include "/opt/fairroot/examples/common/mcstack/FairMCTrack.h"
//#include "../Utilities/utility.h"
#include "/opt/mpdroot/macro/physical_analysis/Flow/Utilities/utility.h"
```

and the update of the variable `phiEP_mc` that access a function that is no longer present in the library `phiEP_mc = MCHeader->GetEP()`.

The process of reducing the `dst` files could not be completed due to software errors regarding the creation of shared libraries. Our main result is to point the way for future software develop and optimizations.

Conclusions

- Heavy-ion collisions are fundamental to our understanding of the universe, recreating near Big Bang conditions.
- The physics goal of MPD is to explore the phase diagram of the strongly interacting matter in the region of highly compressed baryonic matter searching for new phenomena.
- Software optimization of the MPDRoot framework is necessary.

Acknowledgments

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References

[1] Wit Busza, Krishna Rajagopal, and Wilke Vander Schee. Heavy Ion collisions: The big picture, and the big questions. *Annual Review of Nuclear and Particle Science*, 2018.

[2] V. D. Kekelidze, A. N. Sissakian, A. S. Sorin, and (The MPD Collaboration). The Multipurpose Detector (MPD) Letter of Intent, 2008.

[3] MPD experiment – based on NICA, `http://mpd.jinr.ru/experiment/`.

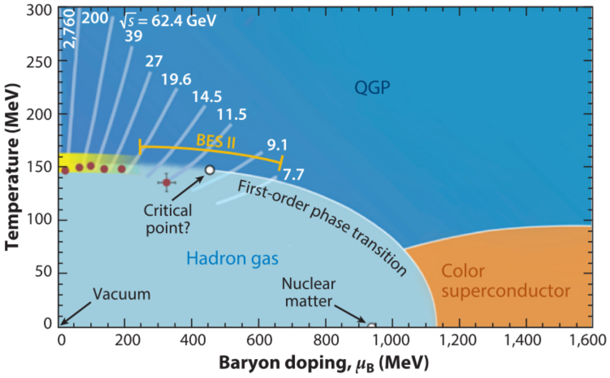

Figure 1: Sketch of our current understanding of the expected features of the phase diagram of QCD as a function of temperature and baryon doping, parameterized by the chemical potential for baryon number μ_B. The transition from QGP to hadrons is a crossover near the vertical axis; the thermodynamics of this crossover is well understood from lattice QCD calculations that are quantitative and controlled in the yellow region. At higher doping, the transition may become first order at a critical point. At higher baryon density and lower temperature, cold dense quark matter is expected to be a color superconductor. This form of matter may be found at the centers of neutron stars. Figure taken from [1].

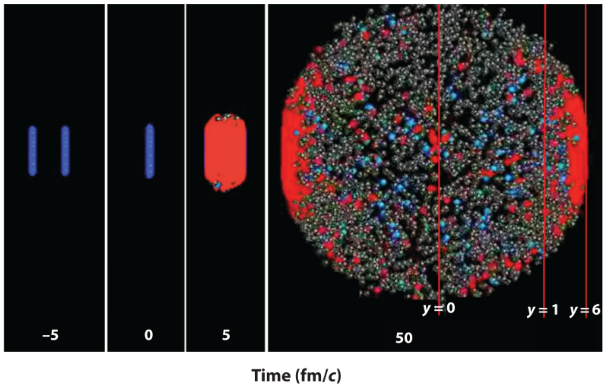

Figure 2: Snapshots of a central 2.76 TeV PbPb collision at different times (different horizontal slices of the space-time picture on the left) with hadrons (blue and gray spheres) as well as quark–gluon plasma (red). Figure taken from [1].

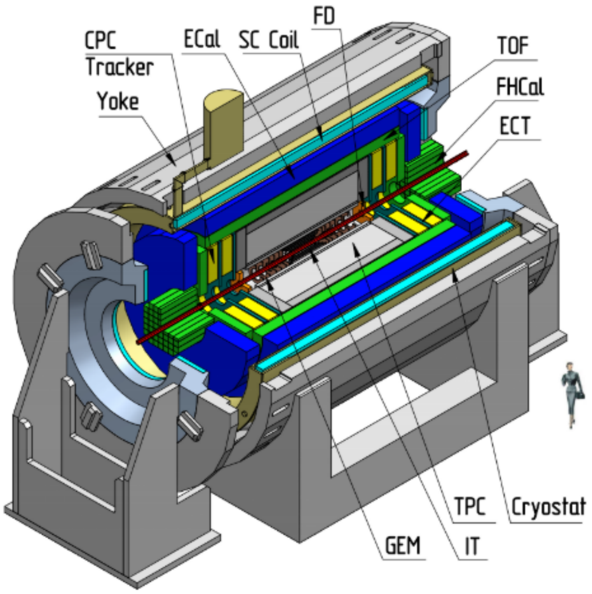

Figure 3: General layout of the MPD device. Figure taken from [3].

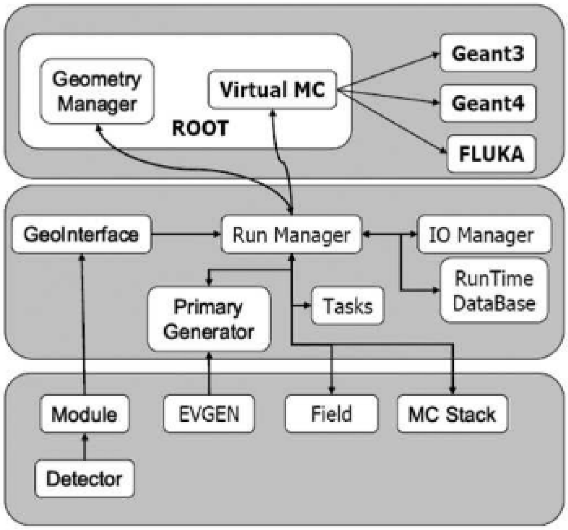

Figure 4: Schematic view of the general part of FairRoot framework. Figure taken from [2].