

# CONCEPTUAL DESIGN OF A SINGLE-ENDED MA CAVITY FOR J-PARC RCS UPGRADE

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## Abstract

The Japan Proton Accelerator Research Complex (J-PARC) Rapid Cycling Synchrotron (RCS) employs Magnetic Alloy (MA) loaded cavities. The rf power is fed by vacuum tubes in push-pull operation. We realize the multi-harmonic rf driving and the beam loading compensation thanks to the broadband characteristics of the MA. However, the push-pull operation has disadvantages in multi-harmonics. A considerable amount of unbalance appears in the anode voltage swing at very high intensity beam acceleration. We propose a single-ended MA cavity for the RCS beam power upgrade, where no unbalance arises intrinsically.

## 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 already reaches the designed beam power; however, the beam commissioning and the particle tracking simulation suggest that the present RCS lattice can accelerate a beam even beyond 1 MW with an acceptable level of beam loss [2].

One of the issues encountered during the beam power upgrade is the output current limitation of the anode power supply for the tetrode vacuum tubes in the rf system. In the previous study [3], we estimated the required current up to 1.6 MW beam power by using the vacuum tube operation analysis [4]. We have shown a possible scenario using the existing rf cavity, in which the resonant frequency is shifted higher and the Magnetic Alloy (MA) cores are replaced with the higher impedance type. However, a further study suggested that the tubes suffer a severe unbalance of the anode voltage at very high intensity beam acceleration.

The rf cavity is driven in a push-pull operation by using two tubes as shown in Fig. 1. Furthermore, the cavity is driven by multi-harmonics in the RCS: the fundamental acceleration voltage, the second harmonic voltage for flattening the bunch shape [5], and the beam loading compensation up to the third harmonic [6].

A combination of the push-pull operation and the multi-harmonic driving causes the unbalance on each tube. The anode voltage swing may exceed the limitation by the unbalance even though the anode power supply can feed enough current to the tubes.

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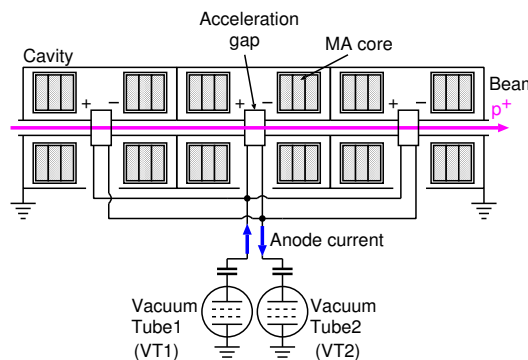


Figure 1: Schematic view of the present RCS cavity in push-pull operation.

Figure 2 shows the calculation results of the anode voltage, the anode current, and the beam current in the push-pull operation at 1.5 MW beam acceleration. The black line indicates the case of the vacuum tube 1 (VT1); the red line indicates the case of the vacuum tube 2 (VT2). The blue line is the result of subtracting VT2 from VT1, which is the voltage applied to the beam. The anode DC voltage is omitted for simplicity.

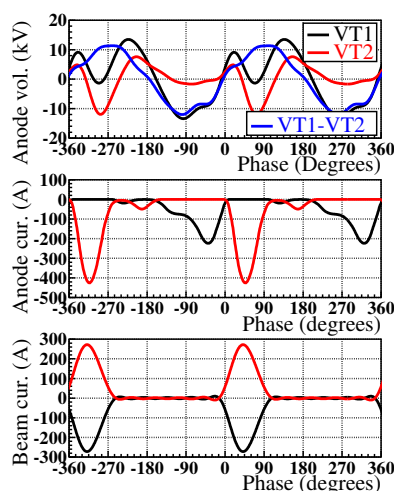


Figure 2: Tube operation analysis result of the anode voltage, the anode current, and the beam current for 1.5 MW beam acceleration in the push-pull operation. The black line represents VT1; the red line represents VT2; and the blue line represents VT1-VT2.

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In Fig. 2, both tubes are operated so that the fundamental harmonic of VT1–VT2 becomes 12 kV. Since the present cavity has three acceleration gaps, each cavity should generate 36 kV so that the maximum acceleration voltage by 12 cavities becomes 440 kV. Although each tube should generate half of that voltage in the ideal push-pull operation, the anode voltage of VT1 is much larger than VT2. This is inefficient usage of the tubes because of the severe unbalance.

We investigated the origin of the unbalance and found that the push-pull operation was not suitable for multi-harmonic driving at very high intensity beam acceleration. An effective solution is to replace the push-pull driven cavity by a single-ended driven one. We describe a conceptual design of the single-ended cavity and the analysis results of the tubes up to 1.5 MW beam acceleration at the RCS.

### ORIGIN OF UNBALANCE

In order to understand the unbalance of the vacuum tubes in the push-pull operation and multi-harmonic rf driving, we consider two single-ended cavities as shown in Fig. 3: a positive-sign cavity that generates a positive gap voltage during the beam passage and a negative-sign cavity that generates a negative gap voltage during the beam passage.

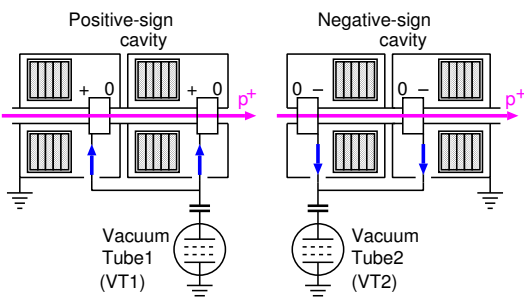


Figure 3: Schematic view of the 'positive-sign' cavity and the 'negative-sign' cavity.

The calculation results of the anode voltage, the anode current, and the beam current for both cavities are shown in Figs. 4 (for the positive-sign cavity) and 5 (for the negative-sign cavity), respectively. Each color on the graph indicates: the green, the blue, and the pink colors are for the fundamental harmonic, the second harmonic, and the third harmonic, respectively. The black line shows the summation of all the harmonics.

The analysis condition is that each cavity tries to generate the fundamental harmonic of 9 kV on each acceleration gap under 1.5 MW beam acceleration, and then the wake voltages up to the third harmonic should be canceled by feeding the anode current harmonics in the anti-phase with respect to the beam harmonics. Both cavities have a resonant frequency of 1.7 MHz, the Q-value of 6, and the shunt impedance of 450 Ω.

Although the anode voltage swing is almost the same for both cavities, there is a big difference between the anode current waveforms. The tubes provide only a negative

sign current to the cavity. As shown in the anode current graph of Fig. 5, the second harmonic works in favor of the negative-sign cavity. The sign of all the three harmonics becomes negative around where the tube should provide the negative current. However, the condition is opposite in the positive-sign cavity. The sign of the second harmonic becomes positive around where the tube should provide the negative current, as shown in the anode current graph of Fig. 4.

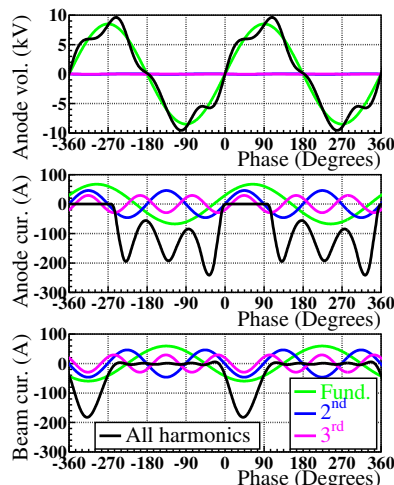


Figure 4: Tube operation analysis result of 1.5 MW beam acceleration at the positive-sign cavity. The green, the blue, and the pink lines stand for the fundamental harmonic, the second harmonic, and the third harmonic, respectively. The black line is the summation of all the harmonics.

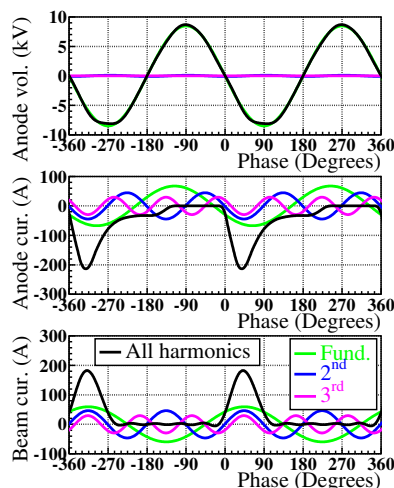


Figure 5: Tube operation analysis result of 1.5 MW beam acceleration at the negative-sign cavity. The green, the blue, and the pink lines stand for the fundamental harmonic, the second harmonic, and the third harmonic, respectively. The black line is the summation of all the harmonics.

The difference comes from the second harmonic of the anode current. The phase difference of the fundamental and

the third harmonic for the beam current with respect to the fundamental harmonic of the anode voltage is the same on both cavities. This fact is confirmed that those waveforms in Fig. 5 are overlapped with the waveforms in Fig. 4 when the horizontal axis in Fig. 5 is shifted by 180 degrees. On the other hand, it is opposite for the second harmonic of the beam current on both cavities.

As a result, the negative-sign cavity needs less anode current than the positive-sign cavity. The anode power supply feeds the DC current into the tube, which corresponds to the integral of the anode current waveform. The negative-sign cavity requires less DC current from the anode power supply than the positive-sign cavity. The negative-sign cavity requires 102 A from the anode power supply, whereas 184 A is required for the positive-sign cavity.

### SINGLE-ENDED CAVITY

It is found that the negative-sign cavity is suitable for very high intensity beam acceleration because the requirement for the anode power supply is relaxed. This is the basic concept of the single-ended cavity for the RCS beam power upgrade.

The schematic view of the cavity is shown in Fig. 6. Four negative-sign single-ended cells are aligned in series, and two of them are connected with the tube by busbars. We can use the existing tube amplifier; however, the tubes are driven in the in-phase operation. The cavity has four acceleration gaps and the fundamental harmonic voltage of 9 kV is generated on each gap. Each cavity cell is loaded with five MA cores which consist of the same material used in the J-PARC Main Ring [7, 8].

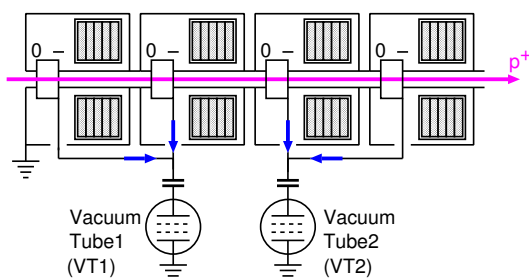


Figure 6: Schematic view of the single-ended cavity for the RCS upgrade.

The single-ended cavity has no tube unbalance intrinsically. Both tubes are operated on the same condition as shown in Fig. 5. This is quite different condition from the push-pull cavity as shown in Fig. 2. The tubes on the single-ended cavity simply generates required gap voltage, whereas the tubes on the push-pull cavity should feed excessive voltage to generate required gap voltage.

The remaining issue is the limitation of the DC current from the anode power supply. Figure 7 shows the calculation results of the DC current for the single-ended cavity on several beam powers. The horizontal axis shows the accel-

eration time of the RCS, and the current varies during the acceleration.

The maximum value of the current is estimated to be less than 120 A, and this is well below the limit of 157 A for the anode power supply. This means that we can use the existing anode power supply by replacing only the push-pull cavity in the single-ended one.

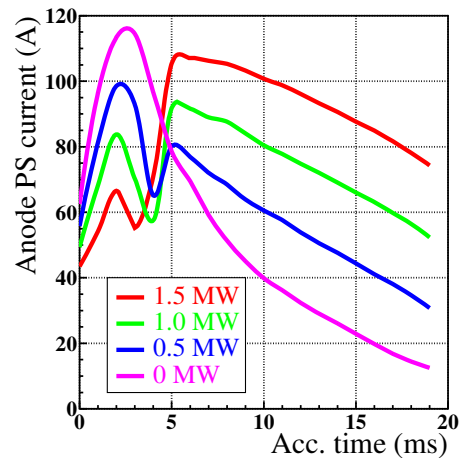


Figure 7: Calculated current of the anode power supply at several beam power during acceleration. The red line: 1.5 MW; the green line: 1.0 MW; the blue line: 0.5 MW; the pink line: 0 MW.

### SUMMARY

We investigated the tube unbalance for a combination of the push-pull operation and the multi-harmonic rf driving in the RCS. We found that the unbalance was caused by the second harmonic of the beam current. Furthermore, we found that the single-ended cavity, which generated the negative-sign voltage during the beam passage, had the advantage of less current from the anode power supply and no tube unbalance for very high intensity beam acceleration. We designed the 4-cells single-ended cavity for the RCS upgrade. The analysis of the vacuum tube and the calculation of the current from the anode power supply suggest that the cavity can accelerate 1.5 MW beam in the RCS.

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