DUAL HARMONIC OPERATION WITH BROADBAND MA CAVITIES IN J-PARC RCS

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Abstract

In the J-PARC RCS RF system, the fundamental rf acceleration voltage and the 2nd higher harmonic one are applied to each cavity. This is possible, because the magnetic alloy loaded cavities have a broadband characteristic and require no resonant frequency tuning. The tube amplifier provides both rf components. We calculate the operation of the tube under the condition of the dual harmonic, the non-pure resistive load and the class AB push-pull mode. We also describe about the single harmonic operation from the view point of the higher harmonic push-push mode.

INTRODUCTION

In the J-PARC RCS, since the bunching factor should be improved to alleviate the space charge effects at the injection, we plan to employ the dual harmonic rf system [1]. Using a Magnetic Alloy (MA) loaded cavities [3], we can get the broadband characteristic without resonant frequency tuning and we can produce the fundamental rf acceleration voltage and the 2nd higher harmonic on each cavity.

We calculated the required tube current fed into the cavity in the case of the dual harmonic rf with the broadband MA cavity in J-PARC RCS [3], and we optimized the Q-value and the resonant frequency of the cavity to minimize that current. Then, we analyze the tube operation with the dual harmonic rf to estimate how we drive the tube amplifier. It is a little bit complicated in the case of the untuned type rf cavity and the case of the dual harmonic rf. In order to perform the analysis, we get the tube parameters from the constant current curve and use them to calculate the tube current.

Furthermore, we operate the cavity not only dual harmonic rf but also single harmonic one in the J-PARC RCS. We found we should take care about the even number higher harmonic rf, generated by the tube amplifier itself, because it drives the cavity in push-push mode, where the cavity impedance is different from push-pull mode impedance.

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DUAL HARMONIC OPERATION OF THE TUBE AMPLIFIER

We analyze the tube operation under the condition of the dual harmonic rf, the non-pure resistive load and the class AB push-pull mode. In order to simplify how to know the amplitude and the phase of the control grid voltage V_d on the dual harmonic rf system, we try to get the relation among I_a, V_a and V_d as described in [4], where V_a and I_a are the anode voltage and current, respectively.

We use the tetrode vacuum tube 'TH558K [5]' at the final stage power amplifier. From the data sheet, we can find the constant current curve described by $V_d = aV_a + b(I_a)$, where a is related to an amplification factor of the tube and $b(I_a)$ has a constant value for certain anode current. From the data sheet, we can find a is about 0.00749. Then, we try to find the form $b(I_a)$. In general, since the tetrode tube has a relation as

$$I_a = k\left(V_d + \frac{V_{sc}}{\mu_{sc}} + \frac{V_a}{\mu_a}\right)^n, \qquad (1)$$

where k is the *perveance*, n is a coefficient that the typical value is $n = \frac{3}{2}$, V_{sc} is the voltage of the screen grid, μ_{sc} and $\mu_a = \frac{1}{a}$ is the amplification factor of the screen grid and the anode, respectively. Then, b has a form as $b = \left(\frac{I_a}{k}\right)^{\frac{1}{n}} - \frac{V_{sc}}{\mu_{sc}}$. From the data sheet, we can get the values as $n = 5$, $\mu_{sc} = 5.882$ and $k = 0.0378$ when the V_{sc} is 2 kV. Consequently, we can calculate the anode current with eq. (1) for the arbitrary V_a and V_d. This is very helpful to find V_d in the case of the dual harmonic rf system. The thin lines in Fig. 1 (a) show the reconstructed constant current characteristic curve of TH558K by using eq. (1).

V_1	306 kV
I_{b1}	5.9 A
I_{T1}	82.9 A
ϕ_{z1}	57.8 deg.
V_2	234 kV
I_{b2}	0.95 A
I_{T2}	32.9 A
ϕ_{z2}	-51.2 deg.
ϕ_s	17.2 deg.

Table 1: The RCS parameters at 2 ms.

Using this scheme, the operation of the dual harmonic rf is estimated in the case of J-PARC RCS. The parameters at 2 ms after the beginning of the acceleration period listed in Table 1 are used, where V is an accelerating voltage, I_b is a beam current, I_T is a vector sum of I_b and the tube current, ϕ_z is the phase of the cavity impedance, ϕ_s is a synchronous phase, respectively. The suffix 1 and 2 denote the fundamental component and 2nd higher harmonic one. In this table, we assume $R_{\rm sh} = 800\Omega$, $Q = 2$, $\omega_r = 1.7$ MHz and three cavity gaps are connected in parallel.

The thick line in Fig. 1 (a) shows the load line of the tube fit with these parameters. From the load line, we can get the anode current as shown in Fig. 1 (b) by using eq. (1), the thick line shows the total anode current I_a delivered to the cavity, thin and thin dotted lines show I_{g1} and I_{g2} calculated by Fourier transformation of I_a. We can also get the dynamic anode admittance by using small change of the anode current and the voltage at a certain control grid voltage as $\frac{\Delta I_a}{\Delta V_a} \cong \left.\frac{\partial I_a(V_a,V_d)}{\partial V_a}\right|_{V_d}$, and it is shown in Fig. 1 (c). The average of the admittance becomes 2.85 mS, hence the anode resistance is 351 Ω.

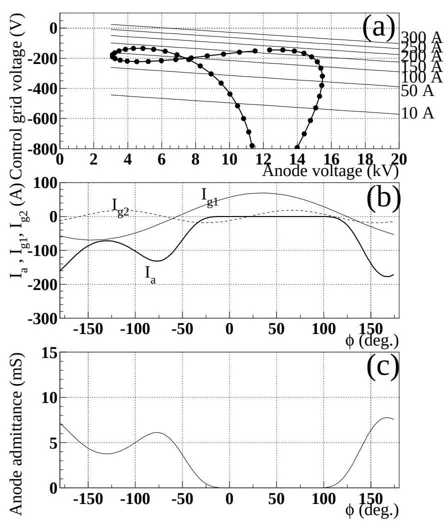

Figure 1: (a) The constant current characteristic curve of TH558K, (b) the anode current wave form in the case of the dual harmonic rf and (c) the anode admittance.

When the push-pull operation is employed at the tube amplifier under the class AB, B and C, we should take care how to drive the control grid voltage. If a power splitter where the rf drive signal is divided into "0 degree for Tube I" and "180 degree for Tube II" with respect to the phase is used to deliver the rf drive signal to realize the push-pull operation, the symmetry of the control grid voltage wave form is broken on each tube in the case of the dual harmonic operation with the broadband cavities as shown in Fig. 2 (a). It makes the tube current asymmetric, hence the power dissipation becomes unbalanced. When the unbalance becomes large and we want to avoid such condition, driving each control grid independently without the power splitter is one choice to improve the tube balanced as shown in Fig. 2 (b).

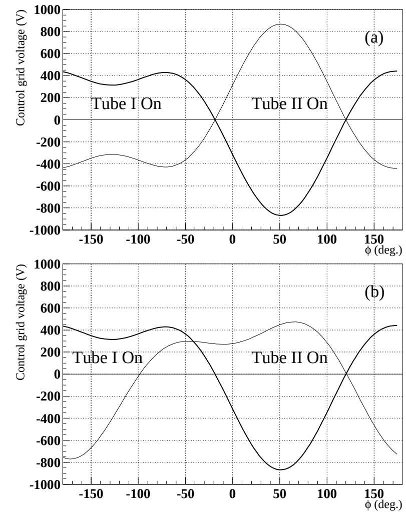

Figure 2: The control grid voltages for improving tube balance.

PUSH-PUSH MODE

For the single harmonic operation with the broadband cavities, we should take care about "push-push mode" by the even number higher harmonic components. Usually, when we analyze the push-pull operation of the tube amplifier, we use the equivalent circuit diagram as shown in Fig. 3. The tube current goes through not only the cavity half cell but also the gap capacitance, so we can get an equivalent circuit diagram for the cavity half cell as the bottom one in Fig. 3. In this case, the resonant frequency of the cavity half cell is defined by L, $C_{\rm cav}$ and $2C_{\rm gap}$.

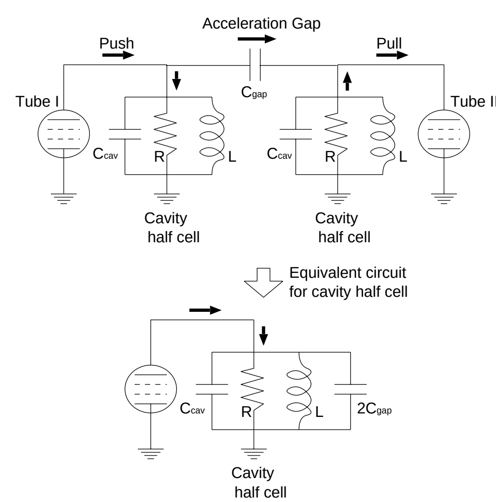

Figure 3: The equivalent circuit diagram for push-pull mode.

On the other hand, the higher harmonic components generated by the tube are also provided into the cavity, and the even number components become push-push mode. In this case, the equivalent circuit diagram is shown in Fig. 4. The tube current does not go through the cap capacitance because the voltage at each cavity half cell becomes same. So, we can get an equivalent circuit diagram for the cavity half cell as the bottom one in Fig. 4. In this case, the resonant frequency of the cavity half cell is defined by L and $C_{\rm cav}$.

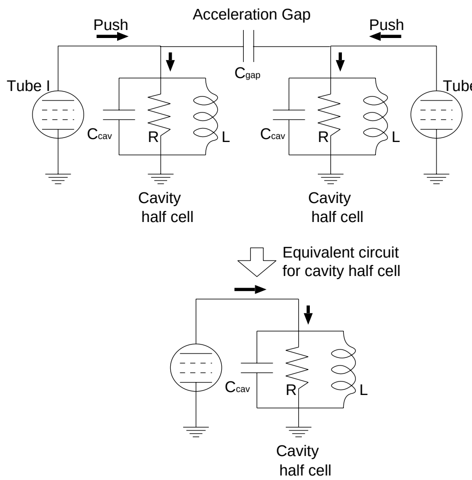

Figure 4: The equivalent circuit diagram for push-push mode.

This means the tube sees a different impedance between the push-pull mode and push-push one. For the broadband cavity, the higher harmonic voltages also appear at the acceleration gap, and especially the 2nd higher harmonic tends to become large by the conditions of the gap capacitance due to the push-push mode.

The Figure 5 and 6 show the measurement results of the impedance for the fundamental component (push-pull mode) and the 2nd higher harmonic one (push-push mode), respectively. In this case, we drive the tube amplifier with a single harmonic as fundamental component in push-pull mode, class AB. As can be clearly seen, the impedance seen by the fundamental component is different from the 2nd higher harmonic one. The resonant frequency for the fundamental one is around 2 MHz, and that for the 2nd higher harmonic one is around 5 MHz.

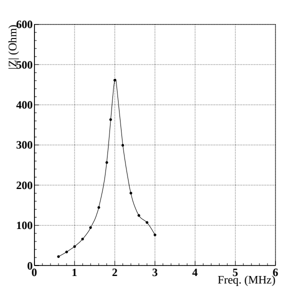

Figure 5: The impedance seen by the fundamental component.

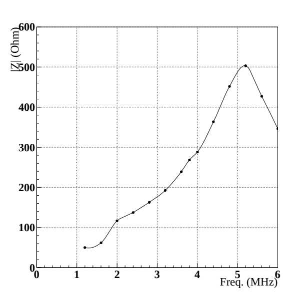

Figure 6: The impedance seen by the 2nd higher harmonic one.

This kind of phenomena appears when the gap capacitance has large compared to the effective capacitance of a cavity half cell. If we have to avoid such problem, one scheme is introducing a figure of eight loop which couples each cavity half cell in a way that the even number harmonic voltage at the cavity gap cancel each other. Another scheme is decoupling each cavity half cell. This means two of the gap capacitance $2C_{\rm gap}$ are connected in series, and the center is connected to the ground potential. Then, the resonant frequency for push-pull mode and push-push mode are identical.

SUMMARY

We analyze the tube amplifier operation in the case of dual harmonic rf and non-pure resistive load. For simplicity, we get the tube parameters from the constant current curve and use them to calculate the tube current. For the push-pull and class AB, B, C operation, we should take care about asymmetry on each tube current. Furthermore, we also describe the single harmonic operation. For the broadband cavities, the higher harmonic voltage is also appeared at each cavity half cell. The even number higher harmonic voltage tends to become large, because it drives the cavity in the push-push mode.

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