FIRST SIMULATION RESULTS OF HEAVY-ION ACCELERATION IN THE RCS OF J-PARC

P.K. Saha*, H. Harada, M. Kinsho, M. Yamamoto and H. Sako
J-PARC Center, KEK & JAEA, Tokai-mura, Naka-gun, Ibaraki-ken, Japan

Abstract

We present first space charge simulation results of heavy-ion (HI) acceleration in the 3-GeV Rapid Cycling Synchrotron (RCS) of Japan Proton Accelerator Research Complex (J-PARC). RCS is 1 MW proton beam power source for the Material and Life Science Experimental Facility (MLF) as well as an injector for the Main Ring (MR). Recently, importance of heavy-ion (HI) physics program in J-PARC are being intensively discussed for studying so-called QCD phase structures at high baryon density by using slowly extracted HI beam of 1-20 AGeV in the MR. Although detail accelerator scheme to adapt HI has not yet been fixed, in this work we studied possibilities of U^{86+} acceleration in the RCS by using ORBIT 3-D simulation code. The simulation results show that a more than 1×10^{11} of U^{86+} ions per pulse can be accelerated in the RCS without any significant beam losses. That gives a total of 4×10^{11} ions for each MR cycle and sufficiently meets experimental requirements concerning primary beam intensity.

INTRODUCTION

Japan Proton Accelerator Research Complex (J-PARC) has 3 proton accelerators and several experimental facilities that make use of high intensity proton beams [1]. The accelerator facility comprises a 400 MeV H^- Linac, a 3-GeV Rapid Cycling Synchrotron (RCS) and a 50-GeV (30-GeV at present) Main Ring synchrotron (MR) [2]. Major experimental facilities are Material and Life Science Experimental Facility (MLF), Hadron Experimental Facility (HD), Neutrino Experimental Facility (NU) and also an Accelerator Driven Transmutation Experimental Facility (TEF).

The importance of heavy-ion (HI) physics program in J-PARC is being intensively discussed recently, which consists of low and high energy programs [3]. The high energy program aims to explore QCD phase structures at nearly one order higher baryon density as compared to the normal nuclear density (ρ_0). The aim is to use slowly extracted HI beam from the MR with kinetic energy 1~20 AGeV. In order to reach baryon density as high as possible, the U+U system is considered by bombarding more than 1×10^{10} U ions per cycle (a few sec) on a fixed U target. On the other hand, advantages of studying strangeness physics produced by HI collisions are also being discussed. The J-PARC energy gives maximum hypenuclear production due to coalescence of high density baryons [4].

However, there exist many issues and challenges to adapt a new HI accelerator scheme in the specifically designed and already running high intensity proton machines. Other than space and budget one big issue is not to interfere any existing or planned programs that make use of proton beams.

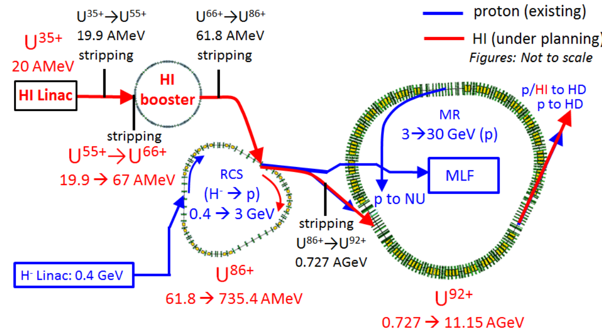

Figure 1: A preliminary scheme for HI acceleration (yet unofficial) to adapt in the existing J-PARC proton facilities.

Figure 1 shows a preliminary HI accelerator scheme (guided by red arrows), added to the existing J-PARC proton accelerators and facilities (guided by blue arrows). The first approach is to use existing RCS and also the MR, where a HI Linac followed by a smaller HI booster ring have to be constructed. There exist many advantages if RCS and the MR can be successfully utilized for accelerating HI to the required energy. Proton beam powers in both machines are approaching to the design goal, while RCS has already demonstrated 1-MW equivalent beam acceleration in early 2015 [5]. The measured beam losses were as low as less than 0.2% and were mostly due to the foil-beam interaction during more than 300 turns H^- change-exchange injection. The beam dynamics issues are well understood, resulting a well beam loss mitigation even at 1 MW, which can be successfully applied for discussing HI beam dynamics issues and realistic measures.

While HI accelerator scheme and how it can be connected to J-PARC facility are under planning, we have investigated the possibilities of HI acceleration in the RCS. The numerical simulation results are presented in this paper.

HI SCHEME IN THE RCS

Figure 2 shows a layout of the RCS. The proton beam energy at injection and extraction are 0.4 and 3 GeV, respectively. The extracted beam is simultaneously delivered to the MLF and MR at a repetition rate of 25 Hz. A new HI injection system is considered to be added at the end of RCS extraction straight section. The uranium ions having 86+ charge states (U^{86+}) will be injected for a single turn from the upstream new HI booster. The injection system can be thus very simple and straightforward, which may not require a large space. However, injection energy of HI has to be

* E-mail address: saha.pranab@j-parc.jp

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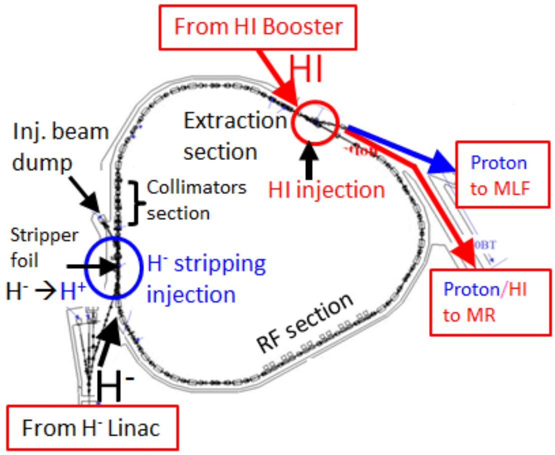

Figure 2: Layout of J-PARC 3-GeV RCS. The HI injection system can be added at the end of extraction straight section.

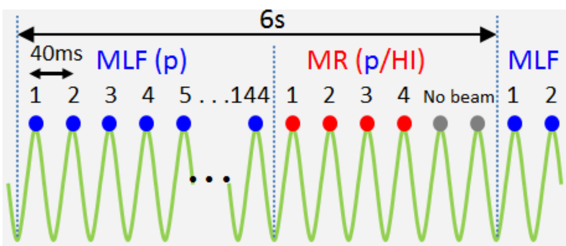

Figure 3: RCS beam delivery pattern to the MLF and MR when MR operates for HD experiments (6s cycle). If HI scheme is added in the RCS, either proton or HI can be accelerated in the RCS for MR cycle depending on MR operation.

matched with B field at bottom set for the 0.4 GeV proton. A higher charge state is necessary in order to avoid any changing of charge state during acceleration due to RCS pressure level (~10^{-6} Pa) is significantly higher than required for a lower charge state injection. One can also gain on the extraction energy through a higher charge state injection, which is useful to achieve maximum yield for the highest charge state at final stripping before injecting into the MR.

Figure 3 shows the pattern of RCS beam delivery cycle to the MLF and MR when MR operates at slow extraction (6s cycle) for the HD users. RCS can inject HI in the MR cycle instead of proton, only when MR operates with HI for the HD users. Unless otherwise MR operates for HI, the whole accelerator complex runs for proton as of now.

SIMULATION RESULTS OF U^{86+} ACCELERATION IN THE RCS

The present simulation is done by using ORBIT code [6], which is recently upgraded successfully for realistic beam simulations with space charge including impedances in synchrotrons [7]. In the simulation, the bending, quadruple and also the sextuple magnets are kept same as optimized for 1 MW proton beam acceleration. The ramping energy, the betatron tunes and the degree of chromaticity correction are then automatically determined and unchangeable. The injection energy of U^{86+} ions are set to be 0.0618 GeV/nucleon (AGeV), which can be accelerated up to 0.735 AGeV. The horizontal and vertical betatron tunes at injection are set to be 6.45 and 6.42, respectively. Figure 4 (top) shows typical rf voltage patterns for U^{86+} (red lines), which are found to be similar to those for proton and can be changed between cycles. However, rf system has to be made capable of changing rf resonant frequency between cycles and/or independent compensation with beam in each cycle. Similar to proton, the 2nd harmonic rf voltage is also applied for the present case in order to reduce the space charge effect at lower energy. The sinusoidal B field and the corresponding successful acceleration of a single particle U^{86+} ion up to the expected 0.735 AGeV is shown in the bottom plot in Fig. 4.

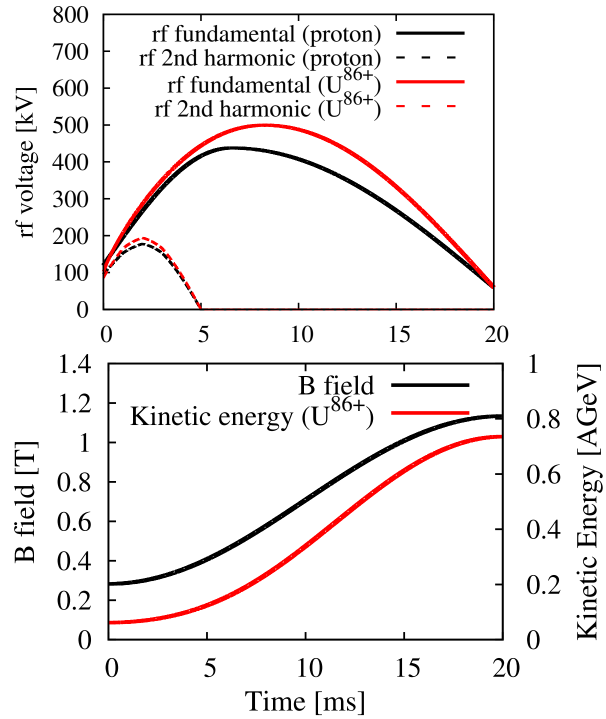

Figure 4: (Top) RCS rf voltage patterns for U^{86+} acceleration are found to be almost similar to those for protons. (Bottom) B field and the corresponding acceleration of U^{86+}.

Next, we performed multi-particles simulations for different intensities up to 1.1×10^{11} U^{86+} ions with a single turn injection from the HI booster in one of the two RCS rf bucket. The space charge limit for U^{86+} ion beam intensity can be roughly obtained by estimating Laslett tune shift (ΔQ) [8] at injection and comparing the value with 1 MW proton case (8.33×10^{13} particles in 2 bunches). Due to lower beam energy ($\frac{1}{\beta^2\gamma^3}$ term) and charge state ($\frac{q^2}{A}$ term), ΔQ for U^{86+} at 0.0618 AGeV is calculated to be more than 300 times higher as compared to that for 0.4 GeV proton. Here, β and γ are relativistic parameters, q and A are the charge and mass of the ion, respectively. An injection of 1.1×10^{11} U^{86+} ions (with a transverse emittance of 100π mm mrad and bunching factor of 0.3) gives a same ΔQ of -0.34 as obtained for the proton at 1 MW.

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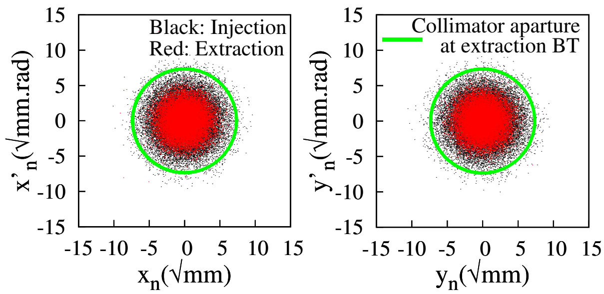

Figure 5: Normalized transverse phase space (black) of a single turn injected U^{86+} beam and the accelerated one at the top energy (red). A more than 99.9% particles at extraction are obtained to be within the 3-50BT collimator aperture as shown by the green circle.

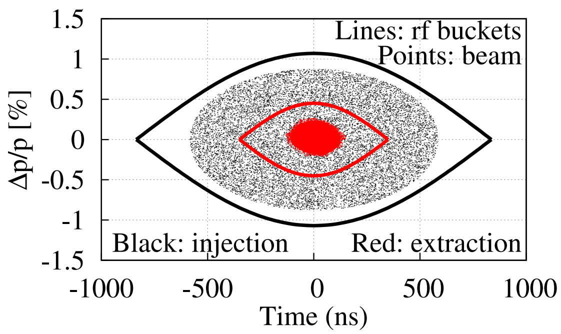

Figure 6: Longitudinal distributions of the U^{86+} at injection and extraction energies.

As detail parameters upstream HI booster are not fixed yet, the transverse and longitudinal beam distributions for RCS injection are considered to be similar to those for protons obtained at the end of injection painting. Figure 5 shows normalized transverse phase space distributions at injection (black) and extraction (red) for both horizontal (left) and vertical planes (right). The maximum emittance at injection was nearly 100π mm mrad, where more than 99.9% particles at extraction energy are obtained to be within the collimator aperture (54π mm mrad) at the beam transport from RCS to the MR (3-50 BT), as shown by the green circle. Due to relatively smaller aperture and limited capacity of the 3-50 BT collimator, it is very important to have the extracted beam with less halo. Figure 6 shows longitudinal beam distribution along with rf buckets. In order to reduce space charge effect at lower energy, injected beam is considered to cover nearly 80% of the rf bucket.

Figure 7 shows the beam survival studied for 3 different intensities. A more than 99.95% beam survival can be obtained even for injecting 1.1×10^{11} U^{86+} ions in the RCS. Differing from the multi-turn H^- charge-exchange injection, there is no foil-beam interaction in the RCS for the HI case in the present proposed plan, resulting a negligible beam losses only caused by the space charge effect. The lower the beam intensity, the lower the space charge effect and hence there is practically no beam losses for 2.0×10^{10} U^{86+} ions injection (green).

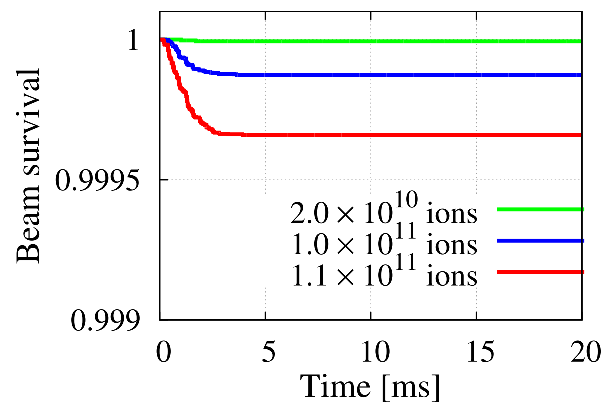

Figure 7: Beam survival as a function of acceleration time for 3 different intensities of U^{86+} ions. An injection of even 1.1×10^{11} ions gives a more than 99.95% beam survival.

The extracted 1.1×10^{11} U^{86+} ions of 0.735 AGeV from the RCS will be fully stripped to U^{92+} in the 3-50BT before injecting into the MR. A total of 4 RCS cycles can be injected in one MR cycle (see Fig. 3. By considering a typical stripping efficiency of 80%, a total of nearly 4×10^{11} U^{92+} ions can be obtained in the MR, which is sufficiently enough concerning the primary beam intensity required for the proposed experiments.

SUMMARY

In order to include HI physics program in J-PARC, a new HI accelerator scheme to adapt in the present J-PARC proton accelerators are in consideration. The RCS and the MR have to be utilized not only to reduce budget and space but also to take advantage of understanding beam dynamics issues learned with protons up to the design beam intensities. The possibilities of U^{86+} ions acceleration in the RCS are studied in this work. The preliminary simulation results show that a maximum of 1.1×10^{11} U^{86+} ions can be accelerated without any significant beam losses. Extracted U^{86+} ions from the RCS will be fully stripped to U^{92+} before injecting 4 RCS cycles into the MR. The expected intensity in the MR is thus nearly 4×10^{11} U^{92+} ions for each 6s MR cycle and sufficiently meets the experimental requirements. However, for further realistic discussions, detail studies are necessary by using realistic injection parameters fixed by the upstream new HI booster.

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