LOW OUTPUT-IMPEDANCE RF SYSTEM FOR 2ND HARMONIC CAVITY IN THE ISIS SYNCHROTRON

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Abstract

In the ISIS facility at Rutherford Appleton Laboratory (RAL) in the UK, a second target station project is under construction. Four 2nd harmonic RF cavities will be installed in the ISIS synchrotron to increase the trapping efficiency, and to mitigate the space charge detuning, allowing a 50 % increase in accelerated beam intensity. A very low output-impedance RF system for the 2nd harmonic cavity has been developed by a collaboration of RAL, Argonne National Laboratory (US) and KEK (Japan). The system consists of a 240 kW triode as a final amplifier with plate-to-grid feedback. The measured output-impedance is less than 30 ohms over the frequency range of 2.7 - 6.2 MHz, which agrees well with calculations. High power tests were performed using swept-frequency at 50 Hz repetition rate. The operation is almost stable, and more than 12 kV peak-to-peak was obtained. The voltage gain of the final amplifier is 25 – 30. This decreases gradually with frequency due to the decreasing input-impedance of the triode. A test with beam is planned at ISIS in the near future.

INTRODUCTION

In the ISIS synchrotron [1], there is a plan [2] to increase the beam intensity. In a high intensity synchrotron, the number of particles accumulated in the ring is limited by space charge forces or the interaction between the beam and the surroundings such as the beam pipe, or the RF accelerating system, or diagnostic devices. Specifically, the interaction between the RF accelerating system and the beam itself, "beam loading", may cause beam loss.

Although an RF system drives an RF cavity as a load, the current generated by the beam itself also flows into the RF cavity. Even if the current produced by the RF system is controlled, the beam current may lead to modulation of the gap voltage. As intensity increases, the phase stability produced by the RF acceleration field may be lost. Acceleration of a high intensity beam under heavy beam loading is the subject of active investigation.

The beam loading effects can be avoided by reducing the output-impedance of RF system. Thus, a new type of feedback amplifier with low output-impedance is being developed. The proposed RF system is a grounded cathode scheme, with an external plate to grid feedback path.

The schematic view of the proposed RF system is shown in Fig. 1. In this system, the triode tube drives an RF cavity (z_k). The plate resistance (r_p) and the amplification factor (μ) characterize the tube.

To reduce the output-impedance, the tank circuit as a feedback path is incorporated between plate and grid (z_{pg}). i_b shows simulated beam image current.

Due to the feedback path, the output-impedance of triode becomes smaller than the plate resistance, r_p. The circuit behaviour is as follows. 1.) i_b flows into z_k, and i_k tends to decrease. 2.) RF gap voltage (v) is reduced, and feedback current (i_f) flows from cathode to plate through z_{pg} and the grid tank circuit (z_{gk}). 3.) Since the input RF voltage (e_{gk}) is reduced, the RF plate current (i_p) is increased. 4.) The supplied current (i_s) to RF cavity is increased, and the output-impedance of triode is lowered.

Although this feedback path makes the voltage gain of triode smaller, it is possible to adjust the feedback ratio appropriately by choosing the impedance of feedback path.

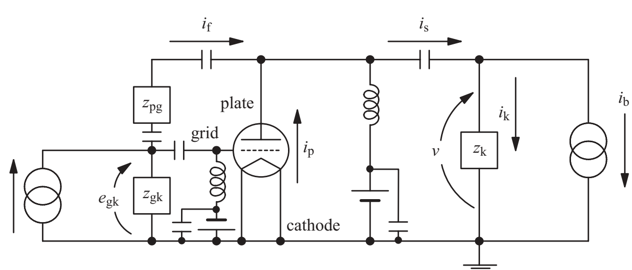

Figure 1: Proposed RF system with a feedback path between plate and grid.

CHARACTERISTICS OF RF SYSTEM

The output-impedance is given by

$$\left(\frac{1}{z_{gk} + z_{pg}} + \frac{1}{\dfrac{r_p}{1+\mu\beta}} + \frac{1}{z_k} \right)^{-1} \approx \frac{r_p}{1+\mu\beta}, \qquad (1)$$

where

$$\beta = \frac{z_{gk}}{z_{gk} + z_{pg}}.$$

The feedback function appears in the second term within the brackets of Eq. (1). The term dominates for a high impedance of an RF cavity, z_{pg} and z_{gk}, so that the approximation of the right hand side of Eq. (1) results. Here, β can be considered as a feedback ratio. So, by setting β appropriately, quite low impedance RF system is

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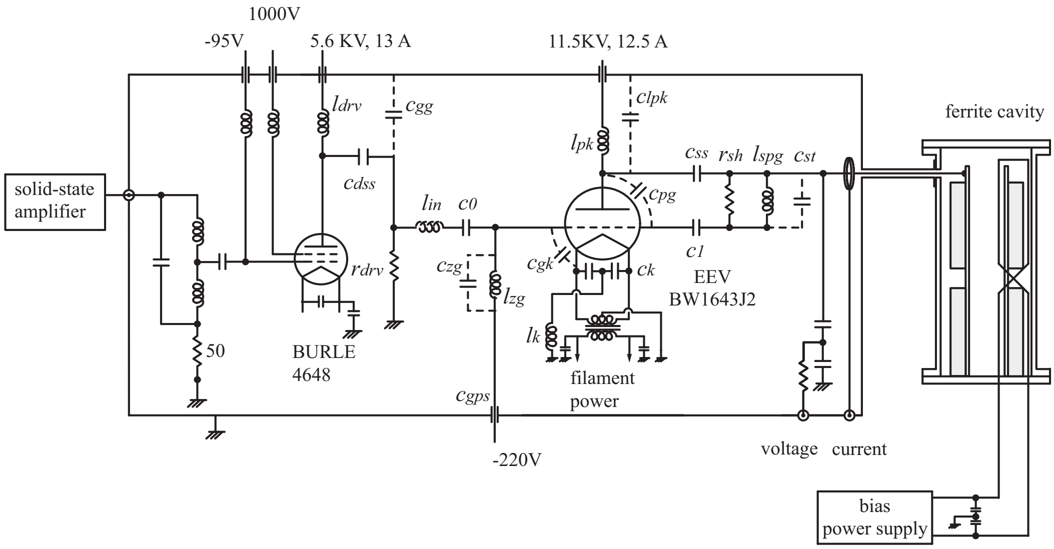

frequency range (MHz)	2.6 - 6.2
tube	
μ, EEV	50
r_{p} (Ω), EEV	350-1000
r_{pt} (kΩ), BURLE	5
feedback path: z_{pg} (resonated at 2.038 MHz)	
r_{sh} (Ω)	1500
l_{spg} (μH)	37.5
c_{pg} (pF)	70
c_{st} (pF)	92.59
grid-cathode: z_{gk} (resonated at 2.075 MHz)	
r_{drv} (Ω)	922
l_{zg} (μH)	16.96
l_{drv} (μH)	67.25
c_{gk} (pF)	225
c_{zg} (pF)	7.287
c_{gg} (pF)	202
l_{in} (μH)	0.01
cathode-ground (z_l)	
l_{k} (μH)	0.1
c_{k} (μF)	0.1
Plate chock	
l_{pk} (μH)	150
c_{lpk} (pF)	5
bypass capacitance	
c_0 (μF)	0.018
c_1 (μF)	0.1
c_{gps} (nF)	5
c_{ss} (nF)	32
c_{dss} (nF)	12

Figure 2: Setup of the RF system.

realized. Here, the contribution of a lead inductance (l_k) in the cathode circuit shown in Fig. 2 is neglected.

In order to increase the feedback ratio, the resonant frequencies and the bandwidth of z_{pg} and z_{gk} are defined appropriately, and z_{gk} is made as large as possible compared with z_{pg} over the operating frequency range. However, since the voltage gain becomes small, z_{pg} cannot be made too small as discussed below.

On the other hand, in the usual grounded cathode scheme, since β is small due to $z_{\mathrm{gk}} << z_{\mathrm{pg}}$, the effect of feedback has been disregarded.

The voltage gain and the input impedance (z_{in}) of triode are approximately given by

$$\text{voltage gain} \approx \left| 1 - \frac{z_{\mathrm{pg}}}{z_{\mathrm{in}}} \right|, \; z_{\mathrm{in}} \approx \frac{z_{\mathrm{pg}} + r_{\mathrm{p}}}{1+\mu}. \qquad (2)$$

Above the resonant frequency of z_{pg}, z_{in} is roughly represented as the sum of r_{p} / (1+μ) and the plate-grid capacitance where the capacitance becomes (1+μ)-times larger by the Miller effect.

If there is no feedback path (i.e. $z_{\mathrm{pg}} \to \infty$), this approximately gives the voltage gain of the usual grounded cathode scheme as μ.

Thus, although the voltage gain of the RF system is decreased as compared with the usual grounded cathode scheme, adequate gain, compared with the cathode-follower, is achieved by adjusting the feedback ratio.

SYSTEM SETUP

Fig. 2 shows the schematic views of the proposed RF system. The EEV triode (BW1643J2) is used as the final tube. The DC bias power supply feeds a bias current to keep the ferrite-loaded cavity at resonance. The resonant frequency versus bias current was measured over the frequency range of 2.6-6.3 MHz. The typical plate voltage for the tube is 11.5 kV and the quiescent current is 12.5 A. A Pearson model 310 monitors the cavity input current.

A solid-state amplifier drives a BURLE 4648 tetrode through a 50 Ω coaxial cable. An all-pass network that employs mutually coupled coils provides impedance matching to the input of the tetrode. The coupling coefficient is optimized for wide bandwidth.

Neglecting some bypass capacitors, z_{pg} comprises a parallel resonant circuit with l_{spg}, r_{sh}, a plate-grid capacitance (c_{pg}) and stray capacitance (c_{st}) of l_{spg}.

Since a finite impedance (z_{l}) exists between cathode and ground, comprised of the lead inductance (l_{k}) and the bypass capacitor (c_k), we define z_{gk} as the impedance between grid and cathode when the cathode is grounded. That is, z_{gk} comprises z_{gg} and a grid-cathode capacitance (c_{gk}). Where, z_{gg} is the impedance between grid and ground seen from grid to the input end of the triode, which comprises l_{zg}, r_{drv}, stray capacitance (c_{zg}) of l_{zg}, stray capacitance (c_{gg}) between the input end and ground, plate resistance (r_{pt}) of tetrode, and plate choke coil (l_{drv}).

The lead inductance (l_{k}) gives a significant contribution to the output-impedance. Eq. (1) is modified, so that the output-impedance including the contribution of z_l is approximately given by

$$\frac{r_p}{1+\mu\beta} + z_l \left(\frac{z_{pg} + z_{gg}}{z_{gg}} \right).$$

Compared with Eq. (1), the z_l multiplied by $(z_{pg} + z_{gg}) / z_{gg}$ increases the output-impedance. Therefore we design the RF system so that z_{l} might be made small.

In designing this RF system, the model system [3] was developed and the test result was made reference.

EXPERIMENTAL RESULTS

The output-impedance is small compared with the impedance of the RF cavity. Measurements were performed using an HP4195A network/impedance analyzer looking into the plate of the final triode, while a 1 kΩ resistor is shunted across the plate to ground and the cavity is disconnected. As the output-impedance depends on the value of plate resistance r_p, various measurements for the plate current of 1.5, 3.8, and 14.5 A were performed. The results are shown in Fig. 3. Increasing the plate current makes the plate resistance smaller, and the output-impedance decreases.

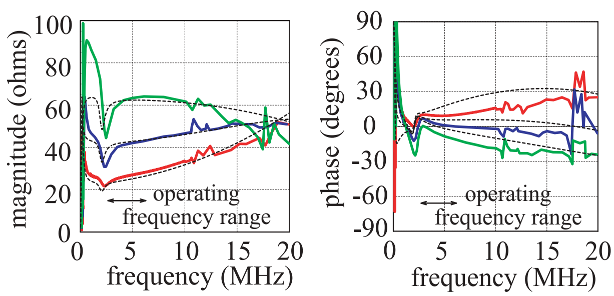

Figure 3: Output-impedance for the plate current of 1.5 (green), 3.8 (blue), 14.5 (red) A. The plate voltage is 8.0, 8.0 and 11.5 kV, respectively. The grid voltage is -210, -180 and -210 V, respectively. The dotted lines show calculations, where the value 1000, 650, 350 Ω of r_p is assumed for the case of 1.5, 3.8, 14.5 A of the plate current.

The RF system operated with a swept-frequency of 2.6 - 6.3 MHz at a 50 Hz repetition rate. Typical RF waveforms are shown in Fig. 4. The maximum voltage of 12 kV peak-to-peak is obtained. Although significant distortions can be seen in the cavity input current waveforms at the lower frequencies, the cavity voltage waveforms are reasonably sinusoidal. At the higher frequencies, the cavity voltage waveforms are also distorted. In order to obtain more reasonable sinusoidal waveforms, further investigation is necessary. However, over the frequency range investigated, the RF generation is stable.

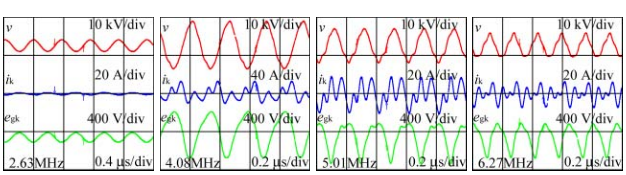

Figure 4: Typical RF waveforms. From upper trace: cavity voltage, cavity input current, and grid input voltage.

The measured voltage gain of the RF system in swept-frequency mode and in the fixed-frequency mode are shown in Fig. 5 with the calculation, where 350 Ω of r_p, and 2 k Ω of cavity shunt resistance are assumed. The calculated magnitude of the input impedance (z_{in}) of the triode is also shown. The measured voltage gain decreases with frequency due to l_{in} and the decreasing z_{in}. As shown in Eq. (2), the voltage gain of the pure grounded cathode scheme will become μ (= 50). Although the obtained voltage gain of this RF system is smaller than μ, sufficient gain is achieved.

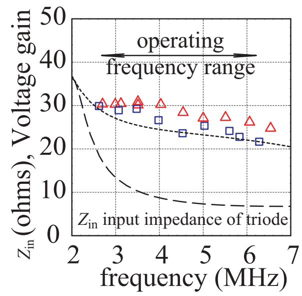

Figure 5: Voltage gain in swept-frequency mode (box) and in fixed-frequency mode (triangle). The dotted line shows the calculation. The dashed line shows the magnitude of z_{in}.

CONCLUSION

An RF system with a new type of feedback amplifier was developed. The RF system uses a grounded cathode scheme with an external plate to grid feedback. The measured output-impedance is comparable with that obtained by the cathode-follower beam buncher in the Proton Storage Ring [4], which is well-known to have a low output-impedance characteristic and a voltage gain of less than 1.

At the lowest operating frequency, expected beam loading is severe due to low acceleration voltage for adiabatic capture. The output-impedance is roughly estimated by $r_p / (1 + \mu\beta)$, and β is expressed by $z_{gk} / (z_{gk} + z_{pg})$. Therefore, the smallest output-impedance is realized at the resonant frequency of z_{gk}. So, the resonant frequencies of z_{pg} and z_{gk} are set at 2.1 MHz, which is near to the lowest operating frequency. In the results, the lowest output-impedance is realized at such a frequency. This RF system has the advantage of its flexibility since it is possible to adjust the feedback ratio. Beam experiments in the ISIS synchrotron are planned for stability investigations.

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