RF CAVITIES AND POWER AMPLIFIER FOR THE COMPACT PROTON SYNCHROTRON

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Abstract

A project to build a compact proton synchrotron is now underway [1-4]. Protons will be accelerated from 2 MeV to 200 MeV within 5 ms with an operation repetition rate of 10 Hz, in the synchrotron ring with a circumference of 11.9 m. The acceleration system is required to be of a wide bandwidth, with the frequency sweeping from 1.64 MHz to 14.26 MHz, and of a high gradient, with the maximum acceleration voltage of 20 kV. The acceleration section, consisting of a 2-cell rf cavity loaded with 4 high-permeability magnetic alloy cores in each cell, has been designed. A push-pull power amplifier with two 35 kW tetrode tubes will be used to drive the 2 cavities in parallel. Calculations and test results on the cavity characteristics will be presented and discussed, including the cavity impedance and equivalent circuit. The simulation results of the amplifier system using the ICAP code will also be given. The prototype of the rf system is being developed, and a high power test will be performed soon.

1 INTRODUCTION

For the compact design of the proton synchrotron [1-4] the acceleration system is required to be of a wide bandwidth and high gradient [5]. A 2-cell rf cavity loaded with 4 high-permeability magnetic alloy cores in each cell has been designed as shown in Fig. 1. The core dimension is 397 mm and 170 mm in outer and inner diameters, and 25 mm in length. The length of each cell is 200 mm, and the total length of the acceleration section is 500 mm. A push-pull power amplifier with two tetrode tubes 4CX35,000C will be used to drive the 2 cavities in parallel.

Figure 1: Structure of the rf cavity.

The rf frequency and required gap voltage as functions of acceleration time are shown in Fig. 2.
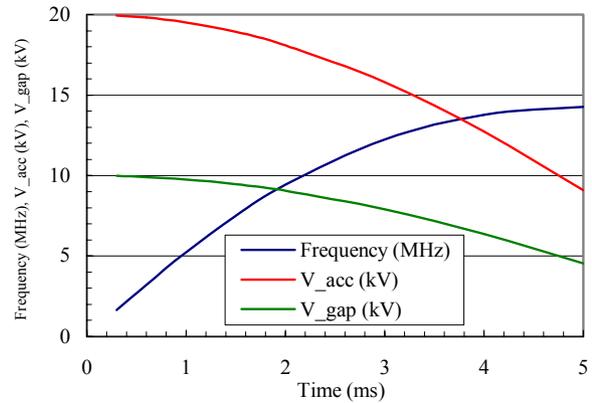
Figure 2: RF frequency and required gap voltage as functions of acceleration time.

2 RF CAVITY

2.1 Test of Cavity Model and Core Permeability

We made a test model with one quarter of the rf cavity, filling with 2 cores only in one side of the gap, and measured the cavity impedance. In this model, the equivalent circuit is a parallel circuit of lumped elements of cores and a gap capacitor C_g. The cavity impedance is:

$$Z_{cav} = \cfrac{1}{\cfrac{1}{j\omega(u'-ju'')L_0} + j\omega C_g}$$

where $u = u' - ju''$ is the complex permeability of cores,

and $L_0 = \dfrac{u_0}{2\pi}h\ln\dfrac{b}{a} = 2\times10^{-7}\times h\ln\dfrac{b}{a}$, where a and b are the inner and outer diameters of cores, and h is the core length.

The measured value of core permeability is:

$$u' = 3000\times(\frac{f}{0.5})^{-1} \quad \text{and} \quad u'' = 6000\times(\frac{f}{0.5})^{-0.8}$$

where f is in MHz.

The calculation results of impedance for different gap capacitance and test results of the cavity model are shown in Fig. 3. It is shown that the test results agree with the calculation results very well. And in this model the gap capacitance is about 28 pF.
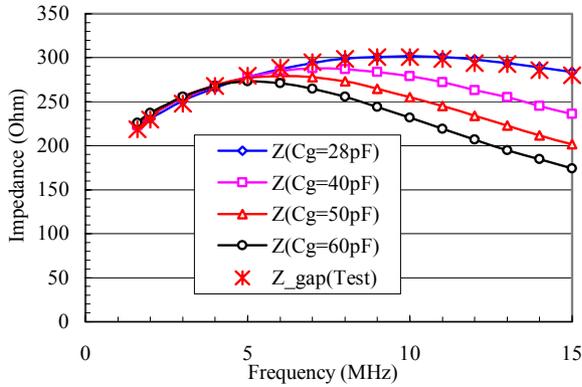
a) Impedance amplitude
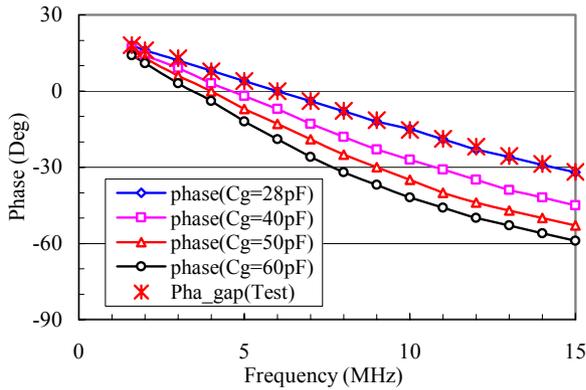
b) Impedance phase

Figure 3: Calculation results of impedance for different gap capacitance and test results of the cavity model.

2.2 Equivalent Circuit of RF Cavity

Since the cavity wall is connected to the ground, for the rf cavity (see Fig. 1) which is driven by a push-pull amplifier, the equivalent circuit is shown in Fig. 4. In Fig. 4, R_{1a}, L_{1a}, and C_{1a} are the core resistance and inductance, and the distributed capacitance at one side of gap for the first cell. R_{1b}, L_{1b}, and C_{1b} are the ones at the other side of gap. C_{g1} is the distributed capacitance at gap area. Similar parameters are used for the second cell.
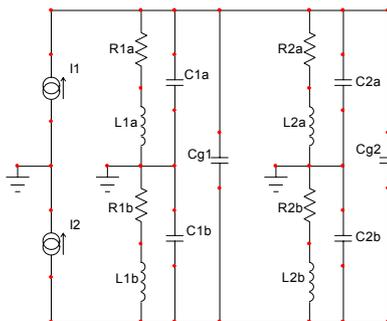
Figure 4: Equivalent circuit of rf cavity.

From the equivalent circuit, each cell of the rf cavity can be separated into two cavities same as the model cavity we made. That is, the total rf system consists of 4 units with 2 cores in each unit. The impedance of each unit given in Fig. 3 shows a good performance of frequency response, and the impedance is used to calculate the necessary rf driving current and power. For our case, the impedance of each unit is about 220 Ohm at 1.64 MHz, and the required maximum rf voltage is 5 kV, so an rf current of 23 A is necessary for each cell. And for one tube, the maximum rf current should be about 46 A, namely, the maximum plate current should be larger than 92A.

3 POWER AMPLIFIER

3.1 Simulation of RF system

In the rf system, two tetrode tubes 4CX35,000C is used to form a push-pull amplifier to drive the two cells of rf cavity. Each side of the cavity gaps is directly connected to the anodes of the two tubes through the DC blocking capacitors. The rf system has been simulated by using ICAP code, as shown in Fig. 5. The input and output capacitances of the tube are 440 pF and 51 pF, respectively. The anode and screen voltage are set as 10 kV and 2 kV, respectively. Due to the wide bandwidth, two rf driving sources are used for the two tubes respectively, and the phase difference between the two rf driving voltages is 180 degrees. The anode power supply is designed to be of maximum DC current of 100 A.
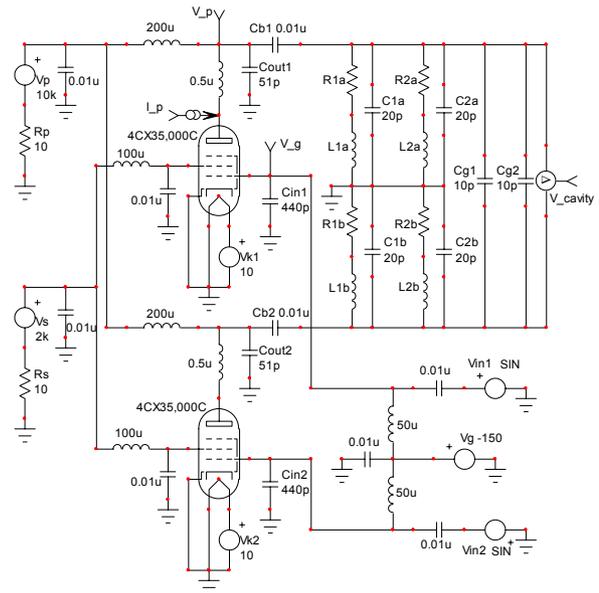
Figure 5: Simulation of rf system by using ICAP code.

Fig. 6 shows the simulation results at different acceleration time. It is shown that we can get the required voltage at gap by applying a driving rf voltage, which is nearly proportional to the ratio of the required gap voltage

to the impedance of one quarter of the rf cavities, which is shown in the black curve in Fig. 6. Fig. 7 shows one example of simulation results at 1.64MHz. From the simulation results, the rf system will work well to satisfy the rf requirements of the proton synchrotron.
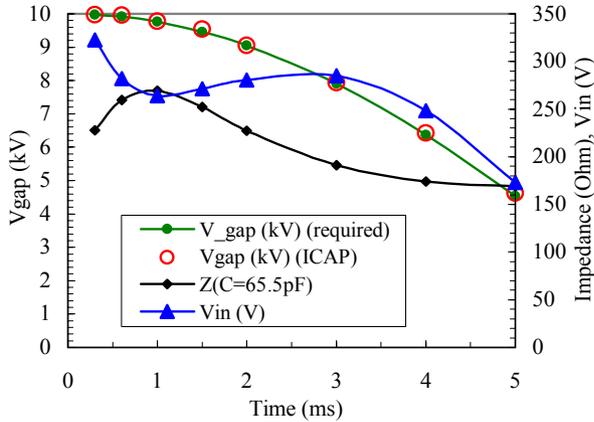
Figure 6: Simulation results of the rf system at different acceleration time.
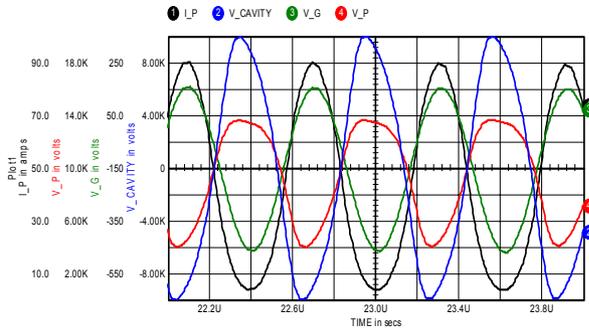
Figure 7: Example of simulation results at 1.64MHz. (I_P, plate current; V_CAVITY, cavity voltage; V_G, grid voltage; V_P, plate voltage)

3.2 Improvement of Cavity Frequency Response

From the simulation results, its also shown that the frequency response of cavity can be improved by inserting a small inductance about several μH between the amplifier tube and cavity, as shown in Fig. 8.
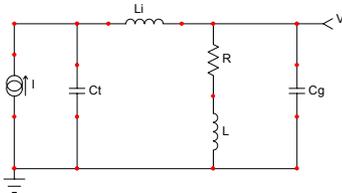
Figure 8: Equivalent circuit with an inductor inserted between the amplifier tube and cavity.

The amplitude ratio of cavity voltage to rf current is:

$$\frac{|V|}{|I|} = \sqrt{\frac{R^2 + \omega^2 L^2}{\left[1 - \omega^2 LC - \omega^2 C_t L_i (1 - \omega^2 LC_g)\right]^2 + \left[\omega R(C - \omega^2 C_g C_t L_i)\right]^2}}$$

where $C = C_t + C_g$.

If $L_i = 0$, then

$$\frac{|V|}{|I|} = \sqrt{\frac{R^2 + \omega^2 L^2}{\left[1 - \omega^2 LC\right]^2 + \left[\omega RC\right]^2}}$$

From the above formula, we can get the same conclusion that the cavity frequency response can be improved by inserting a small inductor (L_i). And the optimized value can be determined in the test process of rf system.

3 SUMMARY

The rf cavity has been designed to be of a wide broadband and high gradient, and a test model with one quarter of the rf cavity has been made. The test results agree with the calculation results very well. The power amplifier system with two tetrode tubes 4CX35,000C has been simulated by using ICAP code. The prototype of the rf system is being developed, and a high power test will be performed soon.

4 REFERENCES

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