FERRITE LOADED UNTUNED RF CAVITY FOR SYNCHROTRON

K. Muto and S. Fukumoto
National Laboratory for High Energy Physics
1-1 Oho, Tsukuba-shi,
Ibaraki-ken, 305, Japan

Abstract: To develop a ferrite loaded untuned rf cavity for a dedicated proton synchrotron for cancer therapy, a prototype cavity was made and tested. With a small modifications, it can be used in the synchrotron.

Introduction

A ferrite loaded untuned cavity for the rf acceleration in the synchrotron was used in Cosmotron in 1953.[1] Since then, however, tuned cavities were used to get high impedances for high acceleration voltages in proton accelerators.

Recently it was revived at Fermilab in the construction of the 250 MeV compact proton synchrotron dedicated to the cancer therapy at Loma Linda University Medical Center.[2] It needs only 330 V as rf amplitude. So the power of rf amplifier is 1 kW, even though the shunt impedance of the cavity is near 50 ohms with a suitable parallel resistor.

A 230 MeV proton synchrotron was designed for the cancer therapy at the University of Tsukuba.[3] To simplify its rf accelerating system with high efficiency, a model of the untuned rf cavity was made and tested. The needed rf amplitude was 450 V. So it needs higher shunt impedance than 50 ohms to use a commercially available 1 kW solid state rf power amplifier.

Model Design

The parameters of the synchrotron, concerning to the rf acceleration, are:

beam intensity	1.3×10^{11}	ppp
harmonic number	1	
acceleration period	0.5	sec
energy range	5-230	MeV
rf frequency	0.88-5.11	MHz
rf amplitude	450-300	V
synchronous phase angle	20-30	deg
cavity length	≤ 1.6	m

In addition to these technical conditions, other restrictions arise from the operation and maintenance of the accelerator. Since the accelerator will be installed in the University Hospital, and will be operated daily for the cancer therapy by a crew of small number without long shutdown, it should be reliable and durable. The simple and maintenance free structure is crucial for the aim.

The comparatively low rf amplitude makes it enable to use an untuned cavity. An untuned cavity is simpler than a tuned cavity, because it doesn't need the coil for bias current and associated current power supply with phase feedback circuits for bias current control.

The mechanical structure of the prototype cavity is shown in Figure 1.

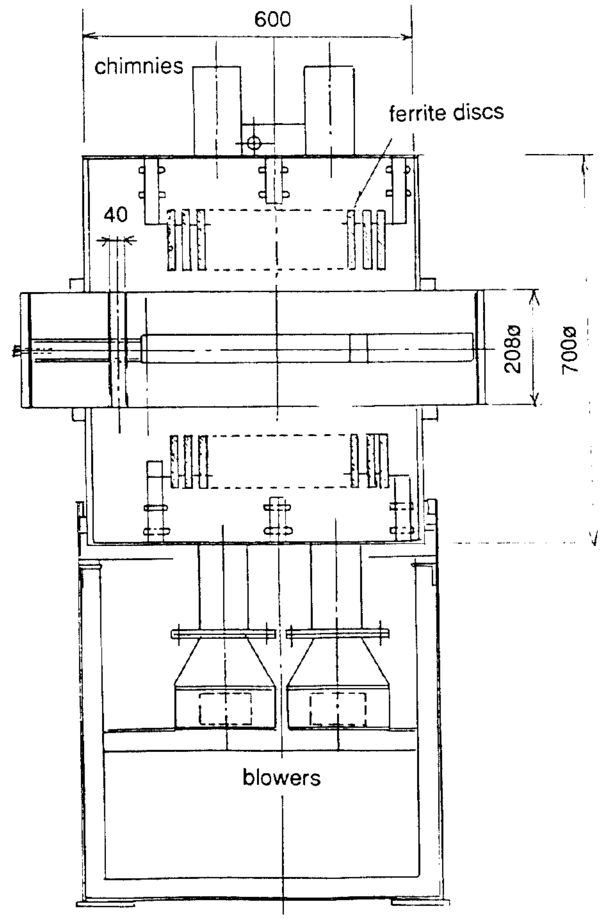

Fig. 1 The structure of test cavity.

The outer diameter is 700 mm, the inner diameter is 208 mm, and the length is 600 mm. It was made of copper with brazing. It is divided in three parts, an upper and a lower semicylinders, and a beam duct with an acceleration gap. These parts are combined with finger contactors between them and fastened with bolts. The lower semicylinder has two blowers at the bottom and the upper one has two chimnies for cooling air outlets. Though the impedance of an untuned cavity is much lower than a tuned cavity, the low accelerating voltage, presently needed, makes it possible to use air instead of water as coolant. This also makes the cavity free from water leakage troubles which might occur in routine operation.

The dimensions of the ferrite discs are 500 mm in outer diameter, 280 mm in inner diameter, and 12.7 mm in thickness. In the cavity, 20 pieces of them are installed on an FRP frame.

The characteristics of ferrite is essential to the cavity. For tuned cavities, high Q and, as a result, low μ ferrite are used to achieve a high impedance at a resonance frequency. But for the untuned cavity, high Q means the large impedance change in frequency sweep and low μ means the low impedance except a low frequency range. In this case, low Q and high μ are essential. Mn-Zn and Ni-Zn ferrites were mixed in the Cosmotron rf accelerating system.[1] This combination was proposed at Fermilab, too.[2] High μ seemed to be achieved by Mn-Zn ferrite at low frequencies and the μ of Ni-Zn ferrite islow but constant in wide frequency range. Q would be damped by an external parallel resistor. If a suitable kind of ferrite is chosen, it can satisfy both these properties for rather small frequency range of 0.88-5.11 MHz. The selected ferrite is T-314, made by Hitachi Metals Ltd., Japan. It is Ni-Zn ferrite with μ = 1200 up to 1 MHz and decreases proportionally to $(\text{frequency})^{-1}$ beyond 1 MHz.

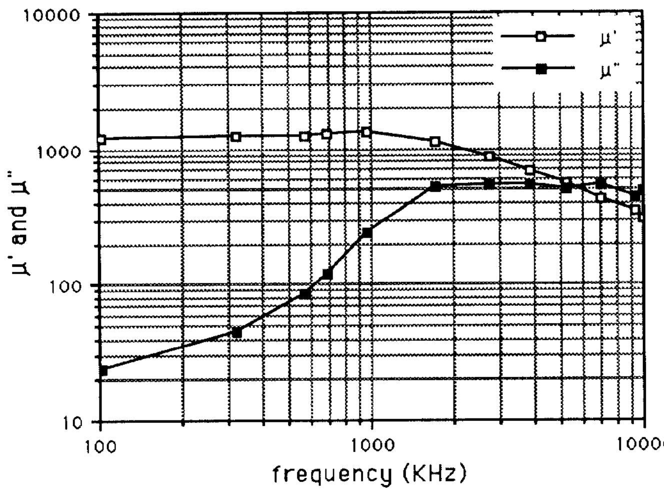

Fig. 2 μ' and μ" of ferrite T-314.

Measurements

The values of μ' and μ" of the ferrite are obtained from the data of a resonant frequency and the magnitude of impedance measured with a network analyzer, Anritsu MS 560J. The impedance (Z) of the cavity is,

$$1/Z = 1/(j\omega L)+j\omega C \ [\Omega^{-1}]$$

where,

$$L = L'-jL"$$
$$= (\mu'-j\mu")\mu_0 n^2 h \ln(r_{ex}/r_{in})/(2\pi) \ [H],$$

h = the total thickness of ferrite discs in meter, r_{ex} = 0.25 [m], r_{in} = 0.14 [m], n = 1 turn since the ferrite discs are in the test cavity. At resonance, the impedance phase is zero, or Im(Z) = 0. It derives $L' = \omega^2 C(L'^2+L"^2)$, and Re(Z) = Z. Then $Z = \omega L"(\omega^2 C^2 Z^2+1)$. Z, C, ω are known. From these equations, μ' and μ" are obtained as,

$$\mu' = 2\pi/[\mu_0 n^2 h \ln(r_{ex}/r_{in})] \times CZ^2/[\omega^2 C^2 Z^2+1],$$

and

$$\mu" = 2\pi/[\mu_0 n^2 h \ln(r_{ex}/r_{in})] \times Z/[\omega(\omega^2 C^2 Z^2+1)].$$

By changing the capacitor across the gap(C) and the number of loaded ferrite discs(h), the resonances are surveyed across the range of 0.1 to 10 MHz. The results are shown in Figure 2.

With extra shunt resistors(50, 100, and 200 ohms) across the accelerating gap, the magnitudes and phases of cavity impedance were measured with the network analyzer. For high voltage application (up to 400 V in rf amplitude), they were obtained from the data of magnitudes of voltage and current and the phase angles between them, measured on an oscilloscope. The typical results are shown in Figure 3.

As shown in Figure 3, the changes of magnitude and phase of cavity impedance in the frequency range(0.88-5.11 MHz) becomes less when the shunt resistor becomes less.

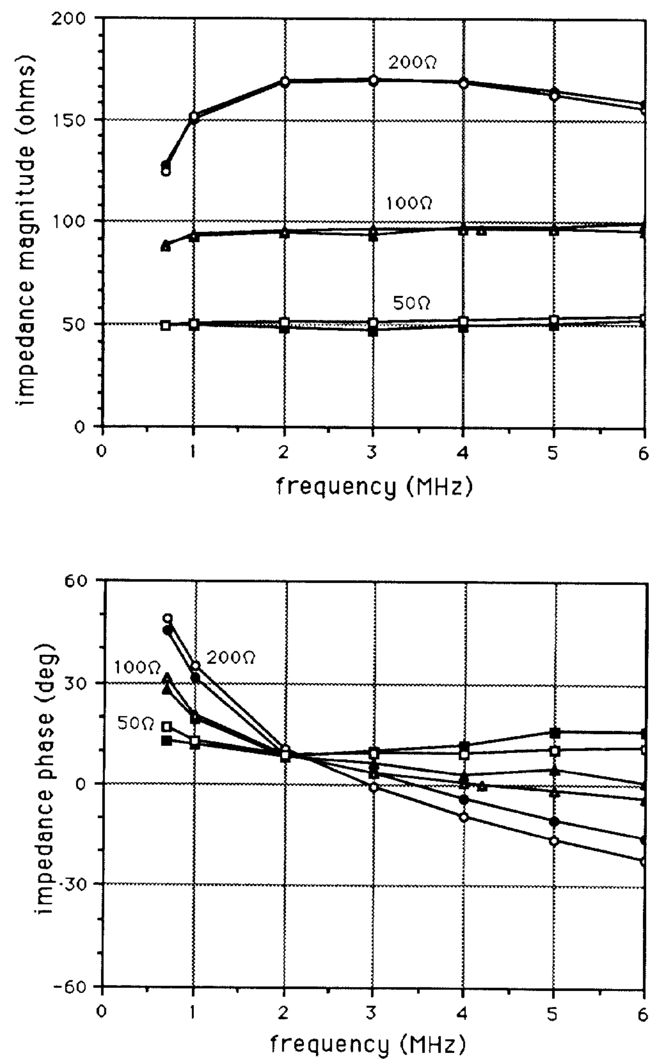

Fig. 3 The magnitudes and phases of impedance of cavity with shunt resistors. The black dots for the measurements under 150 Vrf, and white dots for the measurements by network analyzer.

With a shunt resistor of 50 ohms, the rf power of 2 kW yields 450 V rf amplitude across the accelerating gap, and most of the power is consumed at the shunt resistor as $W = V_{rf}^2/(2R)$. It is better to get the shunt resistor of 100 ohms or higher to decrease the demanded power of rf amplifier. At a shunt resistor of 200 ohms, the change in the phase is 40 degrees. The effect of this phase shift to the acceleration will be compensated by the beam feedback loop.

Discussions

As mentioned above, the maximum rf amplitude needed for the beam acceleration is 450 V. The test rf voltages applied to the cavity are below 400 V. Up to the voltage, the measured values of complex impedance are nearly the same as that of low level measurements.

From the data of high power measurement, the rf power consumptions in ferrite discs and in shunt resistor are separated. In figure 4, the rf power consumptions with and without 200 ohm shunt resistor are plotted. The power consumption with shunt resistor is equal to the sum of the consumption of the resistor and of the cavity(ferrite) without the resistor. The resistor consumes 80 % of total power. It seems better to put the shunt resistor outside the cavity for easy cooling.

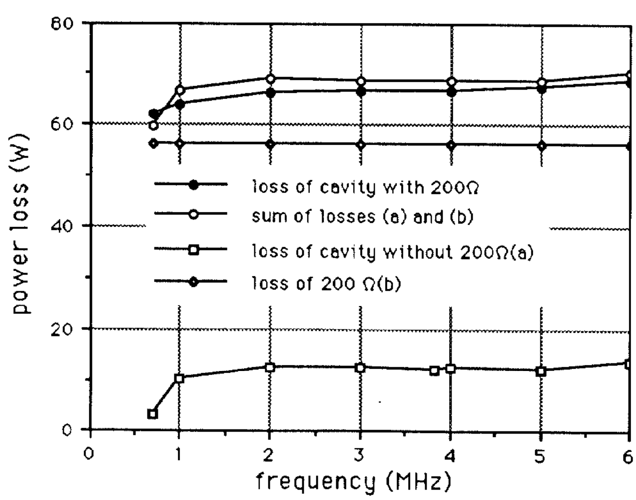

Fig. 4 Power loss in cavity and shunt resistor.

There exists the Snoek's limit, beyond which μ' of ferrite decreases as the rf frequency increases. By positive use of the falling slope of μ' with rf frequency, the untuned cavity maintains comparably high impedance in a wide frequency range. With our ferrite discs, the phase and magnitude of cavity impedance shift widely in the frequency range below 2 MHz. If we use the ferrite discs, μ' of which is higher in low frequency side and begin to decrease around 0.5 MHz or so, the impedance changes in magnitude and phase will be less than ones under test.

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[1] J.P.Blewett et al., "Radio-Frequency System. Part IV-Accelerating Unit", Phy. Rev., vol. 24, pp. 795-800, September 1953.

[2] "Conceptual Design of a Proton Therapy Synchrotron For Loma Linda University Medical Center", Fermilab, June 1986.

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[3] S. Fukumoto et al., "DESIGN OF A SYNCHROTRON FOR PROTON THERAPY", presented at this conference.