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VACUUM TUBE OPERATION TUNING FOR A HIGH INTENSITY BEAM ACCELERATION IN J-PARC RCS

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Abstract

Tetrode vacuum tubes in the Japan Proton Accelerator Research Complex (J-PARC) Rapid Cycling Synchrotron (RCS) are used under a reduced filament voltage condition compared with the rating value to prolong the tube lifetime. For the first time after 60,000 hour of operation in the RCS, one tube has reached the end of its life in 2020. Therefore, the reduced filament voltage works well because the tube has been running beyond an expected lifetime suggested by the tube manufacturer. However, the reduced filament voltage decreased the electron emission from the filament. Although the large amplitude of the anode current is necessary for the high intensity beam acceleration to compensate a wake voltage, a solid-state amplifier to drive a control grid circuit almost reaches the output power limit owing to the poor electron emission from the filament. We changed the filament voltage reduction rate from 15% to 5%. The required power of the solid-state amplifier was fairly reduced, whereas the accelerated beam power remained the same. We describe the measurement results of the vacuum tube parameters in terms of the filament voltage tuning.

INTRODUCTION

The Japan Proton Accelerator Research Complex (J-PARC) Rapid Cycling Synchrotron (RCS) has been conducting beam commissioning to minimize beam loss at the design beam power of 1 MW [1]. One of the most important issue for the stable beam acceleration is compensating a heavy beam loading at the rf system. A newly developed beam loading compensation system based on a feedback method has been successfully installed and commissioned in 2019 [2].

However, when the beam loading compensation system tries to cancel the wake voltage up to the third harmonic component of the beam, some solid-state amplifiers to drive the control grid circuit of the tube amplifier exceed their power limit under the 1 MW beam acceleration. This issue is considered as the limit of the solid-state amplifier's capability at first. Subsequently, we consider the possibility that the tube operation condition is inadequate.

Tetrode vacuum tubes are used in the rf power source of the rf system in the RCS, and also used in Main Ring (MR). The lifetime of the tube strongly depends on the electron emission life from the filament. Reducing filament voltage compared with the rating value is one effective method for prolonging filament life [3, 4]. Specially in the RCS, the reduced rate of the filament voltage is approximately 15% [5]. Thanks to that, so far, the only one tube had been failed in 2020 due to the end of lifetime, its operation time was above 60,000 hours. Low filament voltage conditions appear to be beneficial in maintaining longer life than the tube manufacturer's suggestion.

However, side effects such as insufficient electron emission from filament have been observed when high rf output is required. As a countermeasure, the voltage reduction rate of the filament was changed from 15% to 5%, and the power required for the solid-state amplifier was significantly reduced. The solid-state amplifiers stand even under the 1 MW beam acceleration, where the wake voltage up to the third harmonic is compensated [6]. We describe the measurement results in terms of the filament voltage tuning.

VACUUM TUBE CONDITION

The tetrode vacuum tubes of TH589 manufactured by Thales are used in the RCS and MR. The RCS uses 24 tubes for 12 rf cavities, and the MR uses 18 tubes for 9 rf cavities. The rating value of the filament voltage is 23 V. The operation condition of the filament is different in the RCS and MR; the reduction rate of the filament voltage is approximately 15% in the RCS, whereas it is approximately 5% in the MR. This difference appears as the difference in the reduction rate for the filament resistance.

A thoriated tungsten filament is used in TH589. The thorium helps reducing the working function of the electron emissions on the tungsten surface. Furthermore, the filament is carburized to prevent thorium evaporation. The carburized filament has a higher electric resistance than the original filament. The resistance decreases with the decarburization process on the filament operation [3]. Therefore, the filament resistance is an indicator of the tube lifetime.

Figure 1 shows the measurement results of the filament resistance in terms of the operation time on both the RCS and MR. The red lines represent the case of 24 tubes in the RCS, and the blue lines represent the case of 18 tubes in the MR. The reduction rate of the RCS is lower than that of the MR because the filament voltage is maintained lower and the decarburization is suppressed.

The green triangle marks indicate that the tubes have reached the end of life. Two tubes in the MR ended their lives after approximately 40,000 hours operation time, whereas it was about 60,000 hours in the RCS. Thus the filament voltage reduction rate might affect the tube lifetime. However,

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predicting the tube lifetime only from the absolute filament resistance value is difficult because the tube reaching the end of life in the RCS still had higher resistance than those in MR. We need additional statistics to evaluate the tube lifetime using the filament resistance as an indicator.

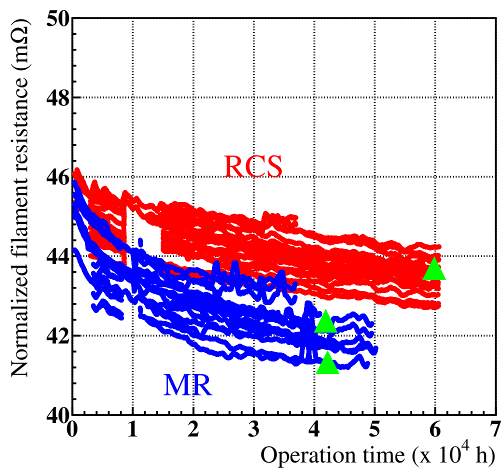

Figure 1: History of the filament resistance for all tubes in the RCS (red lines) and MR (blue lines). The green triangles indicate that the tubes have reached the end of life at those points.

The filament voltage reduction has an advantage from considering the tube lifetime; however, it has a disadvantage for the electron emission efficiency from the filament.

MEASUREMENT RESULTS AT BEAM ACCELERATION

We have measured the parameters of the vacuum tube and the solid-state amplifiers under different conditions of the filament voltage reduction rate at the 1 MW beam acceleration. We test two filament voltage reduction rates: (a) 15% reduction rate which is the original RCS parameter and (b) 5% reduction rate which is near to the MR case.

Figure 2 shows the output current of the anode power supply during acceleration. The black line represents the case (a) and the red line represents the case (b). The output current is similar in both cases.

The same tendency can be observed at the anode voltage. Figure 3 shows the waveform of the anode voltage at the middle of the acceleration. There are two tubes in the tube amplifier because they are operated in the push-pull mode [7]. The upper graph in Fig. 3 indicates the anode voltage of one tube and the lower one indicates the other tube. The voltages are not symmetric because the RCS rf system compensates the wake voltage up to the third harmonic in a cavity. Anyway, the waveforms are similar in both filament conditions.

On the other hand, the solid-state amplifier shows different behavior compared with the anode of the tube considering the filament voltage reduction rate. Figure 4 shows the output

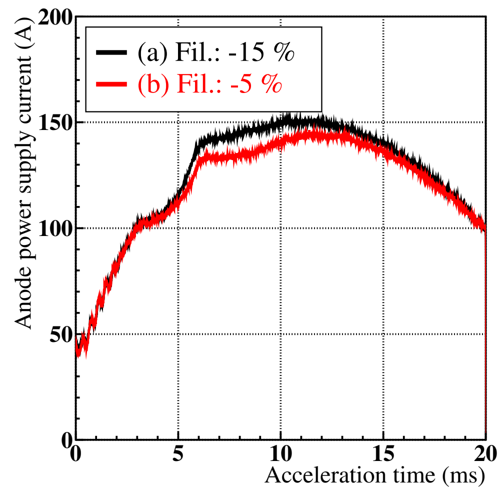

Figure 2: Comparison of the output current of the anode power supply during acceleration in terms of the filament voltage reduction rate. The black line represents the case (a) and the red line represents the case (b).

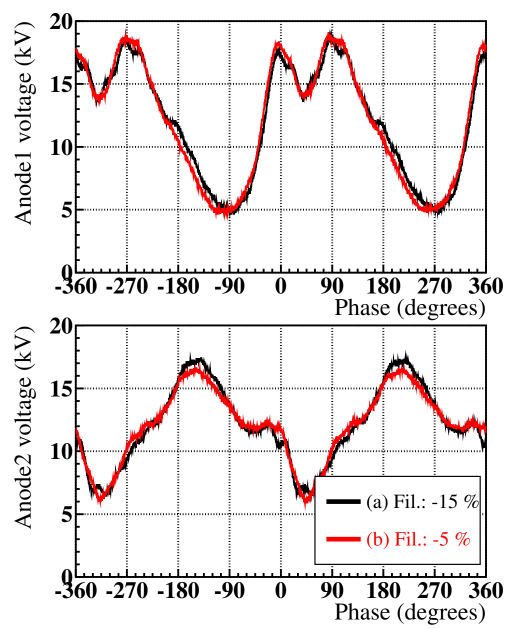

Figure 3: Comparison of the anode voltage waveform in the middle of acceleration. The black line represents the case (a) and the red line represents the case (b).

power of the solid-state amplifier to drive the control grid circuit during acceleration. The maximum output power of 7.4 kW is needed in the case (a), whereas it is only 4.7 kW for the case (b).

Figure 5 shows the waveform of the solid-state amplifier in the middle of the acceleration. The amplitude of the solid-state amplifier voltage in the case (a) is smaller than that in the case (b). Thus, the tube gain is raised by changing the filament voltage reduction rate from 15% to 5%; smaller

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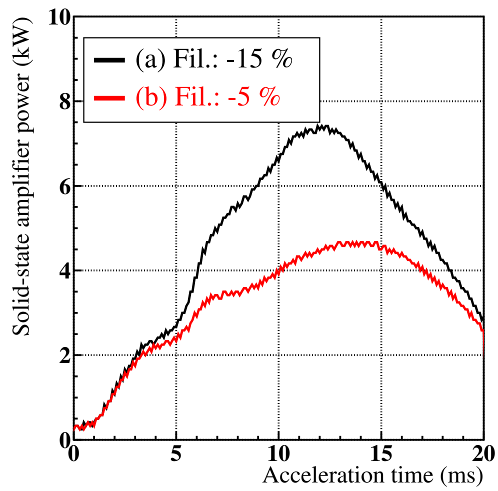

Figure 4: Comparison of the output power of the solid-state amplifier in terms of the filament voltage reduction rate. The black line represents the case (a) and the red line represents the case (b).

power is needed for the solid-state amplifier to obtain the same anode voltage. The tube gain increases, especially during the duration in which a high anode current is needed.

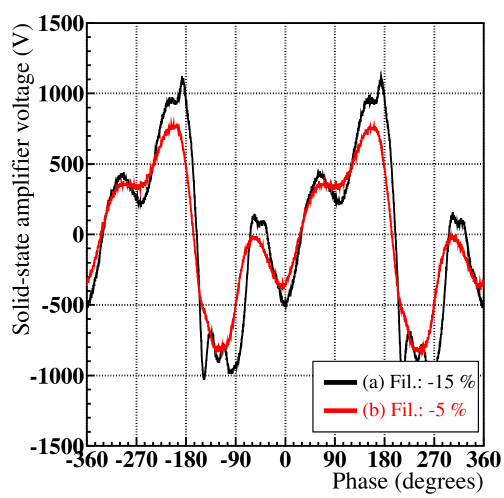

Figure 5: Comparison of the wave form of the solid-state amplifier in terms of the filament voltage reduction rate. The black line represents the case (a) and the red line represents the case (b).

The higher filament voltage reduction rate is insignificant over the region where a smaller amplitude of the anode current is required. For example, the anode power supply current and the output power of the solid-state amplifier in the early stage of acceleration are similar in both filament voltage reduction rate as shown in Figs. 2 and 4.

The tube lifetime is prolonged by using the filament softly. However, the filament voltage reduction rate should not be significantly decreased where a large amplitude of the anode current is necessary. Here, we should accept the shorter tube lifetime and prepare sufficient number of spare tubes to prevent exhausting the tubes.

SUMMARY

We have investigated the vacuum tube operation tuning to accelerate the 1 MW beam.

The RCS rf system uses a large filament voltage reduction to prolong the tube lifetime; it seems to be accomplished from the comparison with the MR tubes. However, the beam loading compensation does not proceed completely up to the third harmonic under the 1 MW beam acceleration. The filament voltage reduction makes the tube gain lower, and the solid-state amplifier can not feed sufficient power to the control grid circuit.

Although it is a trade-off for the tubes between the lifetime and gain, a higher gain is needed to accelerate the high power beam stably. We have to prepare sufficient number of spare tubes in case the filament voltage reduction rate is relieved.

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