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# An Untuned Type RF Cavity using Multiple Power Feeding

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*Abstract*

A ferrite loaded untuned type RF cavity has been fabricated and tested for a compact proton synchrotron dedicated for medical use. Using a new power-feed method named as multi-feed coupling, a gap voltage of more than 1kV has been achieved with the generator power of 1.5kW in the frequency range from 1.5MHz to 10MHz. These values satisfy the requirement of a few hundred volts for the medical synchrotron. The multi-feed coupling has been confirmed to be effective by high power tests. The temperature rise caused by power loss in ferrite cores was less than 25 degrees up from the room temperature at 2 hours after the start of the power feeding when the generator power was 1kW. This cavity can therefore be operated only by the forced air cooling system.

## 1. Introduction

Nowadays a compact proton synchrotron has been hoped to be used efficiently for treatment of tumors. We proposed a medical compact proton synchrotron which consists of combined type magnets with the circumference of about 23m[1]. In the compact synchrotron, due to its short circumference, the cavity voltage required in an acceleration process is relatively lower than that of a large synchrotron, though a wider operating frequency range is needed. Based on this condition, an untuned type RF cavity in which the tuning procedure of resonant frequency is not necessary, has been adopted as an accelerating system for the synchrotron[2]-[3].

Untuned type RF cavities have already been constructed in several laboratories[4]-[7]. These cavities consist of a quarter or a half wavelength coaxial resonator and magnetic materials with large permeability. Power loss caused by the imaginary part of the complex permeability in the magnetic materials plays an important role in obtaining a wide operating frequency range. However, in general, this effect makes it difficult to get a high accelerating voltage in the untuned type RF cavities. We have developed a new power-feed method named as multiple power feeding(multi-feed coupling) so as to increase the accelerating voltage over a wide frequency range compared with the conventional direct or push-pull power feeding. In section 2, the principle of the multi-feed coupling is described in brief. The construction of the high-power model cavity and experimental results of the multi-feed coupling are mentioned in section 3.

## 2. Multiple Power Feeding

An untuned type RF cavity is characterized as a simple RLC resonant circuit, in which R, L and C correspond to the resistance of the cavity, the inductance of the magnetic materials ( ferrite cores ) to obtain a wide operating frequency range, and the capacitance of the accelerating gap, respectively. In the direct coupling which is the usual method of power feeding, RF power generated by the power source is fed into the inner conductor directly and returned to the source through the outer conductor. The cavity voltage $V_d$ is given as

$$V_d = \sqrt{2P|Z_d|} = \sqrt{2\frac{4S}{(1+S)^2}P_g|Z_d|} \qquad (1)$$

where P, $P_g$, $Z_d$ and S are the net power, the generator power, the shunt impedance of the cavity and the value of voltage standing wave ratio(VSWR), respectively. The $Z_d$ depends only on the inductance L of the ferrite cores because their permeabilities are large enough to get the wide operating frequency range. As $Z_d$ increases, a large impedance mismatching between the cavity and the power source occurs and almost all of the generator power is reflected back to the power source. The $V_d$ cannot be in-

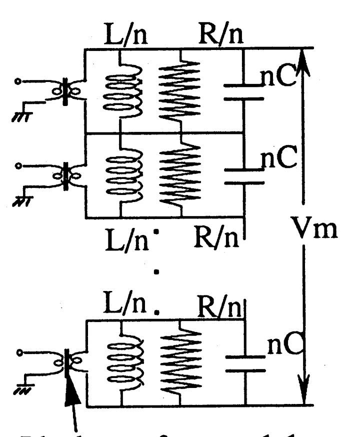


Fig. 1. Equivalent Circuit in Multi-feed Coupling.

creased because of the decrease in the net power fed into the cavity. The reflection power becomes too large to operate the power source under this condition. This effect is the main cause of lower accelerating voltage in the untuned type RF cavity.

In order to reduce the reflection power and increase the cavity voltage, the impedance mismatching must be improved keeping the cavity impedance higher. A new power-feed method, hereafter we call multiple power feeding (multi-feed coupling), was developed to solve this problem. Figure 1 shows the equivalent circuit in multi-feed coupling. The cavity and the generator are divided into the same number of sub-circuits as the loaded ferrite cores. Assuming n the loaded number of the ferrite cores, the cavity is represented by the series connection of n sub-circuits whose impedance is one-nth of that of the direct coupling. The coupling impedance between the cavity and the power source can therefore be decreased to one-nth while the total impedance is equal to that of the direct coupling. In this scheme, the reflection power is much reduced and the cavity voltage is increased by the series connection of the sub-circuits. The cavity voltage in the multi-feed coupling $V_m$ is given by

$$
\begin{aligned}
V_m &= \sqrt{2P|Z_m|} \\
&= n\sqrt{2\frac{4S/n}{(1+S/n)^2}\frac{P_g}{n}\frac{|Z_d|}{n}} \\
&= \sqrt{n}\frac{1+S}{n+S}V_d \qquad (2)
\end{aligned}
$$

where $Z_m$ is equal to the impedance of the sub-circuit given by $Z_d/n$. If the VSWR is large enough, $S>>n>1$, $V_m$ can be $\sqrt{n}$ times larger than $V_d$. However, if the VSWR S is nearly equal to n, $S=n>1$, $V_m$ can be $\sqrt{n}/2$ times larger than $V_d$. Hence, in the real cavity, $V_m$ is expected to be between $\sqrt{n}$ and $\sqrt{n}/2$ times of $V_d$. In this analysis, mutual inductances between the ferrite cores are ignored.

## 3. High Power Experiments

### *3.1 High-Power Model Cavity*

In low power level, the effects of multi-feed coupling have already been verified[2]-[3]. To confirm RF and thermal characteristics in the multi-feed coupling, the high-power model cavity has been fabricated and tested. The cavity has been constructed with a double re-entrant coaxial resonator and Ni-Zn ferrite cores manufactured by Hitachi Metals Ltd. The outer and inner diameters are 550mm and 160mm, respectively. The lengths of the cavity and the accelerating gap, vacuum-sealed by ceramic duct, are 400mm and 20mm, respectively. Photo 1 shows the high-power model cavity. The dimensions of the ferrite cores installed in the cavity are 500mm and 280mm in outer and inner diameters, respectively and 25.4mm in

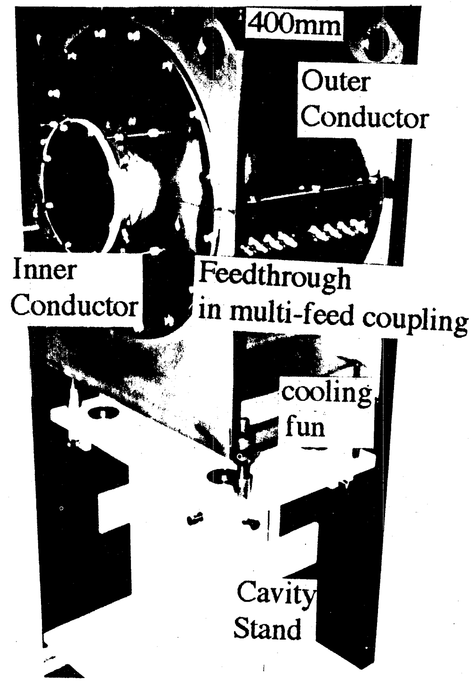


Photo 1. Photo of the high-power model cavity.

thickness with the complex permeability of about (1000,100) at 5MHz. The number of ferrite cores is 8 to increase the cavity voltage. In the multi-feed coupling, the same number of independent RF-power amplifiers are employed. The RF power is fed into the cavity through the one-turn coil wound on each ferrite core in such a way that the magnetic flux is generated in the same direction. At first, low power tests were performed to measure VSWR using a network analyzer. The experimental results show that the cavity can be operated from 1MHz to 10MHz which satisfies the proposed specification of the operating frequency range from 1.57MHz to 8MHz[1].

### *3.2 Measurement of Cavity Voltage*

Figure 2 shows the block diagram of measurements. The cavity voltage induced at the accelerating gap was measured with a voltage divider connected to the direct coupling loop. The voltage divider consists of capacitors of 1pF and 100pF, giving the dividing ratio of 1/100. Figure 3 shows the dependence of the cavity voltage on the generator power and the operating frequency. The generator power $P_g$ means the total power toward the cavity. Up to 2kW, RF power can be fed into the cavity stably in the multi-feed coupling. The cavity voltages at the frequency of 2MHz, 4MHz and 8MHz are indicated with blackened circles, squares and open circles, respectively. It is obvious that the cavity voltage of more than 1kV was achieved with almost flat property in the required operating frequency range from 1.5 to 8MHz. The experimental result satisfies the voltage of 500V required for a medical compact proton synchrotron. Figure 4 shows the frequency dependence of the cavity voltage normalized by the value in the case of the direct coupling. Measurements with the

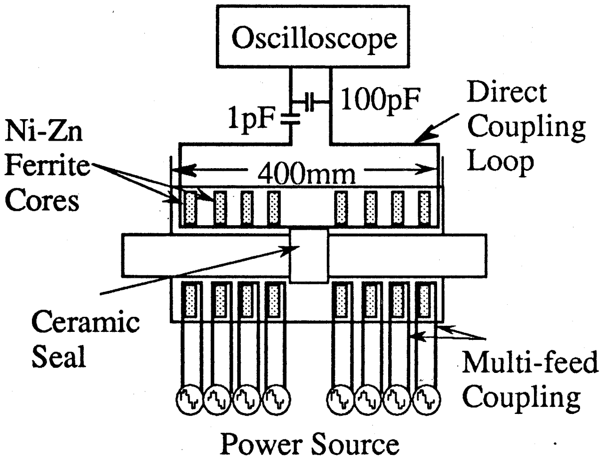


Fig. 2. The block diagram of high power measurement.

feed power of more than 200W were not carried out in the direct coupling, because the waveform of the cavity voltage was deformed. The figure presents the measured values at $P_g$=200W. Blackened circles and solid line indicate the experimental results and the calculated values, respectively. The latter is obtained from equation (2) by using the VSWR measured by the low power experiments. Measured and calculated values are in good agreement. Mean value of the voltage ratio is 1.8 which can be explained by equation (2) substituting n=8 and S=13. It also confirmed

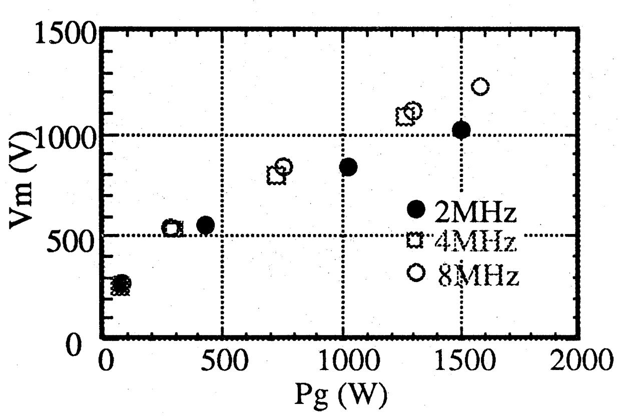


Fig. 3. The generator power and frequency dependence of the cavity voltage.

the effects of the multi-feed coupling.

The cooling system consists of only two forced air-cooling fans which are attached to the lower part of the outer conductor. The temperature rise of the cavity wall and ferrite cores was measured under $P_g$ = 1kW, and the highest values are plotted in figure 5. The temperature reached the equilibrium value, namely, 25 degrees up from the room temperature, at 2 hours after the start of the power feeding. The result shows the cavity can be driven only by the forced air-cooling.

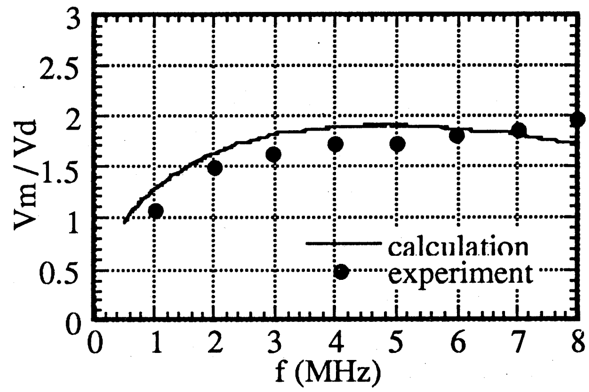


Fig. 4. The frequency dependence of the voltage ratio normalized by the direct coupling.

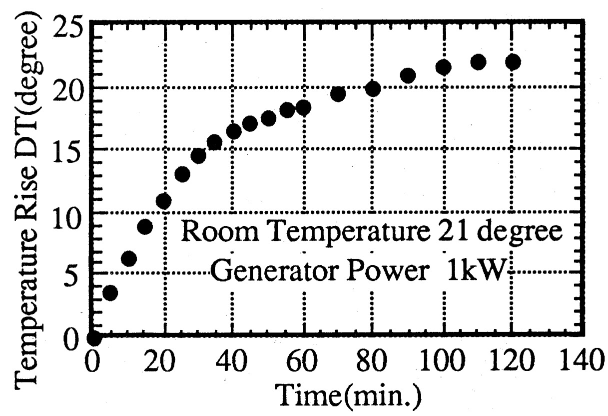


Fig. 5. The temperature rise under Pg= 1kW.

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