WIDE-BAND PUSH-PULL AMPLIFIER FOR HIGH GRADIENT CAVITY

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Abstract

A high gradient cavity(HGC) using high permeability magnetic alloy (MA) cores has been developed at KEK for the JHF(Japan Hadron Facility) proton synchrotrons. In this paper, we describe two types of push-pull amplifiers to drive the cavity, which were constructed for verifying the cavity performance. An accelerating voltage of 20kV across the gap of the HGC was generated by the high power push-pull amplifier. This is equivalent to high gradient field of 50kV/m. The other amplifier and the cavity were prepared for accelerating heavy ions at the HIMAC(Heavy Ion Medical Accelerator in Chiba). For this purpose, it is necessary to sweep the frequency over the wide range from 1MHz to 8MHz.

1 INTRODUCTION

In order to generate a high field gradient with HGC using MA-cores, a high power push-pull type of rf amplifier which uses two 150kW class tetrodes (4CW150,000E) was constructed. The HGC with MA has the following two remarkable features: (1)the ability to generate high gradient field up to 50kV/m and (2)broad band impeadance over the frequency range of 5MHz. The characteristics of the HGC with MA have been reported [1, 2, 3, 4]. We have built in the medium power push-pull amplifier using two 30kW class tetrodes (4CW30,000A) for acceleration of heavy ions at HIMAC.

2 PUSH-PULL AMPLIFIER

A schematic view for the RF system including the cavity and the amplifier is shown in Figure 1. The push-pull amplifier in class-B operation has the following two features: (1)The high rf output voltage close to dc plate voltage can be obtained. That is, the plate dissipation is less than that of an amplifier in class-A operation. (2)The output voltage will be less distorted even if a tuning circuit is not utilized for the load cavity. This is because the even harmonics introduced by nonlinearity of the dynamic-tube characteristics are eliminated at the output by a push-pull connection.

2.1 300kW Push-pull Amplifier

Concerning the tube performance of the push-pull amplifier using two tetrodes 4CW150,000E, the measured and calculated specifications are presented in Table 1.

Parameter	Measured value	Calculated value
DC plate voltage V_p	15kV	15kV
DC idling current I_{po}	2.9A	1.0A
DC plate current I_p	3.71∼6.84A	5.94A
DC screen voltage V_{g2}	1550V	1500V
DC screen current I_{g2}	not measured	466mA
DC grid voltage V_{g1}	−390V	−390V
DC grid current I_{g1}	65∼87mA	44mA
Driving grid voltage E_g	602V	602V
Fundamental plate curr. I_{p1}	−	25.7A
Peak plate voltage E_{pm}	14kVp	14kVp
Peak plate current I_{pm}	not measured	85A
Plate input power W_i	55.7∼102.6kW	89.1kW
Plate output power W_o	−	59.0kW
Plate dissipation W_l	55.4kW(max.)	30.1kW
Voltage at gap end V_{gap}	−14kVp, +7.2kVp	±14kVp
Accelerating voltage V_{acc}	±16kVp	−

Table 1: Tube performance of the 300kW push-pull amplifier.

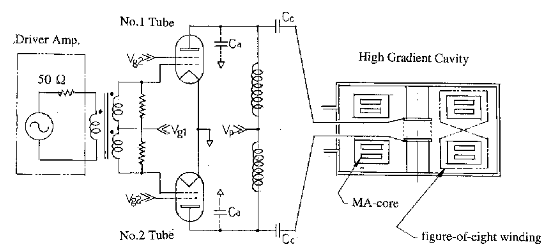

Figure 1: Schematic view for the RF system.

The measured values were taken when the amplifier was operated at 20% duty factor in burst mode sweeping the frequency from 2MHz to 3.4MHz with repetition rate of 2Hz. The calculated values were derived from the operating line on the constant-current curves for the tube by reading the instantaneous values of plate, screen, and grid current during the negative half cycle of the plate voltage swing. In order to compare the measured values to the calculated ones, the calculated values for I_p, I_{g2}, I_{g1}, W_i, W_o and W_l are adjusted to 20% duty factor operation. The measured value of idling current I_{po} was higher than the calculated value. This means that the amplifier was in class AB_2 operation mode, where the conduction angle of plate current was more than 180^o and grid current was flowing. Thus the measured plate dissipation W_l was rather higher than the calculated one.

Since the MA-loaded HGC has a low-Q(< 1) value and the cavity is directly connected to the plate of the amplifier via a low impedance capacitor(C_c) as shown in Figure 1, the plate voltage swing would substantially depend on the cavity impedance. The cavity impedance can be estimated by dividing the peak plate voltage by the peak plate current : $E_{pm}/I_{pm} = 165\Omega$. This would be consistent with the cavity impedance of approx. 178Ω at 2.3MHz which was measured from the plate by a network analyzer.

Since the rf plate current at a positive rf half cycle is nearly zero, the power delivered by one tube is about a half of W_o, which is given by $W_o = E_{pm} \cdot I_{p1}/2$, Thus the power W_o is almost the output power delivered by two tubes. Using the values of E_{pm} and I_{p1} presented in Table 1, the power W_o becomes 295kW in cw mode operation. Taking account of rather high dc screen current I_{g2} in Table 1, we should be carefull that the screen dissipation can not exceed the normal rating of the tube. It would be pointed out that the excessive driving power at the control grid should be avoided because it may allow instantaneous plate voltage drop lower than the dc screen voltage, resulting in abnormal screen dissipation. In addition, if the dc plate voltage can be raised, it may contribute not only to decrease screen dissipation but to reduce the distortion of the accelerating voltage waveform, which may be introduced by plate current saturation.

2.2 60kW Push-Pull Amplifier

The MA-loaded HGC and the 60kW push-pull amplifier with two tetrodes 4CW30,000A were installed at HIMAC. In order to accelerate heavy ions at HIMAC, it is necessary to sweep the frequency over the wide range from 1MHz to 8MHz. The accelerating rf voltage depends not only on the characteristics of the shunt impedance, but also the gain-frequency characteristics of the amplifier. With respect to the 60kW push-pull amplifier, a maximum gain drop at the grid input circuit was 4.6dB at the frequency range from 1MHz to 8MHz. Thus proper voltage control was employed to obtain the constant rf voltage [3, 5, 6].

3 EQUIVALENT CIRCUIT AND COUPLING METHOD

3.1 Equivalent Circuit for the RF system

The impedance seen from the tube was measured by a network analyzer. It includes both impedance of the cavity and the plate circuit of the amplifier. The Figure 2 shows the measured impedance where the fundamental resonance was stayed at 2.3MHz, on the other hand, series resonance was at 14.8MHz and parallel resonance was at 21.5MHz, respectively. The impedance is almost equal to the shunt impedance Z_s corresponding to one-half of the cavity at low frequency region below 5MHz, even though two-halves of the cavity are coupled each other with the capacitance C_g for the accelerating gap. This would be justified by a comparison : $|1/\omega C_g| \gg |Z_s|$, where $|1/\omega C_g| \cong 3.8k\Omega$; $|Z_s| \leq 178\Omega$ around the frequency of 2.3MHz. The value of Z_s can be estimated by the parameters L_p, C_p and R_p of the equivalent circuit shown in Figure 3. The shunt resistance R_p at fundamental resonance is 178Ω as above-mentioned. On the other hand, the impedance seen from the both ends of the gap is almost twice the R_p which is reported by the referenced paper [3]. It would be explained as the impedance quite corresponds to that of two-halves of the cavity.

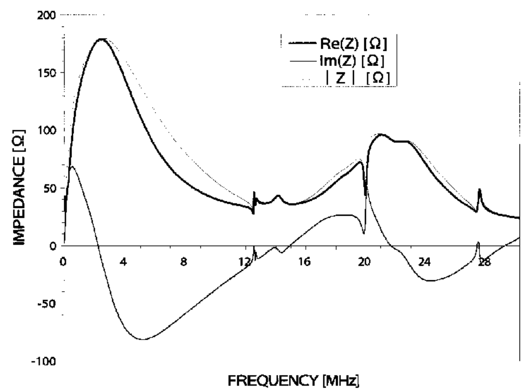

Figure 2: Impedance characteristics seen from the plate of one tube.

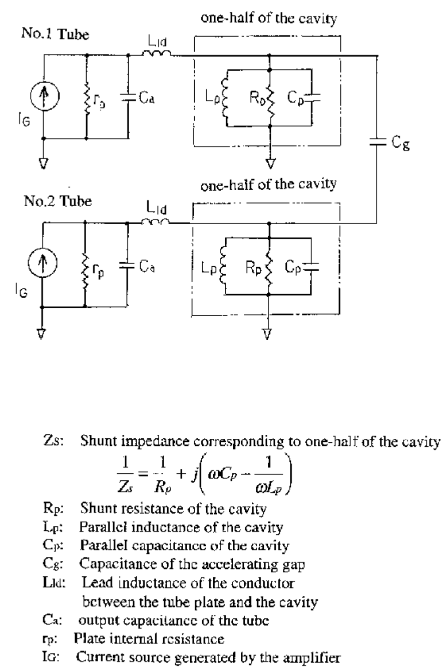

Figure 3: Equivalent circuit for the RF system.

3.2 Coupling Method with Figure-of-Eight Winding

By means of coupling two-halves of the cavity with a figure-of-eight winding looped through each other, the RF cavity is intrinsically capable of operating in a push pull mode [7]. Due to this coupling a load impedance seen from the plate substantially becomes one half of the shunt impedance Z_s. The figure-of-eight winding works as a transformer as shown in Figure 5. The characteristics of load impedance for the cavity with this coupling is also represented in Figure 4. The load impedance which is one half of the Z_s may cause a plate dissipation to increase, because it may deteriorate the matching condition of the impedance between the plate and the cavity.

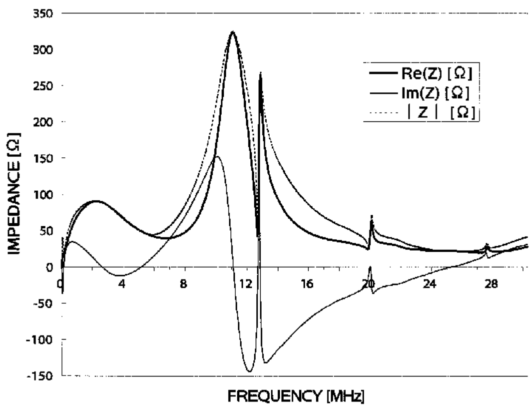

Figure 4: Impedance characteristics of the cavity seen from the plate of one tube; Two halves of each cavity are looped with a figure-of-eight winding.

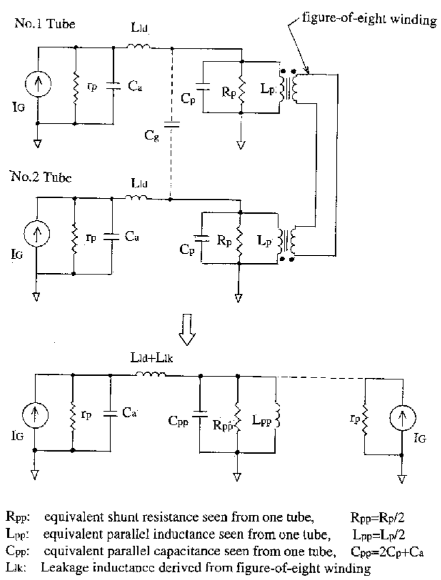

Figure 5: Equivalent circuit for two-halves of the cavity coupled with a figure-of-eight winding.

A parasitic resonance at the frequency around 11MHz can cause harmful distortion to the accelerating voltage. The circuit with this coupling can be simplified as a reactance circuit shown in Figure 6. Applying a same reactance function described in the previous paper [8], parallel resonant frequency f_h will be given by the following equation.

$$f_h = 1/2\pi\sqrt{L_2\left(\frac{C_1C_2}{C_1+C_2}\right)}$$

In the equation, L_2 comprises leakage inductance L_{lk} and lead inductance L_{ld}, C_2 is the tube capacitance and C_1 is the sum of the tube capacitance and total capacitance for two-halves of the cavity. Assuming parameters as shown in Figure 6, f_h is calculated to be about 13.5MHz, which is not so large different from the measured value of 11.0MHz. The figure-of-eight winding intrinsically introduces a parasitic resonance and allows its frequency lower. We did not adopt the figure-of-eight winding.

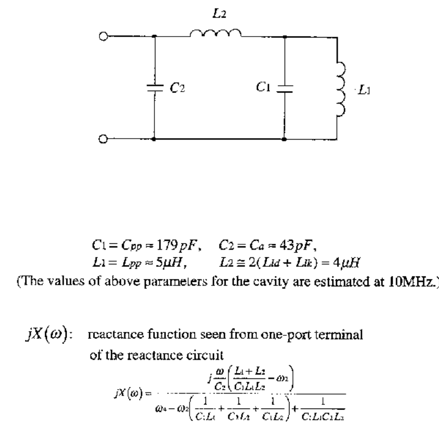

Figure 6: Reactance circuit.

4 CONCLUSION

A push-pull amplifiers using two tetrodes 4CW150,000E has delivered the output power of 295kW in cw mode to generate an accelerating voltage of about 16kV in the HGC. The maximum voltage of 20kV was achieved at a small duty factor operation. Another amplifier using two tetrodes 4CW30,000A has generated an rf voltage of about 4kV at 3MHz when sweeping the frequency from 1MHz to 8MHz. Further investigation and development to improve the gain-frequency characteristics of grid input circuit are going to be carried out.

We have investigated a figure-of-eight winding coupling. We found that the impedance seen from the tube drops to a quarter of the total cavity shunt impedance and a parasitic resonance is inevitably introduced.

5 REFERENCES

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