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INFLUENCE OF A POSITIVE GRID BIASING ON RF SYSTEM IN J-PARC RCS

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Abstract

In order to accelerate a high intensity beam in the RCS, a large amplitude of the rf current is provided by a tube amplifier to compensate a heavy beam loading. Tetrode vacuum tubes are used in the RCS, and the control grid voltage enters into a positive region to feed such a large rf current. The positive grid biasing affects the waveform of the control grid voltage; it is deformed due to the induced control grid current under the condition of the multi-harmonic rf driving. Furthermore, the DC bias voltage drop on the control grid is observed because of the exceeding the ability for the control grid power supply. We describe the influence of the positive grid biasing in the RCS.

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 issues for stable beam acceleration is compensating the heavy beam loading at the rf system. A beam loading compensation system based on the rf feedback method has been successfully commissioned [2, 3].

A final-stage amplifier with tetrode vacuum tubes provides a large amplitude of the anode current into the rf cavity to compensate the heavy beam loading at the high intensity beam acceleration. The acceleration voltage pattern generated by a low-level rf system is amplified by a solid-state amplifier and fed into the control grid of the tube. The large amplitude of the anode current is driven by the large amplitude of the control grid voltage. The operation point of the tube in the RCS is set as the anode voltage of 12 kV and the control grid DC bias voltage is around −350 V, while the amplitude of the control grid driving voltage is often larger than 350 V. Thus, the positive grid biasing happens during the acceleration.

A part of the anode current flows into the control grid under the condition of the positive grid biasing and it is added to the current for the acceleration voltage pattern provided by the solid-state amplifier. Two tetrode vacuum tubes are installed in the final-stage amplifier to drive the cavity in a push-pull mode, and the acceleration voltage pattern is divided by a power splitter and fed into each control grid. The waveform of the voltage is in counterphase on each control grid and the shape is symmetric without positive grid biasing. However, the symmetricity is broken because the current provided by positive grid biasing is not in counterphase on each control grid in the RCS. This is one of the influences of positive grid biasing.

Furthermore, the current flow into the control grid caused by positive grid biasing is added to the current to sustain a DC bias voltage of around −350 V. Although the voltage is provided by a control grid power supply under the control of the constant voltage mode, the DC bias voltage can not be sustained when the positive grid biasing exceeds the capability of the control grid power supply. In such a case, the sudden drop of the DC bias voltage is observed leading to a further increase in the output power of the solid-state amplifier.

We describe the influence of the positive grid biasing on the RCS rf system.

POSITIVE GRID BIASING

Control Grid Circuit

Figure 1 shows the schematic view of the control grid circuit in the final-state amplifier. First, the acceleration voltage pattern signal amplified by the solid state amplifier is divided by the power splitter. The power splitter is fabricated as the waveforms on the two output ports are in the counterphase to drive the cavity in the push-pull mode.

After that, a bridged-T type all-pass network is applied to the control grid circuit as shown in Fig. 1. The impedance seen from the input side of this network always becomes 50 Ω over any frequency, if the following conditions are satisfied:

$$L = \frac{1}{2} R C_{cg} \tag{1}$$

$$C = \frac{1}{4} C_{cg} , \tag{2}$$

where C_{cg} is a capacitance of the control grid. The control grid voltage has low-pass characteristics and the upper cut-off frequency is $2/RC_{cg}$. The RCS uses Thales TH589 tetrode and its C_{cg} is around 1.3 nF. In this case, the cut-off frequency becomes 4.9 MHz when R is 50 Ω.

The control grid DC bias voltage is provided by two control grid power supplies connected to the all-pass network as shown in Fig. 1.

Asymmetric Voltage

Figure 2 shows that the measured control grid voltage and current at the 1-MW beam acceleration. The upper graph

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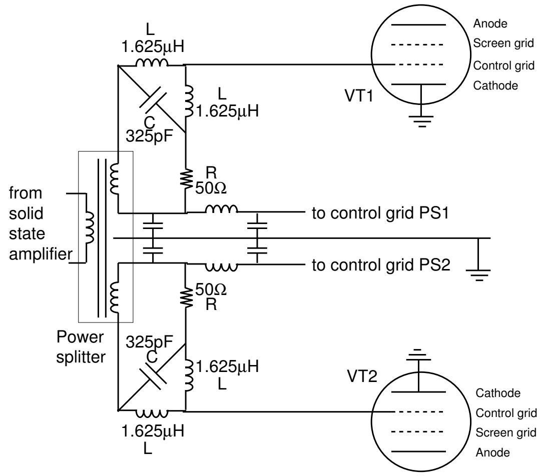

Figure 1: Schematic view of the control grid circuit.

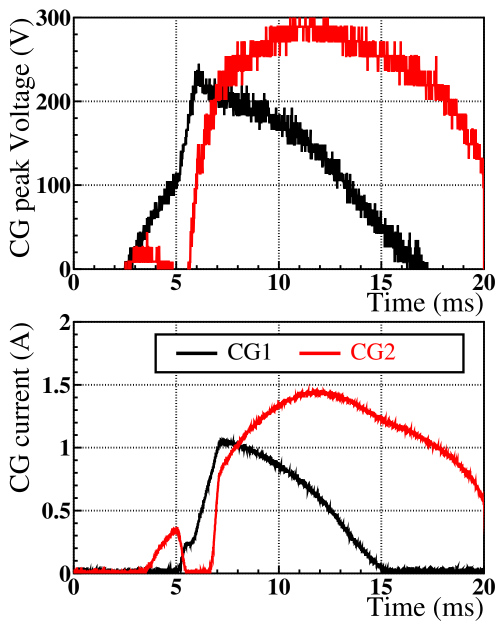

Figure 2: The measured results of the control grid peak voltage and control grid current.

shows the peak voltage detection of the control grid voltages during the acceleration period. The black line indicates the control grid of one vacuum tube (named CG1) and the red one indicates that of the other tube (named CG2). The peak voltage is above 0 V during almost all of the acceleration period; this means the positive grid biasing happens in the region. The lower graph shows the current provide by the control grid power supply during the acceleration period. The timing when the current flows into the control grid coincides with the timing that the positive grid biasing occurs.

Figure 3 shows a snapshot of the waveforms of the control grid voltage and current at the middle of the acceleration. The upper graph shows the measured waveform for the con-

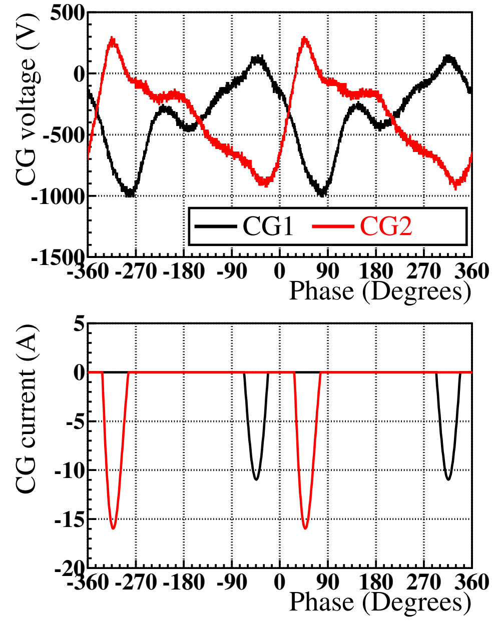

Figure 3: The measured waveform of the control grid voltage and the estimated control grid current.

trol grid voltage; the black line indicates CG1 and the red line indicates CG2. The control grid voltages are above 0 V during the short time range on the both waveforms. The lower graph shows the estimated waveform of the control grid current. As can be seen, spiking currents flow into the control grids when the voltage is above 0 V.

The important point is that the control grid current is not symmetric on both control grids. As mentioned above, the acceleration voltage pattern is divided by the power splitter in counterphase for both control grids; however, the voltage peak is not counterphase due to the multi-harmonic operation. The control grid voltage includes not only the fundamental acceleration voltage but also the beam loading compensation up to the third harmonic [2, 3]. Consequently, the waveform of the control grid voltage is far from the pure sinusoidal as shown in Fig. 3 and the peak position of the voltage is shifted from the counterphase.

The asymmetric control grid current causes the deformation of the waveform for the control grid voltage. Table 1 shows the amplitude of the control grid voltage for each harmonic. As can be seen, the amplitude of each harmonic is not symmetric on both control grids; this should be originally symmetric without positive grid biasing. The deformation of the waveform becomes larger as the control grid current increases. This deformation of the control grid voltage affects the accuracy of the analysis for the vacuum tube operation [4]. The analysis should take into account the control grid waveform deformation in the case of the positive grid biasing.

Bias Voltage Drop

Figure 4 shows the measured control grid DC bias voltage and current during the acceleration. The upper graph shows

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Table 1: Amplitude of the Control-Grid Voltage for Each Harmonic on Both Control Grids

	CG1	CG2
Fundamental harmonic	351 V	392 V
Second harmonic	223 V	180 V
Third harmonic	99 V	140 V

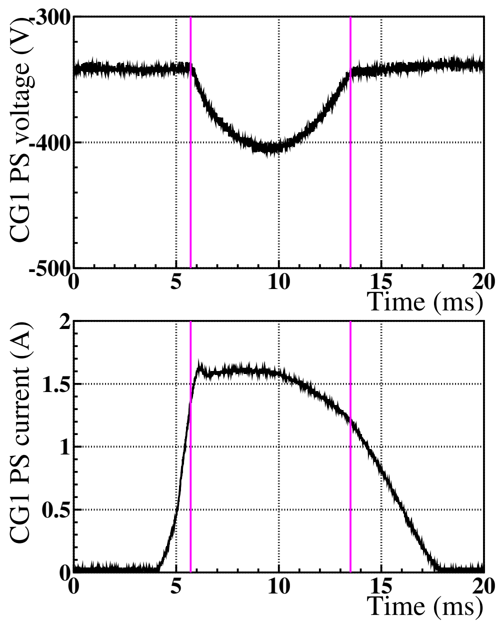

Figure 4: Control-grid DC-bias voltage drop and control-grid current.

the CG1 DC bias voltage, and the lower graph shows the current of the CG1 power supply. As can be seen, a sudden DC bias voltage drop happened in the middle of the acceleration period.

This phenomenon is understood as the control grid power supply exceeds its capability as shown in Fig. 5. The power supply is under control of the constant voltage and some current is constantly flowing into a bleeder resistor of 250 Ω. When the control grid DC bias voltage is set as −343 V, the current of 1.37 A is provided into the resistor from the power supply. On the other hand, the direction of the control grid current supplied by the tube is opposite to the current into the resistor. If the control grid current exceeds the resistor current, the current direction of the power supply is reversed. Consequently, the power supply is forced to decrease the output voltage under the power supply control. The threshold of this phenomenon is indicated by pink lines in Fig. 4.

In this case, the tube operation point is suddenly changed and the solid-state amplifier should feed more power to sustain the control grid driving voltage during this region. This is a severe condition for the solid-state amplifier because the output power reaches its limitation when the control grid current increases more. One solution to decrease the voltage drop is reducing the resistor value. We have changed

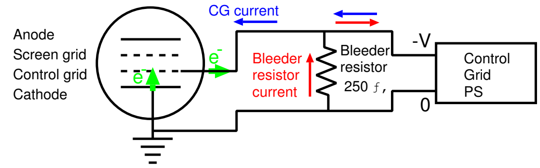

Figure 5: Current flows provided by the control grid power supply and the tube.

the resistor value to 200 Ω as concern about the tube operation point. For further reduction of the resistor value, consolidation of the control grid power supply is required.

SUMMARY

We have investigated the influence of the positive grid biasing in the RCS. The control grid voltage is above 0 V during most of the acceleration period to provide the large anode current into the cavity for compensating the heavy beam loading.

One of the influence is the deformation of the waveform at the control grid voltage. The control grid current is asymmetric on both control grids due to the multi-harmonic rf driving in the RCS. It is essential to include the deformation to estimate the vacuum tube operation accurately.

The other influence is the sudden drop of the control grid DC bias voltage. This is caused when the control grid current supplied by the tube exceeds the current flowing into the bleeder resistor provided by the control grid power supply. This phenomenon is severe for the solid-state amplifier to drive the control grid because the sudden drop means a change in the tube operation point, and it is necessary to feed more power by the solid-state amplifier. In order to decrease such a drop, the reduction of the bleeder resistor value is essential and we have slightly changed the value.

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