PUSH-PULL AMPLIFIER FOR MA-LOADED CAVITY

Y.Sato[*], M.Fujieda[†], Y.Mori, H.Nakayama, C.Ohmori, K.Saito[‡], Y.Tanabe[§],
T.Uesugi[¶], M.Yamamoto[‖], Taixuan Yan[**], M.Toda[1], A.Takagi[1], M.Yoshii[1]
KEK, 3-2-1 Midori-cho, Tanashi, Tokyo 188, Japan
[1]KEK, 1-1 Oho, Tsukuba, Ibaraki 305, Japan

Abstract

A push-pull amplifier with two tetrodes, 4CW30,000A, is used to drive a MA(Magnetic Alloy)-loaded cavity[1]. The amplifier generates an accelerating voltage of 40kV for the barrier-bucket experiment[2] planed at the Brookhaven National Laboratory. For this purpose, it is suitable that the cavity has a broad band impedance and the amplifier also has a wide band width more than 8MHz, although it will be operated around 2MHz of the fundamental RF frequency.

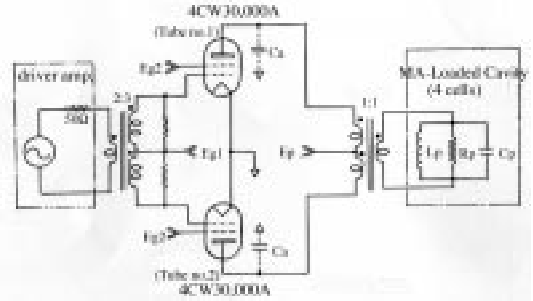

Figure 1: schematic view for the RF system.

1 INTRODUCTION

With respect to the accelerating voltage for the barrier-bucket experiment, requirements are as follows: it is to develop up to about 10kV at the accelerating gap of a cell where the MA-loaded cavity is composed of 4 cells; and it is an isolated sine-wave which should be less distorted; and it has a frequency of 2MHz and repetition rate of 357kHz. In order to meet the requirements, a push-pull amplifier in class B has been designed and tested; and the the impedance including the cavity and the plate circuits of the amplifier has been measured and adjusted as reported hereunder.

2 PUSH-PULL AMPLIFIER

The push-pull amplifier with two 4CW30,000A tetrodes has generated an accelerating voltage of 10kV at every gap of the MA-loaded cavity. A schematic view for the RF system including the cavity and the amplifier is shown in Figure 1.

Particular mention for the given push-pull amplifier are as follows;

- The high accelerating voltage approaching to that of the plate bias-supply will be attained if an adequate driving voltage is applied to the grid input of the amplifier.
- The MA-cores of the cavity are available as cores of choke transformer for the plate power supply.

With respect to tube performance of the push-pull amplifier, the measured and calculated values are presented in Table 1. The measured data was taken when the amplifier was driven by the isolated sine-wave which has a frequency of 3MHz and repetition rate of 357kHz. The calculated values are obtained from the operating line on the constant-current curves for the tube by reading the instantaneous values of plate, screen and grid current during half cycle of the plate voltage swing. The values of current flowing at every 15^{o} of the electrical cycle are get over the operating line on the curves. The values presented in Table 1 are those during the positive half cycle. In order to get the isolated sine-wave which has the same voltage swing for each of a half cycle, we made adjustments for both the screen and grid voltage of each tube.

In Table 1, the measured value of DC plate current is much higher than the calculated value. As it is later described that the parasitic resonance is observed in the plate circuit, we suppose that the applicable current for the parasitic resonance which flows through the tube would be added to the plate current. Furthermore, the current values estimated from the constant-current curves based on $E_{g2} = 1100V$ will be fairly higher than the value calculated from $E_{g2} = 1000V$.

The fundamental power P_f for the isolated sine-wave in barrier mode operation is given by $P_f = \frac{1}{2}\epsilon_p J_p$ With referring ϵ_p and J_p in Table 1, the value of the power is calculated to be about 130kW which is not less than that attained in pulse mode operation. That is to say, we would notice the remarkable swing of the plate voltage and current exceeding normal ratings of the tube.

3 EQUIVALENT CIRCUIT

An equivalent circuit for the RF system including the cavity and the push-pull amplifier is shown in Figure 2. Since the tubes are operated in push-pull class B, one of the two tubes supplies current to the circuit while the other is in cutoff for one -half of each cycle. Consequently the equivalent generator will be one with internal resistance equal to r_p of the tube, where r_p is one of the tube parameters defined as

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[*] Also the Japan Steel Works, Ltd.

[†] Also ICR, Kyoto Univ.

[‡] Also Hitachi, Ltd.

[§] Also Toshiba, Ltd.

[¶] also Univ. Tokyo

[‖] Also RCNP, Osaka Univ.

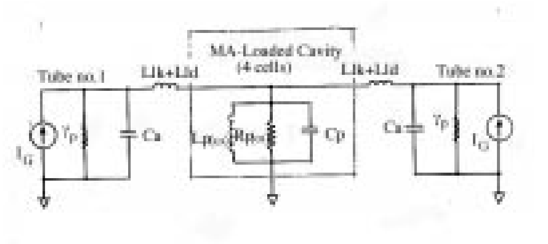
[**] On leave from the Bureau of Basic Sciences of Academic China

		Measured value	Calculated value
Plate voltage	E_p	11kV	11kV
DC idling current	I_{p0}	0.6A	0.6A
DC plate current	I_p	3.85A	2.6A
DC screen voltage	E_{g2}	1100V	1000V
DC screen current	I_{g2}	140mA	96mA
DC grid voltage	E_{g1}	-190V	-190V
DC grid current	I_{g1}	10mA	5mA
Driving grid voltage	ϵ_g	470V	470V
Fundamental plate vol.	ϵ_p	9.7kV	9.7kV
Fundamental plate curr.	J_p	–	26.8A
Peak plate voltage	e_{pm}	1.3kV	1.3kV
Peak plate current	i_{pm}	–	55A
Plate input power	W_i	42.4kW	28.6kW
Plate output power	W_o	–	15.5kW
Accelerating voltage	V_{gap}	9.8kV$_p$	–

Table 1: tube performance of push-pull amplifier

$$\left.\frac{\partial e_p}{\partial i_p}\right|_{E_{g1},E_{g2}} \equiv r_p \text{ :plate resistance.} \tag{1}$$

The r_p can be obtained from a tilt of $\Delta e_p/\Delta i_p$ on the constant current curves with control grid E_{g1} and screen grid E_{g2} being kept constant. The r_p of the tube 4CW30,000A is about 2.3kΩ at effective plate voltage.



$L_p(\omega)$:parallel inductance of cavity, $R_p(\omega)$:shunt resistance of cavity,
C_p:parallel capacitance of cavity, L_{lk}:leakage inductance of loop,
L_{ld}:lead inductance of plate, C_a:plate capacitance of tube,
r_p:plate internal resistance,
I_G:current source generated by amplifier

Figure 2: equivalent circuit for RF system.

The cavity consists of 4 cells, one cell of which has an accelerating gap and is electrically identical to another and is connected at the gap in parallel with one another. Therefore each of parallel inductance $L_p(\omega)$ and shunt resistance $R_p(\omega)$ shown in Figure 2 is a quarter of that of one cell respectively. Both values of $L_p(\omega)$ and $R_p(\omega)$ are dependent on frequency as shown in Table 2 in which the presented values are calculated from measured data for three points of frequency. On the other hand the value of parallel capacitance C_p is 4 times of that of one cell and is calculated to be about 100pF for the given cavity.

The C_a in Figure 2 is plate capacitance of the tube, the value of which is 43pF measured by a network analyzer.

frequency[MHz]	1.4	5.0	10.0
$L_p(\omega)[\mu H]$	68.1	22.1	15.0
$R_p(\omega)[\Omega]$	232	281	341

Table 2: parallel inductance $L_p(\omega)$ and shunt resistance $r_p(\omega)$

The leakage inductance L_{lk} in Figure 2 is derived from leakage flux which links only the coupling loop but not MA-cores. The energy W stored in the volume V in which only leakage flux exists is given by $W = \frac{1}{2}\int_V \mu_0 |\mathrm{H}|^2 dV$, where the magnetic field intensity H produces leakage flux. The energy can also be expressed as $W = \frac{1}{2}L_{lk}I^2$, where the current I flows through the coupling loop. Equating the above two expressions for W, we obtain

$$L_{lk} = \frac{1}{I^2}\int_V \mu_0 |\mathrm{H}|^2 dV \tag{2}$$

Then the volume of L_{lk} is calculated to be about 1μH for the given cavity.

The lead inductance L_{ld} in Figure 2 is self-inductance of the conductor between the coupling loop and the tube plate. It may be expressed as

$$L_{ld} = \frac{\mu_0 l}{2\pi}\left(\log\frac{2l}{R} - 1\right) \tag{3}$$

where l is length of the conductor and R is geometrical mean distance for the conductor itself. The value of L_{ld} is calculated to be about 1.1μH for the given conductor.

4 IMPEDANCE CHARACTERISTIC

By means of a network analyzer, we measured the impedance characteristic observed from the plate of one tube involving the cavity and the plate circuits of the amplifier. Figure 3 shows the characteristic curves which have fundamental resonance at the frequency of 1.3MHz, series resonance at 6.3MHz and parallel resonance at 12.8MHz. On the Table 3 these resonant frequencies and impedances are shown together with the calculated frequencies which are derived from reactance function[3] described below.

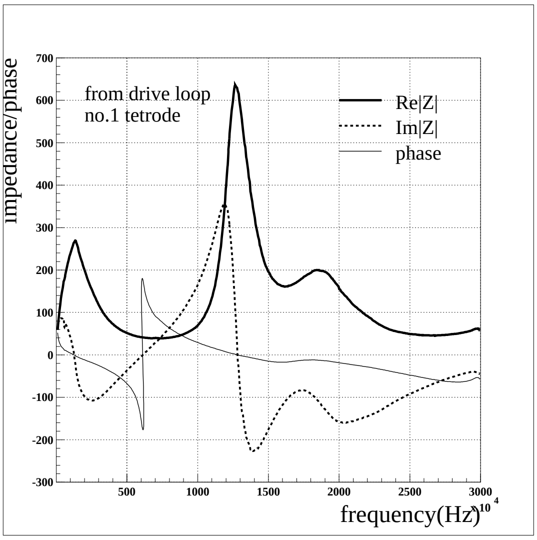
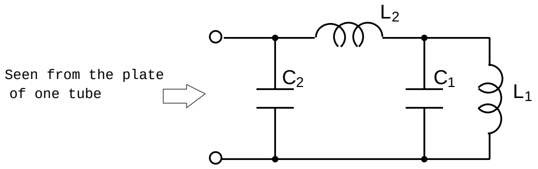


Figure 3: impedance curves

Measured		Calculated resonant freq.[MHz]
Resonant freq.[MHz]	Resonant impedance ReZ[Ω]	
f_0:1.3	260	1.4
f_1:6.3	40	7.1
f_2:12.8	640	13.5

Table 3: resonant frequency and impedance

The equivalent circuit in Figure 2 may be simplified furthermore to the reactance circuit in Figure 4 which would be useful for the purpose of investigating resonant frequency of the circuit.



$$C_1 \simeq C_p + C_a, L_1 \simeq L_p$$
$$L_2 \simeq 2(L_{lk} + L_{ld}), C_2 \simeq Ca$$

Figure 4: reactance circuit

The reactance function $jX(\omega)$ seen from one-port terminal of the reactance circuit can be expressed as

$$jX(\omega) = \frac{j\frac{\omega}{C_2}\left(\frac{L_1+L_2}{C_1L_1L_2} - \omega^2\right)}{\omega^4 - \omega^2\left(\frac{1}{C_1L_1} + \frac{1}{C_2L_2} + \frac{1}{C_1L_2}\right) + \frac{1}{C_1L_1C_2L_2}}$$

Finding for the zero and pole points of the above function, we obtain resonant frequencies as follows;

for low frequency f_0 around 1MHz where L_2 is negligible,

$$\text{parallel resonant } f_0 = \frac{1}{2\pi\sqrt{L_1(C_1+C_2)}} \qquad (4)$$

for intermediate frequency f_1 from 5 to 10MHz,

$$\text{series resonant } f_1 = \frac{1}{2\pi\sqrt{C_1(\frac{L_1L_2}{L_1+L_2})}} \qquad (5)$$

for high frequency f_2 above 10MHz, where $\frac{1}{L_2}(\frac{1}{C_1} + \frac{1}{C_2}) \gg \frac{1}{C_1L_1}$

$$\text{parallel resonant } f_2 = \frac{1}{2\pi\sqrt{L_2(\frac{C_1C_2}{C_1+C_2})}} \qquad (6)$$

In the Table 3, the values of resonant frequencies calculated from the above formulas are nearly equal to those of measured frequencies. Since the voltage waveform developed at accelerating gap should be less distorted for barrier mode operation, the parallel resonant frequency f_2 is expected to be much higher than the fundamental frequency f_0. According to the formula (6), the more the values of C_1, C_2 and L_2 are reduced, the higher frequency f_2 will be obtained.

5 PARASITIC RESONANCE

A few parasitic resonances which would be formed with some combinations among the tube plate capacitor, the coupling loop for inductance, the by-pass capacitors of the plate power supply, etc. were found on the impedance characteristics seen from the plate of one tube involving the cavity and the plate circuits of the amplifier.

Intending to suppress parasitic resonances in the high frequency region above 10MHz, we put a damper set of coil and resistor in the plate lead between the plate of the tube and the coupling loop. The damper is made up of non-inductive resister of 90ohms, shunted by copper wire coil of 1μH which is wound around the resistor. The resistor-coil damper operates on the principle that resistor loads the HF parasitic circuit but is shunted by the coil for the lower fundamental frequency of 2MHz. By means of the damper we have successfully suppressed parasitic resonances above 17MHz, but the parasitic around 12MHz is still observed ont he waveform of the plate current. If the inductance of the damper coil is allowed to increase much more than 1μH, the parasitic around 12MHz will be suppressed and the damper resister will run too hot due to dissipation of the fundamental power, resulting in decrease of fundamental voltage developed in the cavity.

In order to damp the low frequency resonance around 1MHz, we put another damper set in the plate power supply between by-pass capacitors. This damper is made up of no-inductive resistor of 8 ohms, shunted by copper wire coil of 5μH. In this case the 8 ohms-resistor must be fully cooled because considerable amount of current for both the low resonant frequency and the fundamental frequency flows in the resister. By means of this damper we have eliminated the objectionable oscillation around 1MHz which occured at the end of isolated sine voltage generated in the fundamental frequency.

6 REFERENCES

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