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Heavy Ion Acceleration at J-PARC

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Abstract. J-PARC, the Japan Proton Accelerator Research Complex, is an accelerator, which provides a high-intensity proton beam. Recently as a very attractive project, the acceleration of heavy ions produced by supplementary ion sources, called *J-PARC-HI*, is seriously contemplated by domestic as well as international communities. The planned facility would accelerate heavy ions up to U^{92+} with a beam energy 20 AGeV ($\sqrt{S_{NN}}$ of 6.2 AGeV). The highlight of the J-PARC-HI project is its very high beam rate up to ~10^{11} Hz, which will enable the study of very rare events. Taking advantage of this high intensity, J-PARC-HI will carry out frontier studies of new and rare observables in this energy region: (i) nuclear medium modification of chiral property of vector mesons through low-mass di-lepton signal, (ii) QCD critical point characterization through event-by-event fluctuation signals of particle production, (iii) systematic measurements related to the equation of state through collective flow signal or two-particle momentum correlation signal, or (iv) the search of hyper nuclei with multi strangeness including or exceeding S = 3. The current plan of J-PARC-HI aims to carrying out the first experimental measurements in 2025.

1 J-PARC as of today

At J-PARC, which provides one of the most intense proton beams in the world, a number of experimental programs are ongoing. J-PARC consists of a LINAC, Rapid Cycle Synchrotron (RCS), and Main Ring synchrotron (MR). In J-PARC, three experimental facilities are in operation: materials and life-science facility (MLF), neutrino facility (NU), and hadron experimental hall (HD).

#	Title of the Physics Experiments	PAC stage
E07	Systematic Study of Double Strangeness System with an	2 (data taking)
E10	Production of Neutron-Rich Lambda-Hypernuclei with the	2 (finished [4])
E13	Gamma-ray spectroscopy of light Hypernuclei	2 (finished [4])
E15	A Search for deeply-bound Kaonic Nuclear states by in-flight	2 (data taking
E19	High-resolution Search for Θ^+ Penta quark in $\pi^- p \rightarrow K^- X$	2 (finished [4])
E27	Search for a nuclear K-bar bound state K^-pp in the	2 (data taking)
E31	Spectroscopic study of hyperon resonances below KN	2 (data taking)

Table 1. Highlighted PAC-approved experiment at J-PARC HD, as of January 2017 (full list [2]).

Beam commissioning started in November 2006, when all the accelerator and monitoring devices [1] of the LINAC were ready. In January 2007, the proton beam was successfully accelerated to 181 MeV, and the commissioning of RCS and MR followed. Then the production of the first beam of neutrons, muons, kaons, and neutrinos was achieved in May, September 2008, February, and April 2009, respectively. After the summer shutdown in 2010, a slow-extraction experiment (beginning with the E19 experiment) in the HD facility was aiming for operation with more than 5 kW power and more than 15% duty factor, and the fast-extraction experiment (namely T2K experiment) in the NU facility was running at a power of over 100kW, which would increase toward the design power. As of January 2017, the J-PARC physics advisory committee (PAC) approved 14 experiments at the Stage-1 (which is a partial approval to admit scientific interests), and 17 experiments at Stage-2 (which is the final approval after feasibility review and safety reviews). The latter experiments include 4 experiments, which have completed data taking and 5 experiments whose data taking is on-going. The PAC-approved proton-beam experiments can be found in Ref. [2]. Among the variety of experimental programs at the J-PARC accelerator complex [3], several highlighted experiments at the hadron experimental hall are listed in Table 1, and also described in the following subsections.

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1.1 Experiments at Hadron Experimental Hall with Proton Beam

• *E07 experiment* (*S = -2 hypernuclei*): The purpose of the experiment is a systematic study of double-strangeness nuclei with 10 times higher statistics than the previous experiment (KEK-E373). The key reaction is: $K^- + "p" \rightarrow K^+ + X^-$, where "$p$" indicates proton in the nucleus used in the emulsion target, which is also used as precise 3-dimensional tracking detector for event decay topology determination. In total during experimental periods in 2016 and 2017, some $1\times10^9\ K^-$ [per emulsions-set] × 118 [emulsions-sets] were irradiated. The data are now being analyzed.

• *E13 experiment* (*γ-ray hypernuclei*): Charge symmetry is studied by comparing the corresponding energy spacing in the mirror hypernuclei, ${}^4_\Lambda He$ and ${}^4_\Lambda H$. The key reaction for ${}^4_\Lambda He$ is: $K^- + {}^4He \rightarrow \pi^- + {}^4_\Lambda He$. The energy spacing between the spin-doublet bound state of ${}^4_\Lambda He(1^+, 0^+)$ was determined to be 1.406 ± 0.002 (stat.) ± 0.002 (syst.) MeV, by measuring γ-rays for the $1^+ \rightarrow 0^+$ transition with a high efficiency germanium detector array. By comparing with existing data for the same baryon number but with one nucleon difference (a neutron instead of a proton (i.e. ${}^4_\Lambda H$) which is 1.09 ± 0.02 MeV, the result provides a measurement of the charge symmetry breaking (CSB) in ΛN interaction [4].

cycle 5520msec

Beam area	LI | RCS | MLF | MR | HD | NU
HD status	Beam Inhibit
Run number	75
Shot number	370313
Last shot time	17/06/28 05:32:43
MR Power	37.46 kW
MR Intensity (P3)	4.3e+13 PPP
SX Duty	39.45 %
SX spill length	2.04 sec
SX extraction efficiency	99.28 %
HD Power	36.29 kW
HD Intensity	4.2e+13 PPP

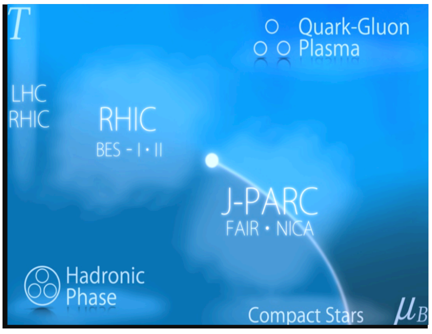

Fig. 1. (left) Example of performance achieved in slow-extraction mode with the MR synchrotron, during the stable physics running period in June 2017. **(Right)** Schematic view of the phase diagram [15] in temperature (*T*) and in baryon chemical potential (μ_B), for QCD/hadronic matter.

1.2 Accelerator Performance with Proton Beam

J-PARC is an accelerator complex currently utilizing a high intensity proton beam. In June 2017, during which stable running for more than one month were performed, 4.3×10^{13} protons per pulse for slow extraction (SX) mode were successfully provided to the hadron experimental hall. In 2016, an intensity as high as 5.9×10^{13} proton per pulse was achieved. Figure 1 shows the screenshot of the accelerator performance during the running period of data taking for the E07 experiment in 2017. In SX mode, the extraction efficiency was 99.28%, and in 2016 as high as 99.54%. Secondary Kaon beam of 2.8×10^5 [per pulse] were provided. (Also in 2017, as high as 3.1×10^5 Kaons per pulse were achieved.) In fast extraction (FX) mode, 2.44×10^{14} protons per pulse (~470 kW, and recorded in Feb. 2017) were provided.

2 Heavy Ion Physics in J-PARC

In order to survey the phase diagram of QCD in temperature and in baryon chemical potential (μ_B), a beam energy scan including lower energy is needed [5] (see Figure 1, right). By performing a beam-energy scan using heavy-ion projectiles, changes are experimentally produced in (i) initial extreme condition, (ii) development of the hydro-dynamical system (with a specific viscosity and entropy), (iii) hadronization (chemical-freeze-out) point, and (iv) kinetic freeze-out point. These data are systematically integrated to evaluate phase boundaries and a location (if any) of critical point. Also, to extract the equation of state for QCD/hadronic matter is one of the ultimate purposes of heavy-ion collision experiments including J-PARC-HI. In heavy-ion collisions at J-PARC energies (see section 2.2), the initial momenta of nucleons from nuclei are sufficiently decreased by the interaction as to overlap with each other at the colliding point ("baryon stopping"). Therefore, a medium at high μ_B can be created. The μ_B of the medium created in the collisions changes depending on the collision energy. This $\sqrt{s_{NN}}$ dependence of the collision dynamics is clearly observed in the rapidity distribution of net-proton numbers. The chemical freeze-out picture for hadron yields suggests that the maximum baryon density at the freeze-out is realized at $\sqrt{s_{NN}}$ = 3 – 5 GeV [8]. This energy range is covered by J-PARC-HI. Analyses based on dynamical models (e.g. JAM model [5]) indicate that the highest baryon density of $\rho/\rho_0 > 5$ at the equilibration time is achieved at these collision energies.

2.1 Higher Interaction Rate

There are several projects, which plan to utilize heavy-ion beams in the energy region up to a few tens of GeV in $\sqrt{s_{NN}}$. At J-PARC, interaction rate of approximately 10^7 to 10^8 Hz, by using higher beam rate up to 10^{11} Hz (with typical target of 0.1% interaction length) is aiming to be utilized [6]. From those interaction rates, the observation of rare events [7] and of event-by-event fluctuation in temperature and in density [8], is expected. Furthermore, the production of rare particles exhibiting strangeness of 3 or larger is expected. By measuring those quantities, a variety of observables can be examined.

• *Chiral Property*: At higher density, a change of chiral properties occurs, and the mass modification and the yield modification are key observables to study this phenomenon (preceding experiment, KEK-E325 [4]). The invariant-mass spectrum of dileptons is directly connected to the spectral function in the vector channel. One of the most important physics goals, which can be addressed, is the in-medium modification of vector mesons.

• *Particle Production Rate*: By changing the beam energy, a variety of transition phenomena of particle-production have been measured in this energy region [9]. At the AGS, only particles/nuclei with a multiplicity (times branching ratio) larger than 10^{-2} were measured, down to antiprotons in charged hadrons, and only ${}^{3}_{\Lambda}H$ in hypernucleus. Neither dileptons nor charmed mesons were measured [7]. Assuming a beam rate of 10^{11} Hz at J-PARC and a target with thickness of 0.1% interaction length, the calculated interaction rate is 10^8 Hz. When we select 0.1% most central events, the trigger rate is 100 kHz. In one month of experiment, we expected to measure 10^7–10^9 dielectron decays of ρ, ω, ϕ, 10^5–10^6 D and J/Ψ at the beam energy of 20 AGeV, and 10^5 –10^{10} hypernuclei. Also the ratios K^+/π^+ and Λ/π^- have a peak called the "horn" at $\sqrt{s_{NN}}$ = 5 – 10 GeV. There are many discussions, which relate these structures to the onset of the deconfinement phase transition.

• *Exotic Particle Production*: There are expectations for the exotic particle production with strangeness of 3 or more. In heavy-ion collisions, hypernuclei are produced both in the mid-rapidity and the target and the beam rapidity regions. In the mid-rapidity region, a few nucleons and hyperons are coalesced to form mainly a small hypernucleus. The yields in the mid-rapidity region become maximal around the J-PARC energies. In the target- and the beam-rapidity regions, fragments are embedded with hyperons produced in nucleon-nucleon collisions to form larger hypernuclei. Therefore, in heavy-ion collisions, a variety of hypernuclei may be produced with a different size, with $S = -1, -2, -3$ and so on with different proton/neutron constitutions.

2.2 Plan up to U^{92+} with 20 AGeV ($\sqrt{s_{NN}}$ = 6.2 AGeV) into the operating J-PARC

There are several merits for J-PARC (proton accelerator) to upgrade into a heavy-ion accelerator: (1) the 2 Synchrotrons (RCS and MR) are already available and functioning (2) only an injector (= "HI-Linac"+ "HI-Booster") is needed (3) the base line data for *p+p* (and *p+A*) are ready to measure (4) a variety of particle species (from lighter HI to ${}^{238}U$) can be accelerated. The plan is accelerating U^{92+} with a beam energy of 20 AGeV ($\sqrt{s_{NN}}$= 6.2 AGeV). Beam loss in RCS synchrotron, is simulated for U^{86+} ion of 4×10^{11}/cycle. The beam loss is less than 0.05% [10], and no any unexpected beam losses. And moreover, the beam loss is very localized at the ring collimator.

2.3 Large Acceptance Spectrometer and A Spectrometer for Hypernuclei Search

For systematic measurements of charged particles, a large acceptance spectrometer called JHITS with general tracking (for higher order of flow measurements, etc.) and with di-muon identification is planned [11]. It is also worth noting that a complementary program using existing proton beam on *A*-target is also possible, which is J-PARC E16 (the 2nd stage PAC- approved) experiment ($\phi \rightarrow e^+e^-$). In order to cover large acceptance both for hadrons and leptons, and to make a magnetic field free volume from the target to RICH, the spectrometer is being designed based on a toroidal magnet. In the toroidal spectrometer, there are silicon vertex trackers (SVTs) around the target, a RICH, toroidal coils, a Time-of-Flight counter (MRPC-TOF), an electro-magnetic calorimeter (PbWO4), and a muon tracker system (steel absorbers + GEM trackers). Also there are many GEM trackers between each detector. Also, a dedicated spectrometer with closed geometry is being designed for a systematic search of hypernuclei [12]. A spectrometer for hyper-nuclear studies is designed at the beam rapidity. It consists of a first dipole magnet, which sweeps out most of produced hadrons that stop at the tungsten collimator. The second dipole contains a TPC, which measures hyper-nuclear decays.

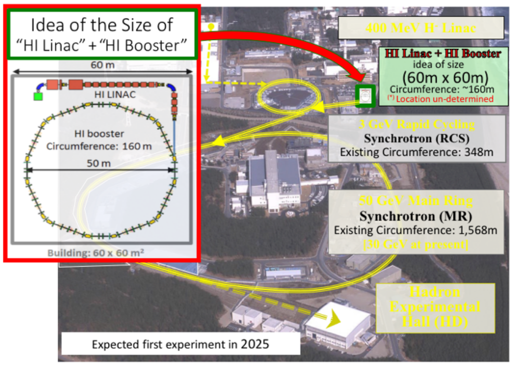

Fig. 2. An idea of size and possible location of the heavy-ion injector (= "HI-Linac" + "HI-Booster"). Note that: neither the size nor the location is determined. The size is based on [11].

2.4 Idea of the Size of "HI-Linac" + "HI-Booster"

An idea of the size and possible location of the heavy ion injectors is schematically shown in Figure 2. And please note that: neither the size nor the location are yet determined. The letter of intent was submitted to the J-PARC PAC (the 22nd PAC, in 2016 June), as "Letter of Intent for J-PARC Heavy-Ion Program [11]". The full list of international collaborations can be found in the LOI. Now, the efforts have been made toward the J-PARC's staging review, and toward the administrational approvals, for experiments starting in 2025.

3 Summary

J-PARC is currently running with the most intense proton beam at 30 GeV. HI acceleration at J-PARC is motivated partially from phase diagram study, at lower beam energy, where high-baryon density is expected. The idea to utilize the existing 2 Synchrotrons (RCS, and MR) at J-PARC, with a new compact-sized injector (HI-Linac and HI-Booster), is the one of the main merits of accelerating heavy-ion at J-PARC.

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