AN UPGRADE SCENARIO OF RF SYSTEM TO ACHIEVE 1.6 MW BEAM ACCELERATION IN J-PARC RCS

M. Yamamoto*, M. Nomura, T. Shimada, F. Tamura
Japan Atomic Energy Agency, Tokai, Ibaraki 319-1195, JAPAN
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 equivalent proton beam. However, beam commissioning and particle tracking simulation suggest that the RCS has possibility to accelerate up to 1.6 MW beam. We consider the possible upgrade scenario of an rf system to accelerate 1.6 MW beam.

INTRODUCTION

The Japan Proton Accelerator Research Complex (J-PARC) Rapid Cycling Synchrotron (RCS) accelerates a high intensity proton beam from 400 MeV to 3 GeV at a repetition rate of 25 Hz. Beam commissioning has progressed successfully, and we have achieved acceleration of a 1 MW equivalent beam without significant beam loss [1]. Although the design beam power of the RCS is 1 MW, the beam commissioning and the particle tracking simulation suggest that the present RCS lattice has possibility to accelerate up to 1.6 MW beam with an acceptable level of beam loss [2].

There are some issues to achieve 1.6 MW beam acceleration. An rf cavity is driven by Tetrode vacuum tubes, and an anode power supply feeds a high voltage DC current to the tubes. The output current of the anode power supply increases with the beam current because a beam loading effect should be compensated to prevent from the distortion of an acceleration voltage wave form. Consequently, one of the major issues in the rf system is the output current limitation of the anode power supply.

A straightforward solution is increasing the output current of the anode power supply, which is actually ongoing. The anode power supply of the RCS employs a series resonant inverter method [3], and the power supply originally consists of 15 inverter units. It is upgraded by adding 3 inverter units on the roof of the power supply housing in 2015 [4], and the maximum output current is increased from 124 A to 148 A.

Furthermore, it is planned to add one more unit in this summer, and then the maximum output current eventually becomes 157 A. However, this upgrade procedure comes to an end because there is no space left on the roof.

We should investigate the conditions in which the output current of the anode power supply is below the limit at 1.6 MW beam acceleration. It is found that the output current exceeds the limit under the present cavity condition. There are two ways to reduce the current: 1) shifting the cavity resonance frequency; 2) increasing the cavity shunt impedance. We describe a possible upgrade scenario of the rf system to achieve 1.6 MW beam acceleration in the RCS by the combination of shifting the cavity resonance frequency and increasing the cavity shunt impedance.

* masanobu.yamamoto@j-parc.jp

RESONANCE FREQUENCY SHIFT

An acceleration frequency range of the RCS is from 1.23 to 1.67 MHz, and the present cavity resonance frequency is set to 1.7 MHz. This means the cavity impedance has inductive characteristics for the fundamental beam harmonic. Shifting the cavity resonance frequency higher means that the cavity impedance becomes more inductive in which a wake voltage helps to raise the acceleration voltage. As a result, the cavity can be driven by smaller anode current to keep the amplitude of the acceleration voltage.

Shifting the resonance frequency has been demonstrated at the beam commissioning. Figure 1 represents the measured beam power dependence of the anode power supply current. The red circles indicate the case in which the cavity resonance frequency is 1.7 MHz, whereas the blue squares indicate the case of 2.1 MHz. As can be seen, the required anode current in the case of 2.1 MHz is smaller than the case of 1.7 MHz above 500 kW beam power.

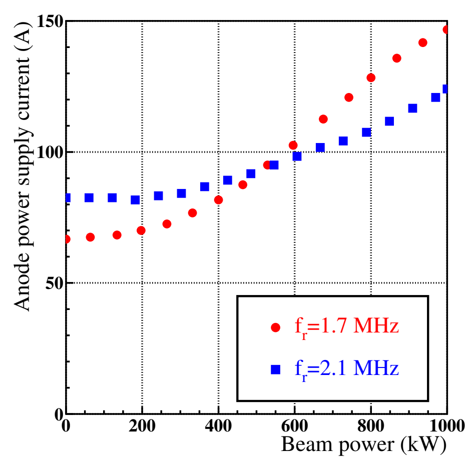

Figure 1: Measured beam power dependence of the anode power supply current. Red circle: cavity resonance frequency of 1.7 MHz; blue square: cavity resonance frequency of 2.1 MHz.

Thus shifting the cavity resonance frequency higher is valid for reducing the anode power supply current at the

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very high beam power. However, we do not employ this higher resonance frequency for daily beam operation so far because an unwanted beam behavior is induced, and it leads to beam loss. Investigation of the beam behavior and some cures are needed if we use this method.

MA CORE DEVELOPMENT

Increasing the cavity shunt impedance is realized by replacing magnetic cores loaded in the cavity. The RCS uses Magnetic Alloy (MA) loaded cavity, and the present cavity uses MA cores called 'FT3M', which is made of 18 μm thickness ribbon [5]. Recently, the J-PARC Main Ring (MR) cavity is upgraded aimed at a higher repetition rate of the acceleration [6]. The cavity uses newly devolved MA cores called 'FT3L', which is annealed with a magnetic field and is made of 13 μm thickness ribbon.

Figure 2 shows the measured frequency dependence of μQf product for the different types of the MA core. The μQf product is used as an index of the shunt impedance because it is proportional to the shunt impedance regardless of the core configuration. FT3L cores with 13 μm thickness ribbon (red line) has 80 % higher μQf product than FT3M cores with 18 μm thickness ribbon (black line).

Furthermore, we have started test production of another FT3L cores, which is made of 10 μm thickness ribbon (blue line). It has 120 % higher μQf product than FT3M cores.

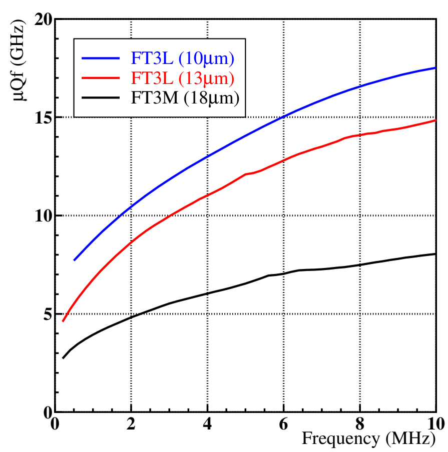

Figure 2: Measured frequency dependence of μQf product. Black line: FT3M with 18 μm ribbon; red line: FT3L with 13 μm ribbon; blue line: FT3L with 10 μm ribbon.

There is a possibility to reduce the current of the anode power supply by replacing the present FT3M cores with FT3L ones.

VACUUM TUBE OPERATION ANALYSIS

The rf cavity is driven by the Tetrode vacuum tubes. In order to obtain the required current of the anode power supply, the vacuum tube operation should be analyzed from a constant current characteristics curve. The cavity is driven by multi-harmonics in the RCS: the fundamental acceleration voltage; the second harmonic voltage for flattening the bunch shape [7]; the beam loading compensation up to the third harmonic [8]. Therefore, the tube operation analysis is performed under the multi-harmonic condition [9].

The analysis needs some input data: the rf voltage pattern during acceleration, the beam harmonics during acceleration, and the cavity impedance. The ordinary pattern is used for the acceleration voltage. The beam harmonics are obtained from the particle tracking simulation [7] up to 1.6 MW-eq. beam. The cavity impedance with FT3M cores is determined based on the measured one of the present cavity. The impedance with FT3L cores is estimated by using μQf product as shown in Fig. 2.

The tube operation analysis is performed by the numerical code [9] in which the anode voltage swing is automatically estimated by inputting the above mentioned data and the control grid voltage. The control grid voltage is adjusted so as to cancel the beam loading effect up to the third harmonic.

Figure 3 is an example of the tube operation analysis in which the RCS accelerates 1.6 MW-eq. beam by the rf cavity using FT3L (10μm) at the resonance frequency of 2.5 MHz. The cavity is driven by two tubes in push-pull operation. The black line indicates one tube (VT1), and the red line indicates the other tube (VT2). The control grid voltage is shown in the upper graph in which the voltage is delivered by an rf power splitter for both tubes [9]. Consequently, the wave form of the control grid voltage becomes antisymmetric.

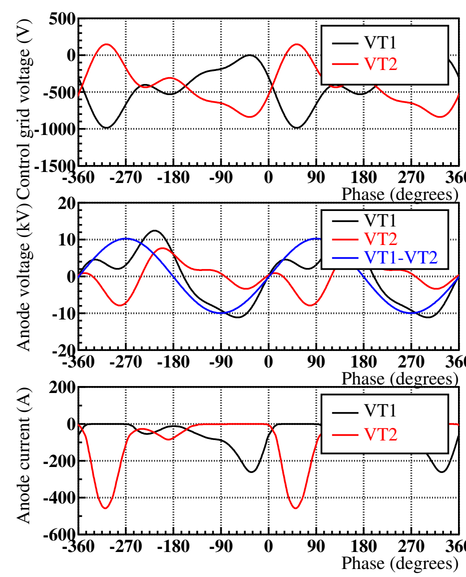

Figure 3: Tube operation analysis result of 1.6 MW-eq. beam acceleration in which the cavity uses FT3L (10μm) cores at the resonance frequency of 2.5 MHz.

The anode voltage is shown in the middle graph in which the blue line indicates the cavity gap voltage determined by subtraction the VT2 from VT1. As can be seen, the wave form of the gap voltage becomes almost pure sin wave by the beam loading compensation, though the anode voltage becomes asymmetric on each tube. The anode current wave form is shown in the bottom graph in which the DC component determined by averaging these wave forms is equal to the current from the anode power supply. The peak anode current and the anode dissipation are within a maximum rating of the tube.

Figure 4 represents the current of the anode power supply on several beam power during acceleration. The vacuum tube operation analysis is performed on each time and each beam power. This is an example in which the cavity uses FT3L (10μm) cores at the resonance frequency of 2.5 MHz. The black line: 1.0 MW-eq. beam; the red line: 1.2 MW-eq. beam; the green line: 1.4 MW-eq. beam; the blue line: 1.6 MW-eq. beam. The current of the anode power supply changes during acceleration according to the changes of the acceleration voltage and the beam harmonics. The peak value is picked up on each beam power to consider how much current is required for the anode power supply.

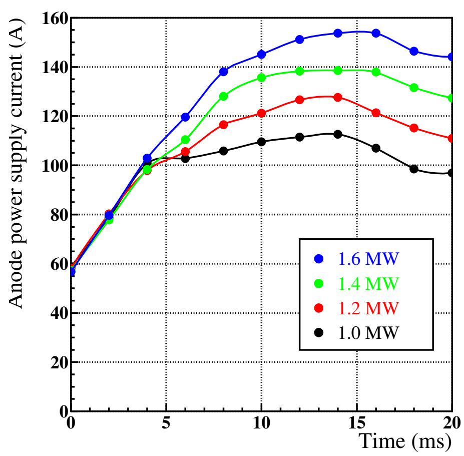

Figure 4: Calculated current of the anode power supply on several beam power during acceleration. Black line: 1.0 MW-eq. beam; red line 1.2 MW-eq. beam; green line: 1.4 MW beam; blue line: 1.6 MW-eq. beam. The cavity uses FT3L (10μm) cores at resonance frequency of 2.5 MHz.

Figure 5 represents the summary of the beam power dependence for the required current of the anode power supply on several cavity conditions. The black, red, and green lines indicate the cavity with FT3M cores, and the resonance frequency is 1.7, 2.1, and 2.5 MHz, respectively. The blue, pink, and light blue lines indicate the cavity with FT3L (10μm) cores, and the resonance frequency is 1.7, 2.1, and 2.5 MHz, respectively.

As can be seen, the required current of the anode power supply can be reduced by shifting the resonance frequency higher and replacing FT3M cores with FT3L (10μm) ones at the cavity. However, the reduction ratio by shifting the resonance frequency from 2.1 to 2.5 MHz is very small.

In conclusion, the cavity using FT3L (10μm) cores at the resonance frequency of 2.5 MHz is a candidate to achieve 1.6 MW beam acceleration because the required current is below the limitation of the upgraded anode power supply. In this case, the unwanted beam behavior should be cured, which is observed at higher cavity resonance frequency.

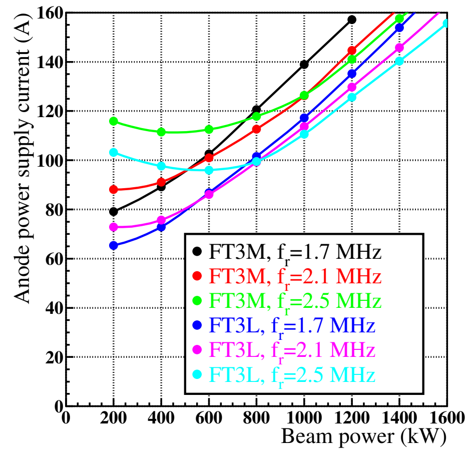

Figure 5: Calculated beam power dependence of the required anode power supply current on several cavity conditions.

SUMMARY

We investigate the upgrade scenario of the rf system for 1.6 MW beam acceleration in the J-PARC RCS, especially for reducing the output current of the anode power supply. It is found that there is a possibility to accelerate 1.6 MW beam by replacing MA cores with higher impedance and also shifting the cavity resonance frequency higher. some cures are necessary for the unwanted beam behavior if we use the higher cavity resonance frequency.

We should also investigate the other equipments of the rf system and utilities such as an electric power line and a cooling water line whether they have enough margin for 1.6 MW beam acceleration.

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