LONGITUDINAL BEAM DYNAMICS SIMULATION FOR GOLD ION ACCELERATION IN THE J-PARC MR

Yasuyuki Sugiyama*, Fumihiko Tamura, Kyosuke Adachi, Hidefumi Okita, Kiyomi Seiya,
Masahito Yoshii, Chihiro Ohmori, Keigo Hara, Katsushi Hasegawa,
Masahiro Nomura, Masanobu Yamamoto, Taihei Shimada
KEK and JAEA J-PARC, Tokai, Ibaraki, Japan

Abstract

The J-PARC Main Ring (MR) is a high-intensity proton synchrotron, which accelerates protons from 3 GeV to 30 GeV. In addition to protons, we are considering accelerating heavy ions to GeV/u energies in the MR as part of the J-PARC heavy-ion program (J-PARC HI). The heavy ions will be injected from the new heavy-ion injector into the J-PARC Rapid Cycling Synchrotron (RCS) and delivered to the MR. As the first stage of the program, Au ions are considered the ion species to accelerate. A full stripping beam of Au ions (^{197}Au^{79+}) with an energy of 500 MeV/u is injected from the RCS to the MR. Au ions are accelerated up to 11.5 GeV/u and delivered to the hadron experimental facility. Since the change in revolution frequency during acceleration of Au ions is larger than that for protons, additional cavities dedicated to ion acceleration or modifications to the existing RF cavity will be needed to cover a wider frequency range. To estimate the RF system requirements for accelerating Au ions in the MR, we conducted a longitudinal beam dynamics simulation. In this paper, we present the simulation results with various harmonic numbers and acceleration times.

INTRODUCTION

The Main Ring synchrotron (MR) [1] in the Japan Proton Accelerator Research Complex (J-PARC) [2] is a high-intensity proton synchrotron which accelerates protons from 3 GeV to 30 GeV. The beam injection starts at t = 10 ms from the cycle start. The acceleration starts at t = 140 ms and finishes at t = 790 ms. J-PARC MR has two operation modes with different extraction schemes. The fast extraction (FX) mode is used for the beam delivery to the neutrino experiment. In the FX mode, the beam is extracted using the extraction kickers in one turn. The other operation mode is the slow extraction (SX) mode for the hadron experiment. Since the hadron experiments require a smooth time structure for a long duration (~2s), the beam is extracted slowly after the debunching process by turning the RF off. MR delivered 900 kW (2.40×10^{14} protons at 1.28 s cycle, FX) to the neutrino experiment and 96 kW (8.48×10^{13} protons at 4.24 s cycle, SX) to the hadron experiment in April 2026 [3].

In addition to protons, we are considering accelerating heavy ions to GeV/u energies in the MR as part of the J-PARC heavy-ion program (J-PARC HI) [4–7]. The heavy ions will be injected from the new heavy-ion injector into the J-PARC Rapid Cycling Synchrotron (RCS) and delivered to the MR. Ions accelerated in the MR are delivered to the hadron experimental facility by a slow extraction process. As the first stage of the program, Au ions with low intensity ($\sim 1.0 \times 10^8$ particles per pulse) are considered the ion species to be accelerated in the MR.

Because the charge and mass of Au ions differ significantly from those of protons, estimating the RF frequency and voltage patterns is essential to determining RF system requirements for Au-ion acceleration in the MR. In this paper, we present the calculation and simulation results with various harmonic numbers and acceleration times.

ION INJECTION TO MR

In the J-PARC HI program, ions are accelerated in the new injector and delivered to the RCS. The new heavy-ion injector consists of an ion source, a superconducting linear accelerator, and a booster synchrotron. In the RCS, single-bunched ions are accelerated in the ring at a repetition rate of 25 Hz. After acceleration in the RCS, ions are fully stripped in the beam transport line and injected into the MR. In the same way as in the case of protons, ions are injected from the RCS to the MR four times. As a result, four bunches of ions are injected into the MR and accelerated in total.

As the first stage of the program, the acceleration of Au^{56+} and Au^{79+} is considered in the RCS and MR, respectively. The energy of the ions extracted from the RCS is 500.4 MeV/u.

FREQUENCY PATTERN

The revolution frequency pattern can be calculated from the magnetic field pattern of the bending magnet and the MR circumference (1567.5 m). For the protons acceleration from 3 GeV to 30 GeV, the magnetic field strength ranges from 0.143 T to 1.15 T, corresponding to a magnetic rigidity of 12.8 Tm to 103 Tm. The lower minimum magnetic field of 0.101 T is required to have a magnetic rigidity of 9.03 Tm for the Au^{79+} ions with energy of 500.4 MeV/u from the RCS. The maximum energy of Au^{79+} ions after the acceleration in the MR is 11.5 GeV/u.

Since the charge-to-mass ratio of Au^{79+} ions is larger than that of protons, the change in revolution frequency during acceleration of Au ions is larger than that for protons. The revolution frequency changes from 144 kHz to 190 kHz for Au^{79+} ions, while it ranges from 185 kHz to 191 kHz for protons.

---

* yasuyuki.sugiyama@kek.jp

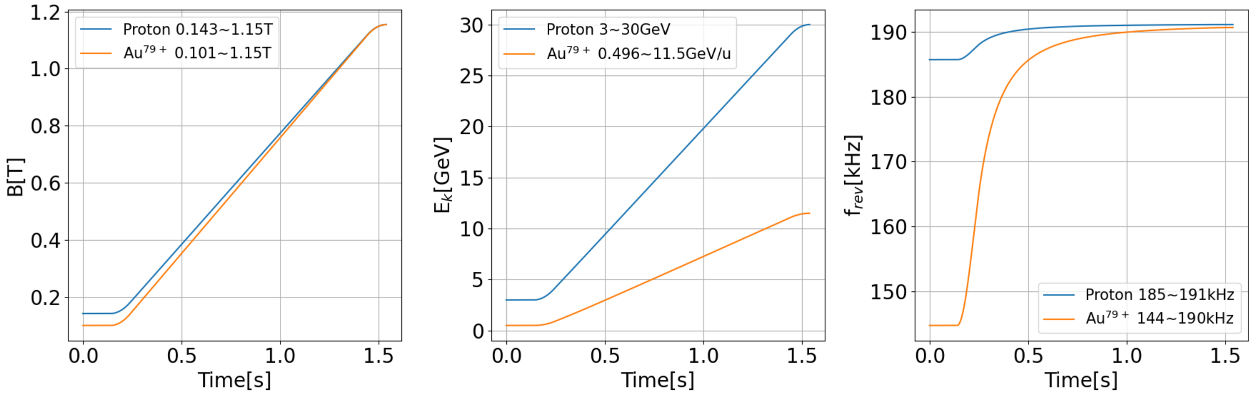

Figure 1: The pattern of magnetic field (left), kinetic energy (center), and revolution frequency (right) of the J-PARC MR for protons and Au^{79+} ions with the acceleration time of 1.4 s.

While protons are accelerated in 650 ms to achieve higher beam power, a longer acceleration time can be used for low-intensity ions to reduce the required RF voltage. Figure 1 shows the patterns of magnetic field, kinetic energy, and revolution frequency of the MR for protons and Au^{79+} ions with an acceleration time of 1.4 s.

HARMONIC NUMBER FOR ACCELERATION

The harmonic number for the RF system needs to be determined to estimate the RF voltage pattern and for the tracking simulation. A smaller harmonic number is desired for a larger RF bucket with the same RF voltage. The minimum harmonic number for the acceleration is $h = 5$, since four bunches are accelerated in the MR and one additional bucket is required to maintain the gap for the extraction kickers.

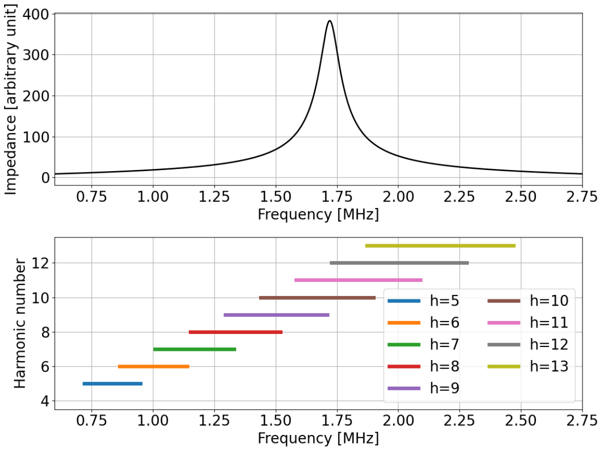

Figure 2: Impedance of the existing RF cavity for protons (upper) and frequency range for each harmonic component for the Au^{79+} ions (lower) in the J-PARC MR.

Figure 2 shows the frequency response of the impedance of the existing RF cavity for protons and the frequency range for each harmonic component for accelerating the Au^{79+} ions. Since the existing RF cavity of the MR for the proton acceleration does not have a large impedance for the frequency range of $h = 5$, a new RF cavity dedicated to the ion acceleration is required in the case of $h = 5$. In the case of the utilization of the existing RF cavity for protons, the harmonic numbers from $h = 9$ to $h = 12$ are candidates for the harmonic number.

In this paper, estimation and tracking simulations are performed for the cases $h = 5$ and $h = 11$.

LONGITUDINAL BEAM TRACKING SIMULATION

The longitudinal beam tracking simulation is performed to determine the RF voltage pattern for accelerating Au^{79+} ions in the MR. The goal of the tracking simulation is to estimate the RF voltage pattern to achieve a momentum filling factor below 0.8, ensuring sufficient space in the RF bucket. The momentum filling factor (MFF) is the ratio of the maximum momentum difference from the synchronous particle with given beam emittance to the bucket height. To simplify the calculation, the ratio of the maximum momentum in phase space to the bucket height is used as the MFF in this estimate.

The longitudinal beam dynamics tracking simulation was performed using the BLonD (Beam Longitudinal Dynamics) [8]. The space-charge and beam-loading effects were not accounted for in the tracking simulation since the ion's intensity is low. The number of macroparticles for the tracking simulation was 10,000 particles per bunch. The distribution that matches the shape of the RF bucket is used as the initial distribution. The emittance of the initial distribution is assumed to be 50 eVs. The tracking simulation was performed with a single bunch from the injection to the end of acceleration. The simulation is performed for the acceleration times of 1.4 s, 2.0 s, 3.0 s, 4.0 s, and 5.0 s.

The RF voltage for the beam injection period (t = 0 ~ 140 ms) is set to achieve an RF bucket height of 0.125% in dp/p. After the acceleration starts at t = 140 ms, the RF voltage increases linearly with time until it reaches its maximum at t = 200 ms. The RF voltage remains at its maximum until the end of the acceleration.

The maximum RF voltage V_{max} is determined from the simulation results to achieve an MFF below 0.8 throughout

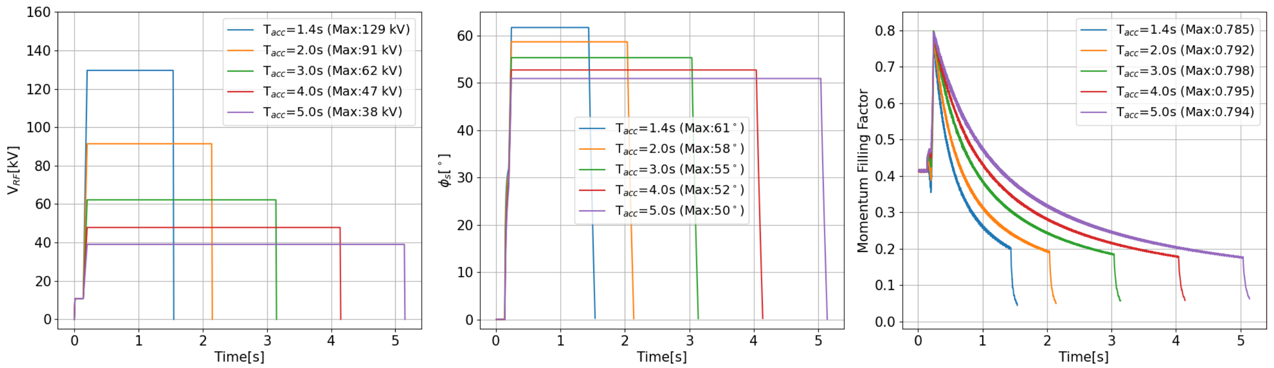

Figure 3: The patterns of RF voltage amplitude (left), synchronous phase (center), momentum filling factor (right) obtained from the tracking simulation for various acceleration times in the case of $h = 5$ for acceleration.

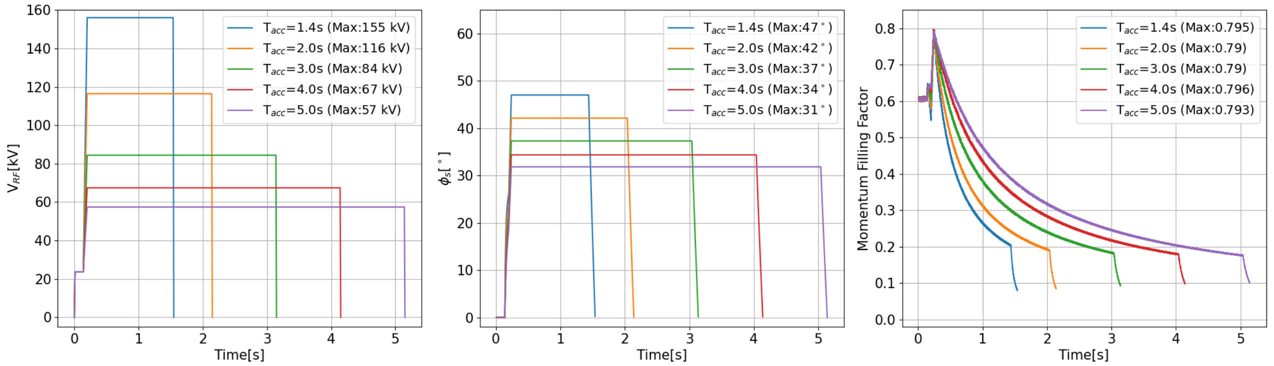

Figure 4: The patterns of RF voltage amplitude (left), synchronous phase (center), momentum filling factor (right) obtained from the tracking simulation for various acceleration times in the case of $h = 11$ for acceleration.

the cycle. At first, V_{max} is set to the minimum voltage that yields an RF bucket height greater than 0.125% in dp/p throughout the acceleration period. Then, V_{max} is adjusted to the voltage needed to reach a maximum MFF of 0.8, based on the momentum distribution obtained from the simulation. Since changes in V_{max} affect the distribution and change MFF during the acceleration, this minimization process is repeated until the maximum MFF reaches close to 0.8.

Figures 3 and 4 show the patterns of RF voltage amplitude, synchronous phase, and momentum filling factor obtained from the tracking simulation for various acceleration times in the case of $h = 5$ and $h = 11$, respectively, for acceleration. For $h = 5$, acceleration with maximum RF voltage below 100 kV is achievable when the acceleration time exceeds 2 s. In the case of $h = 11$ for acceleration, acceleration with a maximum RF voltage below 100 kV and a maximum synchronous phase for an acceleration time larger than 3 s.

DISCUSSION

Since the frequency and voltage required to accelerate the Au ions have been estimated, the RF system configuration needs to be considered to achieve acceleration.

In the case of $h = 5$ with new dedicated RF cavities, we can choose an optimal bandwidth for the cavities and the high-power RF system, but additional cost is required to produce and install them. Because the available space in the MR for installing cavities is limited, the types and numbers of cavities need to be studied.

For $h = 11$ with existing RF cavities, the existing RF system can be used, minimizing additional cost. On the other hand, because the RF frequency range for ion acceleration is much broader than that for protons, the bandwidth of the cavity and the high-power RF system may be insufficient to deliver the required RF voltage, and modifications may be needed. Changing the harmonic number in the middle of the acceleration [9, 10] can help to minimize the required bandwidth. An introduction of the intermediate flat-top will be required to change the harmonic number with multiple bunches in the ring.

SUMMARY

RF frequency and voltage patterns for accelerating Au^{79+} ions in the J-PARC MR are estimated from calculations and longitudinal beam dynamics simulations with various harmonic numbers and acceleration times. With the acceleration time larger than 3 s, the acceleration of Au^{79+} ions can be achieved with the maximum RF voltage less than 100 kV. Further work will focus on estimating the required specifications for the RF system, for both existing and new dedicated cavities. The RF gymnastics, such as changing the harmonic number in the middle of the acceleration at an intermediate flattop, will also be studied to minimize the bandwidth required for the RF system.

REFERENCES

[1] T. Koseki *et al.*, "Beam commissioning and operation of the J-PARC main ring synchrotron", *Prog. Theor. Exp. Phys.*, vol. 2012, no. 1, p. 2B004, 2012. doi:10.1093/ptep/pts071

[2] S. Nagamiya, "Introduction to J-PARC", *Prog. Theor. Exp. Phys.*, vol. 2012, no. 1, p. 2B001, 2012. doi:10.1093/ptep/pts025

[3] K. Yamamoto *et al.*, "Recent status of J-PARC accelerators", presented at the 17th International Particle Accelerator Conference, Deauville, France, May 2026, paper WEP4643, this conference.

[4] H. Sako *et al.*, "Letter of Intent for J-PARC Heavy-Ion Program (J-PARC-HI) J-PARC-HI Collaboration". `https://j-parc.jp/researcher/Hadron/en/pac_1607/pdf/LoI_2016-16.pdf`

[5] K. Aoki *et al.*, "Proposal for dielectron measurements in heavy-ion collisions at J-PARC with E16 upgrades". `https://j-parc.jp/researcher/Hadron/en/pac_2107/pdf/P87_2021-13.pdf`

[6] H. Harada, P. K. Saha, and M. Kinsho, "Simulation Study of Heavy Ion Acceleration in J-PARC", Mar. 2021. doi:10.7566/jpscp.33.011028

[7] K. Ozawa *et al.*, "The J-PARC heavy ion project", *EPJ Web Conf.*, vol. 271, p. 11004, 2022. doi:10.1051/epjconf/202227111004

[8] H. Timko *et al.*, "Beam longitudinal dynamics simulation studies", *Phys. Rev. Accel. Beams*, vol. 26, no. 11, p. 114602, Nov. 2023. doi:10.1103/PhysRevAccelBeams.26.114602

[9] R. Steerenberg *et al.*, "RF gymnastics", CERN, Geneva, Switzerland, Rep. CERN-2011-004, 2011. doi:10.5170/CERN-2011-004

[10] J. Coupard *et al.*, "LHC Injectors Upgrade, Technical Design Report vol. II: Ions", CERN, Geneva, Switzerland, Rep. CERN-ACC-2016-0041, Apr. 2016. doi:10.17181/CERN.L6VM.UOMS