Bull. Inst. Chem. Res., Kyoto Univ., Vol. 73, No. 1, 1995

A Ferrite-Loaded, Untuned Cavity with Multiple Power Feeding

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Received February 3, 1995

A small untuned-type RF cavity using a half wavelength coaxial resonator and Ni-Zn ferrite cores with highly complex permeability has been designed for a dedicated compact medical proton synchrotron in Kyoto University. The operating frequency range is between 1.5 and 7.8 MHz. A new method for power feeding named as multiple power feeding (multi-feed coupling) opposed to conventional direct coupling was developed to increase accelerating voltage. In this method, RF power is fed into the cavity through a one turn coil which is wound on to each ferrite core. For the case with six ferrite cores in the cavity, it is possible to get an accelerating voltage about 1.7 times as large as that of direct coupling.

KEY WORDS: Proton Therapy/ Untuned Cavity/ Multiple Power Feeding/ Multi-feed Coupling

1. INTRODUCTION

Recently, proton therapy has been confirmed to have significant advantages for treatment of tumors. In clinical use, the accelerator system should be able to be operated by non-professionals, for example, a medical doctor, a nurse or a technician, and it should be acceptable in public hospitals. To irradiate various depths of tumors in a human body, proton beam energy must be varied from 70 to 230 MeV. Based on the these relatively low energy region of the proton beam and the need for easy operation of the accelerator system, an untuned-type RF cavity in which no resonating frequency tuning procedure is necessary can be adopted as an accelerating system for the synchrotron.

Untuned-type RF cavities have already been constructed in several laboratories[1-4]. These cavities consist of a quarter or a half wavelength coaxial resonator and magnetic materials with a large permeability. The RF power loss in the magnetic materials caused by the imaginary part of the complex permeability plays an important role in obtaining a wide operating frequency range. However, in general, this power loss in materials makes it difficult to get a high accelerating voltage in the untuned-type cavity. We developed a small ferrite-loaded, untuned-type RF cavity and a new method of power feeding so as to increase accelerating voltage over a wide operating frequency range for the medical proton synchrotron. In section 2, the principle of the new power feed method is described. The construction and performances of the untuned-

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type cavity are depicted in section 3. Experimental verification of the new power feed method is also given.

2. METHOD OF POWER FEEDING

2.1 *Direct Coupling*

At first, the usual method of power feeding, known as direct coupling, is considered. Figure 1 shows a schematic view of the conventional untuned-type RF cavity adopted in Loma Linda University Medical Center[5,6]. Figure 2 shows the equivalent circuit of direct coupling. The untuned cavity is given as a simple RLC resonant circuit. In the figure, R, L and C of the circuit correspond to resistance of the cavity wall, inductance of ferrite cores, and capacitance of the accelerating gap, respectively. Then RF power generated by the RF 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

$$V_d=\sqrt{2P|Z_d|}\,, \tag{1}$$

where P and Z_d are net power and the impedance of the cavity, respectively. They are given by

$$P=(1-|\Gamma|^2)P_g,$$
$$|\Gamma|=\left|\frac{Z_d-Z_0}{Z_d+Z_0}\right|=\frac{S-1}{S+1},$$

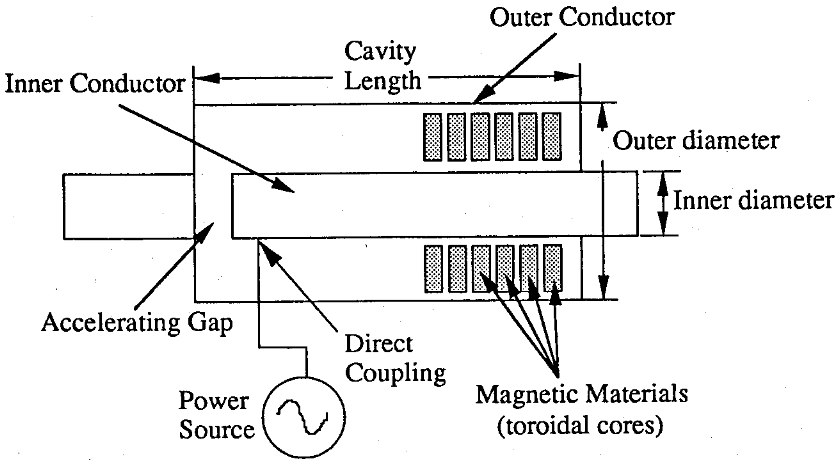
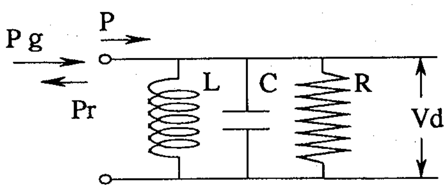


Fig. 1. Conventional untuned-type RF cavity using a quarter wavelength resonator.



P: Net Power, Pg: Forward Power
Pr: Reflection Power

Fig. 2. Equivalent circuit of direct coupling.

Thus, the following equation is obtained,

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

where Γ is the complex reflection coefficient of the cavity, P_g is the forward or generator power, Z_0 is the characteristic impedance of the power source, and S is the value of the Voltage Standing Wave Ratio (VSWR). The cavity impedance Z_d depends only on the inductance L of the ferrite cores because their permeability is large enough to get a sufficiently low operating frequency range, from 1 to 10 MHz typically, in an ion synchrotron. So Z_d increases in proportional to the loaded number of ferrite cores. As Z_d increases, a large impedance mismatching between the cavity and the power source occurs and almost all the forward power is reflected to the power source. Then reflection power is too large to operate the power source normally under this condition. Furthermore, the cavity voltage V_d can not be increased because of the decrease in the net power fed into the cavity. This impedance mismatching between the cavity and the power source is the main disadvantage of the lower accelerating voltage in the untuned-type RF cavity.

2.2 *Multiple power feeding*

In order to reduce reflection power and increase the cavity voltage, the impedance mismatching between the cavity and the power source must be improved by keeping the cavity impedance higher. To solve this problem, a new method of power feeding, here after we call multiple power feeding (multi-feed coupling) was developed. The cavity and the forward power are divided into the same number of loaded ferrite cores to get a large cavity voltage over a wide operating frequency region. This is in contrast to the system described in ref. 5) which employs a shunt resistor across the accelerating gap. The use of the shunt resistor allows the wide operating frequency region to be obtained, but it leads to the decrease of the cavity voltage. Figure 3 shows the equivalent circuit in multi-feed coupling. Assuming n is the loaded number of ferrite cores, the untuned RF cavity is constructed by a series connection of n-number of sub-

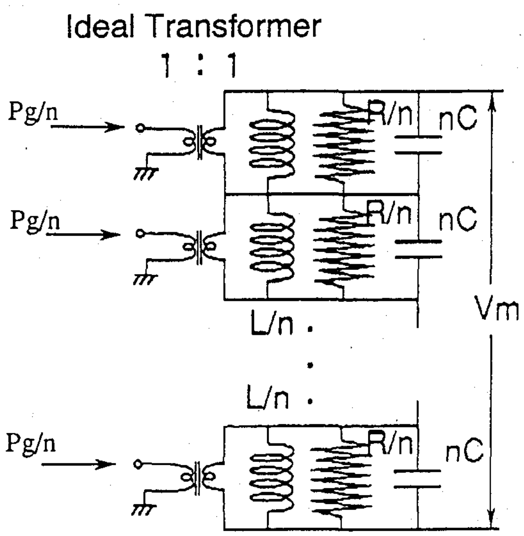


Fig. 3. Equivalent circuit of multi-feed coupling.

circuits whose impedance is one-n^{th} of that of direct coupling. So the coupling impedance between the cavity and the power source can be decreased to one-n^{th} while the total cavity impedance in multi-feed coupling is equal to that of direct coupling. In this scheme, it is expected that the reflection power is much reduced by using the sub-circuits and the cavity voltage is increased by the series connection of n-number of sub-circuits. The cavity voltage V_m is given by

$$
\begin{aligned}
V_m &= \sqrt{2P|Z_m|} \\
&= n\sqrt{2}\sqrt{\frac{4\frac{S}{n}}{\left(1+\frac{S}{n}\right)^2}\frac{P_g}{n}\frac{|Z_d|}{n}}, \\
&= \sqrt{n}\,\frac{1+S}{n+S}V_d \\
&\sim \sqrt{n}\,V_d \qquad\qquad (S \gg n > 1)
\end{aligned}
\tag{3}
$$

where Z_m is the cavity impedance in multi-feed coupling. The $|Z_d|/n$ corresponds to the impedance of the sub-circuit. If the value of VSWR is large enough ($S \gg n > 1$), V_m can be $\sqrt{n}$ times larger than V_d. In this analysis, mutual inductance of each ferrite core is ignored.

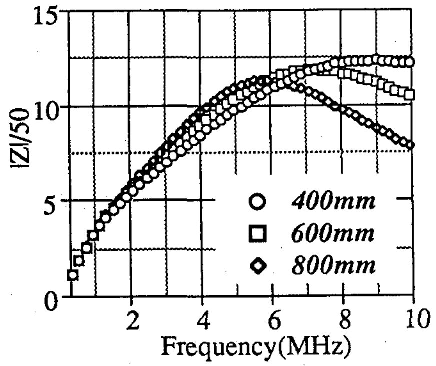
3. LOW POWER MEASUREMENTS AND RESULTS

3.1 *Cavity construction*

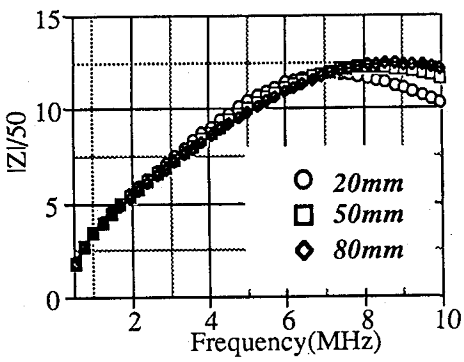
In order to verify the effectiveness of multi-feed coupling, a low power model cavity was made and low power measurements were performed. RF characteristics were measured by the VSWR method[7] using a network analyzer. The specifications of the proposed medical proton synchrotron for Kyoto University[8] and the accelerating system are shown in Table 1. The model cavity was formed by a coaxial resonator and Ni-Zn ferrite cores manufactured by Hitachi Metals Ltd. The shape of the coaxial resonator was chosen using a quarter or a half wavelength. The outer and inner diameters of the cavity were 550 and 160 mm, respectively. The lengths of the cavity and the accelerating gap were 400 and 50 mm, respectively. Cavity impedance is independent of these lengths. Frequency dependence of the cavity impedance as a function of the cavity length and gap length is shown in Figure 4. The cavity impedance only depends on the loaded number of ferrite cores in the operating frequency range of 1.5–7.8 MHz. The dimensions of ferrite cores installed in the cavity were 500 mm and 280 mm in outer and inner diameters, respectively and 25.4 mm in thickness with the complex permeability of (1000,100) at 5 MHz. Block diagrams of the measurement setup are shown in Figure 5. The cavity shape in the direct and the multi-feed couplings were set to be the quarter wavelength and the half wavelength coaxial resonator, respectively. In multi-feed coupling, the RF power was first split into the same number of loaded ferrite cores by the 0 degree power splitter and then each of them was fed into the cavity through the one-turn coil which was wound on each ferrite core. In this method, the winding direction of the one-turn coil must be chosen in order to generate the magnetic field on the same direction in each ferrite core even if the phase of the RF power fed to the coil is different between each other.

Table 1. Parameters of RF acceleration system.

Machine Parameters	
Lattice Composition	Combined Function
Circumference	23 m
Injection Energy	7 MeV
Extraction Energy	70～230 MeV
Proton Velocity (β)	0.12～0.60
Strength of Bending Magnet	0.23～1.43 T
Momentum Spread ($\Delta p/p$)	0.3%
Transition Gamma (γ_t)	1.547
Harmonic Number (h)	1
Repetition Rate	0.5 Hz
Acceleration Pattern	$dB/dt=0$ smooth pattern at acceleration start and stop
RF Acceleration Parameters	
RF Cavity	Ferrite Loaded Untuned
Acceleration Method	Constant Area of RF Bucket
Revolution Frequency	1.564～7.769 MHz
Energy Gain (Vrf)	0～100 eV
Cavity Voltage (Vc)	150～450 V
Synchronous Phase (ϕ_s)	0～22 deg
Acceleration Period	0.7 sec
Cavity Length (includes monitor)	<1 m



(a) Frequency dependence of the impedance on the cavity length. The loaded number of the ferrite cores and the gap length are fixed at 6 and 50 mm, respectively.

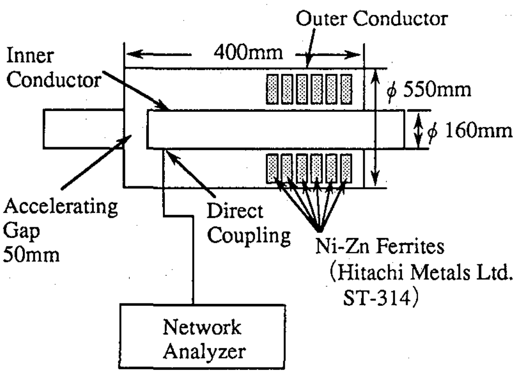


(b) Frequency dependence of the impedance on the gap length. The loaded number of ferrite cores and the cavity length are fixed at 6 and 400 mm, respectively.

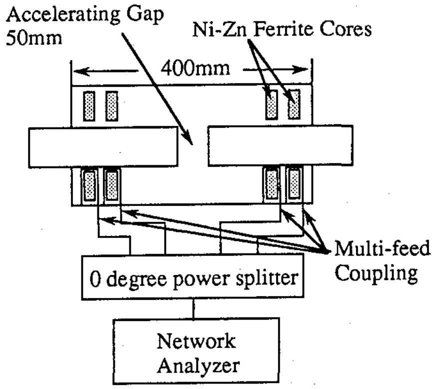
Fig. 4. Frequency dependence of the cavity impedance as a function of the cavity length and the gap length.

3.2 *Measurements of VSWR*

In multi-feed coupling, the VSWR or the impedance of the cavity must be decreased to an n^{th} part of the impedance in direct coupling. The frequency dependence of the VSWR was measured by changing the loaded number of ferrite cores in each coupling. Experimental results

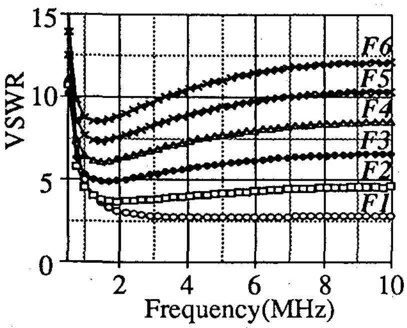


(a) Direct coupling.

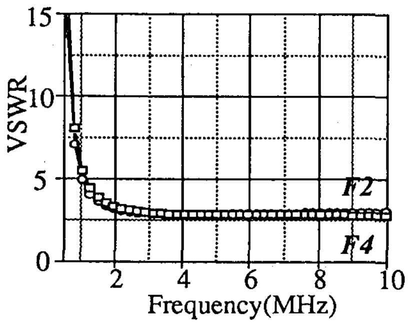


(b) Multi-feed coupling.

Fig. 5. Block diagrams of measurement setup.



(a) The VSWR in direct coupling.



(b) The VSWR in multi-feed coupling.

Fig. 6. The frequency dependence of the VSWR as a function of the loaded number of ferrite cores. F indicates the loaded number of ferrite cores.

are shown in Figure 6. The VSWR in direct coupling increases in proportional to the loaded number of ferrite cores. But in multi-feed coupling, the VSWR is constant, $S\sim2.5$ is about $120\,\Omega$ in the range from 2 to 10 MHz, for any loaded number of ferrite cores, though the total impedance of the cavity becomes large in proportion to the loaded number of ferrite cores. The VSWR in multi-feed coupling is equal to that with one ferrite core in direct coupling, and the decrease of the VSWR due to multi-feed coupling is confirmed. The cavity voltage and efficiency of forward power utilization will be improved and, consequently, the reflection power from the cavity will also be largely reduced. From these results, it is evident that the mutual inductance of each ferrite core can be neglected and the equivalent circuit is valid.

3.3 *Measurements of electric field*

Direct measurements of electric field in the accelerating gap were performed. A schematic diagram of the experimental setup is shown in Figure 7. The electric field was measured by a pick-up antenna consisting of a semi-rigid cable whose tip was exposed to the gap field. The antenna was inserted in the center of the gap. The loaded number of ferrite cores was fixed at 4 in each coupling for comparison. Figure 8 shows the experimental results. Another coupling

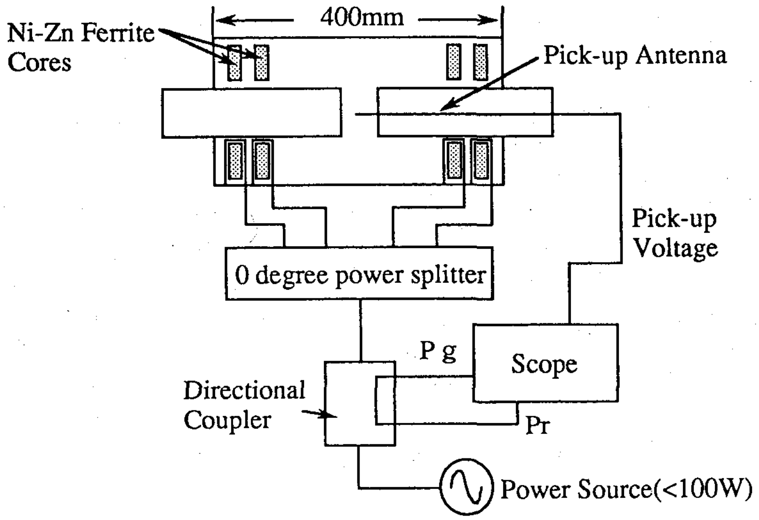
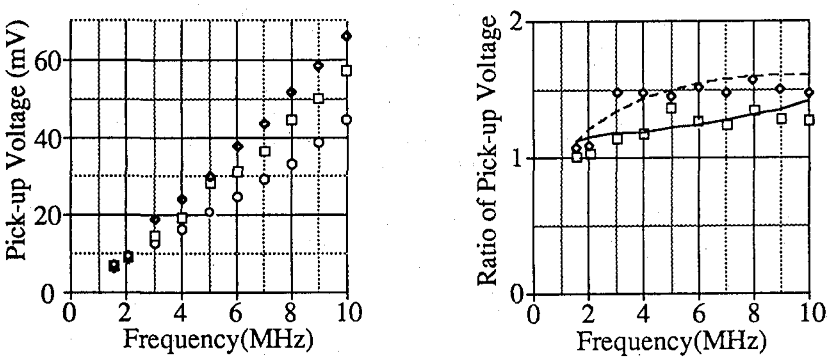


Fig. 7. Schematic diagram of the electric field measurement.



(a) The voltage induced on the pick-up antenna.

(b) The ratio normalized by the voltage of direct coupling.

Fig. 8. The pick-up voltage on a picked-up antenna and its ratio. In (a) and (b), circles show direct coupling, squares show push-pull coupling and diamonds show multi-feed coupling. Solid and dotted lines in (b) show calculated values from equation (2) using measured values of the VSWR.

method, called push-pull coupling usually used in a resonating cavity, was also tested. In the figure, (a) indicates the voltage induced on the pick-up antenna and (b) indicates the ratio normalized by the voltage measured in direct coupling. Solid and dotted lines in (b) are the calculated voltage ratios obtained from equation (3) using the VSWR measured by the above experiments. Measured and calculated values are in good agreement. Moreover, push-pull coupling is considered as a special case of multi-feed coupling, where n equals 2. The mean values of the voltage ratio are 1.3 and 1.5 for push-pull and multi-feed coupling, respectively. In this experiment, the reflection power from the cavity is reduced from 75% of the forward power in direct coupling to 20% in multi-feed coupling. It is also confirmed that the cavity voltage can be increased. These results suggest that this method is feasible for use in the untuned-type RF cavity as an accelerating system for a heavy ion synchrotron because of the increased accelerating voltage.

3.4 *Forward power estimation*

The forward power was estimated to get the cavity voltage described in Table 1 ranging from 150 to 500 V in the operating frequency range from 1.5 to 7.8 MHz. To obtain these values, it is sufficient that the needed forward power of the power source is 500 W. But in a real cavity, the accelerating gap must be shielded by a ceramic duct. The effect of the ceramic duct was estimated by a numerical analysis. The accelerating voltage decreased by 30–50% in this analysis. In order to compensate this decrease of the cavity voltage, the forward power of the power source was determined at 1 kW. Figure 9 shows the estimated cavity voltage in direct, push-pull and multi-feed coupling. The dimensions of the cavity length, gap length and loaded number of ferrite cores were fixed at 400 mm, 50 mm and 6, respectively. In multi-feed coupling, it is possible to get the cavity voltage about 1.7 times as large as that of direct coupling, and the estimated voltage satisfies fully the required values in Table 1.

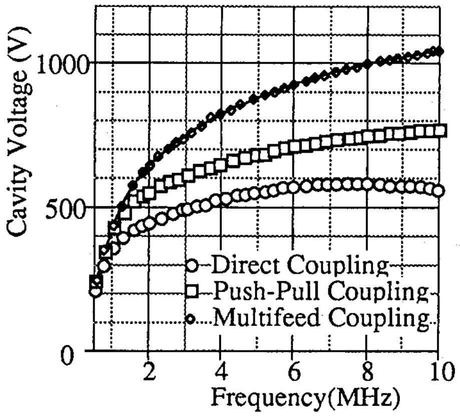


Fig. 9. The estimated cavity voltage with various couplings. The cavity length, gap length, loaded number of ferrite cores, and forward power are fixed at 400 mm, 50 mm, 6 and 1 kW, respectively.

5. CONCLUSION

A new method of power feeding for the ferrite-loaded, untuned-type RF cavity named multiple power feeding (multi-feed coupling) opposed to conventional direct coupling has been developed in order to increase the accelerating voltage and reduce the reflection power from the cavity. RF power is fed into the cavity through one-turn coil which is wound on to each ferrite cores in this coupling. A model cavity which consisted of the half wavelength coaxial resonator whose length is 400 mm and Ni-Zn ferrite cores with highly complex permeability has been designed and made. The operating frequency range for the cavity is from 1.5 to 7.8 MHz which satisfies the values required in the compact medical proton synchrotron. Using multi-feed coupling, for the case with six ferrite cores in the cavity, it is possible to get the accelerating voltage about 1.7 times as large as that of direct coupling. To generate required accelerating voltage in range from 150 to 500 V, the forward RF power with about 1 kW is only needed.

ACKNOWLEDGMENT

The authors would like to present their sincere thanks to Dr. M. Nishi at Energy Research Laboratory, Hitachi Ltd., for his valuable support for the present work. The present work is supported by Grant-in Aid for Scientific Research from the Ministry of Education Science and Culture of Japan.

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