

Worker dose under high-power operation of the J-PARC 3 GeV Rapid Cycling Synchrotron

Kazami Yamamoto^{1,a}

¹J-PARC Center, Japan Atomic Energy Agency, 2-4 Shirakata, Tokai-mura, Naka-gun, Ibaraki-ken, 319-1195, Japan

Abstract. The J-PARC 3 GeV Rapid Cycling Synchrotron (RCS) delivers a 1-MW, high-intensity beam to facilities downstream. In such high-intensity accelerators, the operational beam intensity is limited to keep worker exposure to the residual dose within acceptable tolerances. Therefore, we continue to pursue accelerator commissioning that reduces beam loss. In order to achieve further high-intensity operation, the J-PARC accelerator system has been drastically upgraded over the past two years. As a result, it was found that beam loss decreased, whereas output power increased; the residual doses were kept at the same level or decreased in RCS. A malfunction of a collimator occurred in April 2016, and we replaced it to a spare duct in a hurry. The broken collimator was higher activated, but exposure to workers was kept within the acceptable level.

1 Introduction

The J-PARC 3 GeV Rapid Cycling Synchrotron (RCS) was constructed to deliver a 1-MW, high-intensity beam to the Material and Life Science Experimental Facility (MLF) and the Main Ring (MR) [1]. In a high-intensity proton accelerator such as RCS, beam loss, which constitutes just a small fraction of the beam, causes large doses of prompt radiation and serious radio-activation, which may cause malfunctions in the accelerator components and higher exposure doses to maintenance workers. Therefore, the operational beam intensity is limited to keep workers' exposure to the residual dose within acceptable tolerances.

The J-PARC linac energy was upgraded to 400 MeV during the 2013 summer shutdown period [2], and the peak current of the ion source was increased to 50 mA during the summer shutdown period of 2014 [3]. Due to these upgrades, necessary equipment for 1-MW operation has been prepared. However, it is necessary to gradually increase the beam intensity while taking measures to minimize beam loss and residual dose during maintenance work. In this paper, we report the conditions of radio-activation and worker dose in the RCS after the accelerator upgrade.

2 History of beam power and residual doses

Figure 1 shows the history of the residual doses at typical loss points and the output power of the RCS from 2014 to summer of 2015. Here, we plot two graphs of the residual doses in the RCS. One is the dose on the

charge-exchange foil chamber (which is the highest dose) and the other is the dose on the horizontal steering magnet chamber in the injection H⁰ dump line. (the H⁰ dump is used to abandon unexchanged H⁻ and H⁰ beams during the injection period.)

Figures 2 and 3 show the higher-dose points. Due to a radioactive-material-leak accident from the Hadron experimental hall [4], the J-PARC facility was shut down for more than a half year after May 2013. During this long shutdown period, recovery work from the accident and linac acceleration-energy upgrade were performed. The user operation of the MLF resumed on February 17, 2014. Because the increment of the linac acceleration energy mitigated the space-charge effect, the beam loss of the RCS was reduced and we were able to deliver a 600-kW beam to the MLF [5]. However, we continued operation without any increase from the previous value of 300 kW. Because it had not yet been confirmed that a neutron target could accept a high-intensity beam, we had to limit the beam power from the viewpoint of target protection. Subsequently, the increment of the ion source and improvement of the target for 1-MW operation were completed during the summer shutdown period in 2014.

During this period, we investigated the radio-activation of the foil chamber and found that the radio-activation source was the interaction of the injection and circulating beams with the charge-exchange foil [6]. A method to decrease this activation is to reduce the interaction rate between the beams and the foil. Thus, since it was necessary to expand the painting-injection area to reduce the number of hits of the beams on the foil, we had to correct the modulation of the beta function caused by the edge effects of the injection bump magnet [7]. For this purpose, we installed an additional

^a Corresponding author: kazami@post.j-parc.jp

quadrupole magnet system during the summer shutdown period in 2014. We also installed a new collimator in the

H⁰ dump line to reduce the neutron backscatter from the dump.

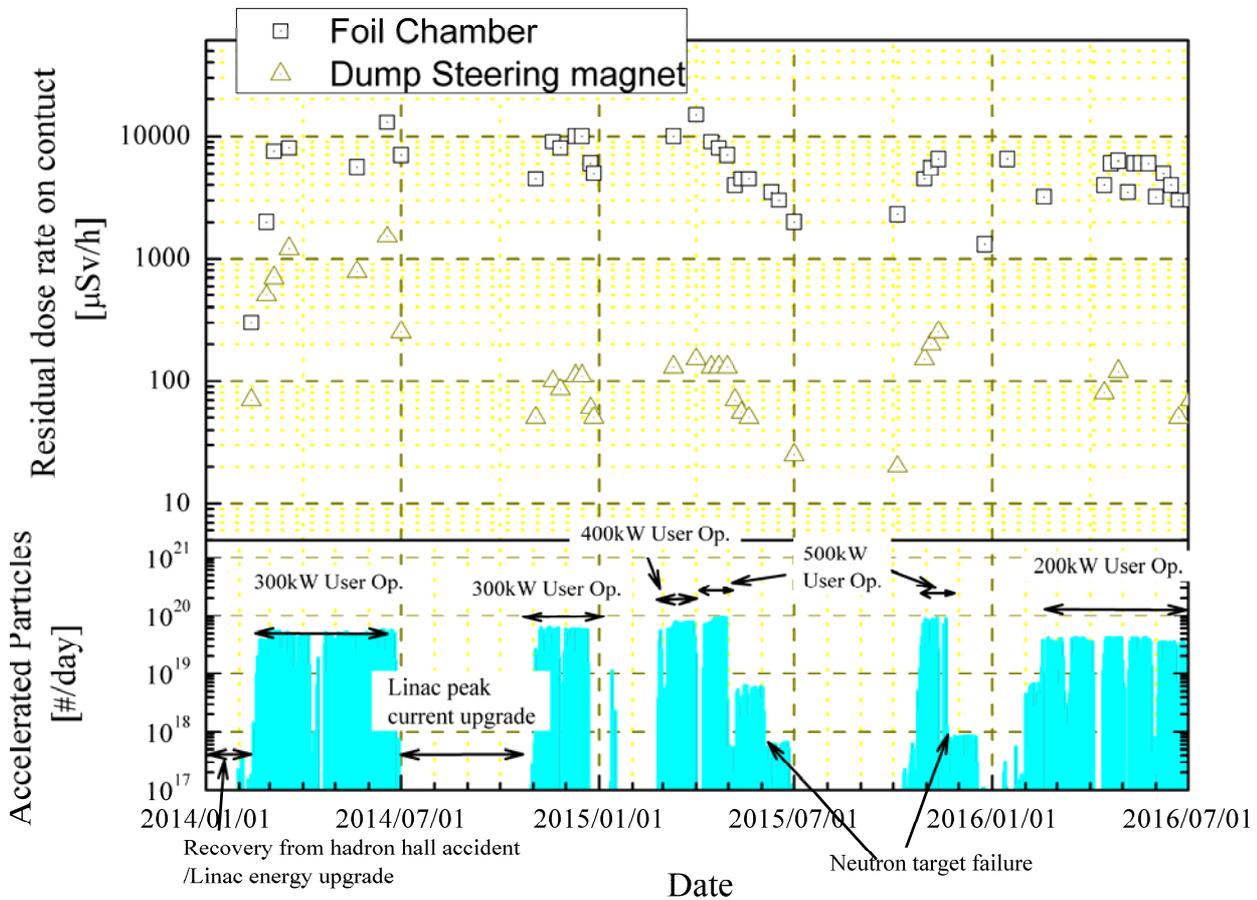


Figure 1. Beam power and residual dose histories of the RCS.

After these improvements, we resumed user operation at 300 kW from the end of February 2015. This was increased to 400 kW in the middle of March and further to 500 kW by the middle of April. Figure 4 shows the residual dose distributions of the RCS before and after the 500-kW operation. Before the operation, we corrected the modulation of the beta function with the new quadrupole magnet system and expanded the painting-injection area [8]. As a result, the dose rate of the foil chamber, which was above 10 mSv/h after a 400-kW operation, was decreased to less than 10 mSv/h. The residual dose of the H⁰ dump line was also decreased by the new collimator. Based on these results, we intended to increase the output power to 600 kW in the middle of May; however, a cooling-water leak occurred in the neutron target at the MLF at the end of April, after which the supply to the MLF was stopped. Following this water-leak incident, operation to the MR only was conducted until July 1. The requirement for MR operation is less than 10% of that for the MLF, and the number of acceleration particles is less than 10%. Thus, all residual doses in the RCS were reduced.

The MLF user program resumed on October 27, but another water leak from the neutron target occurred on

November 20 [9]. A spare target was installed and the user program was resumed on February 20 [10]. Since we did not have any spare neutron target, the output power was subsequently suppressed to less than 200 kW from the point of view of the target protection.

During the short maintenance period in April 2016, one of the ring collimators was broken [11]. Abnormal operation of the control system brought about a vacuum leak of the fifth secondary collimator chamber. Since the numerical simulation result indicated that the beam loss without this collimator would be within the acceptable level, we installed a straight duct instead of repairing the broken collimator. The repair period was reduced to 8 days by this countermeasure.

When we obtained a beam of more than 400 kW for the neutrino target after this malfunction, the residual dose on the replaced duct's surface exceeded 10 mSv/h. After the MR switched operation to the Hadron Experiment, the value reduced to 5 mSv at 6 hours after the beam had ceased operation. Furthermore, after a 2-month cooling-off period, it fell to less than 1 mSv at the time of maintenance work.

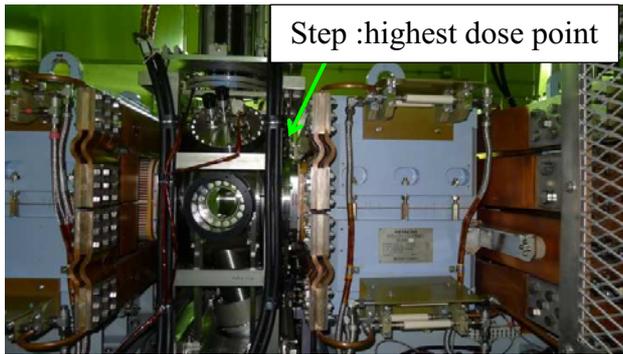


Figure 2: Photograph of the charge-exchange foil chamber.

It has a step between the foil chamber and the bump magnet chamber, and there is the highest dose point.

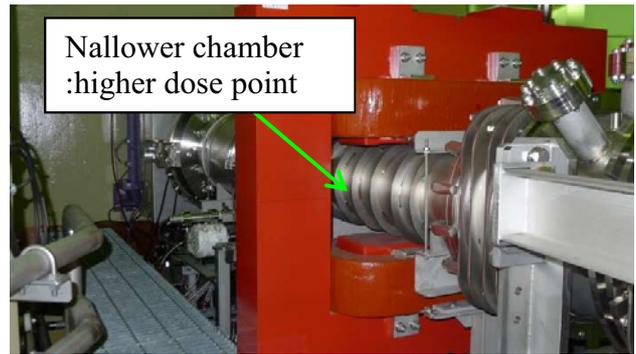


Figure 3: Photograph of the injection H⁰ dump line.

The horizontal steering magnet chamber is higher dose point. This chamber is narrower than the upstream and downstream chambers.

Red :1st Apr., 2015 (400 kW 2week operation with H-painting area of 100π mm-mrad.)

Blue:15th Apr., 2015 (400 kW 6-day and 500kW 1-day operation with H-painting area of 150π mm-mrad.)

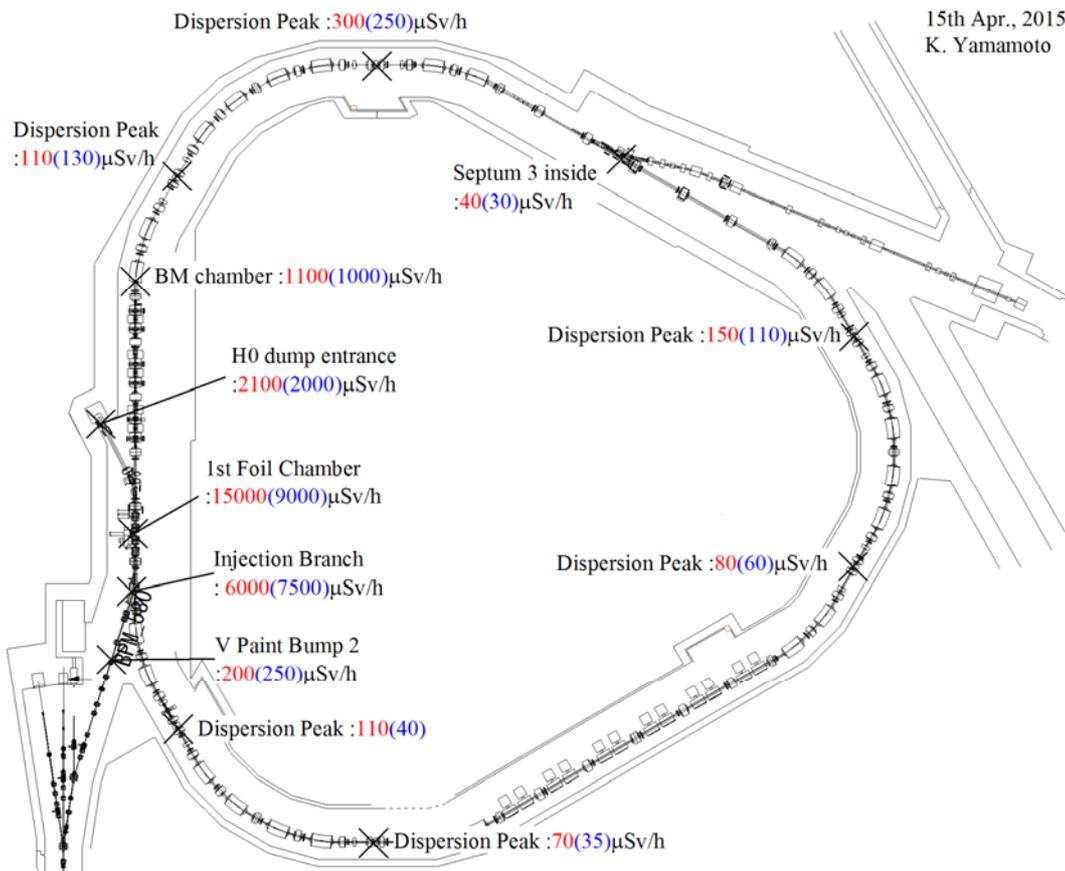


Figure 4. Residual dose distributions of the RCS before and after the 500-kW operation.

3 Worker doses during the maintenance period of 2014

A summary of the worker doses during maintenance work in the summer shutdown period of 2014 is given in Table 1. Since the RCS delivered a 300-kW beam to the MLF just before the summer shutdown of 2014, the residual dose on the foil chamber was slightly higher (7

mSv/h) just after beam shutdown. Maintenance work near the foil chamber commenced after 1.5 months of cooling, and the residual dose was about half of its previous value (just after beam shutdown). During the summer shutdown period in 2014, 53 workers were exposed to a dose of more than 0.01 mSv (this is the minimum dose that can be detected by an Alarm Pocket Dosimeter). A corrective dose to an RCS worker is 3.7 mSv. The number of workers who were exposed to more than 0.1 mSv was 12,

and all of these worked near the foil chamber. The maximum dose for one worker was 0.31 mSv. This worker was involved in the replacing of a vacuum chamber near the foil chamber. Since the vacuum flange diameter of this chamber was very large (400 mm [12]) and there was insufficient work space, it was not easy to achieve an acceptable leak rate of less than 10^{-11} Pa m/s using this flange connection. Therefore, a great deal of time was spent reconnecting this flange near the foil chamber and the exposure dose was increased.

Table 1. Summary of the personal doses during maintenance work in the summer shutdown period of 2014.

Exposure dose [mSv]	Number of workers [#]
0.01–0.05	31
0.06–0.1	10
0.11–0.2	8
0.21–	4

4 Worker doses during the maintenance period of 2015

Since only beam operation to the MR was performed two months before the summer shutdown period of 2015, radioactive nuclides with short half-lives disappeared and the residual dose on the foil chamber was 3 mSv/h. Owing to nuclides with long lifetimes, this value did not decrease significantly during the maintenance period. During this summer shutdown period, 33 workers were exposed to a dose of more than 0.01 mSv, and the corrective dose to the RCS workers was 4.45 mSv. The number of workers who were exposed to more than 0.1 mSv was 22. The maximum dose for one worker was 0.42 mSv. The corrective dose and the number of workers who were exposed to higher doses increased in comparison with the previous year because of recovery work for a malfunction of the injection magnet. Since we removed the upper half of the magnet, which functioned as the radiation shielding, for maintenance, a duct with a high dose within the magnet was revealed and the exposure dose was increased.

The previous beam-commissioning results showed that the injection-beam parameter should be flexibly adjusted to a significant degree to reduce RCS beam loss. In order to secure sufficient flexibility, we needed to extend the physical aperture of the vacuum ducts in the magnets. The vertical apertures of the old ceramic ducts in the vertical bump magnets were adequate for the original beam condition, but the study results indicated that wider beam optics would be better for achieving the finer, low-loss matching condition. Thus, those ceramic ducts were replaced with wider ones (see Figure 5).

There was not such a high residual dose, even after operation at 500 kW. The residual dose distribution was similar to the result under a 300-kW operation in 2014 and higher radiation doses were concentrated in the injection area. Thus, significant doses were also caused by the work in the injection area.

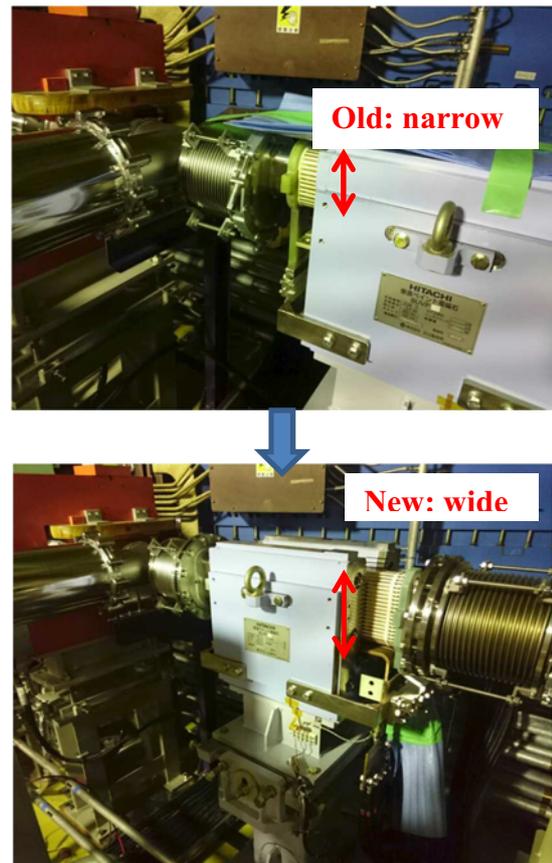


Figure 5: Extension of the duct aperture.

Table 2. Summary of the worker doses during the maintenance work in the summer shutdown period of 2015.

Exposure dose [mSv]	Number of workers [#]
0.01–0.05	11
0.06–0.1	7
0.11–0.2	7
0.21–	8

5 Malfunction of the ring collimator

The beam-collimation system removes the beam halo and localizes the beam loss on itself in order to preserve other accelerator components [13]. The arrangement of this system is shown in Figure 6. It consists of one primary collimator, which scatters the halo particles, and five secondary collimators, which absorb those scattered particles [14]. Radiation shielding was designed to absorb a halo of at most 4 kW by the collimator system. Figure 7 shows the vacuum chamber and radiation shielding of the collimator. It was designed such that the radiation dose from the collimator block could be reduced to about $1/10,000^{\text{th}}$ of its initial value by this shielding [15]. The capacity of the collimator was designed to be 4 kW, but in operation, the MLF output was 200 kW in June 2016, and we estimate that hundreds of Watts of beam loss occurred in the collimator system. In April 2016, a malfunction was caused in the VME system, i.e., the

control system of the collimator. To fix this, we attempted a performance test, during which a vacuum leak occurred. Vacuum pumps stopped suddenly due to vacuum deterioration, and the part where a vacuum deterioration point was separated by a gate valve.

The investigation of the leak point revealed that the fifth secondary collimator was the source of the leak and it was quickly removed. Under these circumstances, the residual dose value on the collimator shielding was 5–10 $\mu\text{Sv/h}$ and that on the downstream chamber of the collimator was about 200 $\mu\text{Sv/h}$. On the other hand, the residual dose of the collimator block, which absorbed the halo particles directly, was 40 mSv/h. We confirmed that the residual dose of the collimator was significantly reduced by the present shielding design.

We did not have a spare unit with which to replace the fifth secondary collimator. However, since the numerical simulation result indicated that the beam loss without this collimator would be at an acceptable level, we installed a straight duct instead of repairing the broken collimator. We spent 8 days on this recovery work. After resumption of user operation, the residual dose of the arc area was not as high as expected. However, there was a step in the new duct due to the difference in the upstream and downstream flange diameters, and a dose of maximum 10 mSv occurred at this step part.

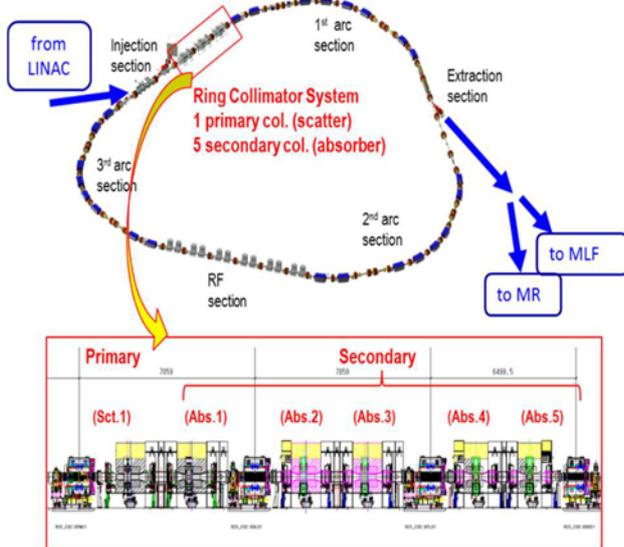


Figure 6: Layout of the collimator.

A total of 31 persons worked to replace the broken collimator and 24 workers were exposed to doses of more than 0.01 mSv. The corrective dose for the workers was 0.62 mSv. The maximum dose for one worker was 0.06 mSv and two workers were exposed to this dose. Their task was to replace and connect the collimator chamber.

Because the maintenance work varied over a range of tasks, coordinators were appointed for each task and the workers were separated. Therefore, we were able to average the worker doses and avoid concentrating on one worker. The exposure dose was less than 20% of that of year-round maintenance work.



Figure 7: Photograph of the collimator.

6 Conclusion

Beam commissioning of the J-PARC RCS was performed to achieve high-intensity operation. As a result, the residual dose around the accelerator component was maintained low enough for maintenance work, even after 500 kW of continuous operation. From a study of the beam under 1-MW output power, we confirmed that the beam loss was proportional to the output power [16]. However, to achieve an output power above 1 MW, we must lower the worker dose near the injection-foil chamber. The first way to reduce the activation of the foil chamber is mitigation of the interaction between the foil and the beam. We will try further optimization of the operational parameters of the correction quadrupole and injection-painting magnets. The second way is to replace the injection system. We will start developing a new injection system that simplifies maintenance work and includes radiation shielding. Regarding the broken collimator, we will investigate the cause of breakdown and install an improved model.

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