ISBN: 978-3-95450-208-0 doi:10.18429/JACoW-IPAC2019-TUPTS035

VACUUM TUBE OPERATION ANALYSIS FOR 1.2 MW BEAM ACCELERATION IN J-PARC RCS

M. Yamamoto*, M. Nomura, T. Shimada, F. Tamura
Japan Atomic Energy Agency, Tokai, Ibaraki 319-1195, JAPAN
M. Furusawa, K. Hara, K. Hasegawa, C. Ohmori, Y. Sugiyama, M. Yoshii
KEK, Tsukuba, Ibaraki 305-0801, JAPAN

Abstract

The J-PARC RCS has successfully accelerated 1 MW proton beam, matching the designed beam power. Therefore, we have considered acceleration beyond the designed beam power, with the next target being 1.2 MW.

An issue for 1.2 MW beam acceleration is the rf system. The present anode power supply is limited by its output current, and the vacuum tube amplifier suffers from an unbalance of the anode voltage swing, arising from the combination of multi-harmonic rf driving and push-pull operation.

We have investigated the mitigation of the maximum anode currents and unbalanced tubes by choosing appropriate circuit parameters of the rf cavity with tube amplifier. We describe the analysis results of the vacuum tube operation for 1.2 MW beam acceleration in the RCS.

INTRODUCTION

The Japan Proton Accelerator Research Complex (J-PARC) Rapid Cycling Synchrotron (RCS) has successfully accelerated a 1 MW equivalent beam without significant beam loss [1]. The RCS provides the proton beam to the Material and Life science Facility (MLF) and the Main Ring (MR). At present, a beam power of 500 kW has been achieved for the MLF user operation and it should be increased up to 1 MW.

It is important to note that a part of the beam from the RCS is also delivered to the MR, which must be accounted for when considering the power for the MLF. A plan to reduce the repetition period of the MR is underway and it is finally down to 1.16 s [2], whereas it is 2.48 s at present. The RCS has to accelerate at least a 1.16 MW equivalent beam to ensure that an average beam power of 1 MW reaches the MLF; thus, we set a target beam power of the RCS at 1.2 MW.

The beam commissioning and the particle tracking simulation suggest that the present RCS lattice can accelerate beyond 1 MW beam with an acceptable level of beam loss [3]. However, the output current of the anode power supply on the rf system has almost reached the limit for the 1 MW beam. Figure 1 shows the measured output current of the anode power supply depending on the beam power.

The output current depends on the resonant frequency of the rf cavity, and the red circles indicate the data from the present cavity with a resonant frequency of 1.7 MHz. The output current can be reduced by shifting to a higher resonant frequency. The blue squares indicate the case at 2.1 MHz, which suggests that the anode power supply can provide enough current even for a 1.2 MW beam.

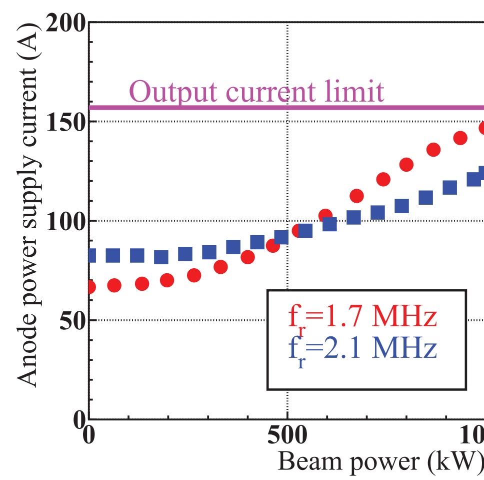

Figure 1: Measurement results for the output current of the anode power supply depending on the beam power. The red circles and blue squares indicate the cavity resonant frequencies of 1.7 MHz and 2.1 MHz, respectively.

However, a vacuum tube operation analysis [4] suggested that the tubes suffer from a severe unbalance of the anode voltage swing caused by the multi-harmonic rf driving under the push-pull operation of the vacuum tube amplifier [5]. The large anode voltage swing induces a screen grid overcurrent at the Tetrode tubes; therefore, such a tube operation should be forbidden. This means that the vacuum tubes can not drive the cavity even though the anode power supply provides enough current to the tubes.

Although an intrinsic solution to avoid the unbalance is to replace the present push-pull cavity with a single-ended one [5], this takes a long time. Hence, we investigated how to relieve the unbalance by choosing appropriate circuit parameters for the present cavity with tube amplifier.

ANALYSIS RESULTS

Figure 2 shows a schematic view of the rf cavity with tube amplifier. There are three acceleration gaps and three magnetic alloy cores that are loaded upstream and downstream of each gap. To adjust the resonant frequency and Q-value, a parallel inductor [6] and a gap capacitor are installed. The inductor has a value of 21.5 μH. When a 200 pF capacitor

* masanobu.yamamoto@j-parc.jp

ISBN: 978-3-95450-208-0 doi:10.18429/JACoW-IPAC2019-TUPTS035

is attached to the acceleration gap, the resonant frequency is 1.7 MHz and the Q-value is 1.7. On the other hand, the resonant frequency is 2.1 MHz and the Q-value is 1.5 without the capacitor.

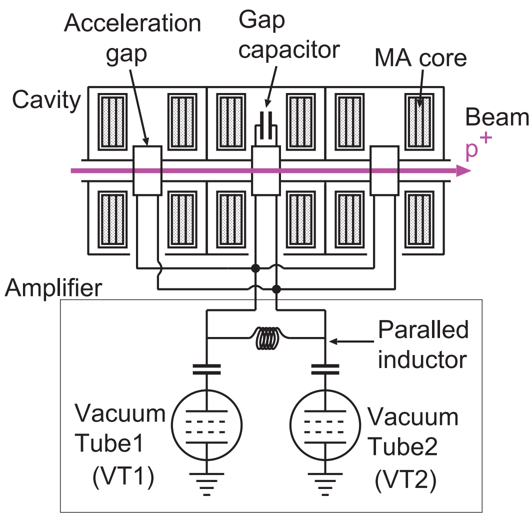

Figure 2: Schematic view of the rf cavity with tube amplifier.

Figure 3 shows the calculated results for the vacuum tubes at a resonant frequency of 2.1 MHz for 1.2 MW beam acceleration. The acceleration period of the RCS is 20 ms, and Fig. 3 shows an example at the middle of the acceleration. The upper graph indicates the anode voltage and the lower graph indicates the anode current. The rf cavity is driven by two tubes in push-pull mode as shown in Fig. 2: the black line indicates the left side of the tube "VT1", and the red line indicates the right side of the tube "VT2".

The pink line indicates the screen grid voltage. When the minimum value of the anode voltage is lower than the screen grid voltage, the screen grid suffers from an overcurrent and the tubes can not drive the cavity. The anode voltage on VT2 is below the limit as shown in Fig.3, and this operation should be avoided.

We performed a parameter search to achieve 1.2 MW beam acceleration by changing the values of the parallel inductor and vacuum capacitor. It was found that the unbalance of the anode voltage swing tends to be reduced by choosing a higher resonant frequency and a higher Q-value than the present parameters.

Figure 4 shows the calculated results with a 12 μH inductor and a 100 pF capacitor. In this case, the resonant frequency is 2.3 MHz and the Q-value is 3. The unbalance of the anode voltage swing is smaller than the case shown in Fig. 3. However, the anode voltage swing is still large and the minimum value of the anode voltage is almost the same as the screen grid voltage. Although further reduction of the anode voltage swing is necessary for stable tube operation, it is difficult to find appropriate parameters other than those presented above.

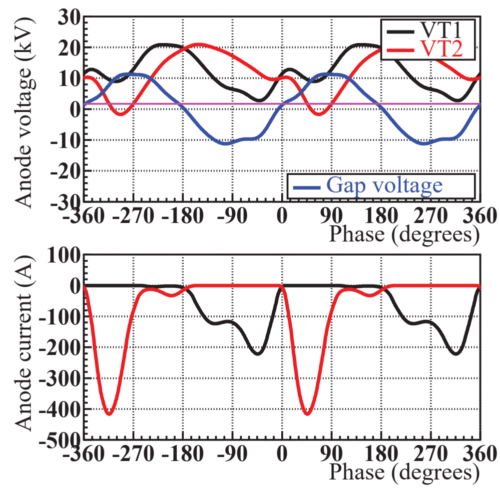

Figure 3: Tube operation analysis of the anode voltage and the anode current under the 1.2 MW beam acceleration at the resonant frequency of 2.1 MHz. The black line represents VT1 and the red line represents VT2. The blue line indicates the gap voltage.

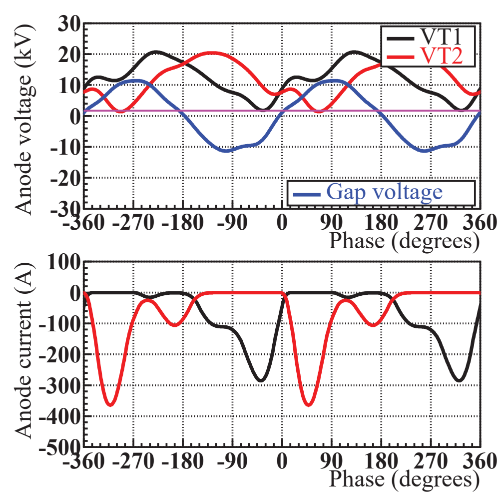

Figure 4: Tube operation analysis of the anode voltage and the anode current under the 1.2 MW beam acceleration after changing of value for the inductor and capacitor. The black line represents VT1 and the red line represents VT2. The blue line represents the gap voltage.

Another way to change the circuit configuration is by splitting the parallel inductor into upstream and downstream parts, wherein a chassis ground of the amplifier is connected in between them, as shown in Fig. 5. This modification makes the current going through the inductor different in the upstream and downstream parts, whereas previously it was the same in both parts. Consequently, the impedance seen by the tubes is changed and it is expected that the anode voltages on both tubes will also be changed.

Figure 6 shows the calculated results under 1.2 MW beam acceleration with the split inductor of 12 μH and 100 pF

ISBN: 978-3-95450-208-0 doi:10.18429/JACoW-IPAC2019-TUPTS035

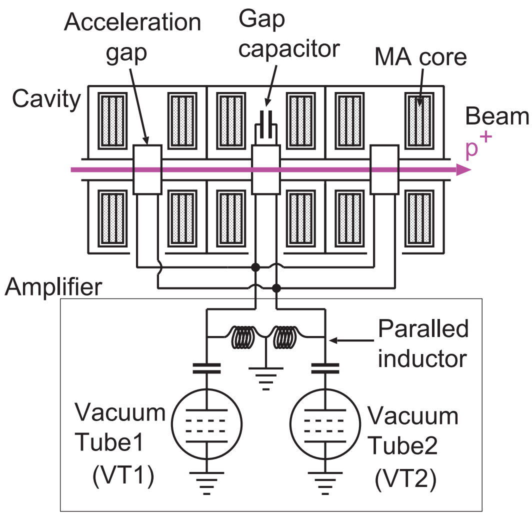

Figure 5: Schematic view of the rf cavity with amplifier using a split parallel inductor.

capacitor. The minimum value of the anode voltage on both tubes is larger than the screen grid voltage. In this case, the fundamental component of the anode voltage on VT2 can especially be reduced by changing the impedance seen by the tubes. The vacuum tube operation analysis was performed over the whole acceleration period, and we confirmed that the minimum value of the anode voltage always exceeds the screen grid voltage.

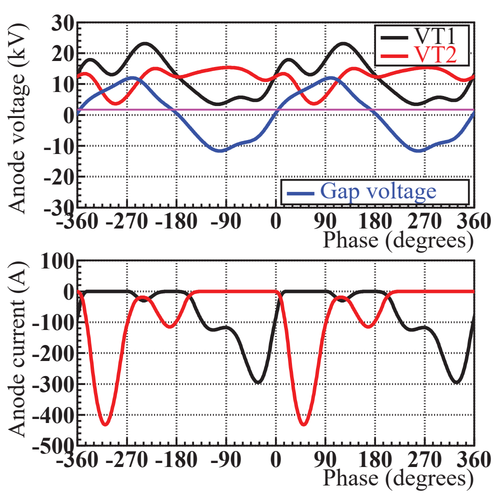

Figure 6: Tube operation analysis of the anode voltage and the anode current under the 1.2 MW beam acceleration with the split inductor. The black line represents VT1 and the red line represents VT2 The blue line represents the gap voltage.

Figure 7 shows the calculated output current of the anode power supply during acceleration with several beam powers. As can be seen, the maximum output current is below the limit even in the case of 1.2 MW beam acceleration. This means we can accelerate the 1.2 MW beam by choosing the appropriate parameters using the split inductor.

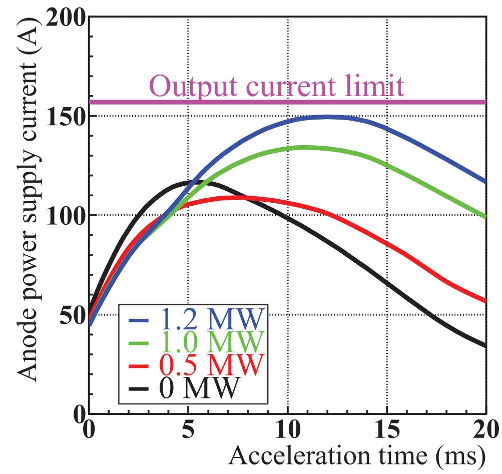

Figure 7: Calculation results for the output current of the anode power supply during acceleration with several beam powers.

SUMMARY

We investigated to achieve the 1.2 MW beam acceleration in the J-PARC RCS. One of the issue is the rf system, and the output current of the anode power supply almost reached its limit under the 1 MW beam acceleration. Although the output current of the anode power supply can be reduced by shifting the resonant frequency of the cavity higher, the unbalance of the anode voltage swing on the vacuum tube still remains due to multi-harmonic rf driving under push-pull operation. We performed the vacuum tube operation analysis to find the appropriate parameters for the cavity with amplifier, and we found that the unbalance is relieved using the split inductor.

REFERENCES

[1] H. Hotchi *et al.*, Phys. Rev. STAB **20**, 060402 (2017)

[2] T. Koseki, IPAC 2018, TUPAK005, p.966 (2018)

[3] M. Kinsho, IPAC 2016, TUXA01, p.999 (2016)

[4] M. Yamamoto *et al.*, NIM A **835**, p.119 (2016)

[5] M. Yamamoto *et al.*, J. Phys.: Conf. Ser. **1067** (2018) 052014

[6] A. Schnase *et al.*, PAC 2007, WEPMN040, p.2131 (2007)