A Ferrite Loaded Untuned Cavity for a Compact Proton Synchrotron

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Abstract

A small untuned RF cavity using a doubly re-entrant resonator and Ni-Zn ferrite cores with highly complex permeability has been designed for a compact proton synchrotron. A new method for power feeding named as multiple power feeding (multi-feed coupling) as against to direct coupling was developed to increase the accelerating voltage. The RF power is fed into the cavity through a set of couplers with the same number as the ferrites. The coupler consists of one-turn loop which is wound on to each ferrite core. The effect of multi-feed coupling was verified by measurements of the VSWR and electric field in the accelerating gap using the low and the high power model cavities.

1. INTRODUCTION

Recently, proton therapy has been confirmed to have significant advantages for treatment of tumors. A compact proton synchrotron dedicated for medical use which consists of combined type magnets with circumference of about 23m has been proposed[1]. In clinical use, the proton beam energy must be varied from 70 to 230MeV to irradiate various depths of tumors. In the compact ion synchrotron, a required accelerating voltage becomes relatively lower than that for a large ion synchrotron due to its short circumference. Furthermore, the medical accelerator system should be easily operated by non-professionals, for example, a medical doctor, a nurse or a technician, and it should be acceptable in public hospitals. Based on these conditions, an untuned type RF cavity in which resonant frequency tuning procedure is not necessary can be adopted as an accelerating system for the synchrotron.

Untuned type RF cavities have been already constructed in several laboratories[2]-[7]. These cavities consist of a quarter or a half wavelength coaxial resonator and magnetic materials with large permeability. 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 makes it difficult to get a high accelerating voltage in the untuned cavity. We have developed a small ferrite loaded untuned cavity and a new method of power feeding so as to increase accelerating voltage over a wide frequency range for the proton synchrotron. In section 2, the principle of the new power feed method is described. The cavity construction and experimental verifications of the new power feed method are depicted in section 3.

2. METHOD OF POWER FEEDING

2.1 Direct Coupling

At first, the usual method of power feeding, known as direct coupling is considered. The untuned cavity is given as a simple RLC resonant circuit, in which R, L and C correspond to resistance of the cavity, inductance of ferrite cores, and capacitance of the accelerating gap, respectively. Then RF power is fed into the inner conductor directly and returned to the source through the outer conductor. The cavity voltage V_d is given as

$$V_d = \sqrt{2P|Z_d|} \ , \qquad (1)$$

where P and Z_d are net power and the shunt impedance of the cavity, respectively. Thus, the following equation is obtained,

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

where P_g is the generator power and S is the value of the voltage standing wave ratio(VSWR). The Z_d depends only on the inductance L of the ferrite cores because their permeability is large enough to get sufficiently lower operating frequency range, 1 to 10MHz typically, in an ion synchrotron. As Z_d increases, a large impedance mismatching between the cavity and the power source occurs and almost all the generator power is reflected back to the power source. Then the reflection power becomes too large to operate the power source normally under this condition. The 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 cause of lowering accelerating voltage in the untuned type RF cavity.

2.2 Multiple Power Feeding

In order to reduce the reflection and increase the cavity voltage, the impedance matching must be improved keeping the cavity impedance higher. To solve this problem, a new power feed method, here after we call multiple power feeding (multi-feed coupling), was developed. In this method, the cavity and the generator power are divided into the same number of loaded ferrite cores. Figure 1 shows the equivalent circuit in multi-feed coupling. Assuming n the loaded number of ferrite cores, the cavity is constructed by a series connection of n sub-circuits whose impedance is one-nth of that of direct coupling. So the coupling impedance between the cavity and the power source can be decreased to one-nth while the total cavity impedance is equal to that of direct coupling. In this scheme, it

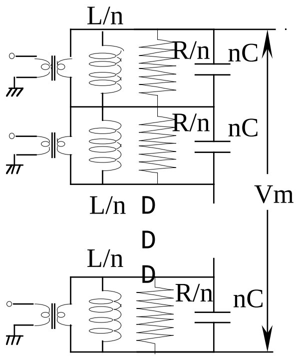


Figure 1. Equivalent circuit in multi-feed coupling.

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 sub-circuits. The cavity voltage V_m is given by

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

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($S>>n>1$), V_m can be $\sqrt{n}$ times larger than V_d. In this analysis, mutual inductance of each ferrite core is ignored.

3. EXPERIMENTS WITH MODEL CAVITIES

3.1 Cavity Construction

In order to verify the effectiveness of multi-feed coupling, a low power model cavity was made and tested at first. RF characteristics were measured by the VSWR method[8] using a network analyzer. The specifications of the proposed compact proton synchrotron and the accelerating system are shown in Table 1. The model cavity was constructed with a double re-entrant coaxial resonator and Ni-Zn ferrite cores manufactured by Hitachi Metals Ltd. The outer and inner diameters of the cavity were 550 and 160mm, respectively. The lengths of the cavity and the accelerating gap were 400 and 50mm, respectively. In results, the cavity impedance is independent of these lengths. The cavity impedance depends only on the number of ferrite cores in the frequency range between 1.5 and 7.8MHz. The dimensions of ferrite cores installed in the cavity were 500 and 280mm in outer and inner diameters, respectively and 25.4mm in thickness with the complex permeability of about (1000,100) at 5MHz. In multi-feed coupling, the RF power was first split into the same number of loaded ferrite cores by the power splitter and then each of them was fed into the cavity through the one-turn coil which was wound on each ferrite core. 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 is different between each other.

Table. 1 @Parameters of RF acceleration system

Machine Parameters	
Lattice Composition	Combined Function
Circumference	23m
Injection Energy	7MeV
Extraction Energy	70-230MeV
Proton Velocity (β)	0.12-0.60
Strength of Bending Magnet	0.23-1.43T
Momentum Spread (Δp/p)	0.3%
Transition Gamma (γt)	1.547
Harmonic Number (h)	1
Repetition Rate	0.5Hz
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	1.564-7.769MHz
Energy Gain (Vrf)	0-100eV
Cavity Voltage (Vc)	150-450V
Synchronous Phase (φs)	0-22deg
Acceleration Period	0.7sec
Cavity Length (includes monitor)	<1m

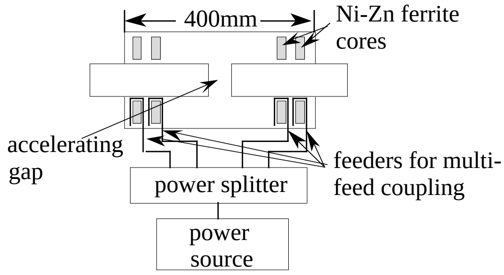
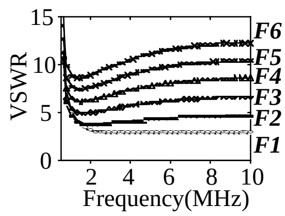


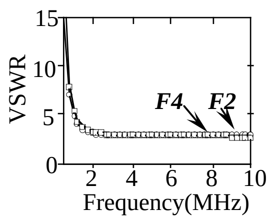
Figure 2. Block diagram for low power measurements

3.2 Measurements of VSWR

In multi-feed coupling, the VSWR or the impedance of the cavity must be decreased to an nth part of the VSWR in direct



(a) Direct coupling.



(b) Multi-feed coupling.

Figure. 3 The frequency dependence of the VSWR as a function of the loaded number of ferrite cores. F indicates the loaded number of ferrite cores.

coupling. Figure 2 shows the block diagram of the low power measurements in the multi-feed coupling. The frequency dependence of the VSWR was measured by changing the number of ferrite cores in each coupling. Experimental results are shown in Figure 3. The VSWR in direct coupling increases in proportion to the number of ferrite cores. But in multi-feed coupling, the VSWR is nearly constant for any number of ferrite cores in the range from 2 to 10MHz, though the total impedance of the cavity becomes large in proportion to the number of ferrite cores. So the VSWR in multi-feed coupling is equal to that with one ferrite core in direct coupling, and the decrease of the VSWR is confirmed. From these results, it is evident that the mutual inductance of each ferrite core can be neglected and the equivalent circuit analysis is valid.

3.3 Measurements of Electric Field

Direct measurements of electric field in the accelerating gap were performed using the low and the high power model cavities. The high power model cavity is the same as the low power model cavity except for the gap and cooling structures. The accelerating gap was vacuum sealed by a ceramic duct. The electric field was measured by a pick-up antenna consisting of a semi-rigid coaxial cable whose tip was exposed to the gap field. The number of the ferrite cores was fixed at 4 in the low power model and at 8 in the high power model cavity. Figure 4 shows the voltage ratio normalized by direct coupling in each model cavity. Figure 5 also shows the generator power dependence of the voltage ratios. In the figures, solid and dotted lines are the calculated voltage ratios obtained from equation (3) using the VSWR measured by the low power experiments. Measured and calculated voltage ratios are in good agreement in each model cavities. In figure 5, the accelerating voltage increases as a function of $\sqrt{P_g}$. The mean values of the voltage ratio are 1.5 and 2.0 for the cases in which the loaded number of ferrite cores are 4 and 8, respectively. These values can be obtained from equation (3) substituting n=4, S=10 for the low power and n=8, S=12 for the high power model cavity. So it is confirmed that the cavity voltage can be increased and the generator power also can be reduced.

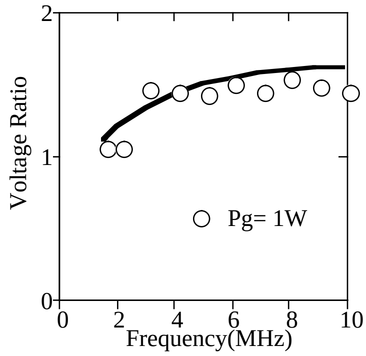


Figure 4. The voltage ratio normalized by the voltage of direct coupling in the low power model cavity.

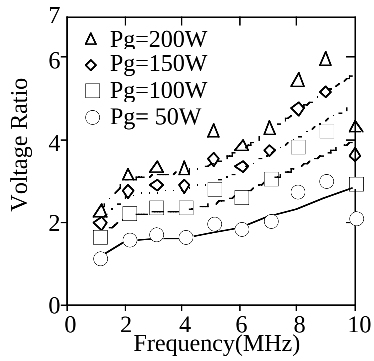


Figure 5. The voltage ratio normalized by the voltage of direct coupling in the high power model cavity. Pg indicates generator power.

4. CONCLUSION

A new method of power feeding named multiple power feeding (multi-feed coupling) has been developed in order to increase the accelerating voltage and reduce the reflection power from the cavity. The RF power is fed into the cavity through one-turn coil which is wound on to each ferrite core. The low and high power model cavities which consisted of the doubly re-entrant coaxial resonator and Ni-Zn ferrite cores have been made and tested. The effects of multi-feed coupling are verified by measurements of the VSWR and electric field of the gap. In multi-feed coupling, for the case with 8 ferrite cores in the cavity, it is possible to get the accelerating voltage about 2.0 times as large as that of direct coupling.

ACKNOWLEDGMENT

The present work is supported by Grant-in Aid for Scientific Research from Ministry of Education Science and Culture of Japan.

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