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

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Abstract

In the J-PARC Rapid Cycling Synchrotron (RCS) rf system, since the fundamental rf acceleration voltage and the 2nd higher harmonic one are applied to each cavity, the impedance of such a cavity has a broadband characteristic. The Q-value of the cavity is chosen to make the higher harmonic beam loading effect as small as possible. The analysis of the required tube current and the beam loading effect on the dual harmonic rf system are described.

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].

The parameters of the RCS in the case of 181 MeV injection energy are listed in Table 1. In this table, the beam current of each harmonic is obtained from the particle tracking simulation.

Number of particles	5.0×10^{13} ppp
Average beam current	3.7∼6.7 A
Synchronous phase ϕ_s	51 degrees (max.)
Harmonic number h	2
for fundamental rf	
Gap voltage V_1	435 kV (Max.)
Freq. range $f_{\rm rf}$	0.94∼1.67 MHz
Beam current I_{b1}	5∼13 A
for 2nd higher harmonic rf	
Gap voltage V_2	235 kV (Max.)
Freq. range $2f_{\rm rf}$	1.88∼3.34 MHz
Beam current I_{b2}	0.5∼11.5 A

Table 1: The RCS parameters.

A Magnetic Alloy (MA) loaded cavity is used for the RCS rf system [2] because of its stable characteristics under high magnetic field. Since it also has an intrinsic low-Q value, it is possible to realize the broadband rf cavity without resonant frequency tuning. It is an advantage that we don't need to care about applying DC bias field to the magnetic cores. On the other hand, the designing of the rf system becomes a little bit complicated in the case of the untuned type rf cavity, especially the dual-harmonic one. We consider the cavity Q-value and the resonant frequency which satisfy the conditions that the frequency range of the cavity should cover not only the fundamental rf but also the 2nd higher harmonic one, the power consumption of the amplifier becomes minimum for both harmonics and the effect of the higher harmonic beam loading is as small as possible.

REQUIREMENT OF THE TUBE CURRENT

In order to calculate the requirement of the tube power amplifier in the case of the dual harmonic rf system, we should consider about the phasor diagram for both components. For simplicity, we consider it for each component separately as shown in Fig. 1 and 2, where the real axis means the phase of each rf voltage. Note that the phase of the 2nd higher harmonic voltage V_2 is different from the fundamental one V_1 because there is a phase relation as $V_{\rm cav} = V_1 \sin\phi + V_2 \sin 2(\phi - \frac{\pi}{2} - \phi_s)$, where $V_{\rm cav}$ is the total cavity gap voltage and ϕ_s is an synchronous phase.

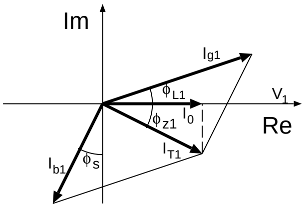

Figure 1: The phasor diagram for the fundamental component.

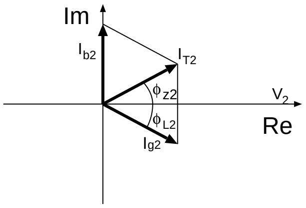

Figure 2: The phasor diagram for the 2nd higher harmonic component.

The amplitude and the phase of each component have the relations as

$$I_{g1} = \frac{I_{T1}\sin\phi_{z1} - I_{b1}\cos\phi_s}{\sin\phi_{L1}}, \tag{1}$$

$$\tan\phi_{L1} = \frac{I_{T1}\sin\phi_{z1} - I_{b1}\cos\phi_s}{I_{T1}\cos\phi_{z1} + I_{b1}\sin\phi_s}, \tag{2}$$

$$I_{g2} = \frac{I_{T2}\sin\phi_{z2} - I_{b2}}{\sin\phi_{L2}}, \tag{3}$$

$$\tan\phi_{L2} = \frac{I_{T2}\sin\phi_{z2} - I_{b2}}{I_{T2}\cos\phi_{z2}}, \tag{4}$$

where I_g is the tube anode current, I_b is the beam current, I_T is the vector summation of I_g and I_b, ϕ_z is the phase of

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the cavity impedance, ϕ_L is the phase difference between the voltage and the tube anode current and the suffix 1 and 2 denote the each harmonic component, respectively. Note that ϕ_s does not appear in eq. (3) and (4) because the phase of the bunch center sits on ϕ_s and zero cross phase of V_2 is also on ϕ_s. And, if $V_2 \to 0$, then $I_{T2} \to 0$ and $\phi_{L2} \to \frac{\pi}{2}$, hence I_{g2} becomes $-I_{b2}$.

In the broadband and the untuned cavity, we select the cavity Q-value and the resonant frequency to minimize the tube anode current for both harmonic components. Using the cavity impedance $Z_{\rm cav} = \frac{R_{\rm sh}}{1+jQ\left(\frac{\omega_r}{\omega}-\frac{\omega}{\omega_r}\right)}$, where $R_{\rm sh}$ is the shunt impedance of the cavity and ω_r is the angular resonant frequency, we can get the tube anode current as

$$\begin{aligned} I_{g1} &= \left[{I_{01}}^2 \left\{ 1 + Q^2 \left(\frac{\omega_r}{\omega_{\rm rf}} - \frac{\omega_{\rm rf}}{\omega_r} \right)^2 \right\} \right. \\ &\quad + 2 I_{01} I_{b1} \left\{ \sin\phi_s - Q \left(\frac{\omega_r}{\omega_{\rm rf}} - \frac{\omega_{\rm rf}}{\omega_r} \right) \cos\phi_s \right\} \\ &\quad \left. + {I_{b1}}^2 \right]^{\frac{1}{2}}, \qquad (5) \end{aligned}$$

$$\begin{aligned} I_{g2} &= \left[{I_{02}}^2 \left\{ 1 + Q^2 \left(\frac{\omega_r}{2\omega_{\rm rf}} - \frac{2\omega_{\rm rf}}{\omega_r} \right)^2 \right\} \right. \\ &\quad \left. - 2 I_{02} I_{b2} Q \left(\frac{\omega_r}{2\omega_{\rm rf}} - \frac{2\omega_{\rm rf}}{\omega_r} \right) + {I_{b2}}^2 \right]^{\frac{1}{2}}, \qquad (6) \end{aligned}$$

where $I_{01} = \frac{V_1}{R_{\rm sh}}$ and $I_{02} = \frac{V_2}{R_{\rm sh}}$.

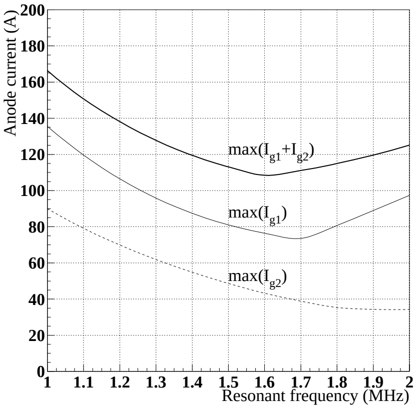

Figure 3: The change of the anode current with respect to the resonant frequency of the cavity.

The calculation results for the maximum of I_{g1}, I_{g2} and $I_{g1} + I_{g2}$ with respect to the cavity resonant frequency are shown in Fig. 3, where the RCS operation parameters are used and the cavity Q-value of 2 is assumed. From this calculation, the resonant frequency around 1.6∼1.7 MHz is reasonable for the dual harmonic rf system. It looks we can reduce the tube current by selecting the lower Q-value from eq. (5) and (6). However, the resonant frequency becomes lower in the case of the lower Q-value because of the large inductance of the MA, and the impedance of the MA also becomes lower by its frequency dependence. Furthermore, we should take care about the higher harmonic beam loading in the case of the high intensity beam acceleration, this is explained at latter section.

HIGHER HARMONIC BEAM LOADING

On the broadband rf cavity, the higher harmonic components of the beam current flow into the cavity, then it causes the bucket distortion if we don't compensate them. The Figure 4 shows each harmonic component, where $h = 2$ means the fundamental component based on the rf acceleration frequency because the RCS has a harmonic number of 2 and two bunches are accelerated in this case. These components are calculated by the particle tracking simulation.

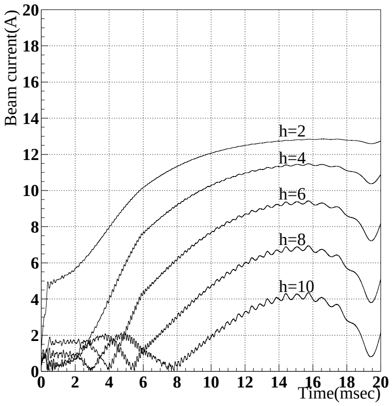

Figure 4: The beam current Fourier components on 2 bunch operation.

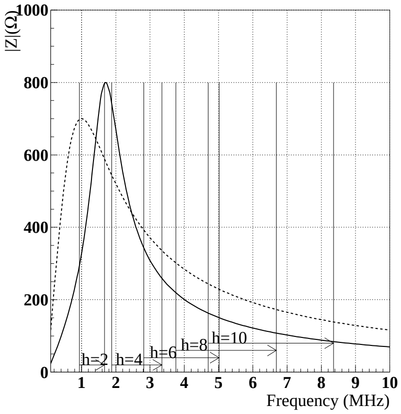

Figure 5: The impedance curve of the cavity for each Q-value.

The Figure 5 shows the comparison of the impedance between the case of $Q = 2$, $\omega_r = 1.7$ MHz, $R_{\rm sh} = 800\Omega$ (Thick line) and the case of $Q = 0.6$, $\omega_r = 1.0$ MHz, $R_{\rm sh} = 700\Omega$ (Dotted line). The band width of each beam current component from h=2 to h=10. is also shown in Fig.

5. Using these cavity impedances, we perform the longitudinal particle tracking simulation including the beam loading effect and the space charge effect. In this simulation, we apply the feedforward beam loading compensation scheme [3] up to h=6 beam current component.

The Figure 6 and 7 show the beam emittance at the extraction in the case of the Q-value of 2 and 0.6, respectively. In the case of the Q-value of 0.6, the beam emittance is larger than the case of Q-value of 2 and some particles are lost during acceleration because of the bucket distortion caused by the higher harmonic beam loading. In order to avoid the beam emittance growth, we should choose the optimum Q-value so that the higher harmonic components of the beam do not see the large cavity impedance.

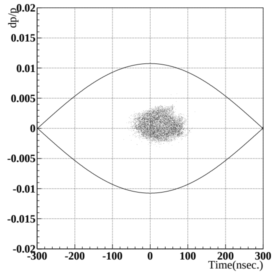

Figure 6: The beam emittance in the case of Q=2.

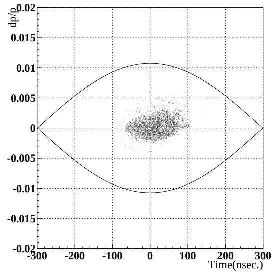

Figure 7: The beam emittance in the case of Q=0.6.

SUMMARY

We calculate the operation of the dual harmonic rf system in the J-PARC RCS, where the low-Q and untuned type rf cavity is used and the cavity impedance covers both harmonics. For the selection of the cavity Q-value, we perform the particle tracking simulation, then we find the very low-Q value of 0.6 causes the emittance growth when the feedforward compensation is applied up to h=6.

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