The J-PARC heavy ion project

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Abstract. A project to study high-density nuclear matter using heavy ion collisions in a beam energy range of few GeV is being prepared at J-PARC. The goal of the project is to perform experiments with beam energies of 1-12 AGeV/c and the collision rate of 10^{11} Hz. The project is divided into two phases. For the first stage, measurements with a limited beam intensity will be performed with upgraded spectrometer of an on-going experiment. Full performance will be implemented at the second phase to study in detail the high density matter and light hypernuclei. Feasibility of measurements for both phases are being evaluated.

1 Introduction

A phase diagram of Quantum Chromodynamics (QCD) is being studied intensively as shown in Fig. 1. For a high temperature region, experiments using high energy heavy ion collisions are performed at RHIC and LHC to observe and study quark gluon plasma. Recently, study of a high density region attracts considerable interest both theoretically and experimentally, since various specific phase structures, such as the first-order phase boundary, the QCD

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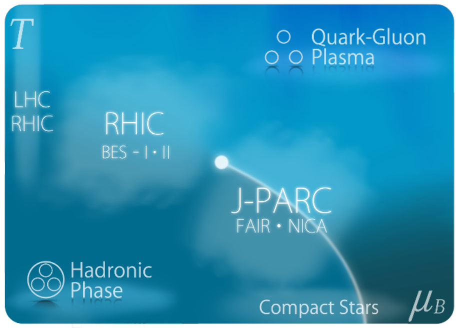

Figure 1. Schematic view of the QCD phase diagram

critical point, and color-superconducting phase, are expected to be realized in this region. In addition, recent observations of gravitational waves from neutron star mergers can give important information on a high density hadronic matter.

Experimentally, heavy ion collisions with center-of-mass energy of few GeV are suitable to generate high density matter. According to past experiments and model calculations, achieved density in such collisions is few times larger than in normal nuclear matter [1]. Several measurements have been performed to study the phase structure in the high density region. Also, measurements of various hadron productions and particle correlations are important to unveil the equation of state of the matter. For example, it is pointed out that hadron interactions in finite density matter can be measured using Lambda particle correlations in heavy ion collisions [2]. In addition, we also measure hadron properties, such as mass, width and decay rates, in the dense medium. Such measurements give important experimental information on hadron in the high-density region.

Several experiments are being prepared to study high-density matter using heavy ion collisions with center-of-mass energy of few GeV. One of the major activities is the Compressed Baryonic Matter (CBM) experiment at FAIR/GSI. At J-PARC, a project for heavy ion experiments are being prepared as well. In this manuscript, details of the heavy ion project at J-PARC are described.

2 Heavy ion program at J-PARC

A project to study high-density nuclear matter using heavy ion collisions in a beam energy range of few GeV is being prepared at J-PARC. We have designed a heavy-ion acceleration scheme and spectrometers for experiments. The goal of the project is to perform experiments with beam energies of 1-12 AGeV/c and the collision rate of 10^{11} Hz.

The project is planned using a staging approach to realize the experiment in a reasonable cost and time scale. As the first phase of the project, we will perform the experiment with upgrades of an existing spectrometer with 10^8 Hz beams. The original spectrometer was constructed for the J-PARC E16 experiment aiming to measure properties of vector mesons in a nucleus to study a chiral symmetry restoration in finite density matter [3]. For the second phase, a new dedicated spectrometer will be constructed and the maximal collision rate will be achieved.

Figure 2 shows a schematic view of the J-PARC accelerator setup in the final configuration and required upgrades for the heavy ion project.

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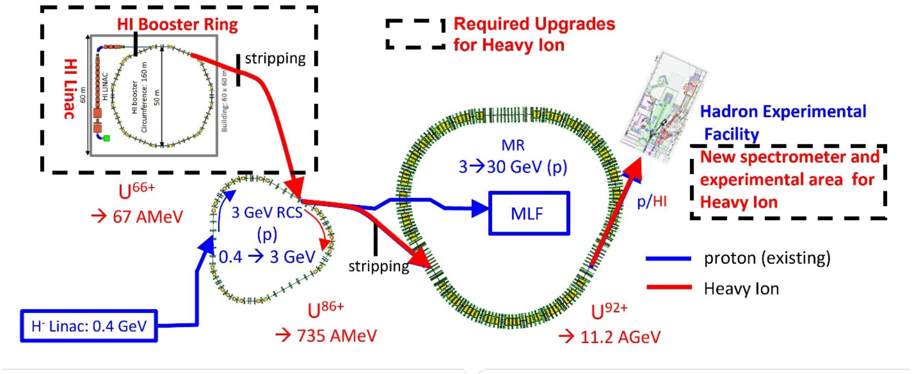

Figure 2. Schematic view of the J-PARC accelerator setup and required upgrades for the heavy ion project

To realize a high intensity heavy ion driver, a new heavy ion injector is planned in combination with existing J-PARC accelerators, which are the 3-GeV RCS and MR [4]. The driver aims to accelerate high-intensity heavy ion beams up to uranium to the energy of 11 GeV/nucleon (*A*GeV). Ions lighter than uranium can be accelerated up to 11-15 *A*GeV. The new heavy ion injector is composed of a new heavy ion LINAC and a heavy ion booster ring.

For the first phase experiment, the heavy ion injector is composed of a heavy ion LINAC and the KEK 500-MeV booster proton synchrotron (KEK-BS), since the required intensity is 10^{-3} smaller than that of the second phase experiment. The heavy ion LINAC for the first phase has the half length of the final configuration and we reuse the KEK-BS as the booster ring, which was used as the injector to the 12-GeV Proton Synchrotron at KEK. For the lower-intensity scheme, the designed maximum energy and the intensity of heavy-ions up to Au delivered from the MR to experimental beam line are 12-15 *A*GeV and 1.0×10^8, respectively. The various ion species are required such as deuteron, Carbon, Oxygen, Calcium and Au.

3 Experiment at phase I

The first phase experiment is proposed as an upgrade of the on-going J-PARC E16 experiment [5]. The goal of the phase-I experiment is to measure electrons and hadrons productions in heavy ion collisions with a reasonable statistics and study the quark phase in a high density region.

The J-PARC E16 experiment measures mass modifications of vector mesons in a nucleus to study partial restoration of chiral symmetry. The mass spectra are measured through an electron-positron decay mode to avoid final state interactions of hadron decays. The spectrometer of the experiment consists of tracking devices and electron identification counters as shown in Fig. 3. Three layers of Gas Electron Multiplier (GEM) Trackers and one layer of Silicon Strip Detectors (SSD) are placed for the tracking and one layer of Hadron Bind Detectors (HBD) and one layer of Lead Glass Calorimeters are placed for the electron identification. The HBD is a gas Čerenkov counter with a window-less and a mirror-less configuration [6].

The existing spectrometer focuses on the measurements of electron and positron pairs in a backward region of the center-of-mass frame, since slowly moving vector mesons are generated in this kinematical region and such mesons are expected to have a large decay

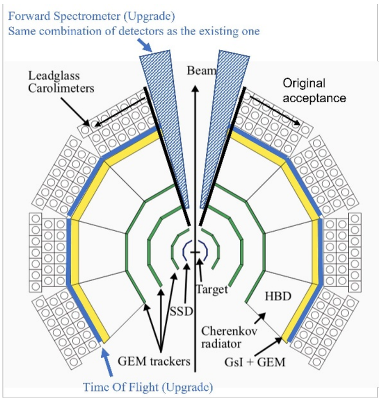

Figure 3. Schematic view of upgrades of the existing spectrometer

possibility in the nucleus. Thus, detectors in the forward region must be installed for the heavy ion experiment to cover a central rapidity region of the collision. In addition, fluctuations and correlations of particle productions are important to study thermal properties of generated matter and additional detectors for hadron measurements must be installed. We are developing a new time-of-flight counters for the hadron identifications.

Experimental feasibility is evaluated using a transport calculation code, JAM2 [7], and GEANT4 simulations [8]. Figure 4 shows evaluated acceptance of generated protons. The coverage of rapidity direction is significantly extended with the planned detector upgrade in the forward region.

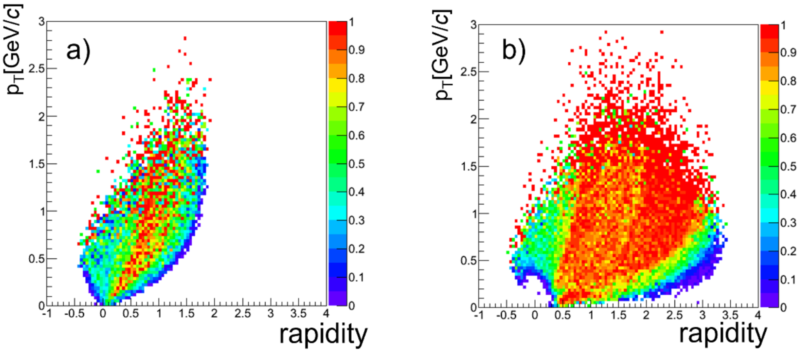

Figure 4. Acceptance of generated protons in heavy ion collisions for the existing spectrometer (a) and upgraded spectrometer (b)

One of the most important measurements using electron positron pairs is a temperature of the generated matter. Temperature can be measured as a slope of the mass spectra in the mass range higher than 1 GeV/c^2 as shown in Fig. 5. According to the recent lattice calculation [9], the energy range of the J-PARC is expected to be the region where the phase transition exists. Temperature will be measured as a function of collision energies. When

 https://doi.org/10.1051/epjconf/202227111004

obtained temperature curve exhibits a non-monotonic behavior, it indicates the existence of the first-order transition. It will be an important signature of a quark phase formation.

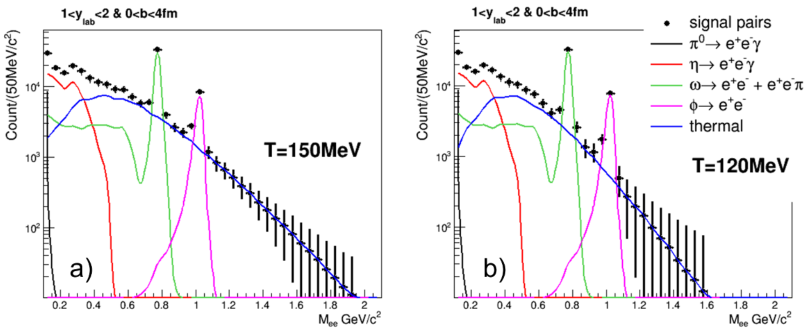

Figure 5. Expected invariant mass spectra of electron positron pairs for radiation temperature of 150 Mev (a) and 120 MeV (b)

4 Experiment at phase II

One major physics goal in the second phase is a detailed study of the high density matter. One of important measurements concerns fluctuations of conserved charges [10]. To realize such measurement, a large acceptance spectrometer to cover a wide rapidity range is required. Also, a high statistics data are needed, because signals of fluctuations are very small. Thus, we need to upgrade both the spectrometer and the accelerator.

Another physics goal is a comprehensive study of light hypernuclei. One can expect effective productions of strangeness particles at J-PARC energies, since the measured K/π ratio is maximal in this energy range [11]. Using a high intensity beam and closed geometry spectrometer, lifetimes and magnetic moments of hypernuclei can be measured precisely.

The planned spectrometer for the second phase is shown in Fig. 6. It contains detectors for hadron measurements and a sweeping magnet for closed geometry measurements. A main detector for the hadron measurements is a time projection chamber.

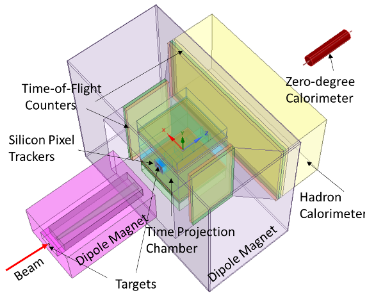

Figure 6. Schematic view of the proposed spectrometer in phase II

In addition, feasibility of other measurements is also under discussion. For example, as a signal of the phase transition between the quark phase and color-superconducting phase, a theoretical model suggests an enhance of invariant mass of electron positron pairs in a low mass region [12]. Such measurement requires extremely high statistics and it will be realized with a high intensity heavy ion beam. Furthermore, feasibility of measurements of higher order flows and correlations and heavy flavor production is being evaluated carefully.

5 Summary

A project using heavy ion beams at J-PARC are planned to study high-density nuclear matter in a beam energy range of 1-12 AGeV/c. A heavy-ion acceleration scheme and spectrometers for experiments are designed. The project has two phases. The first and second phase aims to achieve the collision rate of 10^8 Hz and 10^{11} Hz, respectively.

The accelerator needs new LINAC and booster to provide heavy ion beams. For the first phase, a new LINAC will be constructed and the KEK-PS Booster will be reused. A new large Booster will be constructed for the second phase.

The design of spectrometers are also under discussion. Upgrades of the existing spectrometer will be used for the first phase. Feasibility of temperature measurements in the first phase is evaluated and the proposal is submitted. Final design of the spectrometer for the second phase is being discussed intensively.

Acknowledgement

We express our gratitude to the members of the J-PARC Heavy Ion Program for their fruitful discussions on physics and detectors. We also thank to all accelerator physicists of J-PARC and JAEA Tandem accelerator group for designing acceleration scheme of the J-PARC Heavy Ion Program. This project was supported by MEXT/JSPS KAKENHI Grant Numbers JP19654036, JP19340075, JP21105004, JP26247048, JP15H05449, JP15K17669, JP18H05235, JP20H01935, JP20H05647 and JP21H01102.

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