

A Ferrite Loaded Untuned Cavity for a Compact Proton Synchrotron

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Abstract

A ferrite loaded untuned type RF cavity and its operation scheme for a compact proton synchrotron to be applied to medical use are presented. To produce a high accelerating voltage over a wide frequency range, Ni-Zn ferrite with a highly complex permeability is chosen for the cavity. Two types of mechanical structures, quarter wavelength and half wavelength resonators, are compared for their ability to provide a high impedance. To realize smooth synchrotron control from injection to extraction, an accelerating pattern for the accelerating voltage of the cavity is proposed.

I. INTRODUCTION

A ferrite loaded untuned cavity in an ion synchrotron was first used forty years ago at Cosmotron [1]. In the 1980's, it was adopted in a proton synchrotron dedicated to cancer therapy at Loma Linda University Medical Center[2]. In a proton synchrotron for medical use, a beam energy of 70-250MeV is smaller than that of physical experiments. This beam energy results in a decrease of accelerating voltage in the cavity. Then, a ferrite loaded untuned cavity in which resonant frequency tuning is unnecessary is a suitable choice for a compact medical proton synchrotron of the future.

A 250MeV proton synchrotron with a low emittance extraction scheme using transverse RF noise has been presented by other workers at the Energy Research Laboratory Hitachi Ltd. in another paper in these proceedings[3]. To realize its RF accelerating system, permeability of ferrite and mechanical structure of the untuned cavity were studied by resonant analysis. For medical use, a simple operation not only for extraction but also for acceleration is required because when installed in a hospital, the system is used daily by a small number of nonprofessionals. Then an acceleration pattern to achieve smooth control of the cavity from injection to extraction of the accelerating voltage is proposed.

II. ACCELERATING PARAMETERS

The parameters of the synchrotron for RF acceleration are given in Table 1.

A proton beam of 10MeV is injected from a linac to the synchrotron with combined function lattice and accelerated up to the energy of 250MeV by the accelerating system. After acceleration, the proton beam is extracted slowly. This operation

Table 1

Parameters of RF acceleration system	
Machine Parameters	
Lattice composition	combined function
Circumference	27[m]
Range of Energy	10-250[MeV]
Radius of Curvature of Bending	1.62[m]
Field Strength of Bending	0.28-1.5[T]
Harmonic Number	1
Momentum Spread of Injection	0.3[%]
RF Accelerating Parameters	
Revolution Frequency	1.608-6.813[MHz]
Energy Gain per Turn	0-145[eV]
Accelerating Voltage	162-430[V]
Synchronous Phase Angle	0-22[deg]
Cavity Length	<1[m]

is conducted with a repetition rate of 0.5Hz.

III. CAVITY STRUCTURE

Two types of structures, a quarter wavelength resonator and a half wavelength resonator, were considered. The outer and inner diameters of the cavity are 600 and 200mm, respectively, for each structure. The accelerating gap length is 20mm so as to increase the accelerating voltage allowing capture of a wide range of the momentum spread at injection. The cavity length is 800mm, and total length is 1000mm.

At first, the required complex permeability μ (real, imaginary) and volume of ferrite relative to the cavity volume ΔV were estimated by a calculation using the quarter wavelength resonator. The results of the real part are shown in Fig.1. The imaginary part was estimated by a perturbation method. The electric field distribution is shown in Fig.2. From these results, $\mu > (900, 20)$ and $\Delta V > 2\%$ were needed to get a center resonant frequency of about 4.5MHz and a frequency range of 5MHz. Materials corresponding to these conditions are Mn-Zn and Ni-Zn ferrite. Since it is difficult to manufacture a large toroid using Mn-Zn ferrite, Ni-Zn ferrite was chosen. From these investigations, a model cavity was made and tested. The dimensions of the ferrite toroid installed in the cavity are 500mm outer diameter, 280mm inner diameter, and 12.7mm thickness, with a complex permeability of (1000, 100) at 5MHz. With an extra shunt resistor of 50 Ω across the accelerating

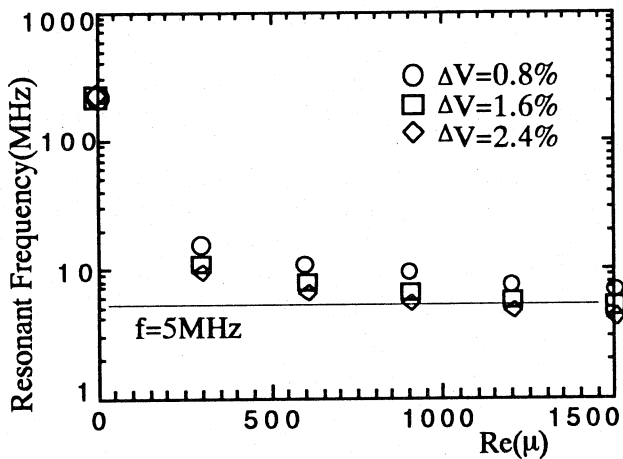


Fig.1 The dependence of permeability on resonant frequency of the cavity. ΔV indicates ferrite volume ratio relative to the cavity volume.

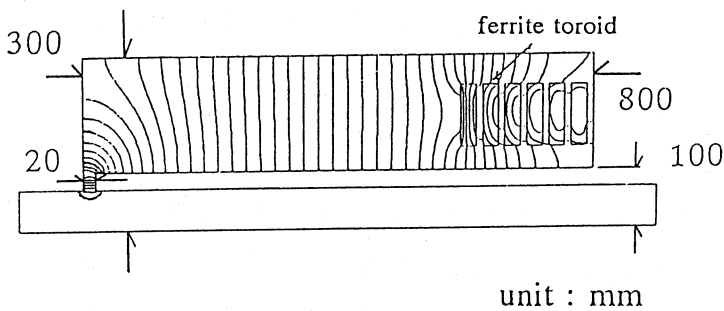


Fig.2 The electric field distribution of the cavity with ferrite volume ratio 2.4%.

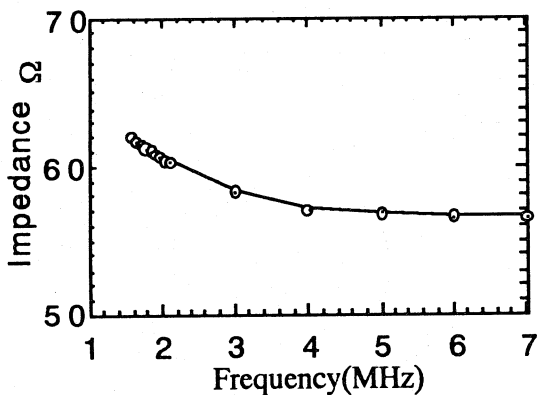


Fig.3 Magnitude of impedance of the cavity with shunt resistor 50Ω .

gap, the measured magnitude of the cavity impedance is shown in Fig.3. The magnitude of the impedance varies from 62 to

56Ω over the operation frequency range.

It is necessary to capture a wider range of the momentum spread at injection and to accelerate first to increase the extraction current. Then the half wavelength resonator shown in Fig.4 was examined under an unloaded condition by a numerical calculation to increase accelerating voltage. The electric field strength at the accelerating gap is about 2 times higher than that of quarter wavelength cavity although the resonance characteristics of this resonator with 2.4% ferrite volume are the same as quarter wavelength resonator's. This was resulted by the cavity shape near accelerating gap which has a smaller outer diameter.

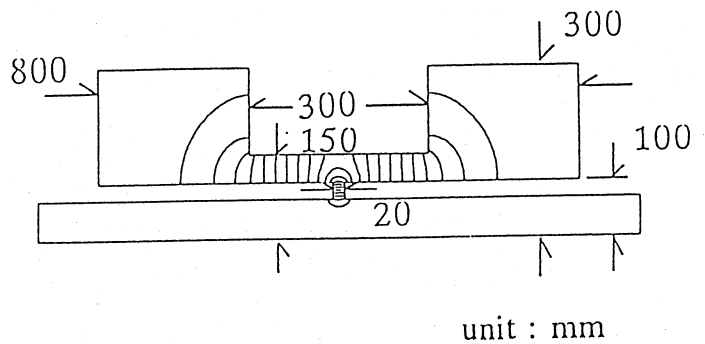


Fig.4 Dimensions of the half wavelength resonator.

IV. OPERATION SCHEME

In the acceleration process, the accelerating voltage and its phase are usually changed by keeping the area of the RF bucket constant without losing the captured proton beam. In order to simplify the synchrotron control system, two conditions are added. The first is a no phase jump at the start of acceleration. The second is that the synchronous phase approaches 0 degrees gradually at the end of acceleration. Under these conditions, strength of the bending magnet $B(t)$ and synchronous phase $\phi(t)$ are described in the following relation:

$$\int \frac{dB(t)}{(\frac{1}{\gamma_t^2} - 1)\sqrt{B(t)^2 \rho^2 c^2 + E_0^2 + B(t)^2 \rho^2 c^2}} = \frac{ph\beta(0)^2(\frac{\Delta p}{p})^2}{2lr} \int \left(\frac{\sqrt{\sin \phi(t)}}{\alpha(\sin \phi(t))} \right)^2 dt, \quad (1)$$

where γ_t is transition gamma, ρ is radius of bending, c is light velocity, h is harmonic number, l is circumference, β is

relativistic factor, $\Delta p/p$ is momentum spread and $\alpha(\sin\phi(t))$ is a compression factor of the separatrix[4]. Since it is difficult to solve this equation analytically, a trial function for $B(t)$ is assumed to extract the phase $\phi(t)$. A calculated accelerating voltage pattern satisfying the above conditions is shown in Fig.5. Accelerating voltage is sequentially increased at the start of acceleration, and decreased to 0 at the end of it. This

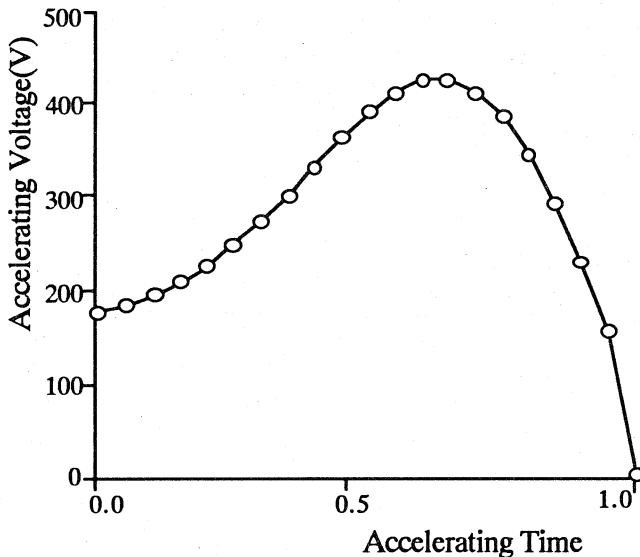


Fig.5 Accelerating voltage pattern during acceleration.

leads to a reduction of the loop gain for the standard $\Delta\phi$ feedback system at the start. At the end of acceleration, the circulating beam become a coasting beam. Then favorable conditions are formed for extraction. Further, the combined function lattice has an advantage for operation because at the simpler tracking between bending and quadrupole magnets. This accelerating voltage may be done by automatic gain control of the cavity feedback system in place of phase control.

V. CONCLUSION

A ferrite loaded untuned cavity for a compact medical proton synchrotron was presented. Required characteristics of the ferrite were complex permeability larger than (900, 20) and a volume ratio larger than 2%. In order to increase accelerating voltage, a half wavelength resonator which has a smaller outer diameter near the accelerating gap was discussed. Finally, an accelerating voltage pattern was proposed to give favorable conditions for extraction and simplified control of the accelerator system.

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