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BEYOND 1-MW SCENARIO IN J-PARC RAPID-CYCLING SYNCHROTRON

K. Yamamoto†, K. Moriya, H. Okita, I. Yamada, M. Chimura, P. K. Saha, Y. Shobuda, F. Tamura, M. Yamamoto and T. Morishita, J-PARC Center, Japan Atomic Energy Agency, Tokai-mura, Japan
H. Hotchi, J-PARC Center, High Energy Accelerator Research Organization, Tokai-mura, Japan

Abstract

The 3-GeV rapid-cycling synchrotron (RCS) at the Japan Proton Accelerator Research Complex (J-PARC) was designed to provide 1-MW proton beams to the following facilities. We have improved the accelerator system and successfully accelerated a 1-MW beam with a small beam loss. Currently, the beam power of RCS is limited due to the lack of an anode current in the radiofrequency (RF) cavity system rather than the beam loss. Recently, we developed a new acceleration cavity that can accelerate a beam with less anode current. This new cavity enables us to reduce the requirement for an anode power supply and accelerate more than a 1-MW beam. We have started to consider how to achieve more than a 1-MW beam acceleration. So far, up to a 1.5-MW beam can be accelerated after replacing the RF cavity. We have also continued studies to achieve more than a 2-MW beam in the J-PARC RCS.

INTRODUCTION

The 3-GeV rapid-cycling synchrotron (RCS) at the Japan Proton Accelerator Research Complex (J-PARC) was constructed and operated to provide high-intensity proton beams to the Material and Life science experimental Facility (MLF) and Main Ring (MR) [1]. We have been continuing the beam study and improvement it to accelerate a 1-MW beam and achieved more than an 800 kW beam operation for MLF users [2]. We also achieved a 1-MW beam operation in a few days with a small beam loss condition [1].

Currently, the beam power of RCS is limited due to the lack of an anode current in the radiofrequency (RF) cavity system rather than the beam loss. Recently, we developed a new acceleration cavity that can accelerate a beam with less anode current. This new cavity enables us to reduce the requirement for the anode power supply and accelerate more than a 1-MW beam. We have started to consider how to achieve beyond a 1-MW beam acceleration. This study summarizes the scenario for achieving more than 1-MW power.

DEMONSTRATION RESULTS BEYOND A 1-MW BEAM POWER

We studied the potential of the RCS beyond a 1-MW power [3]. Figure 1 shows the results of the injection and partial acceleration of various beam currents. Currently, the capacity of the anode power supply of the RF system limits the maximum number of particles that can be accelerated. The RF bucket is distorted due to the wake voltage caused by the high beam current of more than 1-MW, and all beams are lost at the middle stage of acceleration. Therefore, we accelerated the beam to only 0.8 GeV energy, and all beams are extracted at this timing in this study. Figure 1 shows that no significant loss occurs even after the 1.5-MW equivalent beam current injection and partial acceleration. The study results demonstrate the potential of the RCS beyond 1-MW power.

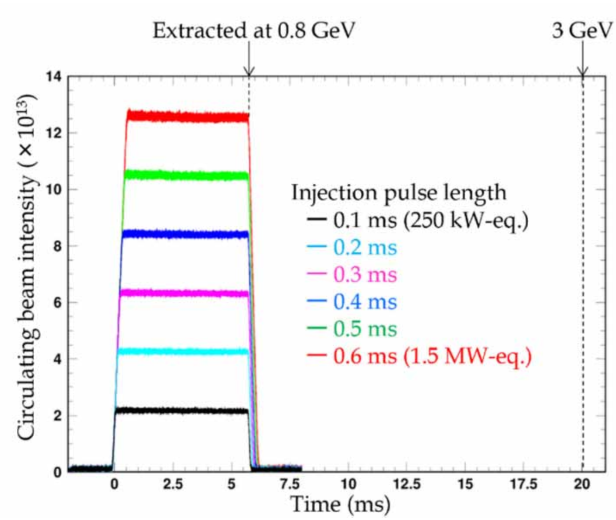

Figure 1: Experimental results; circulating beam intensities from injection to extraction [3].

IMPROVEMENT OF THE RF SYSTEM

We must reinforce the RF system to accelerate more than a 1-MW beam. Therefore, the J-PARC ring RF group developed a new cavity structure that can accelerate more than a 1-MW beam [4]. The conventional RF cavity is driven using a push–pull operation mode, where two vacuum tubes feed the RF power upstream and downstream of the acceleration gap. This configuration has the advantage of suppressing a higher harmonic distortion without the beam acceleration and shortening the cavity length.

However, in a high-intensity beam acceleration case, the multi-harmonic RF driving causes a severe imbalance of the anode voltage, leading to a deficiency in the anode current. Therefore, a new cavity (single-ended cavity) was developed so that only the downstream of the gap was excited [5]. This configuration reduced the input current in

† kazami@post.j-parc.jp

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the cavity. One new cavity was constructed and installed in the RCS tunnel during the summer shutdown period in 2021. Figure 2 shows the schematic view of the conventional and new cavities. Finally, an acceleration of a 1-MW beam was attempted with the new cavity to evaluate its performance. We confirmed it could accelerate a 1 MW beam with ~40% less power consumption. This result indicates that the new cavity accelerates a higher beam current and reduces the power consumption of the present user operation. Now, we have started the mass production of the new cavity. According to the present schedule, the replacement will be completed by 2028. After replacement, the new RF system can accelerate more than a 2-MW beam in the RCS.

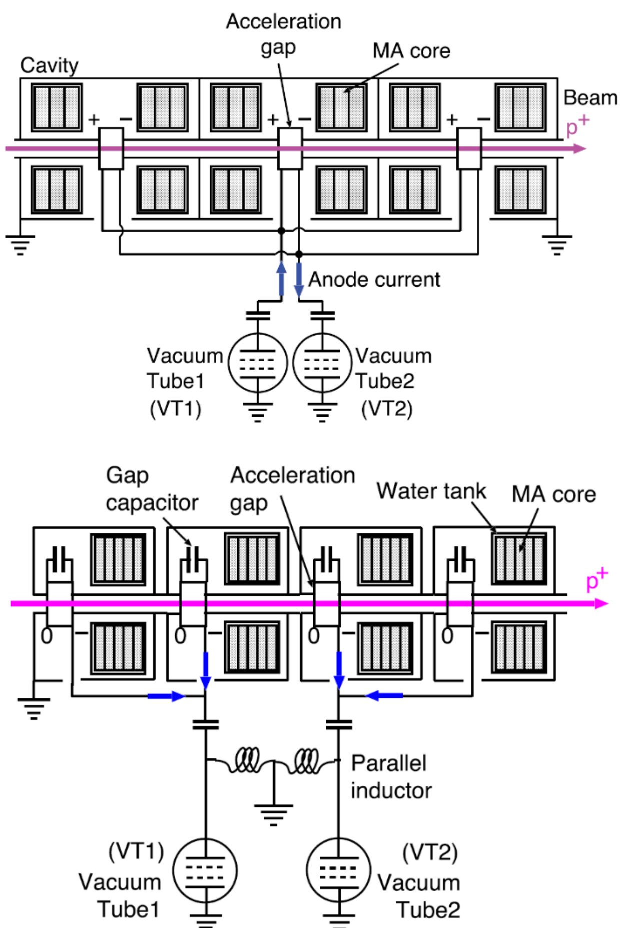

Figure 2: Schematic view of the RCS cavity [4]. Upper figure shows the conventional RCS cavity system in the push–pull operation. Lower figure shows the new single-ended RCS cavity.

SCENARIO BEYOND A 1-MW BEAM

Requirement for the Linac

A prime consideration is increasing the injection beam current from the linac. Table 1 shows the relationship between the RCS output power and the linac parameters. So far, we have achieved a parameter with a peak current of 60 mA and a macro-pulse length of 0.6 ms. This parameter set has an output power of approximately 1.5 MW if the RCS can accelerate it to 3 GeV energy. We have demonstrated a 1.5-MW equivalent beam injection from the linac, but we need further studies to establish the user's operation with these parameters in the linac.

Some parameter choices exist in the linac to achieve more than a 1.5-MW beam power in the RCS. From an injection beam loss reduction viewpoint, a higher peak current is better for the RCS. However, then beam control in the linac becomes challenging in the higher peak current beam. We have demonstrated more than a 100 mA peak beam extraction from the ion source [6]. Therefore, we assumed the maximum peak current as 100 mA (we have never accelerated a 100 mA peak beam in the linac—this result was achieved in the ion source test stand). In the longer macro-pulse case, we demonstrated the beam dynamics with the peak current of up to 60 mA in the linac. Therefore, we can expect the operation condition of less than 60 mA. However, we must reinforce the linac RF system to extend the macro-pulse length. So far, the peak current of 80 mA and the macro-pulse length of 0.75 ms are the targets for future linac upgrades. Optimizing these parameters, we will try up to 2-MW beam acceleration.

Table 1: Relationship between the rapid-cycling synchrotron (RCS) output power, the linac peak current, and macro-pulse length.

RCS output power[MW]		Peak current [mA]					
		50	60	70	80	90	100
Macro-pulse length [ms]	0.5	1.05	1.26	1.47	1.68	1.89	2.10
	0.55	1.15	1.38	1.62	1.85	2.08	2.31
	0.6	1.26	1.51	1.76	2.01	2.27	2.52
	0.65	1.36	1.64	1.91	2.18	2.45	2.73
	0.7	1.47	1.76	2.06	2.35	2.64	2.94
	0.75	1.57	1.89	2.20	2.52	2.83	3.15
	0.8	1.68	2.01	2.35	2.69	3.02	3.36

RCS Upgrade Items

The priority in the RCS upgrade is replacing the RF cavity, but we have investigated the other items that need reinforcement. In the ring RF system, not only cavity replacement but reinforcement of the amplifier chain is also required for more than 1-MW beam acceleration.

When the macro-pulse length is increased, the duration of the field patterns of the injection magnets must also be extended. The sift bump magnets, which make a bump orbit to merge the injection and circulating orbit, can extend the duration of the flat field to 0.7 ms with the present system. The requirements for the paint bump magnets, which make the particle distributions in the phase space, depend on the required paint pattern. We have been investigating the optimal pattern with the particle simulation. The requirements for the correction quadrupole and sextupole magnets are being evaluated with the particle simulation.

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Even with a beam current of 1 MW, the poor choice of some parameters (e.g., betatron tune, chromaticity correction pattern) can lead to beam instability [7]. In the RCS, the primary source of the instability is the transverse impedance of the extraction kicker magnets [8]. A new damping system was developed to suppress the instability [9]. Our simulation indicated that four damping modules are needed to achieve a 1.5-MW full acceleration. We plan to install four damping modules; one module was already implemented with another one being installed this autumn, while the others are under construction.

Furthermore, we evaluated the dynamic range of each beam monitor and found that the beam current exceeds the measurement limit of the direct current (DC) current transformer. Thus, we are considering replacing it.

In the RCS, a hybrid-type thick boron-doped carbon (HBC) foil was used for the charge exchange injection [10]. It had been developed in the High Energy Accelerator Research Organization [11] and can maintain its function under a 1-MW continuous operation and an intermittently 1.5-MW equivalent beam injection. Recently, we have developed pure carbon foil instead of HBC [12]. It shows a similar performance to the HBC. We will evaluate the performance of the HBC and pure carbon foils for higher power operation.

Perspective of the Beam Manipulation Beyond a 1-MW Beam Intensity

Previous simulations indicated that the number of particles in the RCS would be limited to less than a 2 MW equivalent [13]. Thanks to the space charge effect caused by the high-intensity beam of more than 2-MW, an excessive tune shift occurs and causes a large amount of beam loss. Flattening the beam distribution and reducing the high-density portions mitigate the space charge effect. We have been applying the dual-harmonic RF operation for the longitudinal beam manipulation [14]. In the dual-harmonic scheme, the fundamental and the second harmonic RF are excited simultaneously into one cavity, and the higher-order component flattens the longitudinal beam distribution. This scheme enables us to accelerate a 1-MW beam with enough low-loss conditions but not enough for more than a 1.5-MW beam. Recently, we have started to study the triple-harmonic RF operation applied for high-intensity beam acceleration [15]. Figure 3 shows the bunching factor (BF) simulation results with the dual and triple-harmonic schemes. The BF is the peak current divided by the average current, and the higher BF means more flat and low peak density beams. In these calculations, the beam power of 1-MW is assumed.

The BF is around 0.4 after injection in the dual-harmonic case. However, it is approximately 0.5 for the triple-harmonic operation, promising to achieve more than a 1.5-MW beam acceleration with less beam loss. Also, we have gained further beam loss reduction in the 1-MW beam condition. These efforts would also help to achieve more than a 1.5-MW beam acceleration.

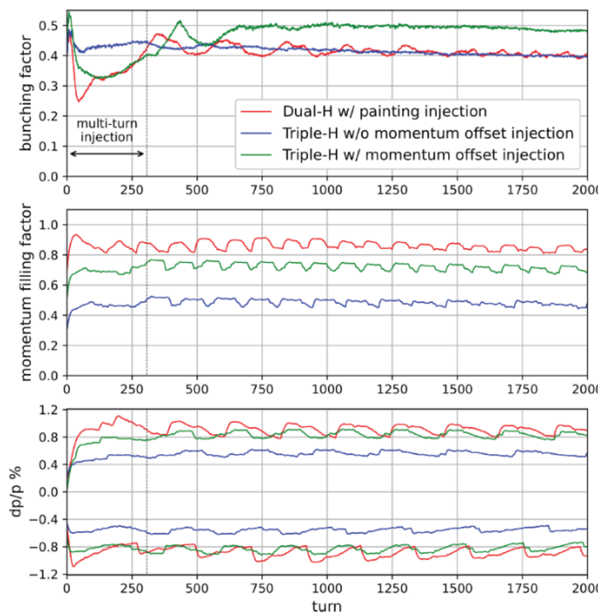

Figure 3: The longitudinal beam simulation results for the dual-harmonic and triple-harmonic operations [15]. The top, middle, and bottom figures show the BF, momentum filling factor, and dp/p, respectively. The horizontal axis corresponds to the number of turns. The details of each parameter are explained in Ref [15].

CONCLUSIONS

We have demonstrated the potential of the RCS beyond 1-MW beam power. The RCS delivers the beams to the MLF and MR. Both facilities have the upgrade plans to maximize those deliverables. It is critical to evaluate the maximum beam power of the RCS to consider the upgrade paths. We will complete the replacement of all cavities with new ones by 2028. We are currently studying to start the more than 1.5 MW beam acceleration test immediately after completing the replacement. For RCS, a list of items that need improvement beyond 1 MW beam acceleration is being developed. Hereafter, we will proceed with the improvement work according to the list. As for the linac, we will work on a detailed study of increasing the peak current and macro-pulse length. To reduce the burden of the linac as much as possible, the RCS plans to study an injection scheme with an extended intermediate pulse length. Finally, we will prepare to conduct beam acceleration tests at the highest intensity possible in 2028. Combining the increase of the linac peak current and the extension of the injection pulse length for the RCS, we will try up to 2-MW beam acceleration for the present.

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