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Future Project of Heavy-ion Experiment at J-PARC

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A future heavy-ion research project at J-PARC to explore QCD phase structures at high baryon density is presented. Acceleration schemes utilizing the existing synchrotorons have been investigated, and a spectrometer has been designed and evaluated with simulation.

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1. Introduction

In the QCD phase diagram, a regime at high temperature and a low baryon density, a QGP has been discovered by observations such as jet suppression [3, 4] and thermal photon radiation at high temperature [5] at RHIC, and its properties have been studied at RHIC and LHC.

At J-PARC, we aim at studies of QCD phase structures, especially the critical end point and phase boundaries, in a high baryon density regime. In this regime, other projects such as RICH BES (Beam Energy Scan) [6, 7], FAIR [8], and NICA [9] are also running or being planned.

The J-PARC heavy-ion project consists of two programs. "Low energy program" is aimed at research for unstable nuclei with a linac beam. In this program, ion species range from Ne(neon to U (uranium). The beam energy will be 1-10 AMeV for U. The goal beam current is 10-30 pμA with 10 ms beam pulse in 25 Hz repetition rate.

"High energy program" is aimed at research of the high baryon density using the 50 GeV MR (Main Ring synchrotron), which is the subject of this paper. We are going to use ion spices from proton to U with reference ions such as Si, Cu, and Au(Pb). Also light ions may be necessary for hypernuclei research. The uranium is particularly important, since the maximum baryon density increases from 7.5 to 8.6 times as large as the normal nucleus density according to JAM model [10]. The beam energy is variable in 1-11.6 AGeV for U ($\sqrt{s_{NN}} = 2-4.9$ GeV), and the maximum energy could be increased to 20 AGeV ($\sqrt{s_{NN}} = 6.2$ GeV) at the designed MR energy corresponding to the proton beam energy of 50 GeV. The goal beam current is 10-30 pμA with 10 ms beam pulse in 25 Hz repetition rate. The goal beam rate is the around $10^{10}-10^{11}$, which is comparable to SIS-100 accelerator at FAIR.

2. Heavy-ion acceleration

There are advantages to use J-PARC RCS (Rapid-Cycling Synchrotron) and MR for heavy-ion acceleration. Since they already exist, a new heavy-ion injector and the injection devices at RCS are required as the major upgrade for heavy-ion acceleration. Since RCS has very large transverse acceptance of more than 486 πmm·mrad and longitudinal acceptance of $\Delta p/p = 1\%$, it has enough acceptance for high-intensity heavy-ion beams. J-PARC accelerators have been proved to accelerate high-intensity proton beams, which are promising for heavy-ion acceleration. The current rate of slowly extracted proton beams at 30 GeV is of the order of a few 10^{13} protons per MR cycle (where a cycle is a few sec), which is planned to reach about 1×10^{14} in 2017. Since the J-PARC accelerator performance is well understood, acceleration of heavy-ion beams may be simulated well.

There are two possible accelerator schemes at J-PARC. Let us use Au beams for example. In Scheme A, we inject beams to RCS at the same rigidity as the current proton beams, corresponding to the beam (kinematic) energy of 72 AMeV. Before injection to RCS, the Au ion is almost fully stripped to Au^{77+}. This ion can be accelerated in RCS at the current vacuum level of 10^{-6} Pa without beam loss. In the calculations, it is shown that the ion can be accelerated both in RCS and MR without major modifications. However, to reach this relatively, we require both a linac and a booster ring to reach this high injection energy. In Scheme B, on the other hand, a lower injection energy of 13 AMeV is used, which requires only a linac as an injector. However, since the charge state at the injection is Au^{32+}, it requires extremely high vacuum level of 10^{-9} Pa, which requires major modification of the vacuum system of RCS.

Fig. 1 shows a more detailed acceleration procedure example in Scheme B. With a superconducting ECR ion source, we expect to have the initial charge state of Au^{32+} and high DC current of 10 pμA. The beam is converted to a pulsed beam at 25 Hz, which corresponds to 3.1×10^{10} ions. The beam is accelerated to 13 AMeV in the linac and then injected to RCS in the multi-turn injection scheme, and fully stripped between RCS and MR, and accelerated to the final energy to 11.5 AGeV in MR. The final beam rate assuming 100% injection efficiency at RCS and MR is 8.0×10^{10} per MR cycle, in this example.

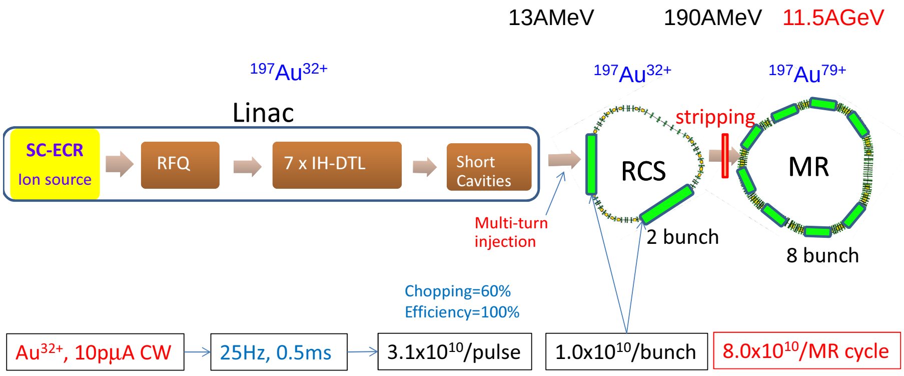

Figure 1: A heavy-ion acceleration scheme with a linac for a Au beam.

3. Physics goals

Physics goals of the J-PARC heavy-ion project is shown here. Dileptons are the most important observables to study properties of high density matter. In-medium modifications of ρ, ω, ϕ mesons could be related to the indication of chiral symmetry restoration [12]. It is complementary with the J-PARC E16 experiment [15] which measures ϕ spectrum modifications in normal nuclear matter in p+A reactions. Comparison of dilepton yield normalized to the cocktail in the low mass region indicates enhancement around J-PARC energy ranges, which may be related to the maximum baryon densities achieved in this region. A dilepton spectrum at the intermediate mass region from 1 to 3 GeV/c^2 may be sensitive to thermal photons from QGP. In J-PARC, both dielectrons and dimuons will be measured. They are complementary measurements and systematic comparisons of dilepton measurements are possible.

Systematic hadron measurements in high statistics available with high-rate J-PARC beams are very important to find possible subtle indications for the critical point and phase boundaries.

Especially, event-by-event fluctuations are proposed as possible probe to search for the critical point. Recently net-charge fluctuations are found to be related directly to the lattice QCD calculations. Higher-order fluctuations are more sensitive to phase structures, but they require higher statistics. J-PARC will have large rapidity and transverse-momentum acceptance, which is important especially for low energy nucleus collisions such as at J-PARC.

In strange mesons and baryons measurements, so called "horn" peak has been observed in the energy dependence of K^+/π^- and Λ/π^- ratios. The peaks are around $\sqrt{s_{NN}} = 8$ GeV, which is slightly higher than the maximum J-PARC energy. The systematic precise measurements of strange hadrons are very important. Also, there has been almost no measurement for Ξ and Ω in the J-PARC energy region, which may be sensitive to the formation of QGP.

Hypernuclei are predicated to have maximum yield at J-PARC, due to coalescence of high-density baryons. $S = -3$ hypernuclei can be produced in heavy-ion collisions, which in contrast is very hard with hadron beams. Hypernuclei studies are one of the major topics at J-PARC, and heavy-ion collisions will enhance the research. For this measurement, precise secondary vertex reconstruction is important to measure small hypernuclei at the heavy-ion spectrometer (shown in Fig. 3). Also, a closed geometry setup for measurements at projectile rapidity region may be considered.

Let us estimate how much particle statistics will be available at J-PARC. We assume the beam rate of 10^{11} Hz and 0.1% interaction length target in heavy-ion collisions (such as Au+Au). If we use 0.1% most central trigger, the trigger rate, which is the data-acquisition (DAQ) rate if it can take all, is 100 kHz. In a month experiment, one can expect dielectron decays from ρ, ω, ϕ of $10^7 - 10^9$. D and J/Ψ of $10^5 - 10^6$ (at 20 AGeV), and hypernuclei (${}^{3}_{\Lambda}$H, ${}^{5}_{\Lambda\Lambda}$H, and ${}^{6}_{\Lambda\Lambda}$He) of $10^5 - 10^6$.

4. Experiment

The heavy-ion experiment at J-PARC requires high rate measurement, since the interaction rate is higher than 100 kHz. Detectors with fast response are required. As a tracker, silicon trackers and GEM trackers are required instead of wire chambers. An extremely fast DAQ system is a key technology to achieve the experiment, probably with a trigger-less DAQ scheme. Due to high track densities, a small pixel size is required for detectors. For instance, at 1 m distance from the target at the most forward angle ($\theta = 2^o$), 3×3 mm^2 is required to achieve 10% occupancy in average. Also, large acceptance close to 4π solid angle is required to cover significant acceptance at low energies up to 1 AGeV. The large acceptance is important for precise event-by-event measurement with maximum multiplicity and to analyze acceptance dependent analysis in rapidity and p_T. To measure tracks at backward angles for fragments and hypernuclei where measurements are easier due to lower track densities, large acceptance is also required.

We design the spectrometer as shown in Fig. 3. The spectrometer consists of a solenoid spectrometer which covers backward acceptance at $\theta > 30^o$, and a dipole spectrometer which covers forward acceptance at $\theta \leq 30^o$. The solenoid spectrometer consists of 4 layer barrel- and end-cap-type silicon pixel/strip detectors with the highest position resolution of a few ten μm. Three

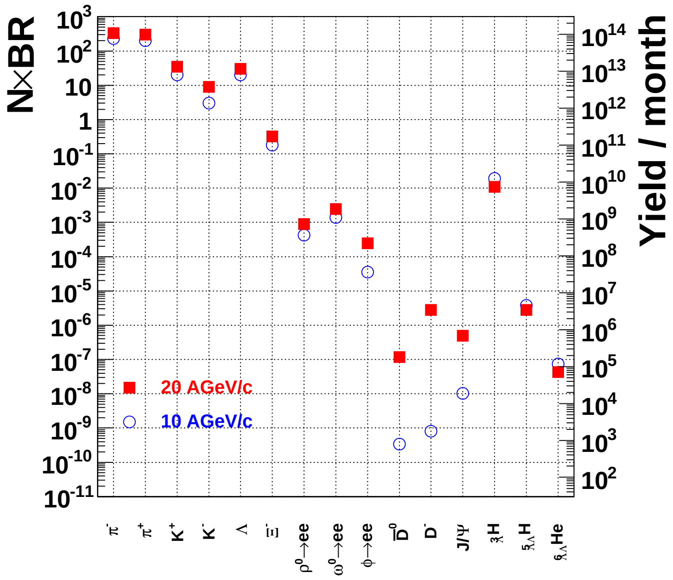

Figure 2: Multiplicity times branching ratio for various particles (left vertical axis) [8, 14, 13] and expected yield at one-month running at J-PARC (right vertical axis).

layer barrel type GEM trackers position at outer radii and a time-of-flight detector (TOF) of RPC (Resistive-Plate Counter) is at the outermost position with the time-of-flight of about 1 m. The solenoid spectrometer measures charged particles and identify them with time-of-flight.

The dipole spectrometer measures charged particles and identifies hadrons, electrons, photons, and muons. It consists of an aerogel-C_5F_{12} double-radiator RICH for electron and muon identification, a dipole magnet, a TOF, a $PbWO_3$ electromagnetic calorimeter (EMCAL) for electron and photon measurement, and muon-tracker system consisting of Fe absorbers and GEM trackers. GEM trackers are inserted between those detectors. The separation of μ from π is done with the TOF with 30 ps resolution at $p < 0.8$ GeV/c, and with RICH with aerogel radiator in $p = 0.8 - 1.5$ GeV/c, and the muon-tracker system at $p > 1.5$ GeV/c. Separation of $e - \pi$ is done in RICH with the gas radiator at $p < 3.4$ GeV/c in 20 mrad Cherenkov light angle separation, and also with EMCAL of 15 radiation length. The centrality is determined by a multiplicity counter inside the solenoid magnet, and a Fe-scintillator sandwich zero-degree calorimeter (ZCAL) at the downstream.

We evaluated performance of the spectrometer with a GEANT4 simulation. Central U+U event data at 10 AGeV were generated using JAM model [10].

Fig. 4 shows combined acceptance of the solenoid and the dipole spectrometers for charged hadrons requiring hits at TOF. The acceptance is 72-98%, including the loss due to weak decays for K^+ and π^+.

The top plots of Fig. 5 show particle identification performance using TOFs at the solenoid and the dipole spectrometers assuming 50 ps timing resolution. Clear separation of π, K, p, and $\bar{p}$

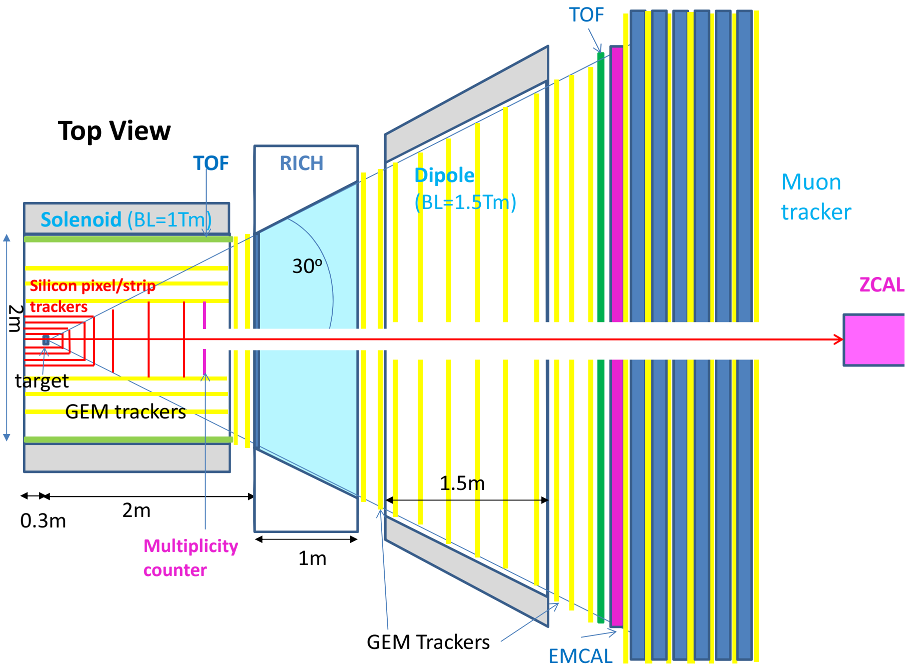

Figure 3: A preliminary design of the experimental setup.

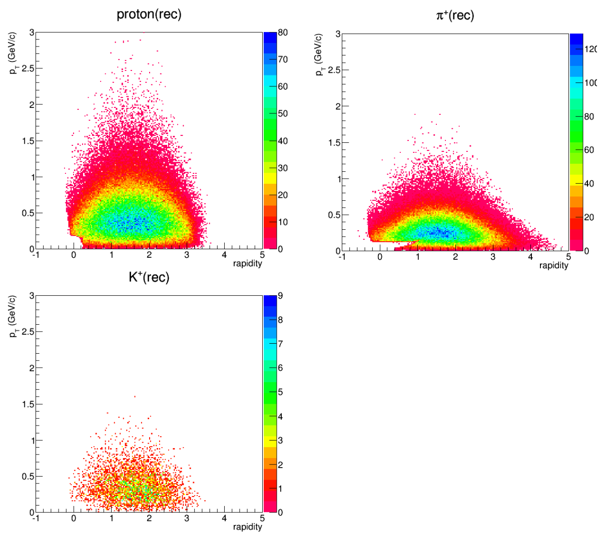

Figure 4: Acceptance of p (top left), π^+ (top right), and K^+ (bottom left) in the rapidity and p_T plane.

is seen, and K and π are separated in 2σ up to the momentum of 2.8 GeV/c.

The bottom plots of Fig. 5 shows the momentum resolution at the two spectrometers. The momentum resolution is approximately $\Delta p/p = 0.4\% \times p$(GeV/c) ($p > 1$ GeV/c) at the dipole spectrometer, and 1.5 % at the solenoid spectrometer, with silicon trackers of 14-23 μm, and that of GEM trackers of 0.2-0.4 mm.

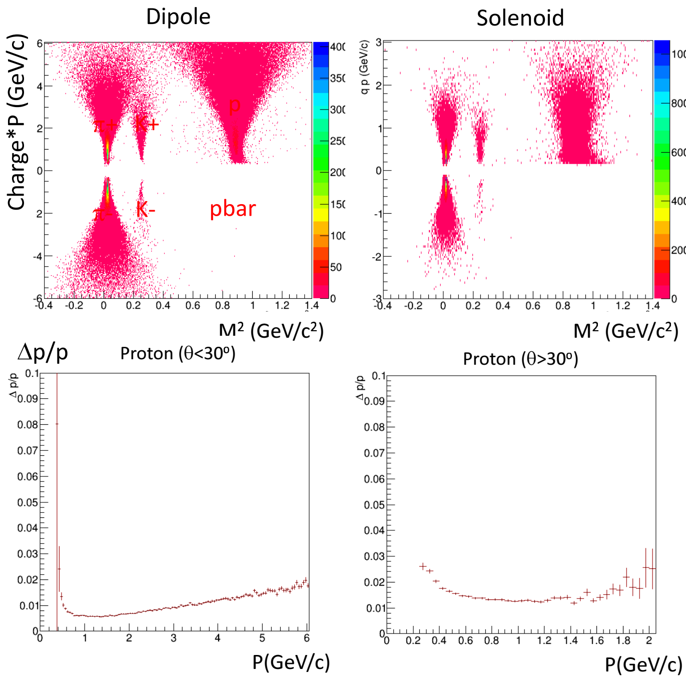

Figure 5: Reconstructed charge times momentum (GeV/c) vs m^2 (GeV/c^2) at $\theta < 10^o$ with JAM events at the dipole (top left) and the solenoid (top right) spectrometers. Relative momentum resolution as a function of momentum (GeV/c) at the dipole (bottom left) and the solenoid (bottom right) spectrometers.

Finally, we demonstrate an expected dielectron mass spectrum at J-PARC in Fig. 6. Dielectrons are simulated for 10^{11} events, corresponding to 1 month running at the DAQ rate of 100 kHz. The simulated hadron spectra are scaled with m_T based on the π^0 spectrum generated with the JAM model [10] at 0.25 % most central events (corresponding to the impact parameter less than 1 fm). Momentum resolution is assumed to be 2 %, and single electron (positron) reconstruction efficiency is assumed to be 50 %. The simulation does not include dector response. The spectrum has a rapidity cut of $1 < y < 2$, and opening angle cut of more than 15^o. A dielectron was further rejected if a single electron (positron) track with a nearby hit in silicon trackers was detected. The efficiency of this procedure is assumed to be 70 %.

5. Conclusions

We aim at a future heavy-ion experiment at J-PARC to explore QCD phase structures at high baryon density. Acceleration of heavy ions is possible at J-PARC with the existing RCS and MR by

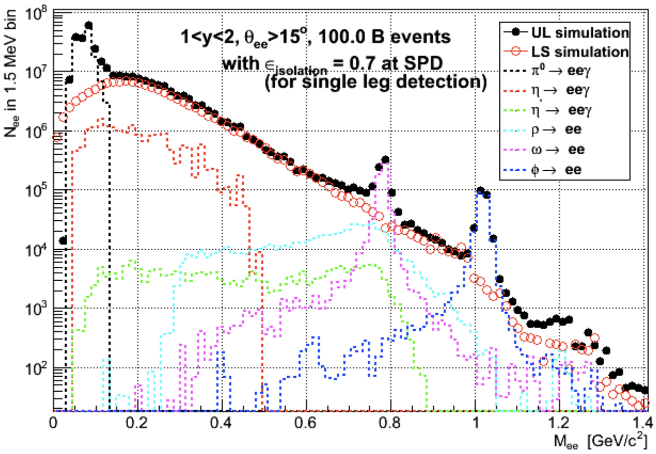

Figure 6: Simulated dielectron mass spectrum with 100 billion events.

addition of a new injector. We are going to measure dileptons and hadrons by challenging highest possible rates. A spectrometer for an heavy-ion experiment has been and designed with good performance for hadrons and electrons. A conceptual design will be summarized and detector R&D will start in near future.

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